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Conventional Water Resources and Agriculture in Egypt

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Conventional Water Resources and Agriculture in Egypt

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Aims and Scope

Since 1980, *The Handbook of Environmental Chemistry* has provided sound and solid knowledge about environmental topics from a chemical perspective. Presenting a wide spectrum of viewpoints and approaches, the series now covers topics such as local and global changes of natural environment and climate; anthropogenic impact on the environment; water, air and soil pollution; remediation and waste characterization; environmental contaminants; biogeochemistry; geo-ecology; chemical reactions and processes; chemical and biological transformations as well as physical transport of chemicals in the environment; or environmental modeling. A particular focus of the series lies on methodological advances in environmental analytical chemistry.

Series Preface

With remarkable vision, Prof. Otto Hutzinger initiated *The Handbook of Environmental Chemistry* in 1980 and became the founding Editor-in-Chief. At that time, environmental chemistry was an emerging field, aiming at a complete description of the Earth's environment, encompassing the physical, chemical, biological, and geological transformations of chemical substances occurring on a local as well as a global scale. Environmental chemistry was intended to provide an account of the impact of man's activities on the natural environment by describing observed changes.

While a considerable amount of knowledge has been accumulated over the last three decades, as reflected in the more than 70 volumes of *The Handbook of Environmental Chemistry*, there are still many scientific and policy challenges ahead due to the complexity and interdisciplinary nature of the field. The series will therefore continue to provide compilations of current knowledge. Contributions are written by leading experts with practical experience in their fields. *The Handbook of Environmental Chemistry* grows with the increases in our scientific understanding, and provides a valuable source not only for scientists but also for environmental managers and decision-makers. Today, the series covers a broad range of environmental topics from a chemical perspective, including methodological advances in environmental analytical chemistry.

In recent years, there has been a growing tendency to include subject matter of societal relevance in the broad view of environmental chemistry. Topics include life cycle analysis, environmental management, sustainable development, and socio-economic, legal and even political problems, among others. While these topics are of great importance for the development and acceptance of *The Handbook of Environmental Chemistry*, the publisher and Editors-in-Chief have decided to keep the handbook essentially a source of information on "hard sciences" with a particular emphasis on chemistry, but also covering biology, geology, hydrology and engineering as applied to environmental sciences.

The volumes of the series are written at an advanced level, addressing the needs of both researchers and graduate students, as well as of people outside the field of "pure" chemistry, including those in industry, business, government, research establishments, and public interest groups. It would be very satisfying to see these volumes used as a basis for graduate courses in environmental chemistry. With its high standards of scientific quality and clarity, *The Handbook of Environmental Chemistry* provides a solid basis from which scientists can share their knowledge on the different aspects of environmental problems, presenting a wide spectrum of viewpoints and approaches.

The Handbook of Environmental Chemistry is available both in print and online via www.springerlink.com/content/110354/. Articles are published online as soon as they have been approved for publication. Authors, Volume Editors and Editors-in-Chief are rewarded by the broad acceptance of *The Handbook of Environmental Chemistry* by the scientific community, from whom suggestions for new topics to the Editors-in-Chief are always very welcome.

Damià Barceló
Andrey G. Kostianoy
Editors-in-Chief

Preface

The agriculture activities in Egypt consume about 80–85% of the water supply of Egypt. Therefore, the food gap will be severe in Egypt in the future considering the rapid growth of population and the expected shortage of water due to the construction of grand Ethiopian Renaissance Dam (GERD) and possibly due to climate change. Consequently, the need for this volume on conventional water resources has arisen to help those who are interested in Egypt's water resources and agriculture.

This volume consists of nine parts. Part I consists of two chapters on "History of Irrigation and Irrigation Projects" The chapter "Evolution of Irrigation in Egypt" presents how irrigation is evolved in Egypt, focusing on Nile metering, barrages and dam construction, and Nile embankment, moving from basin irrigation to perennial irrigation systems. The second chapter titled "The History of Irrigation Development Projects in Egypt" presents the stages of controlling the Nile River flow via building several irrigation projects across the Nile.

The second part also consists of two chapters and presents "Key Features, Administrative and Legal Framework." The chapter titled "Key Features of the Egypt's Water and Agricultural Resources" presents an overview of how Egyptian policy planners and makers pay great attention on the agricultural sector through the vital activities, such as better utilization of agricultural resources, using drainage water reuse, reusing of treated wastewater, improving water use efficiency, managing groundwater resources, and developing a horizontal expansion area through reclaiming new lands. The chapter "Administrative Context and the Legal Framework Governing Water Resources and Agriculture in Egypt" presents and analyzes the legal and administrative frameworks governing both water resources and agriculture in Egypt to identify the strengths and weaknesses in the legal and administrative contexts of water resources and agriculture in Egypt and evaluate the disadvantages and reform. Also, the most important institutions that play a role in water management and agriculture in Egypt are presented.

Part III consists of two chapters covering the "Land Resources for Agriculture Development." The first chapter titled "A Synopsis on Egypt's Digital Land Resources Database Serving Agricultural Development Plans" presents how the database for the land resources was built using the available data and the remote sensing and GIS techniques and how the created database was employed in mathematical modeling for the purpose of assessing land capability, land degradation hazard, and urban sprawl on account of cultivable land. In the chapter "Land and Groundwater Assessment for Agricultural Development in the Sinai Peninsula, Egypt," the author uses GIS and remote sensing to identify the areas in Sinai Peninsula with the most (soil and groundwater) potential for agricultural development and mapped them to be informative to the decision-makers.

Part IV consists of three chapters that deal with "Food Insecurity due to Water Shortage and Climate Change." The chapter "Impact of Climate Change on the Agricultural Sector in Egypt" presents how global warming affects the agriculture sector and presents some adaption strategies to minimize such impacts. In the chapter "Challenges and Issues in Water, Climate Change, and Food Security in Egypt," the author presents an assessment of adaptation strategies for the water resources and agriculture sectors to achieve resilient agricultural production, which is a necessary element to achieve food security. The third chapter in this part titled "Egyptian Food Insecurity Under Water Shortage and Its Socioeconomic Impacts" presents in more detail the problem of food insecurity due to water shortage and its consequences on Egypt.

Part V consists of three chapters which deal with the "Assessment of Water Resources." The chapter "Evaluation of Water Resources Qualities for Agriculture Irrigation in Abu Madi Area, Northern Middle Nile Delta" presents and discusses the results of a typical physicochemical analysis of an area in northeastern middle Nile Delta to assess the water resources quality for different purposes (irrigation, drinking, and fish farms). In the chapter titled "Spatiotemporal Fluctuations in Phytoplankton Communities and Their Potential Indications for the Pollution Status of the Irrigation and Drainage Water in the Middle Nile Delta Area, Egypt," the authors present the observation of phytoplankton communities' fluctuations and a phytoplankton checklist was established for irrigation and drainage water of the Middle Nile Delta so that it can be used as environmental bioindicators and other probable applications. The last chapter of this part titled "Groundwater Assessment for Agricultural Irrigation in Toshka Area, Western Desert, Egypt," evaluates via verified modeling processes the groundwater conditions to determine the sustainability of the groundwater resource in Toshka area. Also, the expected changes in groundwater levels, the amount of recharge, and the suitable discharge from the groundwater for irrigation of 25,500 feddans are based on the safe yield of 102 wells for 100 years.

Part VI consists of two chapters and deals with the impacts of upstream dams on the water resources of Egypt. In the chapter titled "Impacts of Filling Scenarios of GERD's Reservoir on Egypt's Water Resources and Their Impacts on Agriculture Sector," the authors present the results of modeling to assess the impacts of filling options of GERD reservoir and the conservative storage at GERD on the water resources of Egypt and the consequence impacts on the agriculture sector considering the main crops. The chapter titled "Ecohydrogeological Challenges on

Ethiopian Water Projects and Their Impacts on Annual Water Share of Egypt: Case Study of Tekeze Dam" presents and discusses the environmental challenges in the region of Tekeze River (Atbara) in Ethiopia and its impacts on downstream countries like Egypt and Sudan.

Part VII consists of six chapters dealing with sustainable use of water resources and future of mega irrigation projects in Egypt. In the chapter "Estimation of Crops Water Consumptions Using Remote Sensing with Case Studies from Egypt," the authors present a comprehensive review on how space-borne technologies could be used to estimate crops' water consumption with applications on case studies from Egypt. The chapter "Crop Water Requirements and Irrigation Efficiencies in Egypt" presents various strategies to meet the challenges facing Egypt due to water shortage such as adoption of water governance, improving water use efficiency, and optimizing plant production by providing crops only with the water they need based on the climate–plant–soil relationship. In the chapter "Greenhouse Operation and Management in Egypt," the authors focus on the best practices of operating and managing the greenhouse agriculture in order to help the decision-makers to achieve the agriculture strategy in Egypt which aims to increase productivity per unit of land and water through more efficient use of limited resources, as well as to reduce the cost of production unit and thereby increase in the national output and farmers' incomes under the severe shortage of water resources in Egypt. The chapter titled "Improving Agricultural Crop Yield and Water Productivity via Sustainable and Engineering Techniques" presents several proved sustainability and engineering techniques to save agriculture water and to increase the water yield productivity. The last chapter in this section is titled "Mega Agricultural Projects in Egypt." The author discusses Egypt's Mega projects which were implemented and those under implementation and their water needs to minimize the food gap in Egypt. The author in this chapter follows the route of agricultural development in Egypt during the last 200 years until the present time; the mega projects will have more emphasis especially those established during the last 20–30 years. The last chapter in this section of the volume is titled "Role of the Participatory Management in Improvement of Water Use in Agriculture" which focuses on the role of the stakeholder and their effective participation in water management for irrigation and the role of each party to improve the usage of water for a better crop productivity.

Part VIII comprises two chapters dealing with the quantity and quality of the water in the water resources bank of Egypt. The chapter titled "Development of the Rating Curves for Egypt's Water Resources Bank" presents the use of remote sensing and GIS in developing rating curves for estimating Lake Nasser surface area and capacity (volume) in terms of the water level. Lake Nasser in this context is called Egypt's Water Resources Bank. The chapter "Investigating the Water Quality of the Water Resources Bank of Egypt: Lake Nasser" presents the results of water quality investigation of Lake Nasser for irrigation and drinking purposes.

The volume ends with a concluding chapter which presents the most updated findings in the field of conventional water resources and agriculture in Egypt and summarizes the most important conclusions and recommendations of all chapters.

Great thanks and appreciation are due to all who contributed to this volume, with special acknowledgment to the authors; without the efforts and patience of all the contributors in writing, reviewing, and revising the different versions of the chapters, it would not have been possible to produce this unique high-quality volume. Special thanks are due to the Springer team and editors of HEC series who largely supported the authors and editors during the production of this volume.

Zagazig, Egypt Abdelazim M. Negm
20 April 2018

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Part I
History of Irrigation and Irrigation Projects

Evolution of Irrigation in Egypt

Dia-Eldin ElQuosy

Abstract Egypt established fixed boundaries thousands of years ago. The area of the country is approximately one million square kilometers. The cultivated portion of the country does not exceed 5% of the total; while the inhabited portion is no more than 8%. The Nile River crosses the country from south to north. The irrigated area on the floodplain of the river is a narrow strip on both sides which forms the Nile Valley. The Nile Delta starts north of the capital city, Cairo, and ends close to the coast of the Mediterranean. Although Egypt is known as the "gift of the River Nile," many Egyptian scholars prefer to call Egypt "the gift of the Egyptians" – who managed to train the River, to irrigate the lands, and to build one of the most ancient civilizations in the world.

Keywords Basin, Flood, Irrigation, Management, Nile Delta, Nile Valley, Perennial

Contents

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1 Introduction

Egypt is historically known as the gift of the Nile River. This was mainly because of the fact that the country is a barren desert, except for the narrow green valley and the Nile Delta. This green valley crosses from far south to the capital city, Cairo, and is known as the Nile Valley. The Nile Delta is a fertile land and is extending from Cairo in the south to the Mediterranean coast in the north.

The Nile Valley is a floodplain which runs between moderately elevated hills from the east and the west sides. The width of the floodplain is very narrow in the south but gradually widens northward until it reaches its maximum width of about 25 km near the city of Beni Suef, almost 125 km south of Cairo.

The Nile Delta also contains a number of smaller branches of the river which were diverted close to Cairo and flow northward. References differ on the number of these branches (between 5 and 7). Two of them are still active, namely, Damietta branch to the east and Rosetta branch to the west. The third branch which was certainly active in the past was the Ballouzy branch flowing northeast to meet the Mediterranean inside the Sinai Peninsula east of the coastal city Port Said. The remaining branches were widened, deepened, and used as irrigation canals at later stages. This configuration gives the picture of the Nile River and its branches in Egypt at the dawn of history during the Stone Age [1].

The Nile River flows with small amounts of water throughout the year; intermittently large flows occur during 3–4 months every summer. When the summer flow is high, water spreads over the two sides of the floodplain, depositing sediments transported by heavy rain from the upstream origins, and year after the other, the land becomes more sedimentary, more alluvial, and more fertile.

Living on the sides of the Nile River floodplain, the Stone Age man and woman realized that they can utilize the animals. Gradually they managed to train the wild animals to carry them and their belongings from one location to the other. They also realized that they can benefit from the milk they get from the animals, and eventually they learned that husbandry may bring about more children, and therefore wildlife of animals turned to be more and more domestic [2].

The Stone Age era started with humans hunting wild animals and killing them to obtain their food, taking their skin to cover their bodies and use them for the establishment of their shelters. On the other hand, they experienced the cutting of trees to use their timber as fuel they needed to cook the meat of the animals they kill. Then, the Stone Age population gradually changed from nomadic life, i.e., moving from one place to another looking for food for themselves and feed for their animals into settlements where they employed the family members and the trained animals to cultivate parts of the fertile floodplain of the river.

Egypt and the ancient Egyptians, therefore, witnessed the change from continuously moving individuals and groups from one location to the other looking for hunting, food, water, and timber trees into groups of settlers living in one location and adapting to the surrounding conditions.

The first difficulty the new settlers faced was how to convey the water from the river to far away locations. At this point they learned how to dig small streams and how to give them the slope necessary to transport water by gravity from one location to the other. This was the evolution of the conveyance and distribution systems.

The second difficulty was how to lift water from a lower elevation to higher elevations. They managed to invent the Tanbour for small heads and the shaduf for bigger heights. Eventually when they needed to go higher and to increase the amount of water to be elevated higher, the waterwheel (the Sakia) was used, providing increased lifting head, and operated by domesticated animals which can provide better capacity than humans.

The most important development in the field of agriculture and irrigation started with the Egyptians learning how to read and write. The innovative idea of introducing papyrus as a writing material and the innovation of a language that cannot only be spoken but also be written came into action. This was the first step toward building a real civilization which does not end with one generation disappearing but extends by heritage from one generation to the other.

It is surprising that the other Nile countries established civilizations. The simple reason for this was the evolution of irrigation and the cultivation of agricultural land in Egypt and the experience which was transferred from one generation to the other [3].

Rain-fed agriculture which prevails in most of the Nile Basin countries is dependent on erratic rain which may cause floods and damage, or contrarily be intermittent and cause droughts and famine. On the other hand, irrigated agriculture guarantees the optimum supply throughout the plant's growth.

In order to secure the amount of water continuously flowing into the Nile River in Egypt, storage was the secret word in water management which was added to irrigation terminology only recently. With storage the last and most sustainable structure of irrigated agriculture was formed, that is, the storage reservoirs, the conveyance and distribution network, and the on-farm water management system.

This chapter explains, in brief, the evolution of the irrigation systems in Egypt from the dawn of history until the most recent developments, not only to document this surprising progress but also to gain lessons for the coming years which will be improved by learning from the previous generations [4].

2 Irrigation in Egypt: Evolution or Revolution

The irrigation system in Egypt, which was developed throughout thousands of years, can be described as evolutionary (i.e., gradually created and improved with time). Over time new ideas were introduced, and irrigation technology was developed. Egyptians were pioneers in leading the whole world toward novel techniques and the introduction of irrigated agriculture [5].

The next section describes some examples of the revolutionary actions that were recorded in Egyptian history of irrigated agriculture.

2.1 Nilometering

Estimation of the extent of the Nile River water level change with time was an important issue throughout history. The reason for this is the fact that water level was always an indicator of the yearly agricultural production under normal conditions. If the water level was far above normal, devastating floods which may kill humans and animals and destroy fields and properties were expected. When the water level was far below average, drought, famine, and even starvation were imminent.

It was very early in history (before Dynasty 4300 BC) when the clergy were praying for a normal water level during the peak of the flood. This level was estimated at 16 ziraa (1 ziraa = 55 cm). In order to measure the water level, 20 nilometers were established as the distance between Aswan and Cairo. The nilometer consists of a well (stilling basin) which is equipped with a vertical marble gauge. At the top of the well, two copper eagles, one male and the other female, were installed. If the male eagle started whistling first, this was an indication of high flood; otherwise, the flood was low [4].

The normal flood was connected to the calendar year and came between the months of June and September every year. The population and the rulers were satisfied when the water level was between 13 and14 ziraa in the south and between 7 and 8 ziraa in the north (inside the Nile Delta). It can be observed that 16 sons are surrounding the well-known Nile Gold statue in Vatican. In fact, this reflects the importance of the number 16 to the Egyptians of that age.

The Nile water level was highly important:

- To the farmer it meant the amount of water that is going to produce food and how much money he is going to save for the excavation of canals and the construction of dams.
- For the ruler, river water level was connected to the amount of tax they are going to charge. This amount increases with the increase in water level. Tax money was used for the heightening, strengthening, conservation, and guarding of embankments.

  Taxes were divided into four equal quarters: one for land amelioration and raising embankments, one for the king, one for the army, and the forth was kept as emergency reserve.

Thuhutmos the Third (1600 BC) was the first ruler who related the flood to the solar calendar and connected river water levels to the relevant days and months.

Monitoring the Nile water level continued over history, and the Romans related every level to an expected state of affairs. *The relationship was as follows*:

12 ziraa	Famine and starvation
13 ziraa	Adequacy
14 ziraa	Pleasure and happiness
15 ziraa	Safety and security
16 ziraa	Abundancy

The Islamic rule of Egypt (712 AD or 93 higry) established the Rodha nilometer which still exists (see Fig. 1).

The Rodha nilometer is divided into 22 ziraa, each further divided into 24 kirates (for more accuracy), and is a hexagon of eight faces. It was renewed in the years 814 and 861 AD.

Monitoring of the Nile water level in the Islamic rule was mainly to determine the annual kharage (tax) which was based upon the area of land, the crop raised, the soil classification, and the elevation of the taxed land.

2.2 *Construction of Dams*

A revolutionary action toward the conservation of flash flood water and protection of humans, animals, and properties from the devastating consequences of rapidly flowing water was the building of Kofra Dam in Wadi El Garawy east of the Nile River close to the suburb city Helwan located at about 30 km south of Cairo. The dam was built during the age of the Old Dynasty (3300 BC) and was recently (1915) uncovered by a German scientist George Chingford. The date of construction goes back to the year 2650 BC. Some references confirm that the dam is the oldest in the history of the world and is even older than Sabaa Dam in Yemen [4].

Al Kofra Dam is a rock-fill dam with hard clay core. The dam failed at the last stage of construction due to heavy torrential rain event (see Fig. 2).

2.3 *Nile Embankments*

King Menes, who was the hero of uniting the Upper and Lower Egypt under one single crown, was, in the meantime, a master of irrigation engineering. The rule of Ming Menes started around 3000 years BC.

History tells that Menes managed to shut a branch of the Nile down which was flowing at that time to the Western Desert Depression now known as the Oasis. In addition, the river was protected from overtopping by raising the left embankment (west) by the establishment of a longitudinal dyke running parallel to the stream,

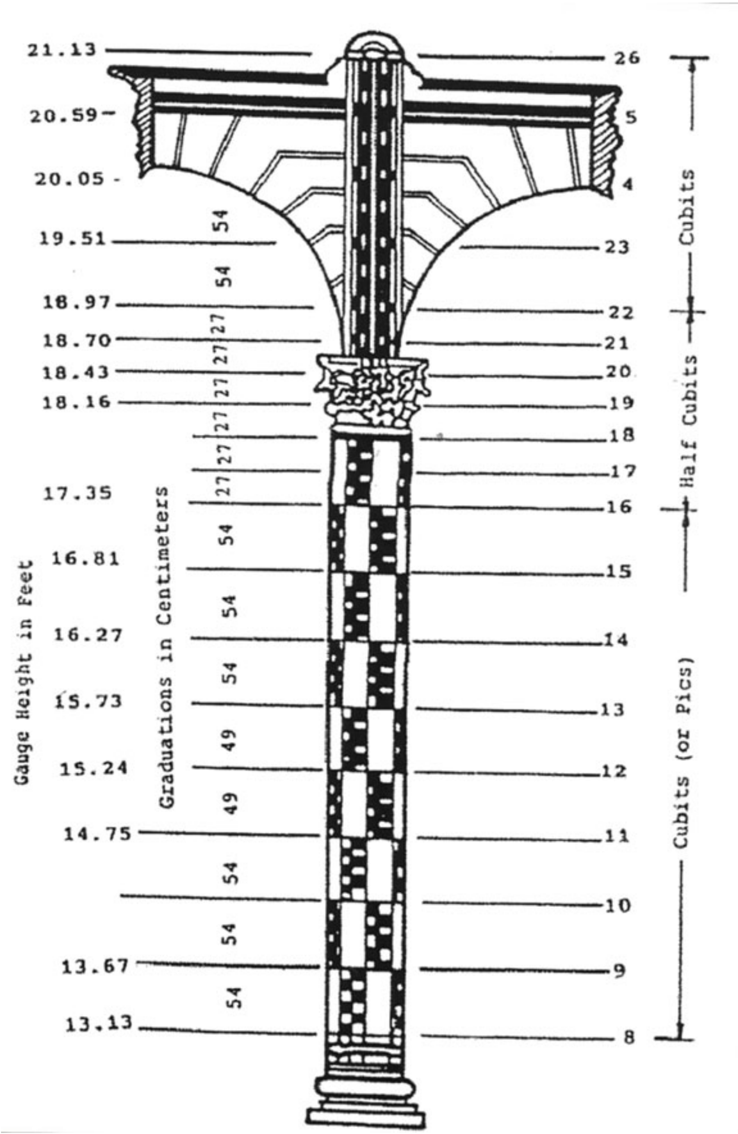

Fig. 1 Rodha nilometer [5]

and cross dykes connected to the Western Hills, forming a set of wide basins and reservoirs.

Flood water loaded with silt deposits was directed to these basins by natural water courses and artificially dug canals, allowing the sediments to be deposited. The right bank was at that time left for the flood water to overtop it and inundate the adjacent lands. With the population increase and the growing demand for food,

Fig. 2 Al Kofra Dam [5]

bringing new lands into cultivation became necessary, and therefore the whole length of the right bank was completed and the Nile was confined completely between the two embankments.

However, the complete enclosure of the river between the two embankments created a real danger to the low-lying lands downstream, especially when the country is subject to severely high floods, and therefore a spillway was open to drain high flood water to the Faiyum Depression called the Lake Mouries Reservoir. After the recession of the flood, water from the lake would flow back to the main stream of the river.

Flood water used to remain in the basins for a period of 45 days every year at an average depth of 1 m. After being underwater for 6 successive weeks, lands were thoroughly inundated and the soil profile completely saturated. The moisture stored in the soil profile was sufficient to bring some crops up to maturity in the following winter and perhaps in summer as well [5].

The area of the basins used to range between 2 and 40,000 feddans (1 feddan = 4,200 m^2) at an average of 7,000 feddan each basin. A chain of basins usually 5–8 in number used to be connected by a main canal. The last basin in the chain was the lowest in elevation and the largest in area; it was provided with a tail escape that returned water straight to the river in order to drain the surplus water of the whole set of basins. Some of the main canals were as wide as 75 m, but the average width was about 10 m.

The basin irrigation system continued over the whole era of the pharaohs, Ptolemies, Romans, down to the Islamic rule of the country.

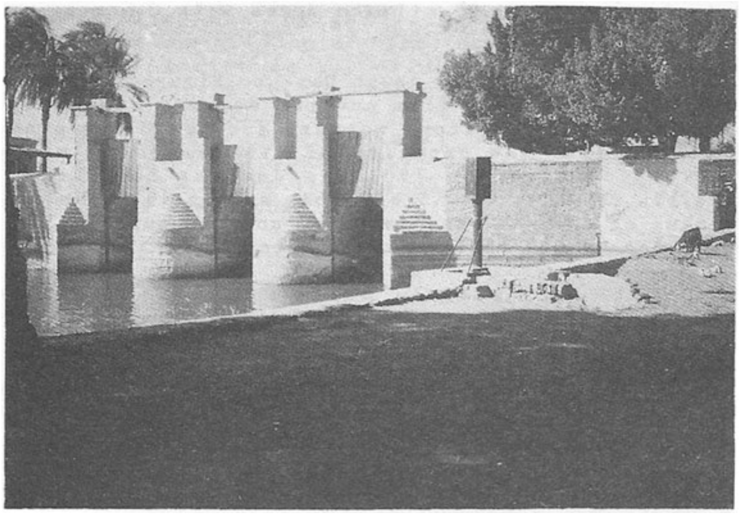

Fig. 3 Lahoun regulator [7]

An extensive area of the Nile berms had been also enclosed by embankments and protected from high water levels which enabled the production of crops all year around [6].

During the Islamic rule, the area of cultivated land grew from 1.5 million feddans to almost 3.0 million. People were encouraged by the extremely just rule to excavate new canals, widening and deepening of existing canals, and construction of control structures and bridges.

The remains of Lahoun regulator in Faiyum, Abu-El Menagga regulator at Qalub, and the elevated channel in Cairo which used to transport water from the Nile to the citadel of Salah el-Din (about 5 km long and 15 m high) are all examples of the masonry hydraulic structures built between the tenth and the sixteenth century (see Fig. 3 for Lahoun regulator and Fig. 4 for the elevated channel).

The Turkish Empire (1517–1798) did not put the same emphasis on agricultural production as the Arabs did, and therefore the cultivated area dropped to less than two million feddans during their rule.

2.4 From Basin to Perennial Irrigation

Basin irrigation was based on the filling of the soil moisture reservoir in the root zone with the necessary moisture storage adequate to raise one crop per year. Perennial irrigation required the availability of water in streams, surface reservoirs, and groundwater aquifers all year round. This enabled raising two (and sometimes more) crops per year [1].

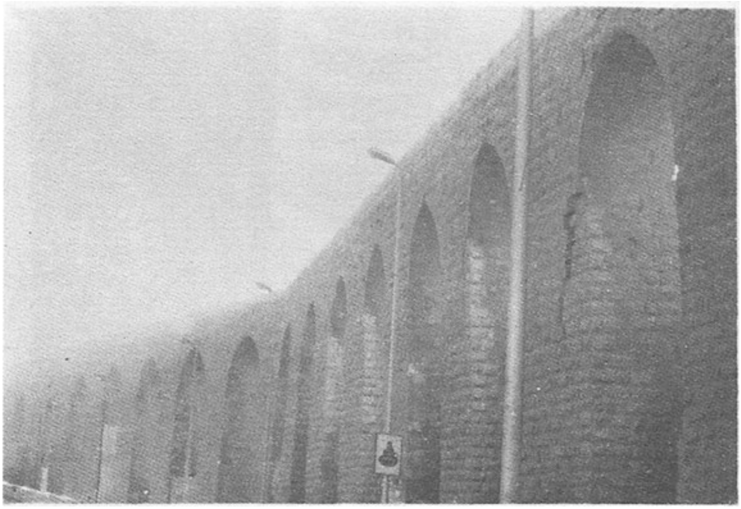

Fig. 4 Elevated channel [7]

It all started during the French occupation of Egypt (1798–1802) when Napoleon was quoted saying, “Si je devrais gouvernance pays, pas une goutted’ ea se perdait dan le mer” which means, “If I am to rule this country, I will not allow one drop of fresh water to flow to the Mediterranean.”

The reason for Napoleon to reveal this statement was the fact that he noticed during his short stay in the country that the flood water comes only for a short period of time (June–September), fills as many basins or reservoirs, and eventually recedes flowing to the Mediterranean.

Further investigation and research revealed that the average natural flow of the Nile River was 84 billion m^3 per year, 32 billion m^3; out of this amount would flow every year unused to the Mediterranean and the remaining 52 billion m^3 would beneficially be used.

Muhammad Ali, who ruled Egypt after the French occupation, took Napoleon’s advice and started working on the potential storage of each drop of flood water.

The starting project of Muhammad Ali was the development of “Summer Canals”. At that time the Nile had seven main branches in the Delta of which the eastern (the Polusaic or Damietta branch now) and the western (the Canopic or Rosetta branch now) were the largest.

Using free labor from compulsory volunteered Egyptians, the ruler ordered the widening, deepening, and sometimes the extension of these canals to cover the biggest area of the middle, eastern and western parts of the Nile Delta. The purpose of the project was to receive as much flood water as possible in these canals, allow part of the water to percolate into the groundwater aquifer, and use the remainder to irrigate low-lying fields downstream [8].

Following the Summer Canals project, Muhammad Ali started the construction of the Delta Barrages on the two large branches in the Delta in order to store water in the river, to create the necessary head upstream to irrigate low-lying lands downstream, and to replenish the groundwater aquifer from which water can be pumped during periods of high demand.

Both the Summer Canals and the Delta Barrages enabled the introduction of perennial irrigation which started with two crops per year of wheat and maize plus other perennial crops like sugarcane, cotton imported from India, and fruit trees, mainly mangoes which were also grown on the Egyptian soil for the first time in modern history.

2.5 Irrigation Lifting Devices

The first lifting device man used to transport water from lower to higher elevation was the bucket. In the Stone Age, man used stone, pottery, or leather buckets for transport. Later, buckets were provided with ropes in order to increase the span from which water is obtained. Wooden pulleys were added through a hinge to form the well-known shaduf which is still in used in some places around the world. The shaduf increased the bucket width and consequently the amount of water lifted and also increased the lifting head in order to reach higher elevated land [9].

The shaduf was used by the ancient Egyptians as early as 1250 BC, as recorded on the Thebes City walls. It consists of a long cross bar pivoted between two vertical posts. The shorter part of the cross bar carries a counterweight of large piece of stone, and the longer part of the robe (or a long stick) is attached to the bucket. Adjustment of the counterweight was done by adding mud to the stone. The lifting head of the shaduf is relatively small; when bigger heads are needed, a cascade of a number of shadufs has to be arranged. When the lifting head is between 0.5 and 1.0 m, one shaduf can irrigate almost 15 feddans of land when operated by one farmer.

The Greek Ptolemies introduced the Archimedean screw to the Egyptian practice, which has been named as “Tanbour”. Tanbour is manually operated for similar lifting heads like shaduf and those with even smaller heads. The sakia, waterwheel, was first imported to Egypt by the Persian King Dara, the first to rule Egypt 1100 years BC. This is driven by hydropower generated from water falls and has been developed in Faiyum during the Roman rule of the country, simply because pressure heads can be generated in the Faiyum region due to its sloping lands.

The wooden small-size sakias were further improved by increasing the diameter of the wheel, increasing the capacity of the buckets, and changing from being animal operated to machine operated.

With the invention of the steam engine, piston pumps imported from Europe started to appear in the Egyptian markets. During the nineteenth century, centrifugal pumps and screw pumps were manufactured in Europe and exported to Egypt to be used with steam engines. The introduction of small diesel pumps stopped almost completely the use of any other lifting devices in the irrigation system in

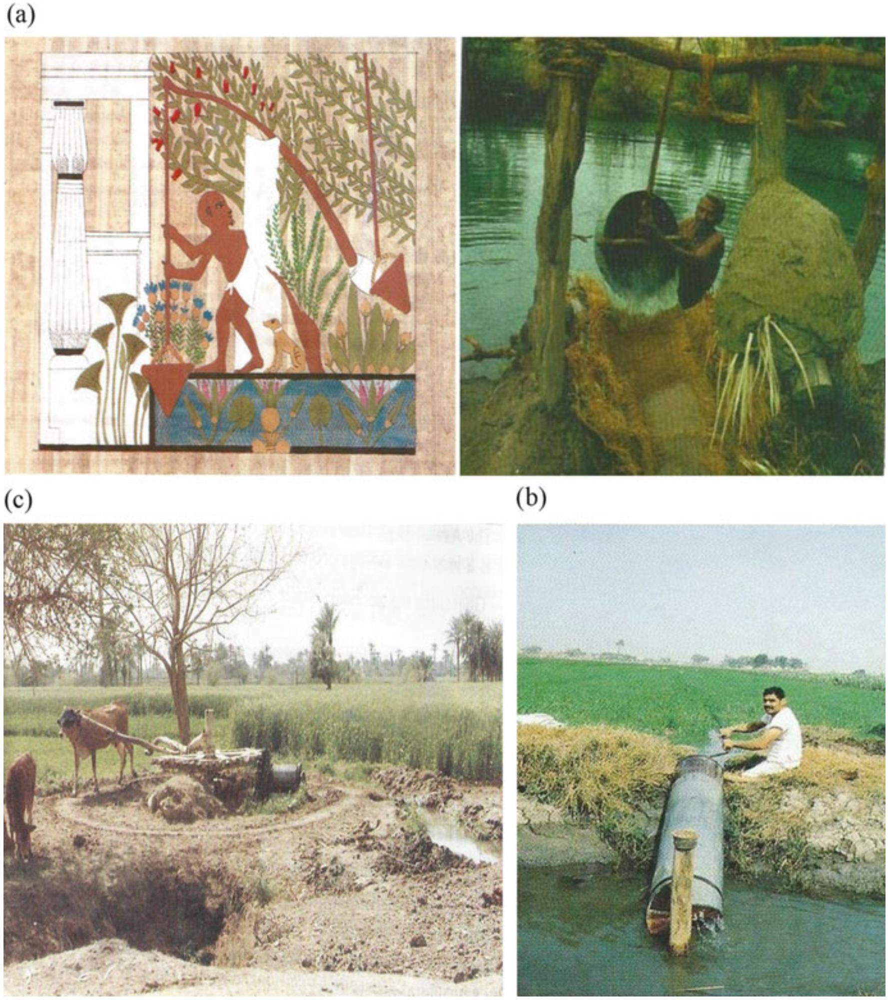

Fig. 5 (**a**) Lifting devices: the shadouf [8]. (**b**, **c**) Lifting devices: (**b**) the tambour (Archimedean screw) [9], (**c**) the sakia (waterwheel) [8]

Egypt. Figure 5a–c shows different ways of water lifting, including the shaduf, the tambour, and the sakia.

3 Geography of the Nile Basin

Claudius, the Ptolemaic ruler who lived in Alexandria during 100–200 AD, was an author of a number of books in astronomy and geography which remained as references for more than 1,000 years. He imagined that the White Nile comes from high snow-covered mountains in Central Africa called, by them, the Moon Mountains. This river flow is discharged by snow melts from the high mountainous zones. The river stream then comes across two northern lakes. From the two lakes, two rivers flow separately but join each other, later forming what is now known as the White Nile. Flowing northward the river receives water from two eastern tributaries, one coming from Lake Tana located at the southeast named the Astapus (Blue Nile) and the second coming further north (also northeast) named the Asaboras (Atbara). The land between the two tributaries was called Moroes. Ptolemy map was further developed by an Arab geographer Al-Khwarizmi, who managed to trace the world map for the first time in history later. Al-Khwarizmi's map is shown in Fig. 6 [1].

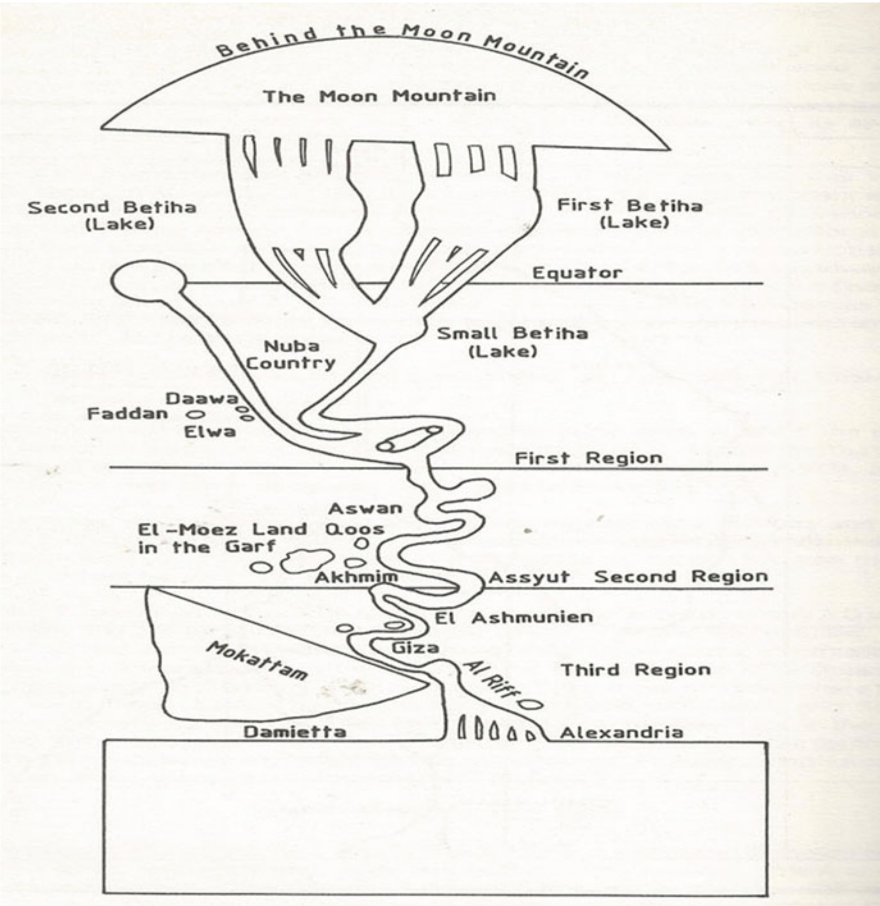

Fig. 6 Ptolemy map of the Nile Valley (after Al-Khwarizmi) [6]

4 Concluding Statement

The previous sections have shown the revolutionary actions taken by the Egyptians throughout history which forms the complete story of evolution of irrigation of the country. The cultivation of land, the irrigation in soils, and the raising of the same crops for such an extremely long period of time without being affected by salinity, alkalinity, waterlogging, or any serious damages or injuries pose a very important question, that is, how can this happen? The answer would always be that this was only due to the application of the appropriate management of the water, soil, plant systems, and the suitable but excellent prevailing climatic conditions.

The coming days, months, and years will certainly show how the existing and future Egyptian generations can be as innovative, as scientific, and as sophisticated as their great grandfathers.

Sustainability is now faced with the main challenges of the rapidly increasing population growth, the possibility of reduced discharge and quota due to political and other reasons, the expected consequences of climate change which might be positive or negative, and the overwhelming impacts of pollution of the water environment.

Whether the existing Egyptian generations can overcome the negative impacts of the above challenges or not, only the future can tell.

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The History of Irrigation Development Projects in Egypt

Dia El-Din El-Quosy

Abstract Irrigation development projects in Egypt started in the dawn of history with the Egyptian Stone Age man changing from a nomad life to settled farming. Irrigated farming needed a permanent source of irrigation water. Storage was, therefore, the first "secret word" in the history of modern irrigation. "Summer Canals" were first adopted at the beginning of the nineteenth century to store the water needed to irrigate low-lying lands downstream, replenish groundwater reservoirs, and allow seepage to adjacent lands on both sides of the canals. The Delta Barrages on the Damietta and Rosetta branches followed to become the first step toward scientifically based irrigation water management. Engineering schools were part of the development process in providing the country with the required modern and up-to-date techniques. Summer Canals, Delta Barrages, and the School of Engineering were all achievements of the great ruler and developer Mohamed Ali Pasha, the first leader after the evacuation of the French colonial era (1798–1802). The excavation of the Suez Canal was connected to irrigation projects when a freshwater canal was fed from the Nile to carry water to the workers and to carry pilgrims to perform "Hajj" to the Holy shrines in Mecca and Medina.

The twentieth century witnessed rapid development in irrigation infrastructures and ended in the existing final shape of the system. Each control structure needs to be reconstructed or renewed when it reached more or less 100 years of its age. Reconstruction projects will also be described in this report.

Moreover, the future of the system and how it will cope with the next developments and the expected challenges will be explored.

Keywords Canal networks, Control structures, Drainage projects, Irrigation management, Regulation

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Contents

1 Introduction

Major irrigation development projects started in Egypt in the dawn of history. Remains of Stone Age man indicated that the change from continuously moving nomad tribal life to settlement family-like residential communities started far south in locations like Toshka and Owainat. This type of change was accompanied by domesticating animals as farm aids rather than killing them for meat, fats for fuel and lighting, and hides for clothing and tents and making household and farm tools from their bones. Instead, farming and production of food and fiber became more popular.

While rainfed areas face the difficulty of getting pasture to feed their livestock, irrigated agriculture was enjoying the availability of freshwater in rivers and lakes for prolonged periods of time. However, life was not that easy; when rain falling on the origins was erratic, natural flow at the end becomes slower, smaller, and insufficient.

The first move toward perennial irrigation, i.e., raising more than one crop on the same piece of land every year, was to store water from times of abundance to use during shortages.

Mohammad Ali was the first ruler to plan for disciplined, modern, and economical agriculture in recent history in Egypt. He managed to convert the uncontrolled canalization as practiced by previous generations into a controlled network of canals. This was first carried out by widening, deepening, and straightening of the wild branches of the River Nile in the Delta.

This process enabled the storage of water in the "Summer Canals," which were several branches of the Nile in the Delta. During the flood season, water storage made it possible to irrigate low-lying lands downstream, replenish groundwater reservoirs, and allow water to seep to the adjacent lands on both sides of the canals increasing their moisture storage. The construction of the Delta Barrages was actually the first step toward scientifically based agricultural development, not only on the Egyptian soil but also over a large area of the world, west, east, north, and south.

The momentum of modern irrigation continued over the second half of the nineteenth century after the end of Mohammad Ali's rule. However, during the period 1859–1869, the country was busy preparing for different hydraulic projects of various shapes and scales. One of these projects included the excavation of the Suez Canal. This project ended with Egypt being a British colony in the year 1882, just because of the large size of debts and loans the country could not afford to repay. British engineers and technicians found in Egypt and India the place where they can experience their talents in producing high-quality varieties of cotton needed to supply Liverpool, Manchester, and other textile manufacturing centers with the raw material they needed. To maximize the benefit from Egypt, they had to improve the irrigation system and develop the best network of irrigation canals, drains, and control structures.

It all started with the construction of the Aswan Dam (1898–1902) followed by a set of "Grand Barrages" which continued over the twentieth century. Mohammad Ali did not miss the opportunity to establish the School of Engineering in the year 1817 almost 200 years ago. Since that date, development projects on the irrigation and drainage systems expanded. The expected age of the structures built during the nineteenth century approximately vanished. Therefore, these structures were renewed or, in most cases, replaced by new modern structures. The process of renewal of the control structures is still taking place.

The purpose of this chapter is to start with the description of the final shape of the control structures on the River Nile and the main canals; the date of startup of each of the buildings, the date of completion, and the purpose of why it was built will be illustrated.

The factors affecting sustainability will also be discussed to investigate the possibility of future generations to continue the development process, optimize the use of the available resources, and explore new resources to cope with the rocketing increase in the Egyptian population.

2 Starting from the End

To obtain an overview of the latest developments in irrigation projects in Egypt, we divide the system into three portions:

1. The reservoir including Lake Nasser in Egypt and Lake Nubia in Sudan both forming the storage reservoir upstream of Aswan High Dam.
2. The main course of the River Nile starting from the immediate downstream of the Aswan High Dam up to the end of the two Delta branches: Damietta in the east and Rosette in the west. This system includes all the control structures both on the main course of the river and the main branches of the hierarchy descending from first-order tributaries (Rayahs) down to the distributary canals and mesqas (very small farm feeding canals) from which farmers lift water to irrigate their fields.

3. The on-farm irrigation system which includes two types of irrigation:
   (a) Conventional gravity surface irrigation in which water is lifted from the mesqa to a field ditch and spread over the land under the effect of gravity either through longitudinal furrows or too small size basins depending upon the size of land (dimensions) and the precision of land leveling
   (b) Modern (pressurized) irrigation systems such as drip and sprinkler which are obligatory practiced in newly reclaimed desert lands in addition to small spots of orchards and vegetable fields in the old Valley and Delta lands

3 The Storage Reservoirs

The Aswan High Dam (AHD) reservoir extends over an area of about 6,000 km^2 over a north to south distance of about 500 km, 350 km inside the Egyptian territory and 150 km inside Sudan. The average width of the lake is about 12 km. The storage capacity of the lake is more than 160 billion m^3 of water when full. This capacity is three times the annual natural flow that Egypt gets (55.5 billion m^3) every year according to the Nile Water Agreement signed with Sudan in the year 1959 in the occasion of the construction of the HAD. The quota of Sudan was set at 18.5 billion m^3, and 10 billion m^3 is left for evaporation which is estimated at more than 1,500 mm/year or an average of little less than 5 mm/day.

The lake is not navigable where waterfalls occur. Water quality in Lake Nasser in Egypt and Lake Nubia in Sudan is excellent, and the salt content does normally exceed 180–220 ppm. Sediments cause some acute and chronic problems in some spots where backwater causes blockage of part of the cross section. This problem is expected to be less effective with the construction of new dams in Sudan, the heightening of old dams (Roseires and Sennar), and the construction of the Great Renaissance Dam in Ethiopia.

However, some indicators confirm the suitability of these sediments as soil stabilizers and for manufacturing of bricks, ceramics, and porcelain in addition to the extraction of many radioactive trace elements. The longitudinal and cross sections of AHD Lake are monitored on a regular basis by the Egyptian Research Institution (mainly the Nile Research Institute of the National Water Research Center). The monitoring is mainly to detect any significant changes in the lake profiles, to trace any changes in the lake water quality, and to assess the volume of water stored in the lake.

Lake Nasser is one of the main sources of freshwater fish in Egypt. It provides the country with about 160,000 tons of tilapia, Nile perch, and other less popular, low-price species. Fish of these varieties generally exist in shallow water. Research is now being targeted toward fish farming in deep waters which will bring about a real breakthrough in the future of fish catch.

The release of water from Lake Nasser is dependent upon the demand for different activities in the country, i.e., agricultural requirements, domestic water supply, industry, and fish farming. Water is also utilized for nonconsumptive purposes like hydropower and navigation. The average release ranges between 70 million m^3/day in winter and more than 250 million m^3/day in hot summers.

The most important projects for the development of Lake Nasser in the short and long term would be in the utilization of silt and the improvement of fish catch and fish farming. The most important factor in lake development would be to maintain utmost care of the environment of the lake from which and on which life of humans, animals, and plants is fully dependent. One of the most promising industries in this respect could be for the production of ice needed to cool or even freeze the fish which is obtained from the lake.

In addition to the fast-growing population in Egypt, two more factors create tremendous concern among the Egyptian citizens; these are:

1. The growing need for water in upstream Nile Basin countries and the large number of dams being constructed in Kenya, Uganda, Ethiopia, South Sudan, and Sudan
2. The large-scale uncertainty about the magnitude of the effect of climate change on the rainfall in Nile Basin countries

However, even with the existence of all these challenges, Lake Nasser was, is, and will remain the major source of guarantee for Egypt to be able to plan for future development in the water and agriculture sectors.

Water pollution is also a concern, and therefore, the development of intensive tourism activities including heavy traffic sailing vessels up and down in the lake is facing strong criticism.

4 Conveyance and Distribution Systems

The conveyance and distribution systems start immediately on the downstream side of the High Aswan Dam. The objective of the system is to deliver water to the four corners of the country to use this water for different development activities. The conveyance and distribution system consists of a hierarchy of open channels and closed conduits starting from first-order canals fed directly from the River Nile, namely, Rayahs, down to the distributary canals and mesqas from which farmers lift water to irrigate their fields. This hierarchy may go down to seven or eight levels before it reaches its last destination.

The total length of irrigation canals excluding distributary canals and mesqas is in the neighborhood of 35–40 thousand kilometers covering the whole cultivated area in the country. The cultivated area extends over almost 8 million feddans (1 feddan = 0.42 ha); of these, 6 million feddans is located in the Nile Valley and Delta with the prevailing soil of heavy to medium textured clay and silt. The remaining 2 million feddans is reclaimed from desert lands on both sides of the fringes of the Nile Valley and Delta. Apparently, these lands are mainly sandy, but they are gradually improved with their water holding and transmission capacity improvement, due to successive cultivation over the years, i.e., farm gates.

The major cropping pattern in the Valley and Delta lands is wheat, berseem (fodder crop similar to clover), and legumes (fava beans, lentils, broad beans, etc.) in the winter and cotton, maize, and rice in the summer. Sugar beets are cultivated as winter crops on the northern part of the Delta, and sugarcane is cultivated as a perennial crop in the southern and middle part of the Valley. Both sugar beets and sugarcane occupy an approximately similar area of around 250–300 thousand feddans. Winter and summer vegetables and winter and summer fruits and citrus are grown on an area of about 800 thousand to 1 million feddans scattered all over the country.

Newly reclaimed lands are installed with modern (pressurized) on-farm irrigation system. They are mainly allocated for the production of vegetables and fruits; however, with the subsidized prices of the government for the purchase of grain (wheat and maize), many new land farmers have changed their process gradually to these crops.

The majority of irrigation canals especially the large-scale branches are not lined. However, in some specific locations where the cross sections are subject to severe seepage or sliding conditions, concrete and limestone pitching is applied.

5 Upstream Control

The distribution system in Egypt is based on 24 h, 7 days a week abstraction, i.e., night storage is not applied, and therefore, none of the irrigation canals is terminal (i.e., the tail end of each irrigation canal is connected to a higher-level freshwater canal or to the nearest drain).

The distribution system is also based on supply management and not on demand management. The difference is that in supply management water is delivered according to calculated quantities of water needed to cover the consumption of the major requirements. Demand management provides each consumer only with the quantity of water they need. Supply management may cause water to be lost due to unforeseen changes in climatic conditions. The consumer may change their minds for using water due to unforeseen reasons or any events which were not planned for during the lag time between water delivery and water use (water released from Aswan reaches the tail end of the system after 11 days).

The reason for the application of supply management rather than demand management is that the latest requires accurate measurement which might not be available everywhere. Supply management is accompanied by the upstream control in which water level (not water quantities) marks the control of the system from the far south to the end in the far north. This situation requires a hierarchy of control structures on all the levels of branch canals.

Control structures include offtakes from feeding canals to branch canal spillways and tail end escapes. Weirs are normally found in the Fayoum Region where steep sloping lands form the main landscape, contrary to the Valley and Delta lands where slopes are so mild and normally do not exceed a few centimeters in 1 km.

The most crucial control structure under flat or gently sloping land conditions is the head regulators. Head regulators, as the name implies, are meant to put a dam in front of the flow to allow for increased head upstream of the dam and then divert the flow from both sides of the dam to allow for the irrigation of low-lying lands downstream.

Head regulators or diversion-regulated dams are commonly used in irrigation systems in Egypt. Since we are here concerned only about significant irrigation development projects in Egypt, this chapter will only be emphasizing the major regulators on the Nile and its main branches.

6 Major Development Structures

6.1 The Delta Barrages

The Old Delta Barrages on Damietta and Rosetta branches of the River Nile were practically the first step toward scientifically based water management in the Nile Delta. The barrages were built by Egyptian manpower/workforce and the best available technology worldwide at that time, which is the French know-how.

The ruler of Egypt Mohammad Ali (1805–1845) and the French Engineer Monsiere Lenan together started the project which was completed years after the rule of Mohammad Ali only. This is because the design did not take into consideration the possible seepage and uplift forces caused by the higher elevation of the eastern barrage (Damietta) on the Rosetta branch. This technical problem was not the only challenge to the country; the spreading of plague, the fighting and wars in the region, and the shortage of skilled labor and the appropriate building material were also the cause of delay in construction and the late utilization of all the benefits of the barrages.

The Delta Barrages marked a moment of conversion of large areas of land from mono-crop to perennial irrigation where it was possible to raise two crops per year. Moreover, perennial crops such as sugarcane and fruit trees were brought to the Egyptian soil for the first time in history. More important was the beginning of cotton cultivation in Egypt which proved over the years to be one of the most suitable crops to grow in Egypt land under the prevailing climatic conditions. It is important to say here that when Mohammad Ali became the ruler of the country at the beginning of the nineteenth century (1805), the number of Egyptians was 2.5 million and the cultivated area was 2.5 million feddans at a cropping intensity of less than 100% (one crop per year). However, by the middle of the century (at the end of Mohamed Ali's rule), the cultivated area increased to 5.0 million feddan, and the cropping intensity became as large as 150% (i.e., less than two crops per year). However, the population also was doubled, i.e., 5 million per capita (Fig. 1).

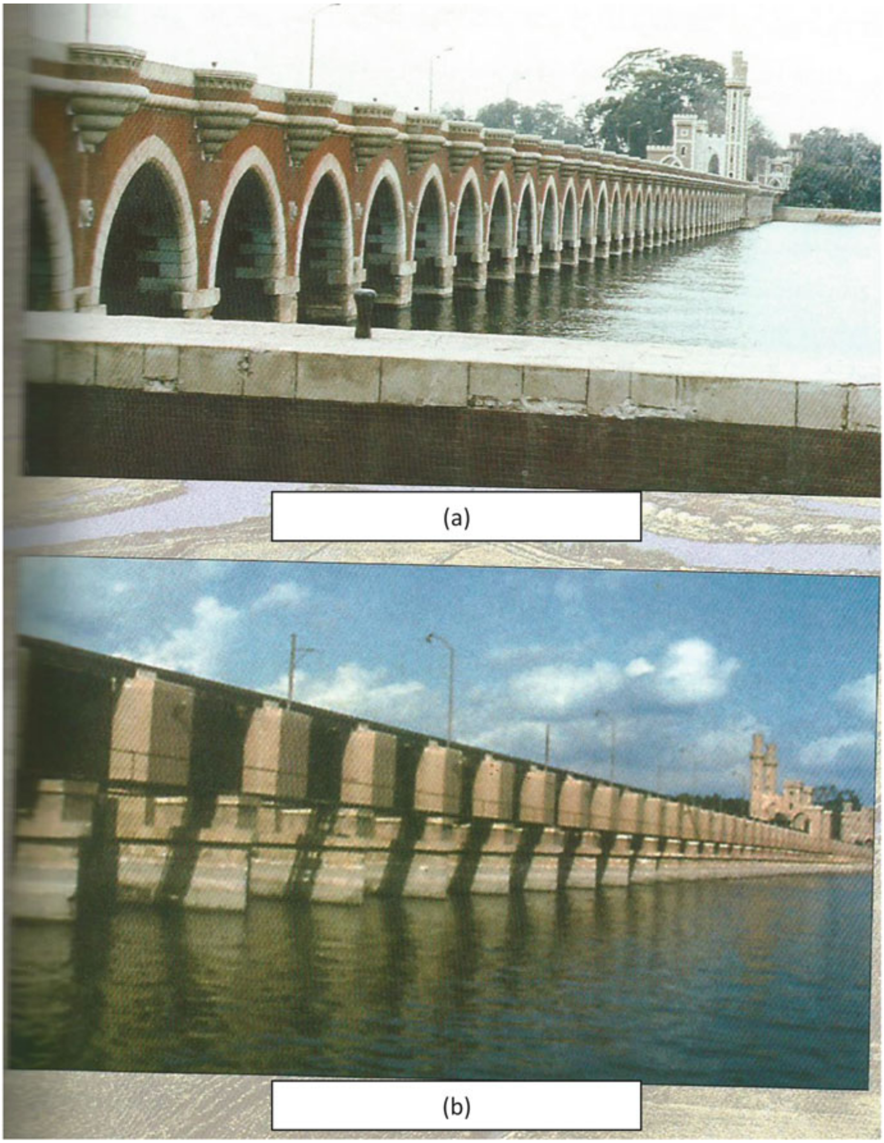

Fig. 1 Mohamed Ali Delta barrages on (**a**) Damietta branch and (**b**) Rosetta branch [1]

6.2 *Excavation of Suez Canal*

Excavation of Suez Canal started in the year 1859 (April) and was completed in the year 1869 (November) with the objective to connect the Red Sea to the

Mediterranean Sea to improve the world trade, transportation, and communication. The Suez Canal was not an irrigation project; however, the Royal Decree issued in this occasion stated that the executing company has to excavate in parallel a canal from the Nile to carry the water needed for the living of the workers, technicians, and engineers supervising the establishment of the Suez Canal project. The route of the freshwater canal was very much identical to the route of Ismailia Canal of today which provides the canal provinces, Suez, Ismailia, and Port Said, with the water needed for different activities.

6.3 *Construction of Aswan Dam*

The construction of old Aswan Dam was the first step toward water storage in Egypt. Starting from the year 1898, the dam was built to store 1 billion m^3 of water on an annual basis. Therefore, the dam reservoir became full during the flood period (August to October), water is abstracted during high demand (May to July) until the reservoir is empty, and refilling starts again with the new flood.

Aswan Dam was heightened twice: first in the year 1912 with the storage capacity increased to 2.5 billion m^3 and second in the year 1932 with the storage capacity raised to 5.0 billion m^3. The irrigation policy was changed with the construction of Aswan Dam to cater for the use of the water stored for expansion projects. Following the construction of High Aswan Dam, the old Aswan Dam was kept only for the generation of hydropower at almost zero storage capacity (Fig. 2).

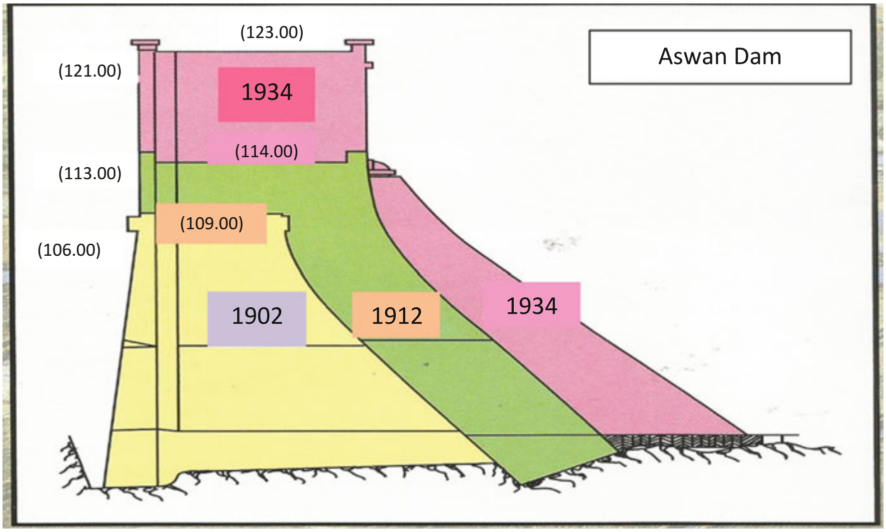

Fig. 2 Schematic of Aswan Dam and the two-stage heightening [2]

6.4 New Delta Barrages

By the year 1935, the age of the Old Delta Barrages became almost 100 years old. It was then inevitable that the function of the barrages is being reduced and the need for more efficient barrages is imminent. Two new barrages downstream the old buildings were established, and the old barrages were left in place as a monument with their gates fully opened all over the year.

The New Delta Barrages were used to divert water to the Eastern Delta through Rayah Tawfiki, to the middle through Rayah Abbasi and Rayah Menoufi, and to the West through Rayah Behiery. It is worth mentioning here that the most significant portion of the Nile flow passes through Damietta branch which feeds the lands of the Eastern and Middle Delta, while Rosetta branch carries only the water needed to irrigate the lands of the West Delta. However, with the large-scale horizontal expansion projects in the Nubaria areas (almost 1 million feddan), a new Rayah (Nasseri) was established to irrigate the newly reclaimed lands.

The average flow through the vents of the Delta Barrages at present is close to 35 billion m^3/year. This amount is sufficient to irrigate an area of about 5 million feddans of the old and newly reclaimed lands. Also, it provides domestic and potable water for a population of more or less 60 million and the industrial requirements in the Delta and the coastal zones in Matrouh, Alexandria, Kafr El Sheikh, Dakahlia, Domiat, Port Said, and the North Sinai capital city of Al Arish.

Although agriculture is practically the primary consumer of Nile water in Egypt (80%), yet, domestic and potable water supply comes second (more than 15%) and provides the industry with part of the requirement they need.

Similar to canal offtake structures on higher-order canals to feed branching canals, offtake structures of potable water treatment plants are scattered over the Nile and branch canals to reach every city, town, village, and small residential communities. Coverage with tap water in Egypt may be as extensive as 95–97% (Fig. 3).

6.5 Grand Barrages on the Nile and Its Branches

To secure efficient water management all over the country, a number of head regulators were constructed over the years on the main course of the River Nile, on the Damietta and Rosetta branches, and on the main canals. Figure 1 shows the latest development of these grand barrages which start with Isna Barrage in the south (some 150 km from Aswan) which diverts to Asfoun and Kallabia Canals on both sides of the river (Figs. 4 and 5).

About 450 km north of Isna Barrage, Nag Hammadi Barrage is constructed to divert water again east and west of the Nile Valley to East and West Nag Hammadi Canals. About 400 km south of Cairo, Assiut Barrage was constructed to divert water to Ibrahimia Canal which provides the lands of Assiut, El Minya, Beni Suef,

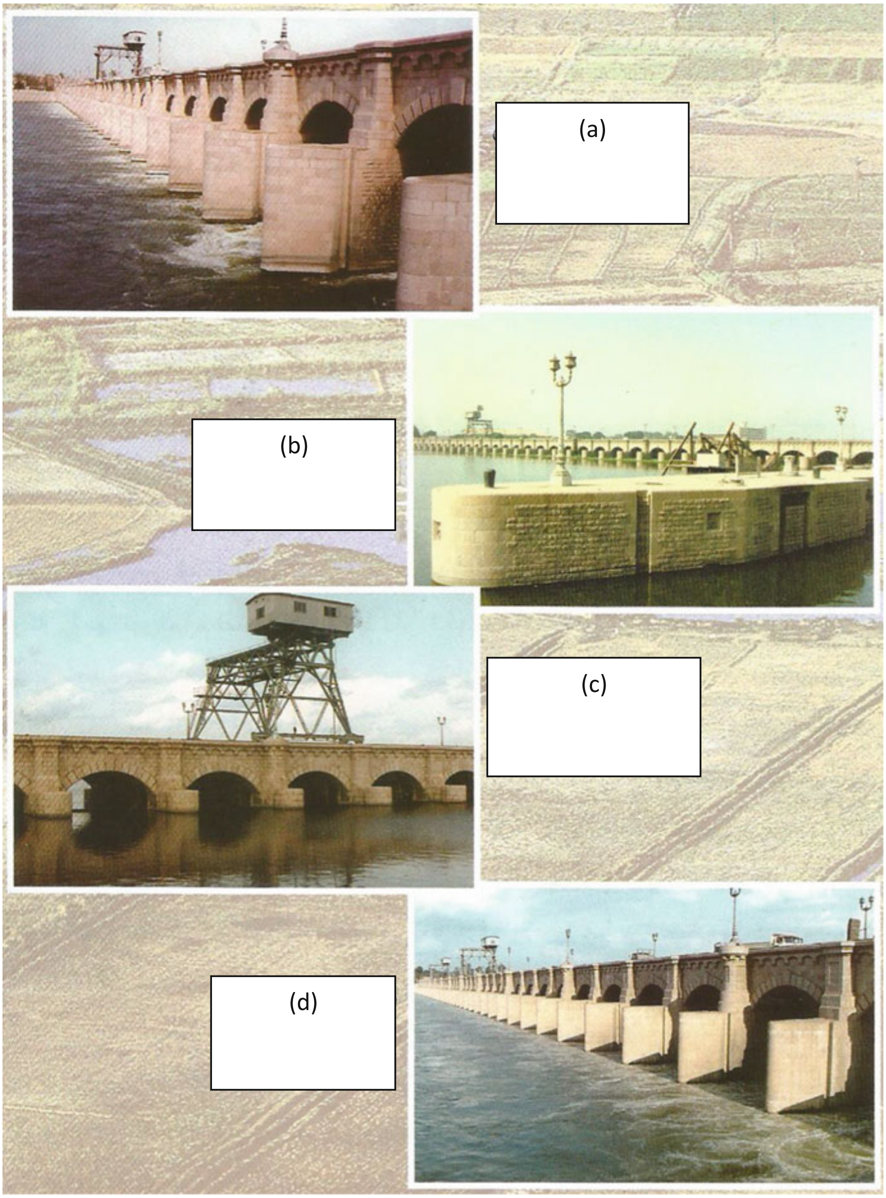

Fig. 3 Upstream and downstream sides of Damietta (**a**, **b**) and Rosetta (**c**, **d**) branches of the New Delta Barrages [3]

and Fayoum with irrigation water. On the Damietta branch, Zifta Barrage and Farskour Barrage regulate flow in the upstream and downstream ends and on the Rosetta branch. Edfina Barrage acts as a tail escape which allows Nile water to flow to the Mediterranean under emergency circumstances.

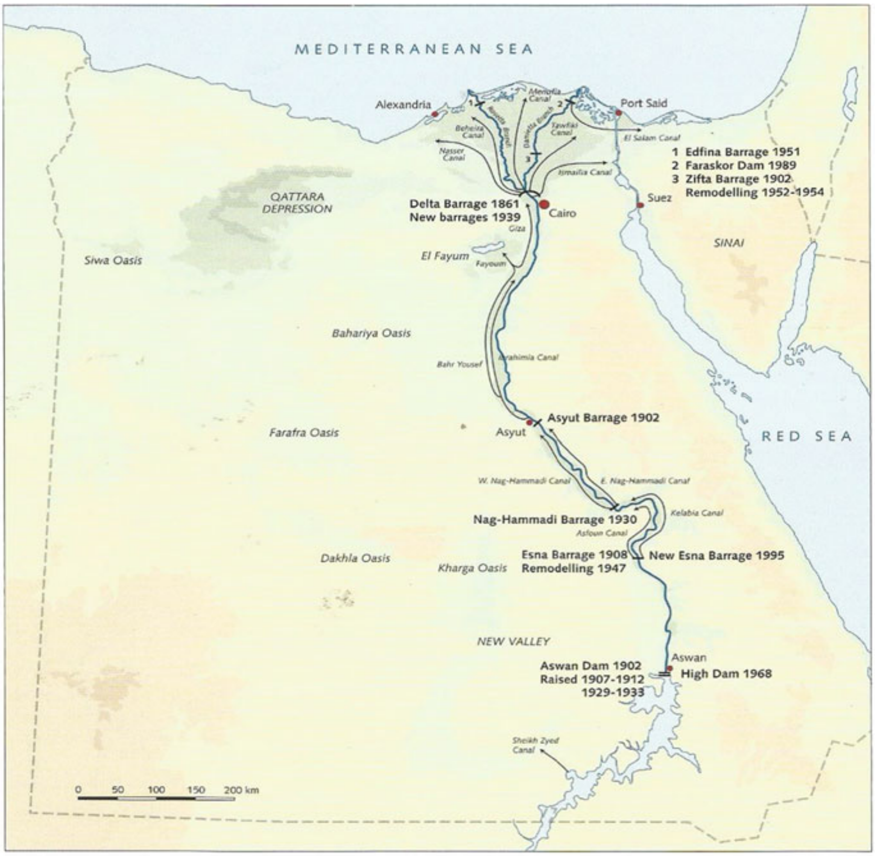

Fig. 4 Main irrigation canals and major barrages on the River Nile in Egypt [3]

6.6 Aswan High Dam

With the growing population and the need to improve the people's standard of living, the historic plans of the country to establish a long-term storage reservoir came to reality in the late 1950s and the early 1960s. Construction of Aswan High Dam is one of the very well-remembered stories of the Egyptian struggle against the imperialists of that age (Britain, France, and Israel). The cost was a series of wars which started in 1948, 1956, and 1967 and ended in 1973 with the evacuation of the last foreign soldier from the Egyptian soil.

From the technical point of view, the Aswan High Dam achieved the following main objectives:

– Enabled the generation of 80% of the country's energy when it was constructed
– The conversion of 700 thousand feddan from basin to perennial irrigation

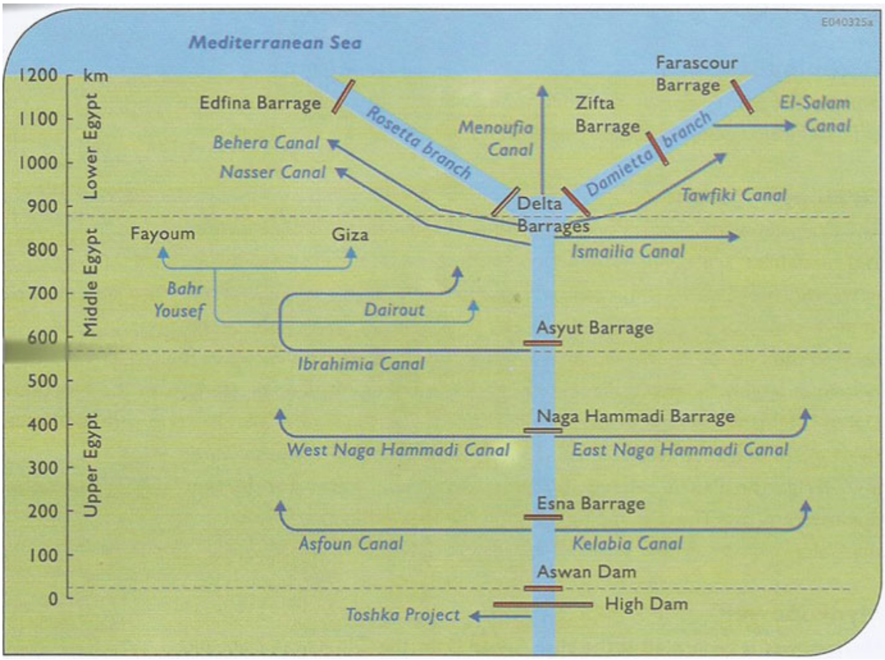

Fig. 5 Schematic diagram of the major barrages on the River Nile in Egypt [2]

– The cultivation of about 1 million feddan with rice in the northern Delta
– The reclamation of almost 2 million feddans of desert and on the fringes of the Nile Valley and Delta bringing them to economic cultivation
– Protected the country from both high and low floods
– Protected the country from the negative impacts of seawater intrusion

Many reporters stress the fact that the Aswan High Dam was behind the successful overcoming of the difficulties caused by the rocketing population growth through the period from the 1950s when the population was only 20 million to this year 2017 with the population touching 100 million. The cultivated area during that period increased from 6 million feddans to more than 8 million feddans. Figure 6a shows a general view of the Aswan High Dam, while Fig. 6b shows its hydropower generation plant.

6.7 *Drainage Projects*

Drainage projects in Egypt became a must after the conversion of some areas from uncontrolled and controlled flooding into perennial irrigation. It is clear that the flood irrigation was performed by allowing water to spread over the area during the flood

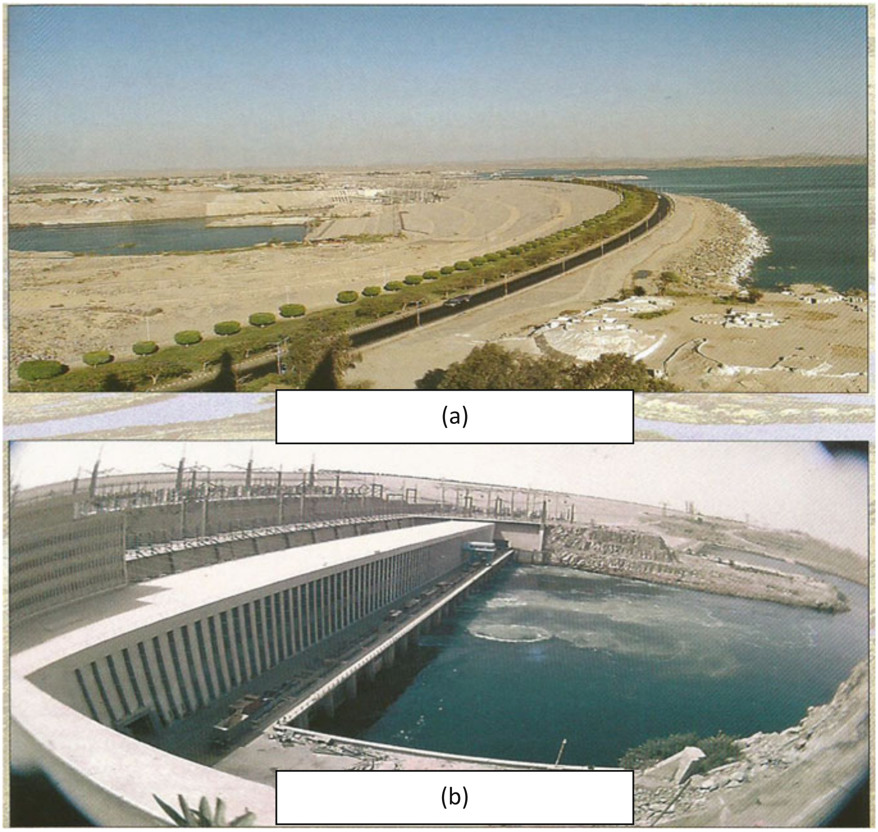

Fig. 6 (**a**) Aswan High Dam and its (**b**) hydropower generation plant [1]

season and remain over the land surface for a long period and allowing the water to flow back to the Nile by the end of the flood period. This process allows for the leaching of any accumulated salts during the dry season both from the land surface and from the soil profile.

When perennial irrigation started at the beginning of the eighteenth century, more than one crop was cultivated in succession every year, and therefore salinity buildup is expected to take place. The solution was to add leaching requirement to irrigation water either intermittently or seasonally. In both cases, the evacuation of salts from the soil profile was needed.

Drainage of agricultural land was practiced to remove salts from the land surface and the soil profile and to control the subsurface water level to maintain this profile well aerated and partially unsaturated. Drainage projects started with the excavation of a hierarchy of open drains starting with the small-field (lateral) drains, connected to collector drains. Collector drains are further connected to main drains and consequently to principle (first-order) drains. The first-order drain may end in the coastal lakes or the Mediterranean Sea either by gravity or by lifting through pumping stations.

By the beginning of the nineteenth century, open-field drains were gradually changed to fire clay and concrete pipes, and the collectors were also changed to concrete pipes. The construction of the High Aswan Dam in the middle of the century marked the change of all the cultivated lands from basin to perennial irrigation, and this change was accompanied by a widespread increase in drainage projects. It can be stated at the time being that all cultivated areas in Egypt are provided with main open drains, and most of these lands are installed with field drains of PVC and UPVC perforated pipes and polyethylene collector drains of different diameters.

The Egyptian General Authority for Drainage Projects (EPADP) and the Drainage Research Institute were established to implement the required projects and to carry out the necessary research in this respect.

The plan after the completion of coverage of all drainage projects is to carry out the necessary maintenance projects, rehabilitation, replacement, and renewal of the projects where the virtual life of the system came to an end (Fig. 7).

6.8 Irrigation Improvement Projects

After all these years of heavy-duty utilization of the irrigation system in the Nile Valley and Delta, the system became aging. The continuous rehabilitation of different elements of the system, the replacement of control structures, and the day-to-day repair of small defects here and there did not become effective anymore. It was, therefore, realized that the only way out is to have comprehensive programs for overall improvement including both the conveyance and distribution network and the on-farm irrigation elements.

One of the major steps taken toward improvement was the replacement of old barrages in Isna, Nag Hammadi, and Assiut by new modern head regulators. The replacement of Dairote head regulator feeding Bahr Yussef Canal, the main source of irrigation and domestic water supply to Fayoum Governorate, is under consideration at the time being.

Second, some first-order canals like Rayah Tawfiki fed from the Nile upstream to the Delta Barrages, and providing large areas in the Eastern Delta with their water requirements was also subject to the replacement of the old offtake structure with a new modern offtake.

Third, some first-order canals, like Ismailia Canal, were subject to significant rehabilitation works by lining long stretches from which water was seeping on both sides, creating flooding problems for villagers and inundating the lands on both sides of the canal. The lining of Ismailia Canal was a piece of state-of-the-art technology carrying out the works when the canal is entirely in service just because it was not possible to close the canal which transports potable water to the three governorates of Suez, Ismailia, and Port Said hosting millions of citizens.

Trials on the improvement of on-farm irrigation systems started with the issue of a law that prohibits the use of surface irrigating in newly reclaimed desert lands.

Fig. 7 Types of drainage machines used in Egypt [3]. (**a**) Concrete pipes (diameter 100 mm). (**b**) Corrugated PVC pipe (diameter 80 mm). (**c**) V-plough, trenchless drainage machine. (**d**) Concrete large-diameter pipes (150–400 mm). (**e**) Large-diameter corrugated PVC pipe (200–400 mm)

Gravity irrigation is only allowed in Valley and Delta old lands which are mainly composed of heavy clay soils.

The "Egypt Water Use and Management Project" (EWUP) was the first attempt to improve on-farm irrigation in three pilot areas in Kafr El Sheikh, Giza, and Minya Governorates. The second major attempt was in Dakahlia Governorate in which a project "Integrated Soil and Water Improvement Project" (ISAWIP) was implemented in a prototype area of thousands of feddans. The first project (EWUP) was technically assisted by the USAID and the second by the Canadian aid (CIDA).

The two projects brought in a World Bank Technical Assistance on Irrigation Improvements Projects (IIP) and an Integrated Irrigation Improvement and

Management Project (IIIMP). The principal idea behind these projects is to create the minimum conditions required to integrate different on-farm activities including irrigation, drainage, cropping, soils, climate, fertilizers, agricultural processes, land leveling, plowing, etc. All in one package and try in the meantime to improve the situation of one of these elements at a time.

Apparently, the starting point was irrigation. Studies on the lining of main irrigation canals and the replacement of such canals by closed conditions and pipelines did not bring about dramatic changes. These significant alterations had been seen as cost-ineffective simply because of the disadvantage of earth canals: (1) evaporation from the free water surface, (2) seepage from both sides, and (3) the growth of aquatic weeds and water plants. All these disadvantages were not as costly in their opinion as for the cost of lining or replacement of open channels by closed conduits.

It has to be mentioned here that under some site-specific conditions, long stretches of open canals are replaced by closed reinforced concrete culverts especially when these canals cross residential areas because the open channels in some of these cases were used as solid garbage collectors and sewage disposal locations from the inhabitants of the adjacent areas.

The Irrigation Improvement Projects financed by the World Bank and cost recovered from the beneficiary farmers were based on the following principles:

1. The change from the multipoint lift on the mesqa by one point lift at the beginning of the stream
2. The change from an earth mesqa to line or to a pipeline according to topographic conditions
3. The mesqas elevated in order to reach all the areas served by gravity
4. The change from conventional sluice gates to automatic downstream control gates capable of being operated according to the situation of downstream abstraction
5. The formation of Water User Association (WUA) being fully in charge of the operation of the mesqa, water distribution among farmers, cleaning of the mesqa, and resolving any disputes between the mesqa users
6. The formation of Irrigation Advisory Service (IAS) groups to carry out water extension and advise the farmers on issues of water saving, simple rehabilitation actions, water management procedures on the farm scale, and upstream and similar issues

Since the cost of the Irrigation Improvement Projects was paid by the World Bank and reimbursed by the farmers, the issue was subject to different debates all concentrated on the cost-effectiveness of the projects. At a particular stage, the IIP was upgraded to IIIMP to cater for a “system approach” in which irrigation, drainage, soils, crops, and machinery were integrated into the improvement package. In the meantime the different supply items, i.e., Nile water, groundwater, rainfall, and flash floods, and different demand items, i.e., potable and domestic water, industrial requirements, fish farming, etc., were also integrated into the “system.”

The irrigation improvement projects implemented so far are only the first step toward improvement. They indeed will be followed up by further steps to bring both the conveyance and the on-farm system to the form that is compatible to the present challenges and capable of finding the most appropriate most up-to-date and state-of-the-art techniques to be used to face these challenges.

7 Concluding Remarks

Since the dawn of history, the Egyptians are always concerned about how to develop their irrigation system and how to improve this system to meet the ever-increasing demand for food and natural fiber. The last 200 years witnessed large alteration, promotion, and upgrading of the irrigation system through the introduction of new irrigation development projects. The Summer Canals Project was first implemented to increase storage capacity of floodwater as well as to replenish groundwater reservoirs by downward percolation. The construction of the Delta Barrages marked an important step toward the introduction of modern management.

Although the excavation of the Suez Canal appears to be an essential transportation project, yet, it was accompanied by vital water conveyance open channel to transport Nile water to the site of the Suez Canal project.

For the first time in the Egyptian history, a dam was built on the Nile to store floodwater at Aswan. The Aswan Dam (1898–1902) started with a storage of 1 billion m^3 every year, heightened in 1912 to an increased capacity of 2.5 billion m^3 and again in 1932 to reach a storage of 5.0 billion m^3. From 1912 onward, a set of barrages were constructed on the Nile and its two branches in the Delta which enabled a complete and comprehensive management of irrigation water in the Nile Valley and the Delta.

The Old Delta Barrages constructed in the nineteenth century were replaced by new barrages in the year 1932–1935, adding new improvement element to the system. The construction of Aswan High Dam in Aswan proved to be the worldwide project of the century due to its several advantages to the country.

The renewal of the barrages which exceeded their virtual age has now been carried out in Isna, Nag Hammadi, and Assiut, and new barrages were constructed at the tail end of Damietta branch close to Farskour.

The country put drainage projects as a priority after the construction of Aswan High Dam, and the maintenance and replacement of old projects are taken as continuity of drainage project.

The irrigation improvement projects as implemented by the Ministry of Irrigation and partially by the Ministry of Agriculture are first steps in the attempt to bring the old on-farm irrigation system to a new look. The newly improved irrigation system should be capable of (1) improving food and fiber production, (2) conserving the available water and infrastructure resources, and (3) increasing in the meantime the farmer's income as essential and precious human resources of the country playing a significant role in the overall development.

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Part II
Key Features, Administrative and Legal Framework

Key Features of the Egypt's Water and Agricultural Resources

Mohamed Abdel Meguid

Abstract In Egypt, the estimated cultivated land (irrigated and rain-fed areas) is about 24,960 km^2 from the total area of 1 million km^2. There are four main agroecological zones that are identified as follows: (1) the North Coastal Belts, (2) the Nile Valley, (3) the Inland Sinai and the Eastern Desert, and (4) the Western Desert.

Crop cultivation in Egypt takes place during three consecutive cropping seasons: the winter, summer, and nili (Kharif) seasons, depending on the irrigation rotation. At the same time, there are areas cultivated with annual crops, such as sugarcane and fruit trees. This crop diversification makes the total cropped area 13.7 million feddans, i.e., crop intensity of 172%.

Concerning the land tenure structure in Egyptian agriculture, it is clear that fragmentation of the agricultural land is a major characteristic of Egyptian agriculture, especially in the old land. Such fragmentation has always had a negative impact on the rate of growth in the agricultural sector.

Egyptian policymakers pay special attention on the agricultural sector for its importance in ensuring food security to the rapidly growing population through the vital activities, such as better utilization of agricultural resources, using drainage water reuse, reusing of treated wastewater, improving water use efficiency, managing groundwater resources, and developing a horizontal expansion area through reclaiming new lands.

Keywords Agriculture, Egypt, Water resources

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Contents

1 Introduction

Egypt has a total area of about 1 million km^2. The population is estimated at 90 million in the year 2015, and it is expected to increase to 100 million by 2025. Egypt is mostly a rainless country with a semiarid to extremely arid climatic condition and displays the classical features of arid zone hydrology [1, 2]. The average yearly rainfall as a whole is only 10 mm/year. The Northern Coastal Zone areas and Sinai possess a reasonable winter rain with an average less than 200 mm/year [3]. Unfortunately, the precipitation is not used efficiently because most of the water goes to the sea and in some cases causes disaster on its way there. The estimated yearly total runoff that could be harvested in such cases is about 1 billion m^3/year.

Since ancient times, the Nile River has been the artery of life for the surrounding population from time immemorial. Moreover, any sort of development (i.e., agriculture, industrial, cultural) mainly depends on the availability of Nile water. The downstream flow of the river ends in Egypt with the Nile Delta located between two branches (Rosetta and Damietta). The Egyptian territory covers an area of about 1 million km^2. However, the Nile morphology and the barren deserts that bound the Nile Valley and Delta constitute a geographical barrier that prevents Egyptians from fully utilizing their territories [4]. This is why about 99% of the population is concentrated in 5.5% of the country area mainly located in the Nile Valley and Delta which has led to high intensity of population concentrated mainly in the capital (>20.000 person/km^2) [5].

Egypt is one of the countries facing great challenges due to its limited water resources represented mainly by its fixed share of the Nile water (55.5 billion m^3/year), most of which originates from external resources, and its aridity as a general characteristic [5]. Formulation of Egypt's water resources policy for the twenty-first century requires a major shift from the classical pattern used in water resource planning and management to a new innovative paradigm. Dynamic interrelationships among water resource system components impose the integrated approach on policymakers. The Egyptian Government prepared its first national policy after the construction of the Aswan High Dam in 1970 [6]. Since then, several water policies were formulated to accommodate the dynamics of the water resources and the changes in the objectives and priorities. The latest policy was issued in January 2005. It included several strategies to ensure satisfying the demands of all water users and expanding the existing agricultural area through reclaiming new lands. It also gave farmers the chance to share in the different responsibilities concerning the water distribution system and the drainage water reuse besides choosing their own crop pattern [6, 7].

In fact, the agricultural sector plays a central role in the Egyptian economy, contributing 14.5% to GDP of output; and it is the largest employer as it accounts for more than 30% of the work force [6, 8].

2 Geology and Geomorphology of Egypt

In Egypt, the Nile Delta and the Valley consist of alluvial deposits (gravel, sand, and Nile mud). The Fayoum Depression is of lacustrine deposits and Nile mud. The thicknesses of different layers have changed since the Aswan High Dam was constructed [9].

Within Lake Nasser, at Wadi Halfa, the Nile flows for more than 300 km in a narrow valley bordered by abrupt cliffs of sandstone and granite before reaching the first cataract which starts about 7 km upstream of Aswan. Narrow strips of alluvial land could be cultivated on both banks of the Nile in many parts of the Wadi Halfa-Aswan reach, but these, together with other features below the 180 m contour, are being located in the area of the High Dam Lake (Lake Nasser). Downstream of the cataract, the valley begins to broaden, and flat strips of cultivated land between the river and the cliffs gradually increase in width northward. The total area of Upper Egypt (the Nile Valley) is about 12,000 km^2, stretching over a distance of more than 1,000 km. Lower Egypt (the Nile Delta) is twice the area of Upper Egypt [9]. Beside the apex, it spreads in a plain studded with an intricate network of canals and drains. In this area, seven major branches of the Delta are mentioned by various historical documents and in ancient maps [10]. These branches are the Canopic Branch (the present Rosetta Branch), Bolbitinic Branch, Sebennitic Branch, Fatmetic Branch (the present Damietta Branch), Mendisy Branch, Tanitic Branch, and Pelusiac Branch. Five of these branches generated and silted up in the course of time, whereas two branches, Rosetta (about 239 km) and Damietta (about 245 km), are still running [10]. The whole mesh loses itself in a coastal marsh belt of wastelands (Berari), punctuated with a number of coastal and inland lagoons.

The Nile Delta appears as a triangle broader at the base than the sides. The length of the Delta from south (the Delta Barrages) to north (the Mediterranean Sea) is about 170 km and its breadth is 220 km. The area of the Nile Delta is about 22,000 km^2, and it represents about 63% of the Egyptian fertile land. The northern coast of the Nile Delta has three shallow lakes: Manzala (in the east), Burullus (in the middle), and Idku (in the west).

Formerly, all the lands of the Nile Valley and Nile Delta were watered by inundation of the basin system. The silt of the water, before the construction of Aswan High Dam, gave an annual increase in sediment (1 m of mud every 1,000 years). In the past, these silts were carried by the Nile water to form the fine fertile land. Nowadays, no silt reaches the Egyptian lands, and the cultivated areas have been lost their fertility [10].

3 Climate

3.1 Temperature

The climate in Egypt is generally moderate; it is mostly hot or warm during the day and cool at night. In the coastal regions, daytime average temperatures range between a minimum 14 °C in winter and maximum 30 °C in summer [11]. In Egypt, there are three types of climatic condition: the Mediterranean climate on the northern coast, the desert climate in the inland areas, and finally the climate of the coast of the Red Sea and desert as well but also a bit milder [11].

3.1.1 Mediterranean Coast

Winter is mild and looks more like spring: highs are around 18/19 °C and lows around 9–10 °C; this is the only period of the year in which weak or moderate rains occur. Summer is long, hot, muggy, and sunny, with highs around 30 °C, but tempered by sea breezes. The humidity is high especially in the Delta of the Nile River [11].

3.1.2 Inland Areas

The climate is desert, with virtually no rain; the temperatures increase gradually as you head south. The diurnal temperature range is remarkable, due to clear skies and low relative humidity. Winters are mild and sunny, but nights are cool or cold, ranging from 5–7 °C in the central area to 10–11 °C in the southern area (see Aswan), but in the coldest nights, the temperature can approach freezing. The winter days are pleasantly mild or warm, about 20–22 °C on average. In the inland areas, summers are scorching, with highs ranging from 36–37 °C in the central area to 40–42 °C in the south, and during this season, the sun reigns. In the warmest periods, in the south the temperature can reach 50–52 °C [11].

3.1.3 Coasts of the Red Sea

The climate is desert, but tempered by the sea, the rainfall is very little or totally absent as in the inland areas, but the temperature range is lower and the humidity is generally higher. In summer, the days are therefore very hot and humid, with minimum temperatures around 25 °C and maximum temperatures around 34–35 °C, except when the wind blows from the desert, raising the temperature while lowering the humidity. On the coast east of the Sinai, where the prevailing wind in summer comes from the desert, the heat is more intense but moisture is lower. During winter, the temperature on the coast is very mild, so that highs hover around 21–22 °C, while the minima stay around 10–12 °C [11].

3.2 Rainfall

An extremely arid climate prevails in the Nile Valley: high temperature, low relative humidity, high evaporation, and negligible rainfall (1.4–5.3 mm/year) [12]. Climatic aridity gradually decreases northward. At the Delta Barrages and Tanta, the annual rainfall is 20.8 mm and 45.5 mm, respectively. The climate of the deltaic coastal belt of Egypt is an extension of that of the Western Mediterranean Coast. The annual rainfall is about 160 mm in Rosetta and 102 mm in Damietta.

Winds are generally light, but violent dust storms and sand pillars are not rare. El-Khamasin winds blow occasionally for about 50 days during spring and summer [12].

The Fayoum Depression is in the arid part of Egypt with annual rainfall of about 14 mm; mean annual maximum and minimum temperatures are 29.5 °C and 14.5 °C, respectively; mean annual evaporation is 6.9 mm/day; and mean annual relative humidity is 66%, 32%, and 51% at 6 a.m., noon, and 6 p.m., respectively [12].

The Fayoum Depression is part of the Western Desert. Being the nearest to the Nile Valley and after being connected with the River Nile by a large irrigation canal (Bahr Yusuf), the Fayoum Depression is considered part of the Nile Region. The lowest part of the depression is occupied by a shallow saline lake – Lake Qaroun – which is about 4.5 m below sea level and about 200 km^2 in area. The depression has a total area of about 1,700 km^2. Its floor is just above the lake level and is about 23 m above sea level (ASL) [12].

3.3 Wind

Maximum wind speeds, magnitudes of wind vectors, and persistence are found mainly in the coastal areas of Egypt and in the vicinity around Nasser Lake. In other parts of Egypt, these variables are relatively low.

The direction of the major wind in coastal areas and north of Egypt is coming mainly from northwest to northeast direction. In most sites nearby or at coastal areas, the wind speed culminates in the summer season. This may be attributed to the effect of high contrast between sea surface temperature and that of land [13]. In the further south of Egypt, the wind comes from southwest to northeast direction [13].

It was found that mean energy density from the wind at 50 m above ground level ranged from 100 to 1,200 W/m^2. At the same time, maximum available energy density ranged from 200 to 2,300 W/m^2 [13].

The Wind Atlas for Egypt confirms the existence of a widespread and particularly high wind resource along the Gulf of Suez. The Wind Atlas further indicates that the wind energy resource in large regions of the Western and Eastern Desert – in particular west and east of the Nile Valley between 27°N and 29°N, but also north and west of the city of Kharga – is much higher than hitherto (sunny and mild, suddenly turned cold) assumed. The mean wind speeds predicted are between 7 and 8 ms^{-1}, and the power densities are between 300 and 400 W/m^2, estimated at the height of 50 m above ground level “a.g.l” [13].

3.4 Solar Radiation

The Solar Atlas in Egypt was issued in 1991, indicating that Egypt as one of the sun belt countries is endowed with high intensity of direct solar radiation ranging between 1,970 to 3,200 kWh/m^2/year from north to south. The sunshine duration ranges from 9 to 11 h with few cloudy days all over the year, and total sunshine hours vary between 3,200 and 3,600 h/year [14–16].

4 Agroecological Zones in Egypt

4.1 Types of the Agricultural Lands

Egypt has total area of about 1 million kilometers, under arid and hyperarid climatic conditions, of which only a small portion is agriculturally productive [4]. There are types of agricultural land (old and new lands) [17].

4.1.1 Old Lands

The old lands represent the largest irrigated area in Egypt and are found in the Nile Valley and Delta. These include lands which were claimed from the desert many generations ago and are intensively cultivated, mostly using water from the Nile. These lands are characterized by alluvial soils and are irrigated by traditional surface irrigation systems, which, compared to modern and improved irrigation systems, have a very low field water application efficiency of around 50% [17].

The main water issues of interest in the old land are related to water management at the farm level and lowering the high water table and reduced salinity. These could be rectified partly through an improvement of irrigation and drainage system networks.

4.1.2 New Lands

New lands (old-new lands and new-new lands) include lands that have been reclaimed relatively recently – particularly since the construction of the Aswan High Dam – or areas that are currently in the process of being reclaimed. They are located mainly on the east and west sides of the Delta and are scattered over various areas of the country. New lands cover about 2.5 million feddans [17]. The River Nile is the main source of water for irrigation, but in some desert areas, they use groundwater. Exercised sprinkler systems and drip irrigation exist in the new land. Historically, land reclamation is the largest governmental agricultural investment.

4.2 Basic Features of Main Agroecological Zones

Egypt is endowed with four main agroecological zones having specific attributes of resources base: climatic features, terrain and geographic characteristics, land use patterns, and socioeconomic implications [18, 19]. Such zones are identified as follows:

1. North Coastal Belts, including northwest coastal areas and north coastal areas of Sinai.
2. The Nile Valley, encompassing the fertile alluvial lands of Upper Egypt and the Delta and the reclaimed desert areas in the fringes of the Nile Valley.
3. The Inland Sinai and the Eastern Desert with its elevated southern areas.
4. The Western Desert, oases, and southern remote areas, including East Owenat Tock and Drab El Arabian Areas and oases of the Western Desert.

4.2.1 North Coastal Areas

The north coastal areas of Egypt contain two major subzones: the northwest coast and the north coastal areas of Sinai [4].

Northwest Coast

The northwest coast of Egypt has a belt about 20 km long. This belt extends for about 500 km between Amria (20 km west of Alexandria) and El Salloum near the border of Libya [4].

The northwest coast (NWC) is characterized by Mediterranean climate condition, with average high and low temperatures of 18.1 °C–8.1 °C in the winter and 29.2 °C–20 °C in the summer, respectively. In NWC, the rainfall ranges between 105.0 mm/year in El Salloum and 199.6 mm/year in Alexandria. Most of the rainfall occurs during the winter months (November to February). There is significant variation in rainfall from one location to another, which is mainly attributed to the orientation of the coast at many locations. The prevailing rainfall gradient from the north shows that the average rainfall gradient decreases sharply from 150 mm near the coast to 50 mm at 20–70 km inland. The water supplied is mostly from rainfall, and groundwater resources are limited and usually of low quality especially with respect to varied salinity content.

The coastal area has wind speed with an average of 18.5 km/h in the winter season. It represents the highest average wind speed in Egypt. However, the wind speed drops gradually inland.

In this area, the soil and its properties is highly influenced by geomorphic and pedogenic factors. The main soil units can be summarized as follows:

1. Coastal oolitic sand dunes.
2. Soils of the lagoon depressions.
3. Consolidated dunes.
4. Deep sand and clay loam soils.
5. Moderate to limited depths of sandy to clay loam.
6. Soils of the alluvial fans and outwash plains over the plateau.

North Coastal Areas of Sinai

This area covers about 56 thousand km^2 (13.3 million feddans) which represents 5.6% of Egypt's land surface [4].

The length of the northern strip is about 5 km and has a very gentle slope in the south–north direction reaching about 20 m above sea level (ASL) in the southern parts. However, the medium slope develops toward the inlands and has an elevation which may reach 90 m (ASL). Physiographically, North Sinai is characterized by the Tina Plain in the east which is formed of Nile alluvial deposits in the lowest lying areas of Sinai. It is located in the middle of the Bardaweel Lagoon (Shallow Lake). In the south of Bardaweel, the desert plains extend with large areas of sand dune belts and sand sheets. The coastal zone in this area is dissected by the largest wadi in Sinai, Wadi Al-Arish, which emerges from elevated gravelly plains and terraces in the south to a distance of about 20 km until the Mediterranean Sea Coast.

The North Sinai areas are characterized by the dry Mediterranean climate type with relatively rainy, cool winters and dry hot summers. Air temperatures are similar to those of the NWC but with large variations diurnally, seasonally, and geographically. The annual wind speed is around 14.0 km/h, and the prevailing wind direction is northwest and north.

The amount of rainfall in the Sinai decreases from the northeast toward the southwest with the greatest amount of rainfall being found in Rafah (304 km/year) in the northeast. The annual average along the Mediterranean Coast amounts to 120 mm/year. Rainfall decreases in the uplands to the south to about 32 mm/year. On the whole, the average annual rainfall in the entire Sinai Peninsula is 40 mm, of which 27 mm are estimated to come from individual storms that may provide 10 mm at a time.

Rainfall occurs in the Sinai mainly during the winter season (November to March) and during spring or fall. Rainfall is practically absent from May to October. Along the Mediterranean Coast, 60% of the rain occurs in the winter, while 40% falls during the transitional seasons. Due to differences in water availability, growing seasons differ in the different parts of the Governorate of North Sinai.

The desert soils of Northern Sinai are of three different origins: Aeolian, alluvial, and soil formed in situ. The latter is related to land form and is found in the plateau region of Wadi Al-Arish on either calcareous or volcanic parent material.

The majority of alluvial soils were formed under recent climatic conditions. They constitute the present wadi beds, and they are characterized by a granulometric differentiation according to flood intensities and sedimentation times. As a consequence, soil in the upstream of the wadis is coarser in texture than the soils further downstream. In the dune area, the soils are generally different than in the gravel plain. The dune area is dominated by soils with almost no signs of soil-forming processes. Saline soils are found exclusively in the coastal zone. Haplic calcisols are dominant in the desert region in the gravel plains. The Tina Plain in the west was formed of Nile alluvial deposits as a natural extension of the old Nile Valley. The soils are heavy textured with high salinity contents due to water logging condition attributed to the near-sea and low-lying location.

Water resources are varied with rainfall runoffs if the rainfall exceeds 10 mm per rainy storm. When runoff occurs, wadi beds will begin to carry water depending on the amount and duration of rainfall. It is estimated that 60% of the mean rainfall in Sinai is lost to evapotranspiration.

Groundwater in Sinai may be classified into two types. Shallow groundwater occurs mainly within a weathered layer of igneous and metamorphic rocks, Quaternary rock, recent deposits such as wadi fill, or sediments and sand dunes. Deep groundwater mainly occurs as semi-confined aquifers of per-Quaternary formation. Groundwater resources in the north coastal area are limited in nature and in general of low quality. A third water resource is being introduced to the area, namely, "Al-Salam Canal" which will convey mixed Nile and agricultural drainage water across the Suez Canal to reclaim about 400,000 feddans in Northern Sinai [20].

4.2.2 Nile Valley and the Reclaimed Desert Fringes

This zone covers an area of about 40,000 km^2 (the Nile Valley and the Nile Delta cover an area of 11 and 29,000 km^2, respectively), representing 4.0% of Egypt's land surface [4, 19].

The Nile Valley system extends from the Mediterranean shores of the Nile Delta to the north till Aswan in the south over an area extending from 22 to 32 latitude north under arid and hyperarid conditions. It represents the most fertile lands in Egypt. In this system, the crop productivity is intensive and highly diversified throughout the year. However, it has been the subject of several desertification factors and processes through the last few decades. Some of these factors and processes have been dealt with through technical and legislative measures which resulted in the significant decline of adverse impacts [18, 19].

The old Nile water conveyance system is still functioning with additional major canals conveying fresh Nile water to the newly reclaimed desert soils in the fringes of the Valley which are of relatively higher elevations.

Sizable amounts of the agricultural drainage water of the old Valley are recycled in the conveyance system and mixed with the fresh Nile water to be used for horizontal expansion of cultivated areas. Groundwater (mostly recharged by the Nile water) is of relatively limited use in the Valley but is specially used in the desert fringes [18, 19].

Soils vary but include the fertile deep alluvial soils of the old Nile Valley, soils of the river terraces at different relief which are deep soils with gravelly and reddish subsoils in addition to the soils of the fringes including desert calcareous soils of varied textures, and noncalcareous soils characterized with low soil fertility and inferior soil physical, chemical, and biological properties [18, 19].

4.2.3 Inland Sinai and the Eastern Desert

The Inland Sinai and the Eastern Desert cover an area of about 223,000 km^2, representing 22.3% of Egypt's land surface [4]. It extends to north of the southern region, from which it is separated by a huge depression stretching in an N-SE trend as far as about 60 km. This depression which averages 10 km width opens from northwest. It is influenced by several drainage systems. These systems include the Gulf of Suez system at the western and southwestern sides, Gulf of Aqaba system located at the eastern and southeastern fringes, and the pereimial channel overflow which takes place at several wadis dissecting the western and southwestern fringes of El Tieh tableland [18, 19].

The Inland Sinai occupies the central portion of El Tieh tableland. To the west, it is limited by the upstream portion of Al-Arish and its tributaries. This excavation stretches in a NW-SE direction for about 40 km attaining a 15 km width at the Bir El Malha area. Due to this depression, both Egma and El Tieh tablelands are completely separated. The surface of these tablelands is intensively dissected with drainage lines, flows toward north, and joins together into Al-Arish [18, 19]. The Eastern Desert is comprised of the following landforms:

1. The high rocky mountains: generally, the surface of the Eastern Desert is very rugged and rises in some places to more than 2,000 m ASL especially in the southern areas.
2. The desert floor: it is covered with countless sounded highly polished pebbles of brown flint or white quartz, materials brought down by ancient streams and spread out near the former shoreline.
3. The drainage channels: they are intensely dissected by valleys and ravines, and all their drainages are external. Most of the drainage lines run along major fault lines, and it is noticeable that while the eastward drainage lines run to the Red Sea by numerous independent wadis, the westward drainage lines run to the Nile Valley. Coastal mountains form the water divide.

The Eastern Desert represents the plain which covers the whole area of the Sinai, El Gifgafa, El Qaa, and the plain to the east of the Suez Canal. It has a fine to moderate, texture, brackish. Soil from the Eastern Desert varies widely according to their contribution to the terrain [18, 19].

4.2.4 Western Desert, Oases, and Southern Remote Areas

The Western Desert covers an area of about 681,000 km^2 which represent 68.1% of Egypt's land surface. This immense desert to the west of the Nile spans the area from the Mediterranean Sea south to the Sudanese border. This region is the driest one in Egypt and is famous for winds [4].

Land resources available in this region are one of the characteristics of weak and low resilience with widespread physical, biological, and chemical restraints. Most of these resources are located in a closed fragile ecosystem which is isolated from the Nile Valley system.

This region consists of three plateaus, separated by two depressions [4]:

- The Nubian Plateau, where the Nubian Sandstone Aquifer System (NSAS) extends below. Dakhla and Kharga Depressions are located in this Plateau.
- The Middle Plateau, where Farafra and Baharyia Depressions are located.
- The Northern Plateau, where Wadi El-Natrun and Qattara Depressions and Siwa Oasis are located.

The Western Desert extends from the southern boarders toward the northwest coastal areas in the north as a massive plateau with a general slope toward the north, starting from an elevation of about 1,000 m ASL to the extensive Qattara Depression at 134 m below sea level. The Western Plateau is distinguished with a uniform flat surface 40% of which is covered with sand dunes and extensive areas of sand sheets (the sand sea). Several depressions of varied areas are scattered in the Western Desert including the famous oasis of Siwa in the north, Baharia and Frafra in the central section, and Dakhla and Kharga in the south. These oases that are distinguished with artesian wells of large discharge of freshwater are mainly closed and fragile ecosystems where the population is concentrated.

This region's environmental and climatic conditions are characterized by severe drought, with rare rainfall and extreme temperatures. Winds (over the Western Sahara in the west or the north) stretch from the Mediterranean to the Western Sahara with falling speed. These winds are the main factors for erosion and sedimentation in the Western Sahara area. Clear evidence of these processes is the formation of the Great Sand Sea of sediment erosion of the Qattara Depression is located in the north.

The soil classification is a weakly developed red desert that has a chrome top of the red desert soil typical, and they are very thin or nonexistent. The formation of these soils indicates that the hot dry climate was the main soil-forming factor. The soils are formed of sand and are calcareous in nature.

Water resources are mainly that huge Nubian Sandstone, which extends with different thickness in the majority of the Western Sahara region layers. This major water resource is of excellent qualities in most areas. The renewal ability of the resource was investigated extensively with conclusions confirming a nonrenewable or very slowly renewable status.

5 Trend of Water Supply and Consumption in Egypt

According to the Ministry of Water Resources and Irrigation [14], the main source of water in Egypt is the Nile River. The Nile Water Agreement with Sudan allocates 55.5 billion m^3/year to Egypt [6]. This amount is guaranteed by the multiyear regulatory capacity provided by the Aswan High Dam.

Rainfall in Egypt occurs mainly in the winter in the form of scattered showers. The average annual amount of rain water effectively used is 1.3 billion m^3/year. This amount cannot be considered a reliable source of water because of the changing spatial and temporal high.

Groundwater in the Western Desert and the Sinai are often deep and nonrenewable. The estimated total volume of groundwater is about 40,000 billion m^3. However, it is estimated that the current abstraction is 2 billion m^3/year. The main obstacles to the use of these huge resources are the deep depths (up to 1,500 m in some areas) of the groundwater and the deterioration of water quality in the increasing depths.

The shallow groundwater in the aquifer of the Nile is considered as independent source of water. It is recharged from the Nile leakages, irrigation canals, banks, and losses nomination of irrigated land. And, therefore, it should not be added to the total return of Egypt's water resources. The abstraction from this aquifer is estimated at 6.7 billion m^3 in 2013.

Seawater desalination was given low priority in Egypt as a supplier of water because of the high cost of treatment compared with the rise of other sources. Desalination is practiced in the Red Sea coastal region to supply the villages and tourist resorts with enough supplies, where the economic value covers the costs of treatment. Other groundwater desalination units have been constructed at several locations in the Sinai as a water supply for Bedouins. It may become more crucial in the future if the growth of the demand exceeds available water resources. However, its use will depend on technological development in this field. The current water use from desalination is about 0.1 billion m^3/year [21].

Treated domestic sewage is being reused for irrigation with or without blending with freshwater. It is estimated that the total quantity of reused treated wastewater in Egypt is about 1.3 billion m^3 [21]. The increasing demands for domestic water will increase the total amount of sewage reuse.

The amount of water that returns to drains from irrigated lands is relatively high (about 25–30%). The total amount of reused water is estimated to be 11.1 billion m^3 in 2013–2014. The reuse practices increase the overall efficiency of the system as comparable to the efficiency of modern irrigation systems [14].

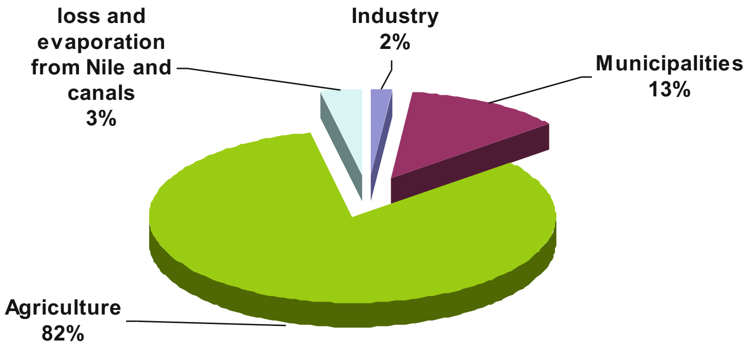


Fig. 1 Water withdrawal by sector in 2013–2014. Source: [21]

5.1 Water Demand for Agriculture

The total requirements of all socioeconomic sectors are estimated to be more than 76 billion m^3/year [21]. A gap between freshwater resources and the country's requirement already exists. As a result, Egypt is considered below the water poverty line and at the top of the list of water-scarce countries in the year 2000. This gap is expected to widen in the future. The possibility of increasing the freshwater resources from conventional sources is doubtful. In the meantime, nonconventional sources such as desalination or cloud seeding are also infeasible and expensive. In addition, water requirements of different sectors increase rapidly with time due to rapid population increase, ambitious agricultural expansion, and elevated living standards. In 2014, total water withdrawal was estimated at 76 billion m^3 which includes 62.35 billion m^3 for agriculture (83.3%), 9.95 billion m^3 for municipalities (12.8 %), 1.2 billion m^3 for industries (1.6%), and 2.5 billion m^3 loss and evaporation from Nile and canals (3.3%) as shown in Fig. 1. From this figure, it is clear that the agricultural sector is the highest freshwater consumer. The prediction of future water requirements will be accelerated with a combined effect of rapid population growth and an increase of food demand and living standards [5, 6].

5.2 Utilization of Water in the Irrigation System

5.2.1 Surface Water

Irrigation started around 6,000 years before the current era (BCE) in Egypt using the Nile water flooding on the surrounding banks. Around 3,000 years BCE, the first irrigation infrastructures (embankments, dams, and canals) were constructed by Egyptians, in some cases under forced labor, to divert the Nile waters into basins and expand the irrigated areas. Irrigation development included and still includes both increase in areas (horizontal expansion) and increase in water use efficiency (vertical expansion). Horizontal expansion results in the irrigated areas of Egypt being classified into:

1. The old lands of the Nile Valley and Delta.
2. Oases.
3. The new lands reclaimed since the Aswan High Dam construction (1970), generally less fertile, on the old lands' fringes, as well as in new locations outside the Nile Valley and Delta such as the Western Desert.

The irrigation system in Egypt is considered a closed one that has the main inlet which is the Nile River and other minor resources represented in the rainfall in the coastal zone and the deep groundwater in the desert. However, the outlets of the system are mainly crop evapotranspiration and outflow from the drains to the Mediterranean Sea.

Egypt's irrigation system extends over 1,200 km south of Aswan to the Mediterranean Sea, and this makes it possible for a year-round cropping. The cultivated farms are served by around 31,000 km of public canals (1,000 km of main canals and 30,000 km of secondary canals), 80,000 km of field channels (Mesqas), and 17,000 km of public drains [21].

The Canal System

Released water downstream the Aswan High Dam is distributed among regions through canals and pumps that divert water from the Nile River. These canals have regulators or weirs at spatial intervals depending on their slopes and the locations of the lower order canals. In general, the canal hierarchy includes secondary branch and distributary canals. This canal system is called public canals where the government is responsible for its operation and maintenance. The public canal system delivers water to private channels called mesqas serving an area from 50 to 200 feddans. Mesqas feed farm ditches, which are called merwas serving up to 20 feddans. Operation and maintenance of mesqas and merwas are done by the water users, who benefit from the extension services offered by the agricultural cooperatives [7].

Branch canals that take off from the main or lateral canals deliver the water to smaller distributary canals, which in turn deliver water to the mesqas. Because the water level in the system is below field level in most of the area, the water has to be raised through diesel pumps (or the traditional water wheels). In some areas, the farm intakes directly receive water from the distributaries. Besides the gravity diversion of Nile water, water is also diverted by more than 100 major pumping stations along the Nile and its branches.

The Drainage System

An intensive open drainage network was constructed along the Nile system downstream Aswan High Dam in order to transfer the excess irrigation water safely to the Mediterranean Sea and terminal lakes. This drainage network helped in improving the agricultural conditions such as lowering water table and leaching soil, which consequently increased the crop yield. Construction of an open drainage system started at the end of the nineteenth century when the soil was affected dramatically by the high water table and an increase in the salinity level. The open drainage network, at present, covers the whole cultivated land in the Nile Valley and Delta with a total length of about 16,686 km, of which 67% is in the Delta region and the rest is in Upper and Middle Egypt. In the Delta region, the open drainage network diverts about 12 billion m^3/year of drainage water out of the system with average salinity greater than 2,000 ppm. In the Nile Valley (Upper and Middle Egypt except for Fayoum), the open drainage system diverts about 4.0 billion m^3/year to the Nile stem (from Aswan to Cairo). The drainage water of the Fayoum governorate is released to Lake Qaroun and Wadi El Rayan at about 0.5 billion m^3/year [7].

Water Management Zoning

The water management zoning [22] can be classified into six zones as the following:

1. The Nile Valley in Upper Egypt.

   This zone represents the old irrigated batch along the Nile. It extends between the Aswan High Dam and upstream Assiut Barrage. The irrigated area in this zone is about 1.0 million feddans, 35% out of which is irrigated through pumping from the river. Within the irrigation system, the drainage agricultural water returns to the river by gravity [22].
   The climate is warm with high temperature compared to the northern areas. The dominated crop in this zone is sugarcane, and the second competing crops are maize in the summer and wheat in the winter [22].

2. The Nile Valley in the Middle Egypt.

   The middle Nile zone represents the old irrigated area. It extends between Assiut Barrage and upstream the Delta Barrage. The irrigated area in this zone is about 1.1 million feddans, where very little of the area is irrigated by pumping from the river (not more than 4%) on the eastern side of the river. Within the irrigation system, the drainage agricultural water returns to the river by gravity [22].
   Cotton and maize are the major dominant crops in the summer season, while wheat and berseem are the major crops in the winter season [22].

3. Fayoum area.

   The Fayoum area is a natural closed system located in the desert. The water delivery system is different and characterized by a steep hydraulic gradient. Water allocation is made on a continuous basis. The irrigated area in this zone is about 0.4 million feddans, where very little of the area is irrigated by pumping and the drainage water flows, by gravity, to Lake Qaroun and Wadi El Rayan Depressions in the desert [22].
   Cotton and maize are the major dominant crops in summer season, while wheat and berseem are major crops in winter season [22].

4. Newly irrigated areas.

   The newly irrigated areas extend north of Middle Delta until the coast of the sea and lakes (including Salam Canal area). The irrigated area in this zone is about 1.0 million feddans. Drainage water reuse is one of the main water practices in this zone, and the drainage water disposal is discharged to the lakes and the sea. This is characterized by a high water table and higher soil salinity [22].
   Rice is the major dominant crop in the summer season, while vegetables and berseem are major crops in the winter season [22].

5. Old irrigated area in the middle delta.

   The old irrigated area in the Middle Delta is about 1.5 million feddans. Drainage water reuse is one of the main features in this zone. It is characterized by a high water table [22].
   Cotton, maize, and rice are the major dominant crops in the summer season, while wheat and berseem are major crops in the winter season [22].

6. Old irrigated area in the southern Delta.

   The old irrigated area in the southern Delta extends over the region from Cairo to about 10 km northern Tanta. The irrigated Area is about 1.2 million feddans. The groundwater is available and of a good quality [22].
   Cotton and maize are the major dominant crops in the summer season, while wheat and berseem are the major crops in the winter season. Rice is grown in the governorate of Sharkia [22].

5.2.2 Groundwater

The Main Aquifers in Egypt

Groundwater in Egypt is found virtually everywhere in the sandy and gravely layers (aquifers) underneath the Nile flood surface and the nearby desert areas. Egypt's groundwater aquifers are located underground the Western Desert, Northern Sinai, Eastern Desert, and Southern Sinai [4, 23].

In term of groundwater hydrology, Egypt can be divided into the following groundwater provinces: (1) the Western Desert, (2) the Eastern Desert, (3) the Nile Valley including the Delta, (4) the Sinai Peninsula, (5) the Northern Coastal Zone, and (6) Wadi El-Natrun. Each hydrological location has different characteristics [22–27].

1. Western Desert

   The Western Desert extends from the Nile Valley in the east to the Libyan borders in the west and from the Mediterranean in the north to Egypt's southern borders. It is divided into the northern section, which includes the coastal plain, the Northern Plateau and the Great Depression, Natrun Valley, and Baharia Oasis, and the southern section, which includes Farafra, Kharga, Dakhla, and El-Owainat [28].

2. Eastern Desert

   Recently, the Eastern Desert area received a great amount of attention due to different development expansion activities to enlarge the agricultural, industrial, and touristic investments in these areas [29].
   In the Eastern Desert, the direction of groundwater flow is from the east to the west. The aquifer system attains a small range of log-transformed hydraulic conductivity. It ranges between 3.05 and 3.35 m/day [29].

3. Nile Delta and Nile Valley

   Policy options for agricultural groundwater abstraction in the Nile Valley and the Nile Delta have been developed recently. This approach is based on the specific characteristics of the groundwater aquifer in both the Nile Valley and Delta as a renewable water source in hydraulic contact with the surface water irrigation system. The Nile aquifer is characterized by its high productivity rate of (100–300 m^3/h) with relatively shallow wells at low pumping cost. Being a shallow aquifer, it is extremely vulnerable to pollution by surface-induced sources. Conjunctive use of surface and groundwater is widely practiced by farmers, especially during periods of peak irrigation demands. Since the aquifer is directly connected to the Nile River system, thus, it is directly affected by programs for reducing conveyance losses in waterways [28].

4. Sinai Peninsula

   In estimating the groundwater potential in the Sinai, distinction is made between shallow groundwater in the Quaternary aquifer and deep groundwater in the fissured carbonate and Lower Cretaceous (Nubian sandstone) aquifer.
   The total current use is about 90 million m^3/year. A large portion of the water is pumped from the Quaternary aquifer in the northern part of Sinai (El Arish, Rafah, Bir el Abd) [1].

5. Northern Coastal Zone

   The northern coastal aquifer runs parallel to the coast and is composed mainly of fine-grained limestone, but near the coast, it consists of alluvial deposits. The thickness ranges between 40 and 60 m. The aquifer is naturally recharged from rainfall, in addition to other local sources (leakage from water and sewage networks). The aquifer contains saline water (~20,000 ppm) and is mainly influenced by the Mediterranean and Lake Mariut inflows. However, limited thin freshwater body (200–1,000 ppm), floating on the upper saline water (1,000–3,000 ppm), has been developed in the alluvial sandy coastal dunes [30].

6. Wadi El-Natrun

   Wadi El-Natrun is a part of the Western Desert adjacent to the Nile Delta. It is a narrow depression located approximately 90 km south of Alexandria and 110 km northwest of Cairo.

   The Wadi is oriented in a NW-SE direction between the latitudes 30° 17′ and 30° 33′ N and between longitude 30° 02′ and 30° 30′ E. Its length is about 50 km, and it is narrow at both ends (2.6 km in the north and 1.24 km in the south) and wider in the middle (8 km). The Wadi lies 23 m below sea level and is characterized by a series of 20 small disconnected lakes.

   Groundwater quality is moderate (1,000–2,000 ppm), total dissolved solute (TDS) in the south and southwest, changing to poor (2,000–5,000 ppm) in the east. The increase in salinity is also encountered at greater depths. Groundwater is a mixture of fossil and renewable groundwater. The main recharge source is groundwater lateral seepage from the Nile Delta aquifer system and the infiltrating rainfall water [31].

Utilization of Groundwater in the Irrigation System

The management of groundwater is often fragmented among different stakeholders (government agencies, nongovernmental organizations (NGOs), farmer organizations, private sector, investors, etc.) based on the scale of involvement in the project area.

In general, the main water sector is the agricultural sector [32]. It consumes about 85% of the available freshwater and returns about 25% of the total allocated amount to the system (agricultural drainage and deep percolation).

The two most important groundwater aquifers are the Nubian Sandstone Aquifer System of the Western Desert and Nile Valley and Delta system. The deep and nonrenewable fossil water of the Nubian Sandstone Aquifer System covers about 65% of Egypt and extends into Libya, Sudan, and Chad [29]. Clearly, Egypt's demand already exceeds its apparent supply, and this is likely to be exacerbated in the future with increasing demand for expanding agriculture, population growth, urbanization, and higher living standards. As the volume of surface water from the

Nile cannot be guaranteed with shifting regional politics and uncertainties, groundwater exploitation will undoubtedly accelerate [33].

There are known to be more than 31,510 productive deep wells and 1,722 observation wells distributed throughout the Nile Delta, Nile Valley, coastal zone, oases and Darb El Arbain, and eastern Oweinat. These include wells for domestic and agricultural supply [28].

The 82% of Egypt's water demand is required for agriculture. Approximately 70% of this demand is satisfied by surface water diverted in the Nile Valley; the contribution from groundwater is most commonly on the fringes of, or outside of, irrigation project command areas. Around 25% of the total volume allocated to irrigation is thought to contribute to return flow and groundwater recharge via agricultural drainage and deep percolation. In the newly settled areas around oases and other depressions in the desert, the water supply systems on a subregional and local level include *mesqas* (small/tertiary canals used for water supply and irrigation), wells (government and private), collectors, and field drains [33].

In the newly settled areas of the Western Desert (west of the Nile), agriculture is mainly dependent on groundwater abstracted through deep wells from the Nubian Sandstone Aquifer System. Shallow aquifers in the mid- and southern desert are contiguous with the deep aquifer providing potential for further groundwater development, and there are plans to expand agricultural land around oases in the Western Desert with irrigation from both shallow and deep wells. The main obstacles to utilizing this resource are the great depths to the aquifer (up to 1,500 m in some areas) and deteriorating water quality at increasing depths, while in the Nubian Sandstone Aquifer System, the development of groundwater is naturally limited by pumping costs and economies of scale [33].

The shallow aquifer of the Nile Valley and Delta is considered nationally as a renewable water source with extraction largely from shallow wells with a relatively low pumping cost. This aquifer is considered as a reservoir in the Nile River system by the Ministry of Water Resources, with a large capacity but with a rechargeable live storage of only 7.5 billion m^3 year. The abstraction from this aquifer was estimated at 7.0 billion m^3 in 2009. Conjunctive use of surface water and groundwater is practiced widely by farmers, especially during periods of peak irrigation demand and at the fringes of the surface water irrigation network, where groundwater is the only source. In the Nile Delta areas, a distinction is made between "old" and "new" lands facing a shortage of irrigation water. In the old land, the main source of irrigation water is the Nile River, but toward the end of irrigation canals, groundwater is in many cases the only source which depends on the saturated thickness of the aquifer, storability, transmissivity, and infiltration rate [33].

The present developmental schemes are confined to shallow wells dug in Wadi aquifer system and desalination of groundwater. The total groundwater usage was estimated about 5 million m^3/year and is likely to reach about 8 m^3/year at present. There is a potential for further development, especially on the Nubian sandstone aquifer through deep wells (200–500 m) and in the large Wadis, which drain in the Nile Valley and Lake Nasser. In addition to the fresh groundwater, large amounts of brackish groundwater are expected to be available in the region. This requires proper assessment and prediction of possible change in salinity as a result of development. One of the areas of special interest is the Red Sea coastal area where a variety of aquifers are present. Signs of water availability are the flowing springs [33].

The development of groundwater in the country is highly uneven and shows considerable variations from place to place [23]. Studies of desert groundwater proved that the daily discharge of East Ewainat aquifer is 4.7 million m^3 and the discharge of this aquifer is 150 billion m^3 to be extracted in the long term (about a hundred of years). This amount is adequate for irrigating approximately 189.6 thousand feddans, assuming water requirements for 1 feddan in the desert are estimated at approximately 7,500 m^3 annually (300 days of irrigation). Meanwhile, the daily discharge of New Valley aquifer is 3.1 million m^3, and the discharge of this aquifer is 100 billion m^3 to be extracted in the long term. This amount is adequate for irrigating approximately 133.3 thousand feddans. The daily discharge of Sinai aquifer is 1.6 million m^3, and the discharge of Sinai aquifer is 50 billion m^3 to be extracted in the long term. This amount is adequate for irrigating approximately 66.7 thousand feddans. Thus, the daily discharge of nonrenewable groundwater is 9.4 million m^3, and the discharge of nonrenewable groundwater is 300 billion m^3 to be extracted in the long term. This amount is adequate for irrigating approximately 389.6 thousand feddans. However, the daily discharge of renewable groundwater is 3.6 million m^3, and the discharge of renewable groundwater is 100 billion m^3 to be extracted in the long term. This amount is adequate for irrigating approximately 143.7 thousand feddans. The total daily discharge of groundwater is 13.0 million m^3, and the total discharge of groundwater is 400 billion m^3 to be extracted in the long term. This amount is adequate for irrigating an area estimated at approximately 533.3 thousand feddans [4].

The increasing dependence on groundwater as a reliable source of water has resulted in indiscriminate extraction in various parts of the country without due regard to the recharging capacities of aquifers and other environmental factors. On the other hand, there are areas in the country, where groundwater development is suboptimal in spite of the availability of sufficient resources and canal command areas suffering from problems of water logging, soil salinity, and soil fertility due to the gradual rise in groundwater levels [23, 33]. Poor irrigation practices cause the water table to rise, leading to secondary salinization and sodication through capillary rise and evaporation of the groundwater. Water salinization due to overpumping in the coastal areas is very common in Egypt leading to serious water quality deterioration. The misuse of groundwater is another serious problem, which minimizes the aquifer capacity or the freshwater potentials. The current trends in the growth of population (2.6%), urbanization, and industrialization will substantially increase pressure on the quantity and quality of water. However, the country's limited water resources will come under further pressure as demand increases with rapidly growing population [33].

5.2.3 Evolution of Irrigation System

Irrigation potential is estimated at 10.92 million feddans. The total area equipped for irrigation was 8.45 million feddans in 2002; 85% of this area was in the Nile Valley and Delta [34]. In 2010, 8.92 million feddans were equipped for full control irrigation, including 6.74 million feddans in the old lands (76 %) and 2.17 million feddans in the oases and new lands (Fig. 2).

Surface irrigation is practiced in the old lands combined with water lifting systems, while pressurized irrigation – sprinkler and localized irrigation – is compulsory by law on the new lands. The latter use a cascade of pumping stations from the main canals to the fields, with a total lift of up to 50 m. Located at the end of the systems, the new lands that are at the fringes of the old lands are more at risk of water shortage, and pressurized irrigation is more suitable for the mostly sandy soil of those areas. Crops, therefore, tend to be higher value crops such as tree crops and vegetables in these new lands [35].

There are some restrictions in the use of modern irrigation technologies in Egypt's agriculture such as high capital costs for drip and sprinkler irrigation and limited areas of crops and fragmentation; it is difficult for the farmer to adopt modern techniques due to low level of knowledge and skill of the farmers. Also, the modern techniques cannot be applied in the northern region in order to prevent the interference of seawater. Moreover, most field crops such as cotton, rice, maize, wheat, and clover are only irrigated by the surface system.

In Egypt, just as in other countries, the irrigation system management is operated by the state. The Ministry of Water Resources and Irrigation is the only body that authorizes water use and is mandated to control and manage all freshwater resources in Egypt including the surface and subsurface water. In addition, the Ministry is responsible for constructing, supervising, operating, and maintaining of all the irrigation structures and drainage networks as well as providing all other

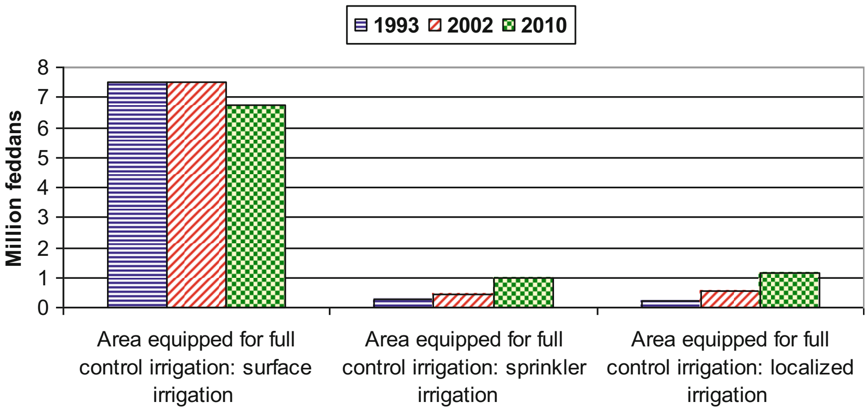


Fig. 2 Irrigation systems in Egypt. Source: compiled and computed from AQUASTAT database [34]

sectors with their needs of good-quality freshwater. It is represented at the governorate level through general irrigation directorates, which are then subdivided into inspectorates and districts, ensuring proper coordination among agencies involved in water resources such as Ministries of Agriculture and Land Reclamation and Power. At the farm level, farmers bear the responsibility for the construction, operation, and maintenance of the system [36, 37].

6 Key Features of the Egyptian Agricultural

Crop cultivation in Egypt takes place during three consecutive cropping seasons, the winter, summer, and nili (Kharif) seasons, depending on the irrigation rotation. Winter season crops (including wheat, barley, beans, and clover) are irrigated during the period October–December and are harvested in May. The summer season crops (rice, cotton, maize, and sugarcane) are irrigated from April to June and are harvested in October. The Nili season crops (mainly maize, peanuts, and cotton) take place during the months of July and August, and harvest takes place in November. In case of vegetables and fruits, they are grown all year-round, depending on their type [6].

6.1 Cultivated Land

The cultivated area is more than 9 million feddans. The agricultural year is divided into two seasons, i.e., summer and winter. Consequently two crops are usually grown: summer crop and winter crop. In some cases, farmers tend to cultivate a third crop during the period between summer and winter, which may extend for about two months. At the same time, there are areas cultivated with annual crops, such as sugarcane and fruit trees. This crop diversification makes the total cropped area 13.7 million feddans, i.e., crop intensity of 172%. Among different regions in Egypt, crop diversification varies according to the climatic and soil conditions. There are two main crops of high water consumptive use, namely, sugarcane and rice. The area of sugarcane of about 265,000 feddans is concentrated in Upper Egypt, where temperature is relatively high. The Nile Delta is the main area of growing rice especially in its northern part where the soil is affected by the seawater intrusion.

Although the country lost part of its fertile land to urbanization, this has been balanced by expansion of agricultural areas. Expansion in agriculture is carried out horizontally and vertically through crop intensification by cultivating the land more than once a year. In 1966, cultivated lands were 5.7 million feddans, while in 2013 cultivated areas were 8.954 million feddans [21], as shown in Table 1 and Fig. 3.

Table 1 Planted area (1966–2013)

Year	Planted area (1,000 feddan)	Year	Planted area (1,000 feddan)	Year	Planted area (1,000 feddan)
1966	5,688	1982	5,822	1998	7,761
1967	5,623	1983	5,797	1999	7,848
1968	5,710	1984	5,853	2000	7,836
1969	5,785	1985	5,943	2001	7,946
1970	5,756	1986	6,019	2002	8,148
1971	5,747	1987	6,063	2003	8,113
1972	5,772	1988	6,183	2004	8,279
1973	5,785	1989	6,270	2005	8,385
1974	5,781	1990	6,918	2006	8,411
1975	5,846	1991	7,023	2007	8,423
1976	5,874	1992	7,134	2008	8,432
1977	5,796	1993	7,179	2009	8,783
1978	4,838	1994	7,173	2010	8,741
1979	5,826	1995	7,813	2011	8,619
1980	5,820	1996	7,563	2012	8,799
1981	5,876	1997	7,726	2013	8,954

Source: compiled and computed from Egypt in figures [21]

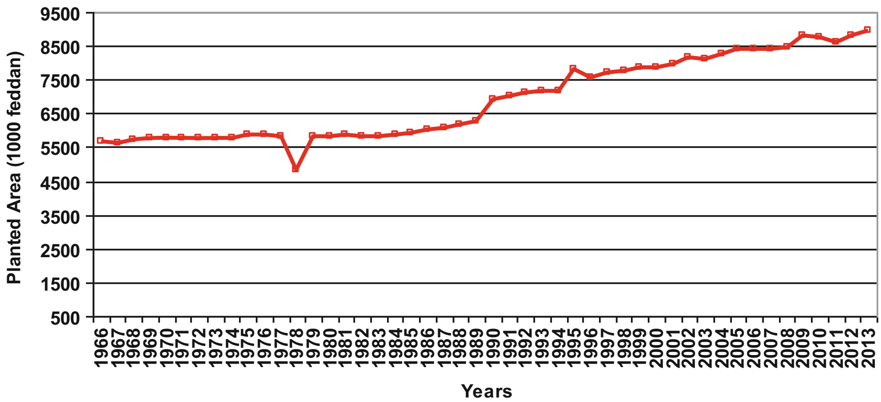


Fig. 3 Planted area (1,000 feddans) in Egypt. Source: [21]

Concerning the development of reclaimed land, the cultivated areas were 7,800 feddans in 2005 and increased to 16,600 feddans in 2013. Table 2 shows the reclaimed areas from 2005 to 2013 [21].

Table 2 Development of reclaimed land

Year	2005–2006	2006–2007	2007–2008	2008–2009	2011–2012	2012–2013
Area (1,000 feddans)	7.8	2.2	2.1	0.7	3.3	0.5

Source: compiled and computed from Egypt in figures [21]

6.2 Cropping Pattern

After construction of the Aswan High Dam, different problems have affected the cropping pattern significantly. Given the heavy price and area restrictions, the cropping pattern shifted away from major field crops with controlled prices toward untaxed, higher value products. The cropped area of cotton and grains, whose prices were highly controlled, declined relative to other high-value, less-regulated crops, such as clover, rice, vegetables, and fruits. The relative importance of wheat has declined from 15% in the period 1955–1959 to 12% in 1975–1979. The same happened for maize and broad beans, which had negative implications on food security. Also, the relative importance of cotton has declined from 17.8% in the period 1955–1959 to 14.3% in the period 1970–1974 and further declined to 11.7% in the period 1975–1979 [6]. Meanwhile, the relative importance of rice, clover, sugarcane, and horticultural crops has increased noticeably.

Moreover, the cropping patterns have been changed with the liberalization of the agricultural sector. Indeed, the liberalization of the agricultural sector in the early 1980s brought about fundamental changes in the cropping pattern. With the liberalization of the sector, agricultural output increased significantly as cultivation of most crops became more profitable for farmers [6, 38].

However, the response of the aggregate cropping pattern to the liberalization strategy was very slow.

Egypt's agricultural system is one of the most intensive in the world from the point of view of the use for surface unit, which is cultivated two or three times a year, on the basis for limited land and permanent irrigation.

An analysis for cropping pattern of Egyptian agriculture in the year 2014 indicates that it based on basic groups: cereals, fibers (cotton mainly), green fodder, sugar crops, legumes, vegetables, and fruits [39]. According to Agriculture Directorates of Governorates, the total area under winter crops was about 5.897 million feddans. Summer crops amounted to 5.378 million feddans, while nili crops were about 3.781 million feddans. Fruits was about 0.537 million feddans [39].

These crop rotations are found in old lands, while, in the new lands, major crops are primarily fruits, oil trees, and vegetables planted in larger fields [36].

Table 3 and Fig. 4 represent the winter cropping pattern structure. Clover and wheat occupy about 87% from total cropped area in winter season [38].

Table 3 Cropping pattern in Egypt

Winter season		Summer season		Nili season	
Crop	Area (feddan)	Crop	Area (feddan)	Crop	Area (feddan)
Wheat	3,377,876	Cotton	286,724	Maize	319,745
Barley	78,679	Sugarcane	329,153	Sorghum	2,025
Bean	116,169	Maize	2,139,258	Rice	2,287
Lentil	862	Sorghum	335,182	Onion	11,750
Fenugreek	5,280	Rice	1,419,378	Soya bean	10
Chickpeas	1,382	Summer onion	7,956	Sesame	160
Lupine	1,211	Peanut	14,778	Clover	41,427
Sugar beet	460,488	Soya bean	22,423	Sunflower	19
Clover	1,670,809	sesame	59,612	Other field crop	658
Flax	3,405	Sunflower	15,161	–	–
Winter onion	125,520	Clover	558,300	–	–
Garlic	22,153	Other field crop	189,630	–	–
Other field crop	29,300	–	–	–	–
Total area	5,896,539		5,377,555		378,081

Source: Ministry of Agriculture and Land Reclamation, Economic Affairs Sector, Agricultural Economics [38]

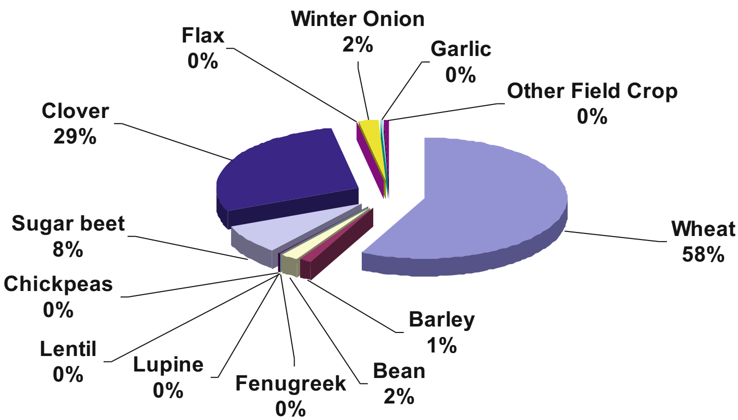


Fig. 4 Winter cropping pattern in Egypt. Source: compiled and computed from Ministry of Agriculture and Land Reclamation, Economic Affairs Sector, Agricultural Economics [47]

In the summer season, the main crops are maize, rice, clover, sugarcane, sorghum, and cotton [38]. The relative importance of them is 41%, 27%, 10%, 6%, 6%, and 5%, respectively, as shown in Table 3 and Fig. 5.

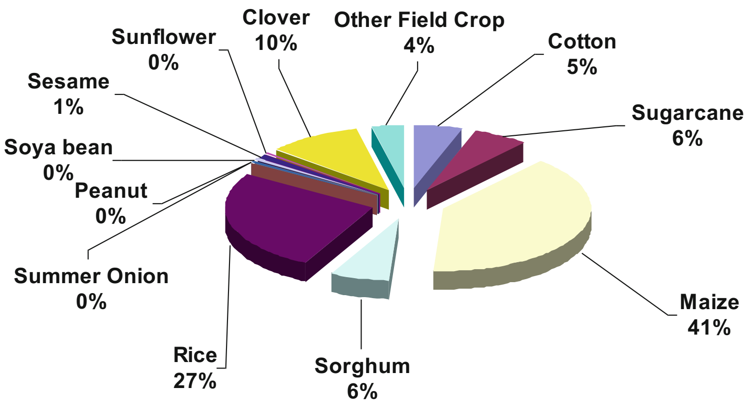


Fig. 5 Summer cropping pattern in Egypt. Source: compiled and computed from Ministry of Agriculture and Land Reclamation, Economic Affairs Sector, Agricultural Economics [47]

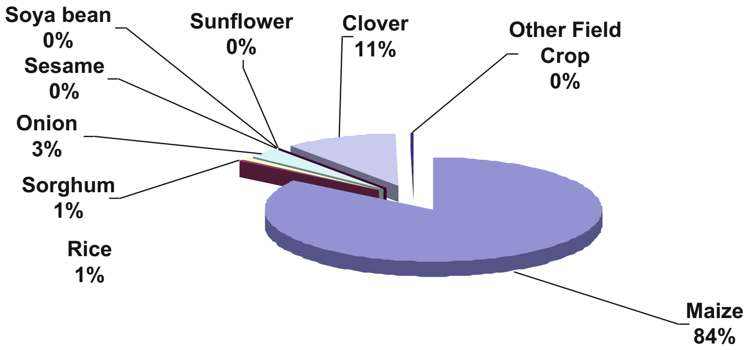


Fig. 6 Nili cropping pattern in Egypt. Source: compiled and computed from Ministry of Agriculture and Land Reclamation, Economic Affairs Sector, Agricultural Economics [47]

In the nili season, the structure of cropping pattern differs from the summer and winter seasons [38]. The main crops are maize and clover that occupy about 95% from total cropped area. The main constraint of this crop season is mainly the time of crops planting and harvesting in addition to weather. For this reason, the crops cultivated in the nili season mainly appear in Upper Egypt, as shown in Table 3 and Fig. 6.

Concerning the structure of fruit cropping pattern, Table 4 and Fig. 7 represent the main crop pattern in Egypt. The main fruit crops are oranges, mango, olive, grapes, and citrus that represent 22%, 16%, 14%, 12%, and 10%, respectively, from total cropped area [39].

Table 4 Fruit cropping pattern in Egypt

Crop	Area (feddan)	Crop	Area (feddan)
Oranges	370,087	Apricot	16,447
Citrus	160,328	Pear	12,182
Grapes	192,934	Apple	79,383
Mango	265,350	Peach	75,086
Banana	74,622	Plum	2,574
Fig	69,351	Olive	237,454
Prickly pear	4,344	Almond	6,518
Guava	38,616	Mixed trees	10
Pomegranate	43,605	Others	3,689
Total area	1,652,580		

Source: Agriculture Directorates of Governorates; Publisher: Economic Affairs Sector [39]

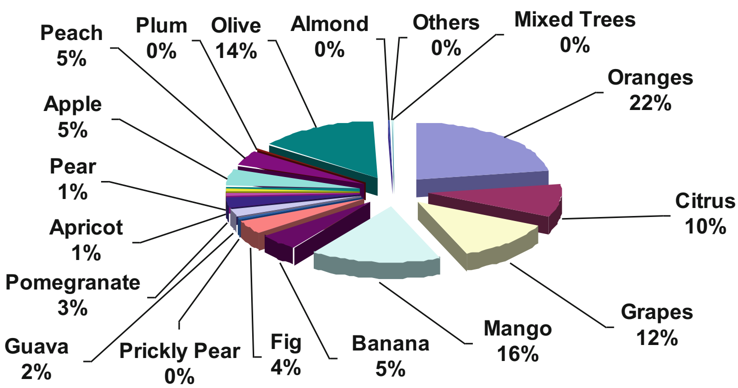


Fig. 7 Fruit cropping pattern in Egypt. Source: compiled and computed from Ministry of Agriculture and Land Reclamation, Economic Affairs Sector, Agricultural Economics [47]

6.3 Regional Allocation of Irrigation Water Use

According to Bader [36], Lower Egypt regions consume most of the available irrigation water resources. The regions consume about 21,582 million m^3. In this region, Dakahlia Governorate is the largest water-consuming governorate; its total irrigation water needs are 4,045 million m^3/year. The second largest governorate is El-Behaira with an annual water consumption of 3,965 million m^3/year. Middle Egypt governorates consume about 6,375 million m^3/year. El-Menia governorate uses about 2,168 million m^3/year that represents the fifth position in irrigation consumption. Upper Egypt governorates consumed 6,685 million m^3/year.

Qena consumed the larger portion of irrigation water, which is about 2,203 million m^3/year.

6.4 Water Requirement Pattern

The water requirement pattern depends mainly on the cropping pattern. It is calculated from the cropping pattern based on multiplying the specific crop cultivated area by the per feddan water requirement and summed to estimate the total water requirement in winter, summer, and nili seasons.

Crop water requirements used in the study were directly taken from government figures available and published by the Central Agency for Public Mobilization and Statistics (CAPMAS). The data on irrigation requirements are available as annual figures, and it is assumed that these annual requirements can be allocated over the months of plant growth cycle [40, 41].

Of course, the structure of water requirement pattern depends on per feddan crop water requirement as shown in Table 5 and Figs. 8–10. In the winter season, clover is considered the most water-consuming crops in both old and new lands as irrigation requirements for this crop was about 2,773 and 2,608 m^3, respectively.

In the summer season, sugarcane and rice had the highest water consumption per feddan. Their water requirements amounted to about 8,854 and 5,821 m^3, respectively, in the old land [39, 40].

In the nili season, the relative importance of area cultivated by maize and clover occupies about 95% from total cropped area. The water requirements for each maize and clover are about 2,436 m^3 as shown in Table 5. Moreover, the rice crop consumes about 6,187 m^3 [39, 40].

7 Land Tenure Structure in Egyptian Agriculture

The land tenure system in Egypt changed with the 1952 Agrarian Reform which reduced the holdings of the largest landowners and set ceilings by families (100 feddans) and individuals (50 feddans). The Land Reform positively affected a number of beneficiaries, most of whom had been share croppers: they received their land and became official tenants, with fixed rents amounting to seven times the annual land tax, which was fixed according to the quality of the land. In 1991, regulations were changed to fix the rent at 22 times the land tax, and now the rent changes every 2 or 3 years. In 1993, the Government issued a Privatization Law, which includes provision for the return of lands to the owners from the pre-Agrarian Reform period. It gives them the right to rent their land freely or to cultivate it themselves [36].

Table 5 Winter water requirement pattern in Egypt

Winter season			Summer season			Nili season		
	Old lands	New lands		Old lands	New lands		Old lands	New lands
Crop	Water requirement (m^3/feddan)	Water requirement (m^3/feddan)	Crop	Water requirement (m^3/feddan)	Water requirement (m^3/feddan)	Crop	Water requirement (m^3/feddan)	Water requirement (m^3/feddan)
Clover	2,773	2,608	Maize	3,914	2,171	Maize	2,436	2,436
Wheat	1,677	1,751	Sorghum	2,980	1,583	Sorghum	1,947	1,947
Barley	1,354	1,751	Rice	5,821	n.a	Rice	6,187	6,187
Faba bean	1,371	1,008	Yellow maize	3,914	n.a	Yellow maize	2,436	2,436
Lentil	1,837	1,930	Peanut	3,895	2,686	Nili onion	3,161	3,161
Fenugreek	1,356	n.a	Sesame	2,740	n.a	Potato	2,532	2,532
Chickpeas	1,704	n.a	Soya bean	2,955	2,272	Tomato	2,532	2,532
Lupin	1,441	n.a	Sunflower	2,322	2,070	Other vegetables	2,532	2,532
Flax	1,234	1,660	Summer onion	3,658	n.a	Other field crops	2,532	2,532
Winter onion	1,862	1,610	Potato	2,861	1,562			
Garlic	1,478	1,220	Tomato	2,861	2,146			
Sugar beet	2,007	1,415	Other vegetables	2,861	n.a			
Potato	2,003	760	Other field crops	2,861	n.a			
Tomato	2,003	1,066	Sugarcane	8,854	n.a			
Other vegetables	2,003	877	Cotton	3,102	n.a			
Other field crop	2003.0	n.a						

Source: Ministry of Agriculture and Land Reclamation, Economic Affairs Sector, Agricultural Economics Bulletin [39] and CAPMAS, Central agency for Public Mobilization and Statistics, Water Resources and Irrigation Bulletin [40]

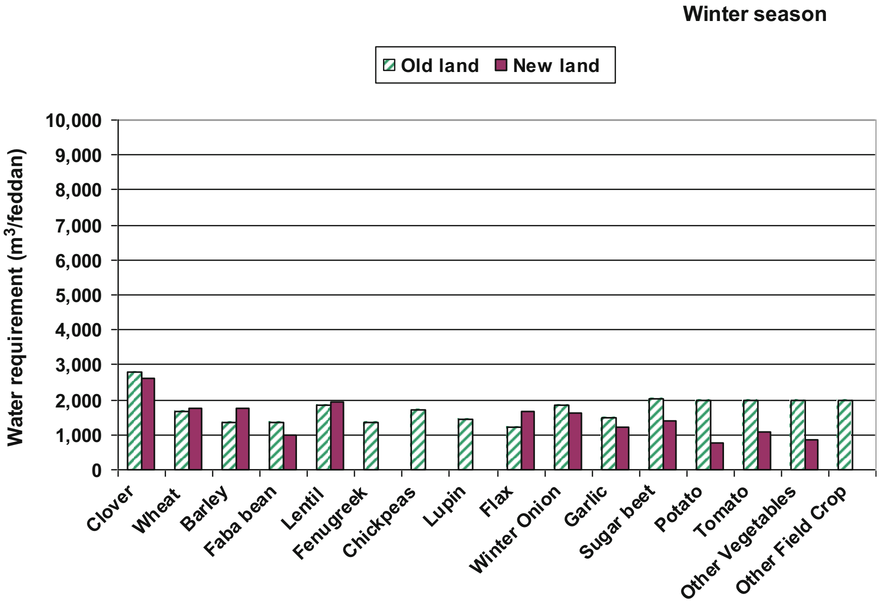


Fig. 8 Winter water requirements pattern structure in old and new lands. Source: compiled and computed from Ministry of Agriculture and Land Reclamation, Economic Affairs Sector, Agricultural Economics [40]

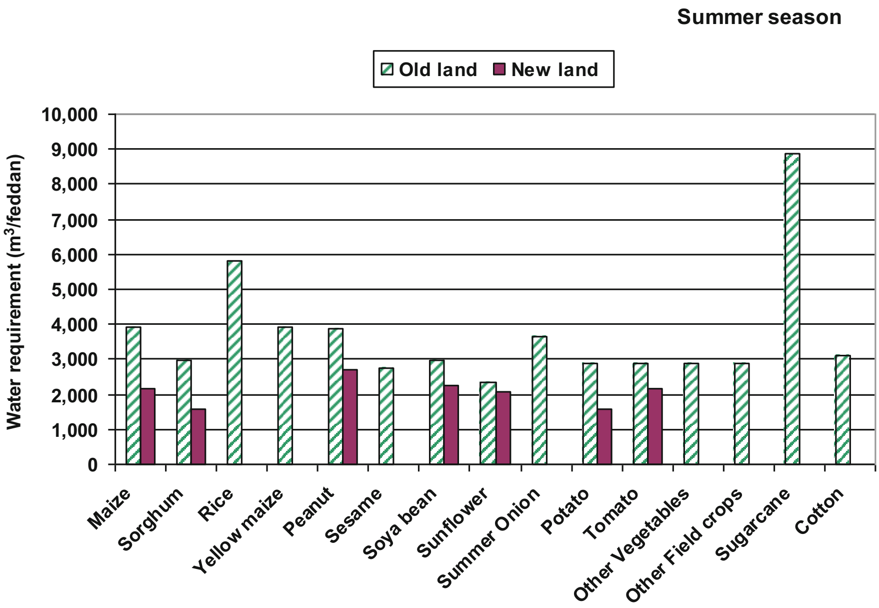


Fig. 9 Summer water requirement pattern structure in old and new lands. Source: compiled and computed from Ministry of Agriculture and Land Reclamation, Economic Affairs Sector, Agricultural Economics [40]

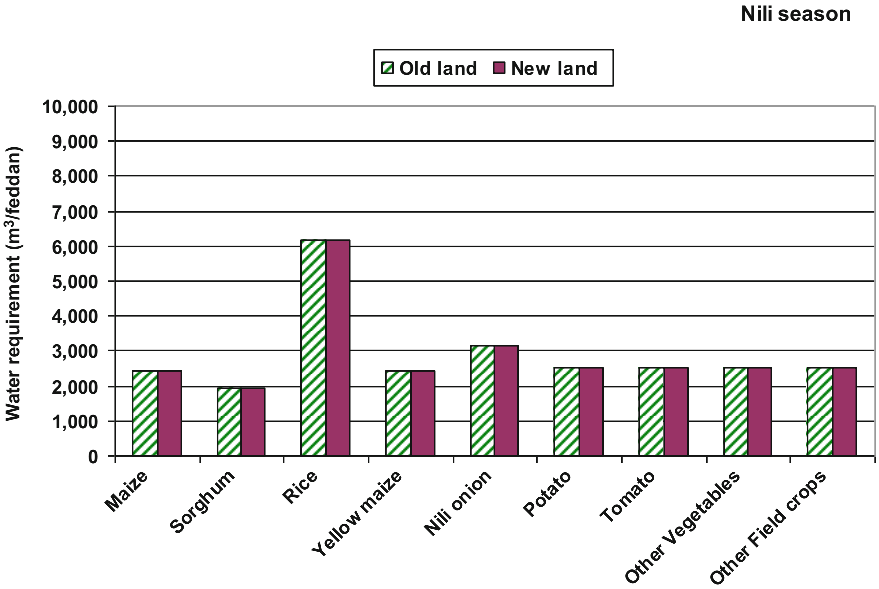


Fig. 10 Nile water requirement pattern in old and new lands. Source: compiled and computed from Ministry of Agriculture and Land Reclamation, Economic Affairs Sector, Agricultural Economics [40]

7.1 Egyptian Agricultural Landholding Structure

Tables 6 and 7 show the number and area of landholdings during the period 2009–2010 [42]. The following conclusions are drawn:

1. In the old land, the number of holdings land are 5,404,395, while the number of holding land in the new land are 341,186, with a total number of 5,745,581.
2. In the old land, the area of agricultural land is 9,730,785 feddans, while in the new land is 3,099,272 feddans, with a total of 12,830,057 feddans.
3. The increase in the number and the area of holdings was mainly applied to the category of individuals.
4. The number and the area of holdings within the category of agrarian reform are very limited.
5. In the old lands, about 46% of landholders are holding less than one feddan, while 22, 11, and 13% of landholders are holding one feddan, two feddans, and three feddans, respectively, as shown in Fig. 11.
6. In the new land, the number of landholders according to the area of agricultural land is slightly similar as shown in Fig. 12. However, the area of holding land is different. The area of holding land more than 1,000 feddans represents 28% of the total areas.

Table 6 Number and area of landholders by categories of land (old and new lands)

Type of land	Total holding		Individual		Company		Agricultural cooperation		Agrarian reform		Government		Others	
	Number of landholder	Area (feddan)	Number of landholder	Area (feddan)	Number of landholder	Area (feddan)	Number of landholder	Area (feddan	Number of landholder	Area (feddan	Number of landholder	Area (feddan	Number of landholder	Area (feddan)
Old land	5,404,395	9,730,785	5,401,432	8,964,832	587	626,745	1,023	43,224	153	–	857	86,189	163	9,793
New land	341,186	3,099,272	340,461	2,399,284	408	603,815	135	42,555	–	–	145	47,504	34	6,113
Total	5,745,581	12,830,057	5,741,893	11,364,116	995	1,230,560	1,158	85,779	153		1,002	133,693	197	15,906

Source: agricultural census results – Directorate General Agricultural Census [42]

Table 7 Number and area of landholder by categories of area in the old and new lands

Categories of area (feddan)	Total holding in the old land		Total holding in the new land	
	Number of landholder	Area (feddan)	Number of landholder	Area (feddan)
<One	2,143,888	923,638	9,649	4,568
1	1,068,634	1,322,103	28,537	34,315
2	531,455	1,177,899	46,760	104,635
3	630,359	736,217	22,770	71,608
4	99,302	416,972	15,322	64,038
5	170,336	922,730	63,124	332,749
7	60,993	485,444	16,017	127,626
10	16,006	749,340	22,755	252,668
15	24,704	398,017	8,585	137,276
20	23,516	531,344	9,646	213,278
30	12,027	429,660	4,838	169,814
50	5,425	332,043	2,478	153,236
100	2,456	413,590	1,716	295,895
500	218	138,224	187	18,672
>1,000	213	753,557	192	712,443
Total	5,404,395	9,730,785	252,576	2,792,829

Source: agricultural census results – Directorate General Agricultural Census [42]

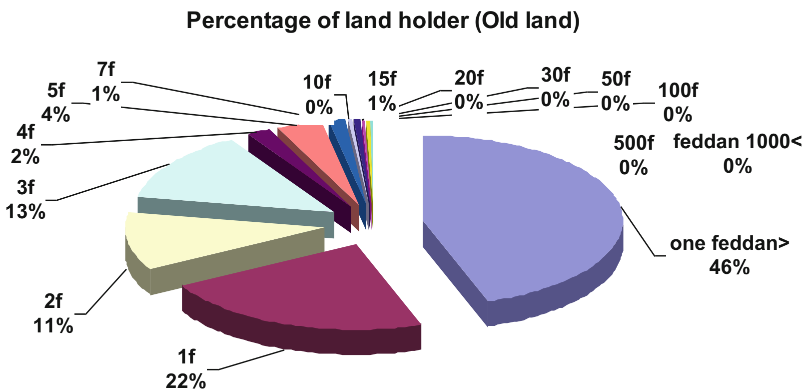


Fig. 11 Percentage of landholder area in the old land (f = feddan). Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [21]

7. Fragmentation of the agricultural land is a major characteristic of Egyptian agriculture. It indicates a small size of the unit of production. One and the same holding is divided into a number of plots, separated either by another holder's land, irrigation, or a drainage canal. "Dispersal" means the distribution of a holding into scattered plots within the same village or in other villages within the same district.

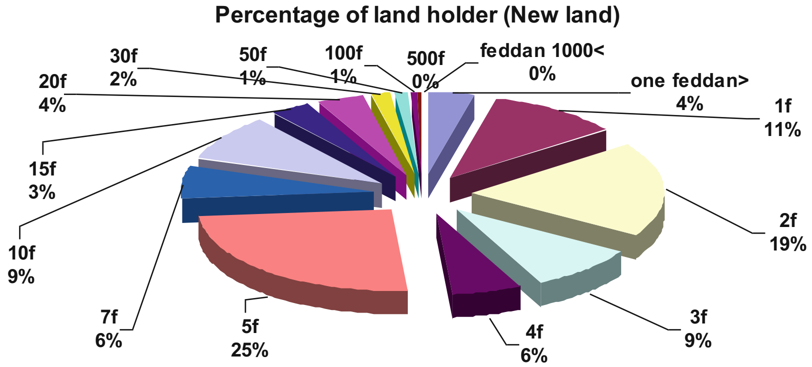


Fig. 12 Percentage of landholder in the new land (f = feddan). Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

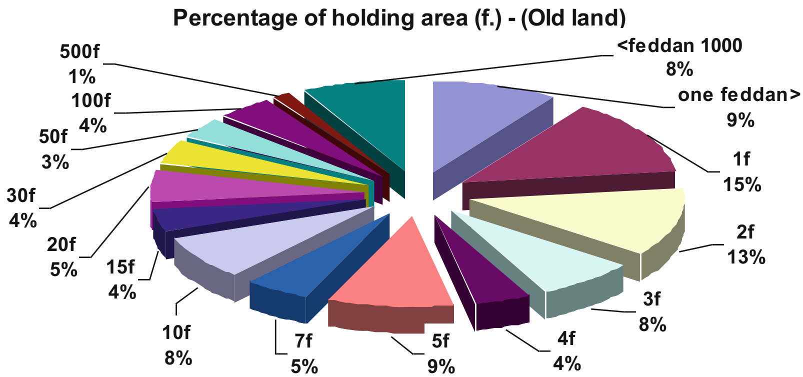


Fig. 13 Percentage of landholder area in the old land (f = feddan). Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

8. In the old land, the agricultural land is highly fragmented as shown in Fig. 13, while the agricultural land in the new land is less fragmented (Fig. 14).
9. Fragmentation and dispersal of landholdings are attributed to the following factors:

   - Overpopulation with a relatively constant area of the agricultural land denotes an increasing demand for land given a relatively constant land supply.
   - The system of inheritance which leads to a sequential partition of land legacy among heirs.
   - The consecutive Agrarian Reform laws which led to a remarkable drop in large holdings and a subsequent increase in small holdings. The laws prohibited rescinding lease contracts and made them renewable and inheritable, thus leading to further disintegration of the land over time.

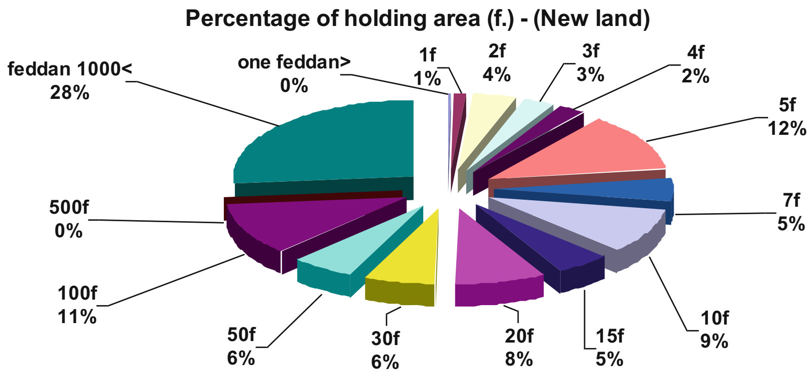


Fig. 14 Percentage of landholder area in the new land (f = feddan). Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

Such fragmentation and dispersal of the agricultural landholding have negative impact on the rate of growth in the agricultural sector [5]. This is evidenced by the following:

1. The difficulty in implementing modern agricultural techniques.
2. The loss in the cultivable land due to the fact that a part of it is used for constructing some facilities (e.g., building, irrigation, and drainage purposes and for passages around and inside small holdings).
3. The high cost of agronomic practices and the low efficiency of agricultural labor.
4. The waste of time and effort caused by moving the machinery and animals from one area to another on the farm.
5. The inefficient use of irrigation water, due to disintegration and dispersal.
6. Negative impact on marketing as well as on the income of farmers.

7.2 Agricultural Land Tenure Structure

Land tenure in Egypt takes three forms:

1. *Ownership:* where in the holder and the owner is the same person.
2. *Rent:* wherein the holder is not the same person as the owner. Therefore, the right of possession lies with a person (the landlord) and the right of utilization lies with another person (the tenant).
3. *Mixed holding:* wherein the holder is the owner of one part of the landholding and the tenant the other part, i.e., both of them has the ownership as well as the utilization rights for one part of it but only the utilization right for its other part.

4. The Egyptian agricultural lands can be rented according to two different modes:
   - *Cash rental:* It is the most common mode of land rent. The landlord and the tenant, being the two parties of a contract, agree that the second party pays the first party at a fixed time a certain amount of money as a rental for the area of land for which the contract has been issued.
   - *In-kind rent:* The landlord agrees with the tenant to pay a fixed portion or a percentage of the crop (or crops) after it reaches maturity.

7.2.1 Crop Sharing

This pattern has been regulated by the Agrarian Reform laws. The landlord provides the land and the buildings. He also pays half of the costs of seeds, fertilizers, irrigation, pest management, and harvesting and land tax. The tenant bears the cost of manpower, maintenance of irrigation and drainage canals, and half of the other expenses. After the harvest, the yield is equally divided between the landlord and the tenant.

The Agrarian Reform Law stipulates that the landlord's share should not, in any case, exceed one half of the yield, after deduction of the expenses.

7.2.2 Predetermined Crop Share

A specified quantity of the yield is given to the landlord as rent for his land. The condition for this type of land rent, according to the Agrarian Reform Law, is that the total value of the landlord's share(s) should not exceed seven times the value of the land tax.

Table 8 and Figs. 15–18 show that the most dominated agricultural land tenure structure is the ownership which represents 94% of the total land tenure in both old and new lands [42].

Table 8 Agricultural land tenure structure

	Ownership		Rent		Mixed holding		In-kind rent (investment)	
	Number of landholder	Area (feddan)	Number of landholder	Area (feddan)	Number of landholder	Area (feddan)	Number of landholder	Area (feddan)
Old land	4,039,509	8,270,143	187,234	398,844	25,248	51,679	50,856	529,026
New land	1,199	6,081	45	106	0	0	45	73

Source: agricultural census results – Directorate General Agricultural Census [42]

Fig. 15 Percentage of landholder in the old land. Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

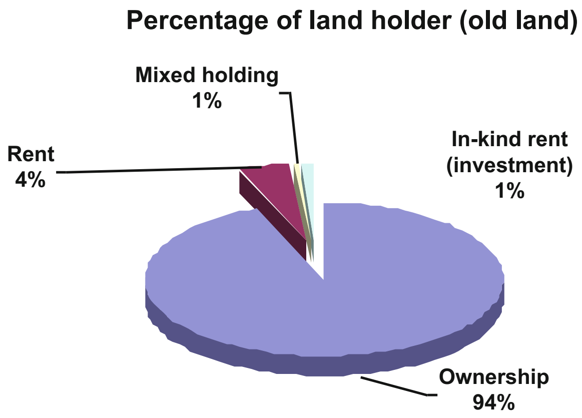


Fig. 16 Percentage of holding area in the old land. Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

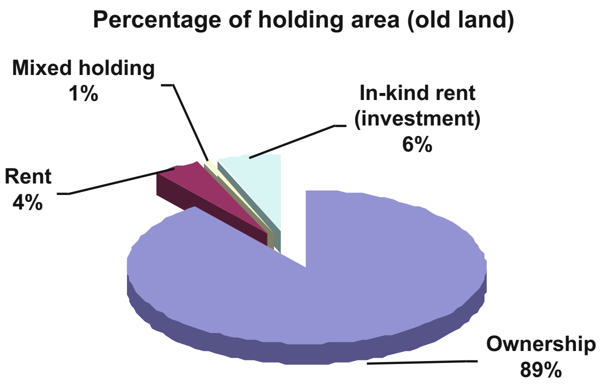
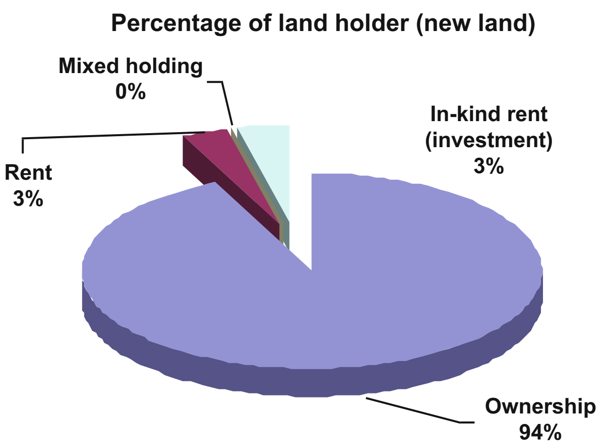


Fig. 17 Percentage of landholder in the new land. Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]



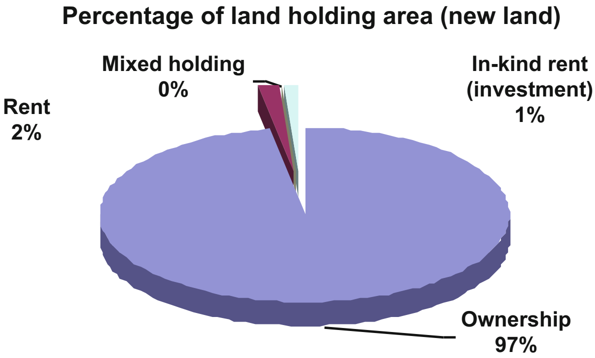


Fig. 18 Percentage of holding area in the new land. Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

Table 9 Landholding pattern by categories of age

Year	Number of landholder in the old land	Number of landholder in the new land
<20	848	62
20 Year	26,658	1,245
25 Year	102,290	4,087
30 Year	192,588	7,410
35 Year	482,656	21,308
40 Year	646,588	33,415
45 Year	1,081,611	66,583
50 Year	950,057	51,394
55 Year	879,199	43,732
>60	1,038,927	45,328

Source: agricultural census results – Directorate General Agricultural Census [42]

7.3 *Impact of Landholding Pattern on Socioeconomic Variables*

The holding pattern has, no doubt, a direct influence on the economic and social standard of the holder's family.

7.3.1 Age and Gender

Age

The study of the various age groups of landholders [42], as shown in Table 9 and Figs. 19–21, reveals the following:

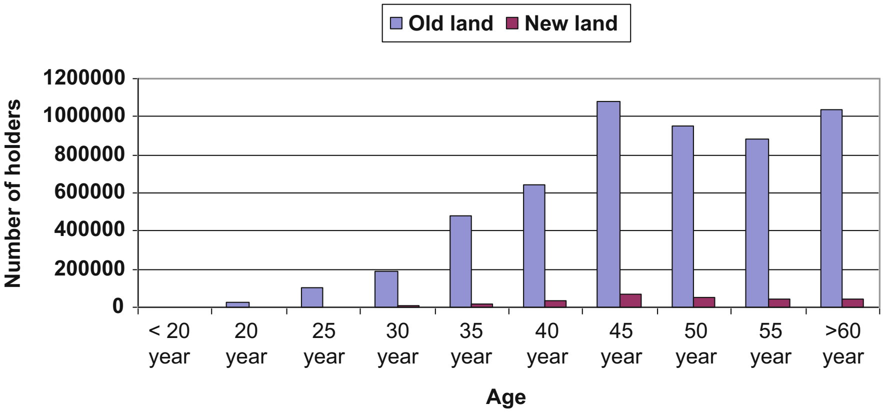


Fig. 19 Landholding pattern by categories of age in old and new lands. Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

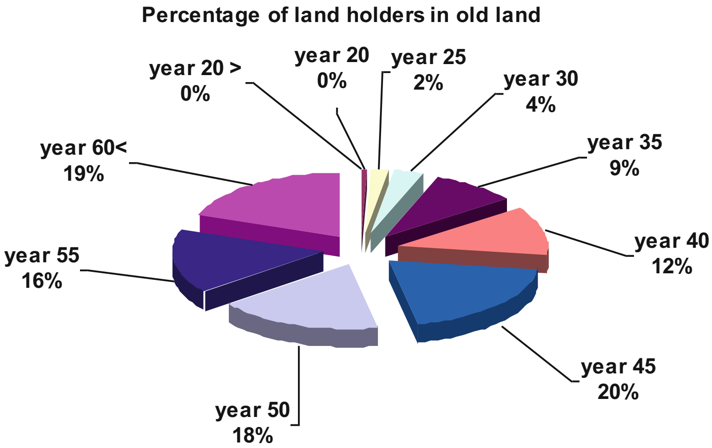


Fig. 20 Percentage of landholding pattern by categories of age in the old land. Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

1. In both old and new lands, the largest category of landholders is mainly in the age group of 45 years. The second largest group of landholders is of age 50–60 years.
2. The third group concerns the group of landholders between 30 and 40 years. The percentage of landholders for this age group is 23% and 25% in old and new lands, respectively.
3. The remaining number of landholders is classified in the age group of less than 30 years.

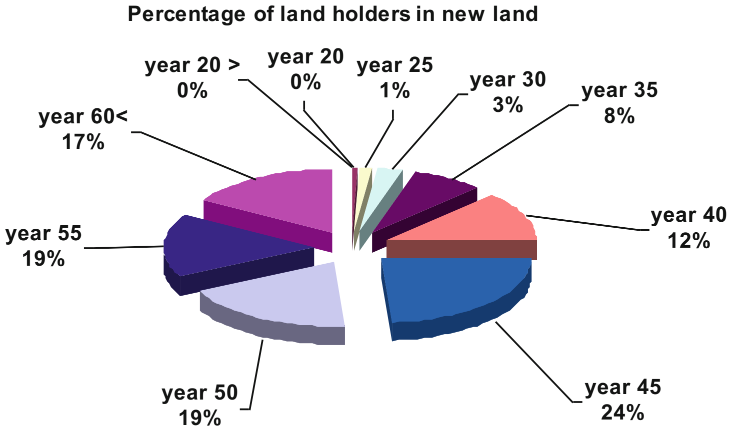


Fig. 21 Percentage of landholding pattern by categories of age in the new land. Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

Table 10 Landholding pattern by categories of sex

Gender	Old land				New land			
	Number of landholder	(%)	Area (feddan)	(%)	Number of landholder	(%)	Area (feddan)	(%)
Male	5,188,653	96	8,691,750	97	64,592	96	173,029	98
Female	212,779	4	273,081	3	1,295	4	6,305	2

Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

Gender

In both the old and the new lands, male landholders constitute 96% of the total number of landholders, while female landholders constitute only 4% as shown in Table 10.

In both the old and the new lands, the largest portion of female landholders falls within the category of less than one feddan. In this category, the percentages of female landholders are 50% and 25% in the old land and new land, respectively. The percentages take a downward trend as the area occupied by the holding increases. The limit of female landholders is about 100 feddans, while in the category of male landholders, the male owners can reach to more than 1,000 feddans [42].

7.3.2 Farmer's Education Level

The Egyptian countryside suffers from a high level of illiteracy [42]. The educational levels vary according to the size of the holdings, as shown in Table 11 and Figs. 22–27 which can be summarized as the following:

Old land:

1. Semiliterates constitute a large portion of the landholders in each area of land category. Semiliterates reach more than 43% among holders, and they are holding 46% of the total area.
2. Illiterates constitute the second portion of the landholders. Their number represent of 31% of the total number of landholders, and they are holding about 21% of the total area.
3. Primary education constitutes the third portion which is representing 18% of the total landholders and 15% of the total area.

Table 11 Pattern of the holding on education in old and new lands

	Old land		New land	
Education level	Number of landholders	Area (feddan)	Number of landholders	Area (feddan)
Illiterates	1,653,670	1,913,959	71,964	217,822
Semiliterate	2,302,111	4,064,302	119,003	932,888
Primary education	74,455	142,847	4,587	44,668
Intermediate education	977,679	1,385,409	50,424	3,336,990
Tertiary educational	77,653	123,806	2,651	18,543
University graduates	315,864	1,334,505	25,945	569,037

Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

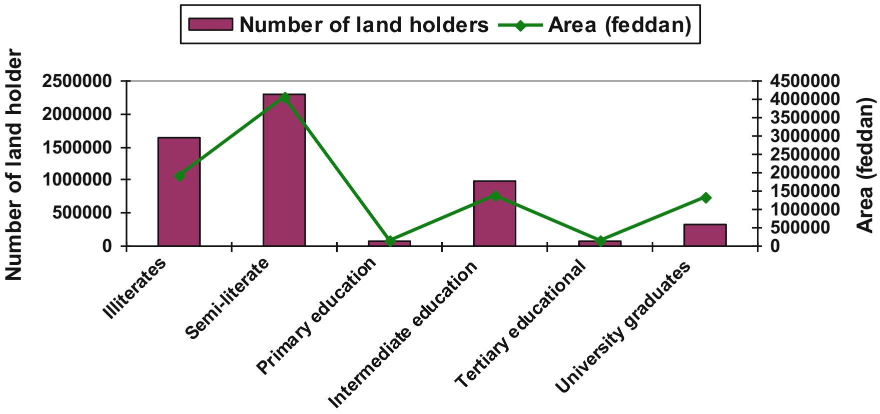


Fig. 22 Pattern of the holding on education in the old land. Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

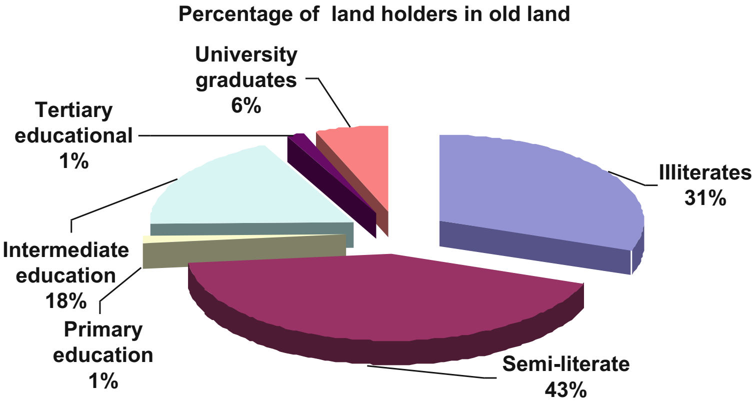


Fig. 23 Percentage of landholders (education category) in the old land. Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

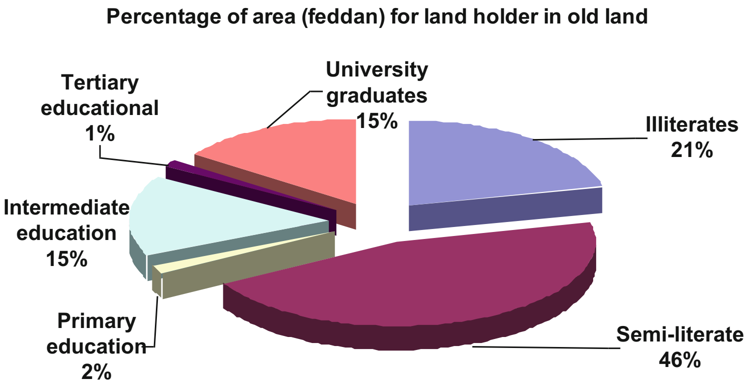


Fig. 24 Percentage of area for landholders (education category) in the old land. Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

4. The share of holders of intermediate education (senior secondary) certificates exceeds the share of university graduates with regard to the number of land-holder and the area of agricultural land.

Generally speaking, the percentage of illiterate or semiliterate holders of agricultural land is greater than 74%. This has a negative impact on the rate of growth of agriculture since these holders are not in a position to appreciate the concept of technology transfer in their crop land.

New land:

1. Similar to the situation of the old land, semiliterates constitute a large portion of the landholders in each area category. Semiliterates reach more than 44% among holders. However, they are holding 18% of the total agricultural land.

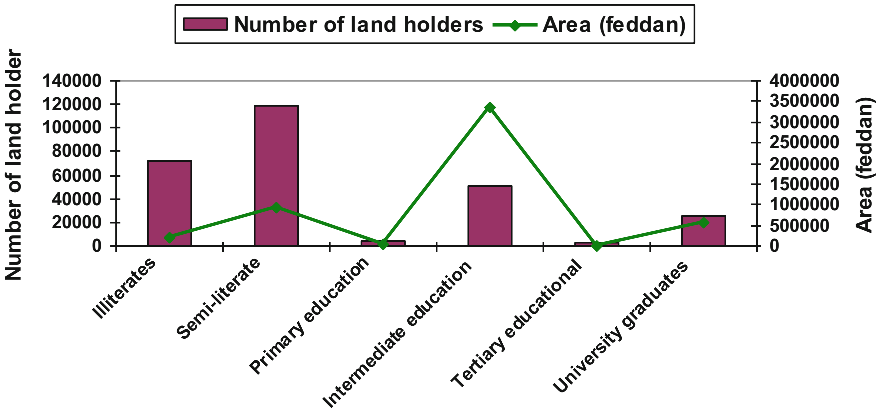


Fig. 25 Pattern of the holding on education in the new land. Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

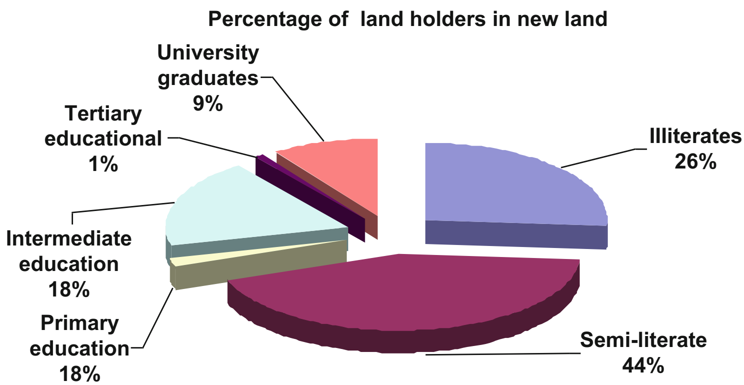


Fig. 26 Percentage of landholders (education category) in the new land. Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

2. Illiterates constitute the second portion of the landholders. Their number represent of 26% of the total number of landholders, but they are holding only 4% of the total agricultural land.
3. Intermediate educations constitute the third portion which is representing 18% of the total landholders. However, they are holding a large portion of agricultural land (66% of the total area).
4. University graduates constitute the fourth portion which is representing 9% of the total landholders, and they are holding 11% of the total agricultural land.

Generally speaking, the percentage of illiterate or semiliterate holders of agricultural land is greater than 70%. They may have a negative impact on the rate of growth of agriculture. However, they are holding about 22% of the total agricultural

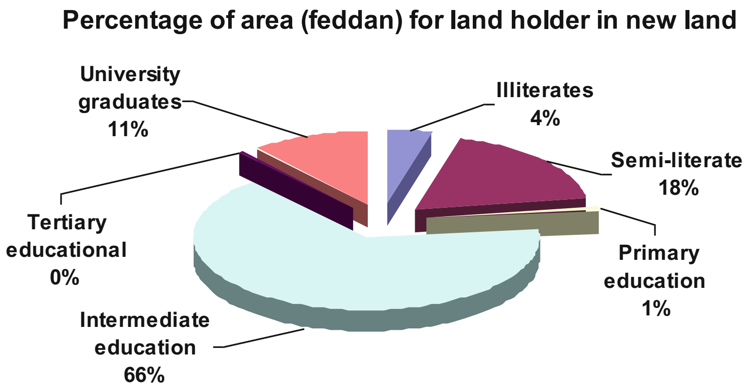


Fig. 27 Percentage of area for landholders (education category) in the new land. Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

land. The percentage of the educated holders is 30%, but they are holding 78% of the total agricultural land, and they may appreciate the concept of technology transfer in their crop land.

7.4 The Holding Structure and Mechanization

In the old land, a total of 1,689,341 machines is used for agriculture proposes [21]. However, it must be clearly stated that the holding of farming machinery is not similar to mechanized farming practices but it reflects the availability of mechanical power. The mechanical holdings are not greater than the number of agricultural landholders (5,404,395). The percentage represents about 31% of the agricultural landholdings [21].

In the new land, a total of 163,064 machines is used for agriculture proposes which represents about 64.5% of the agricultural landholdings (252,576) [21]. This indicates that the farmers in the new land depend on farming machine for agricultural practices.

7.5 Impact of the Pattern of the Holding on the Number of Laborers

From Table 12 and Figs. 28 and 29, it appears that farming practices are mainly depending on the household members. The number of household members is about 28,378,590 and 1,478,348 in the old and the new lands, respectively [42]. This general trend is highly related to that the holders tend to have a large family due to

Table 12 Pattern of the holding on the number of household members and laborers in old and new lands

Area (feddan "f")	Old land				New land			
	Number of landholders	Number of household members	Number of laborers (permanent)	Number of laborers (temporary)	Number of landholders	Number of household members	Number of laborers (permanent)	Number of laborers (temporary)
<One f	2,143,716	10,687,405	974,011	4,360,989	9,640	46,205	8,573	15,420
1f	1,068,557	5,815,523	982,203	2,236,190	28,534	145,343	35,302	45,759
2f	531,408	3,058,015	623,076	1,129,692	46,756	253,103	71,358	77,278
3f	230,311	1,369,274	289,369	502,234	22,765	124,024	31,984	39,944
4f	99,278	604,080	131,029	217,799	15,322	86,227	22,529	26,993
5f	170,265	993,382	235,096	344,353	63,117	337,124	96,577	102,848
7f	60,936	372,328	79,929	132,332	16,011	90,557	21,226	30,012
10f	65,920	395,326	87,713	136,320	22,738	127,643	31,593	42,648
15f	24,646	151,507	32,843	51,295	8,573	50,277	12,731	16,036
20f	23,423	141,839	30,165	46,933	9,629	55,801	13,598	17,692
30f	11,929	72,231	15,232	24,046	4,818	27,575	6,456	9,268
50f	5,310	32,781	6,861	10,624	2,427	13,700	3,030	4,572
100f	2,176	12,756	2,839	4,080	1,564	8,386	1,860	2,857
500f	133	737	168	212	124	183	154	199
>1,000f	75	273	70	64	56	268	69	64
Total	4,501,432	28,378,590	3,619,854	11,118,317	274,574	1,478,348	366,535	471,295

Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

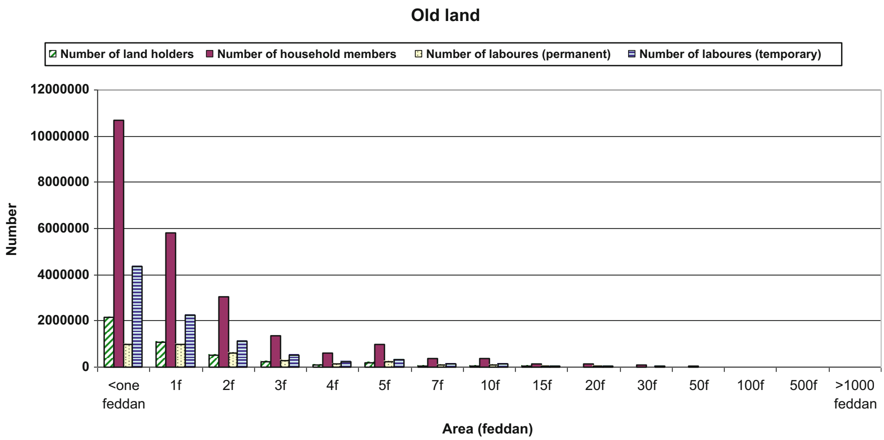


Fig. 28 Pattern of the holding on the number of household members and laborers in the old land. Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

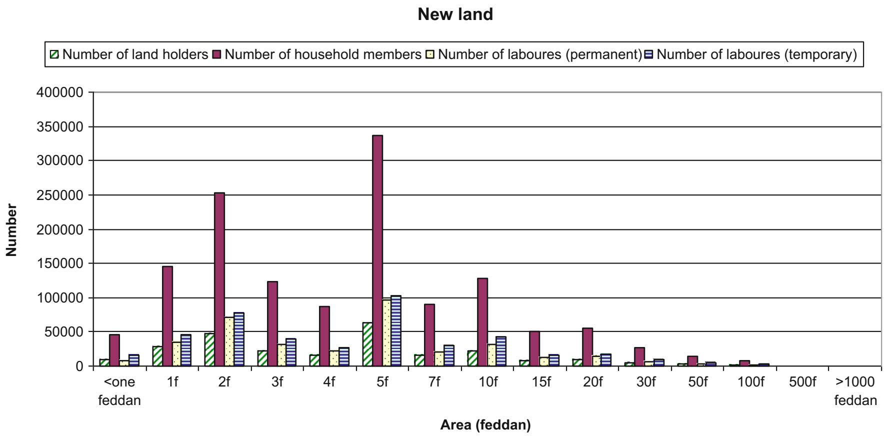


Fig. 29 Pattern of the holding on the number of household members and laborers in the new land. Source: compiled and computed from agricultural census results – Directorate General Agricultural Census [42]

the predominance of the familial pattern in agriculture. In the old land, the share of landholding with large families is locating at categories of landholding less than one, two, three, and four feddans, while in the new land, it is locating at categories of landholding less than two, three, and five feddans.

The agricultural system is mainly depending on its labor (15,576,011 laborers). In the old land, the total number of permanent and temporarily laborers is 3,619,854 and 11,118,317, respectively, with a total of 14,738,181 workers, while the total number of permanent and temporarily laborers is 366,535 and 471,295, respectively, with a total of 837,830 workers.

8 Investment on Agriculture Sector

8.1 Impact of Agricultural Investment on Agricultural Sector

Figures 30 and 31 show that average investments in Egypt amounted to LE 147.85 billion for the period 2000–2013. In year 2013, it is clear that the oil sector absorbed the largest share of this investment, estimated at 16.33%, followed by the transportation sector (11.4%), the electricity sector (7.07%), and finally came the agricultural sector (5.14%) [37, 43–47].

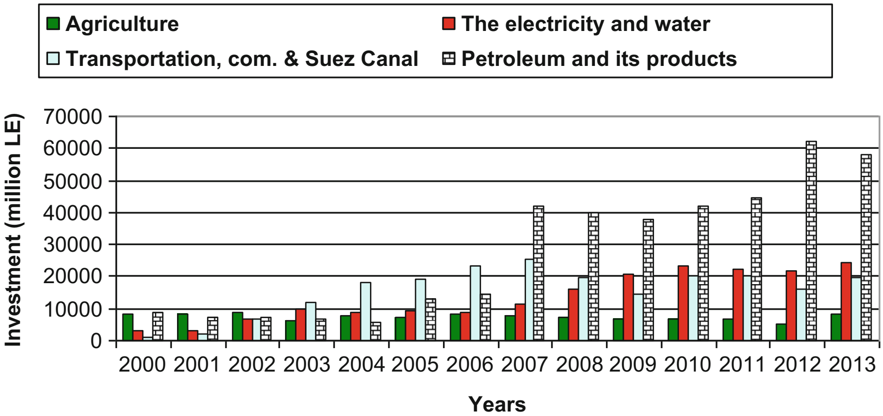


Fig. 30 Investments in Egypt. Source: compiled and computed from Ministry of Agriculture and Land Reclamation, Economic Affairs Sector, Agricultural Income Bulletin, different issues of [37, 43–47]

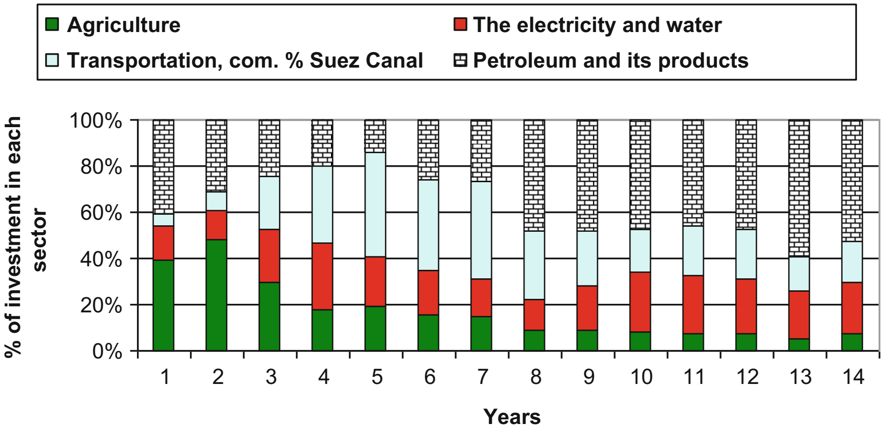


Fig. 31 Percentage of investments in each sector. Source: compiled and computed from Ministry of Agriculture and Land Reclamation, Economic Affairs Sector, Agricultural Income Bulletin, different issues of [37, 43–47]

In year 2013, Figs. 32 and 33 indicate that total investment, gross domestic product, and agricultural employment increased to LE 160 billion, LE 12,223.2 billion, and LE 2.157 million workers, respectively. Also, the figures show that total exports and imports and deficit in the balance of trade also increased to LE 181.2 billion, LE 405.4 billion, and LE 224.2 billion, respectively. In addition, the figures indicate that agricultural exports and imports accounted for 10.05% and 10.37% of the total exports and imports, respectively. According to Fig. 32, the share of agricultural imports and exports as a proportion of total exports declined in 2005, 2006, and 2007. This indicates how much liberalization of agricultural trade affects agricultural foreign trade in both exports and imports.

Agricultural investments accounted for 5.14% of the total investments, agricultural loans accounted for 17.04% of the total loans, and agricultural savings accounted for 6.05% of the total savings. Moreover, the number of workers in the agricultural sector was 5,065 in year 2000 and increased to a number of 7,222 in

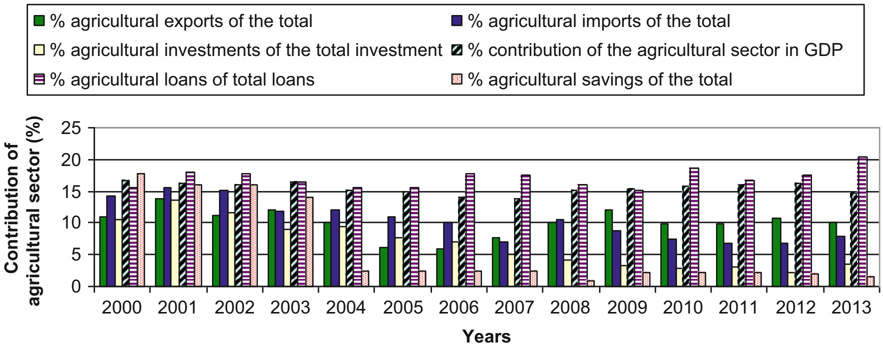


Fig. 32 Contribution of the agricultural sector. Source: compiled and computed from Ministry of Agriculture and Land Reclamation, Economic Affairs Sector, Agricultural Income Bulletin, different issues of [37, 43–47]

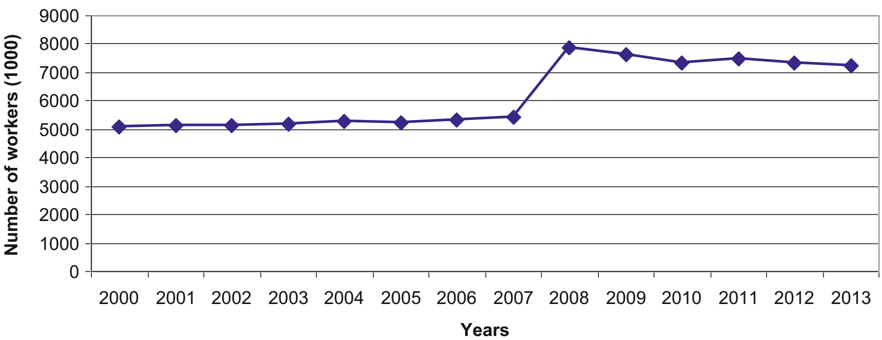


Fig. 33 Number of workers in the agricultural sector. Source: compiled and computed from Ministry of Agriculture and Land Reclamation, Economic Affairs Sector, Agricultural Income Bulletin, different issues of [37, 43–47]

year 2013 as shown in Fig. 33. However, the proportion of agricultural labor has decreased after the year of 2009 due to modern technologies that have increased production efficiency.

8.2 Investment and Developing the Agricultural Sector

Investment is an indicator reflecting the importance of agriculture sector. The agricultural, irrigation, and drainage investments have increased year after year due to the launch of the new land projects. Within this sector, it is clear that the private sector is playing an increasing role in agricultural investments. On the other hand, most of governmental investments were in research, institutional support, and agricultural extension under the Agricultural Liberalization Policies [36].

The agricultural sector contains three main subsectors: plant production, livestock production, and fishery production. Plant production contribution to agricultural income is estimated at 68.26%, followed by animal production and fish production with contribution estimated at 23.11% and 8.63% of the total income, respectively [48]. It can also be noted that contributions of plant production inputs' value, animal production inputs' value, and fish production inputs' value to total value of agricultural inputs amounted to 32.16%, 65.66%, and 2.19%, respectively [48]. Such results indicate the necessity to allocate the majority of investment, estimated at LE 7372.28 on average for the period 2000–2013, to the plant production subsector.

Plant production activity depends on cultivating old and new lands. And despite the fact that old lands are characterized by high production value and net revenue, in addition to low value of inputs compared to new lands, it is not economically feasible to allocate investments to old lands due to its limited area and difficulty to add new areas to the currently available ones. However, increasing production from old lands depends on vertical expansion, which can be achieved by using high yielding varieties and modern farming technologies. Regarding the crop production from new lands, horizontal expansion requires reclaiming new areas and adopting good agricultural practices that depend on transfer of the know-how technology.

9 Outward Water Management

9.1 Crop Pattern

Table 13 shows the cropping pattern suggested by the Sustainable Egyptian Agricultural Development Strategy [20]. The 2030 Sustainable Agricultural Development Strategy aims at achieving economic and social development in the agricultural sector, through achieving a number of goals including an efficient

Table 13 Cropping pattern suggested by sustainable agricultural strategies

Commodity	Estimates for 2030
Cereals	
Wheat	4,200
Rice	1,300
Maize	3,700
Total cereal crop	10,258
Sugar crops	
Sugarcane	350
Sugar beet	800
Total sugar crops	1,150
Oilseed crops	
Groundnut	350
Sesame	100
Total oilseed crops	525
Legume crops	
Broad beans	400
Other legume	45
Total legume crops	445
Fiber crops	
Cotton	1,000
Other fibers	21
Total fiber crops	1,021
Fodder crops	
Perennial clover	2,200
One-cut clover	650
Total fodder crops	2,850
Vegetables	
Total vegetable crops	2,645
Fruits	
Total fruit crops	1,755

Source: compiled and computed from Ministry of Agriculture and Land Reclamation [20]

utilization of natural agricultural resources, and food security through reaching self-sufficiency of strategic agricultural crops.

9.2 *Better Utilization of Agricultural Resources*

Table 14 summarizes the main key targets for 2030 regarding achieving a better utilization of agricultural resources. The total water quantities expected to be saved as a result of improvement of field irrigation systems and reducing areas planted by

Table 14 Estimated land area and water quantities in 2030

Item	2030
Projected land area (million feddans)	11.5
Areas projected to be reclaimed (million feddans)	5.0
Cropped area (million feddans)	22.9
Intensification (%)	200
Quantity of water used in irrigation (billion m^3)	64
Field water use efficiency (%)	80
Total water quantities expected to be saved as a result of developing the irrigation system (million m^3)	12,400
Average water share per feddan	5,565

Source: compiled and computed from Ministry of Agriculture and Land Reclamation [20]

rice are 12.4 billion m^3 of water by 2030. Accordingly, the drainage reduction by rice area reduction would be about 2,000 m^3/feddan. With a possible 500,000 feddans rice area reduction in the southern Delta, the expected decrease of drainage would be about 1 billion m^3 [49, 50].

Also, the key targets for 2030 are increasing in total cultivated areas to reach 11.5 million feddans and maximizing the benefit from rain-fed agriculture in the north coast to cultivate some crops [20].

9.3 *Potential for New Lands Using Drainage Water Reuse*

Horizontal expansion is one of the major policy instruments of the Egyptian Government to relief the population pressure in the Nile Valley and Delta. Within the Horizontal Expansion Plan, it was agreed by the Ministry of Agriculture and Land Reclamation and Ministry of Water Resources and Irrigation to reclaim 2.68 million feddans (2.18 million feddans from Nile water, 0.30 million feddans from deep groundwater, and 0.20 million feddans from reuse of treated wastewater).

Until 1997, about 0.815 million feddans were actually reclaimed and went into production. In 1997, a new Horizontal Expansion Plan was adopted that aimed to develop 3.4 million feddans, including the reclamation of 1.2 million feddans from the previous (1982) plan, which was completed in the year 2002. In this plan, the drainage water reuse plays an important role in meeting the demand for the new reclaimed land where over 60% of the drainage water reuse allocated for new reclaimed land by year 2017 [51].

The drainage water reuse will be increased to 8.4 million m^3 by the end of 2017 (3.52 million m^3 for the old land and 4.95 million m^3 for the new land) [51].

9.4 Reuse of Treated Wastewater

In an arid country such as Egypt, where water is scarce in general, wastewater reuse should be encouraged and promoted whenever it is safe and economically feasible, especially in terms of public health. Every effort should be undertaken to safely make use of reclaimed wastewater and encourage development of more treatment facilities. Treated wastewater is a valuable resource and has certain economic advantages. With proper management, crop yield may be increased by irrigating with wastewater. Such nutrients inputs can reduce or eliminate the need for commercial fertilizers [52].

According to Abdel-Gawad and El-Sayed [53], reuse of sewage after primary treatment in agriculture has been in practice since 1925 in the Eastern Desert area of Gabal Al Asfar outside Cairo (25 km NE) where an area of 20,000 feddans of desert land is fully cultivated. Reuse of primarily treated sewage was only possible during the first 20 years of operation of Gabal Al Asfar's treatment plant, and the flow reaching the plant doubled the capacity of the primary treatment works. The productivity of the reclaimed land was increased, but with the use of untreated sewage. Thus, the soil began to suffer due to the accumulation and retention of fat and grease in the top soil. Sampling of the subsurface and groundwater in the vicinity of Gabal Al Asfar sewage farm proved this water to be extensively and extremely polluted with a broad variety of pathogens.

The experience of large-scale and organized reuse of treated wastewater effluent is still limited in Egypt. However, there are a number of large-scale pilot projects, mostly irrigating trees beside some field crops, for example, in Abu Rawash, Sadat City, Luxor, and Ismailia. This situation is rapidly changing in the major cities of Egypt due to the installation of modern wastewater treatment plants (WWTPs) that provide secondary treatment, which offers an opportunity for water resources planners to fill the gap between supply and demand [53].

Treated wastewater is being reused for irrigation with or without blending with freshwater. The increasing demands for domestic water will increase the total amount of sewage available for reuse. It is estimated that the total amount of reused treated wastewater in Egypt was about 1.4 billion m^3 in 2000 [53]. However, the key target for reusing the treated water will actually depend on the quantity and salinity of water in the drain.

In order to achieve the ultimate goal for reusing the drainage water, the Egyptian strategies [49] include some important measures such as the following:

1. Improving the quality of drainage water especially in the main drains.
2. Separating sewage and industrial wastewater collection systems from the drainage system.
3. Continuous monitoring and evaluation of the environmental impacts due to the implementation of a drainage water reuse.
4. Limiting the use of treated wastewater to cultivated nonfood crops such as cotton, flax, and trees.

9.5 Groundwater Resources Management

Recently, the Ministry of Water Resources and Irrigation has launched the strategy of water resources development and management in Egypt until 2050. The new strategy takes into consideration major issues of future concern such as scarcity of water, pollution control, securing water quality and water saving, industrial and agricultural waste disposal, protection of groundwater resources, and environmental problems of climate change. The strategy provides a clear framework for the role of groundwater in Egypt and its management needs and challenges. As for technical constraints, the strategy stressed the importance of capacity building and enhancing of the skills and expertise required to meet the future needs [19]. Also, the strategy for groundwater development encourages agricultural development of desert areas. These areas would involve initiating new communities that can absorb part of the highly concentrated population in the Nile Valley and Delta. Such an approach will increase the future demands for groundwater, which consequently will need continuous monitoring and evaluation of the groundwater aquifers to avoid any possible deterioration in these aquifers due to misuse.

Concerning the renewable aquifer underlying the Nile Valley and Delta, the strategy for groundwater [49] envisages the conjunctive use of Nile surface and groundwater through:

1. Using the aquifer as a storage reservoir to supplement surface water supply during peak periods and recharging during the minimum demand periods.
2. Using of modern irrigation methods (sprinkler or trickle) in the new lands that uses groundwater as the source of water.
3. Using a vertical well drainage system in Upper Egypt to avoid water logging and increase crop productivity.

Concerning Groundwater Aquifers in the Western Desert and Sinai, groundwater occurs at great depths and needs a large investment to be profitable [49]. Therefore, future strategies to use groundwater in the Western Desert and Sinai include:

1. Using of the modern technologies to determine the main characteristics of each aquifer including its maximum capacity and safe yield.
2. Designing an integrated plan for the new small community structures for using all available natural resources.
3. Using nonconventional sources of energy such as solar and wind to minimize the costs of pumping.
4. Using new technologies for farm irrigation in desert areas to minimize field losses.

In addition, the Government is examining the possibility of using low-salinity brackish groundwater to irrigate certain seasonal crops. This water is available at shallow depths in the Western and Eastern Deserts and at the borders of the Nile Valley. The average salinity of such water varies from 3,000 to 12,000 ppm. Nonconventional sources of energy, such as solar and wind energies, would be used in the treatment process to minimize the cost and increase the economic value. This source will supplement rainfall to increase land productivity by cultivating two crops per year instead of one [49].

These future strategies for groundwater development assessment and utilization involve the use of modern technologies, water quality management, public awareness, continuous monitoring and evaluation, user's participation in water management, institutional strengthening, coordination between ministries, international cooperation, and research and development.

9.6 Improvement of Water Use Efficiency

9.6.1 Irrigation Improvement Project

Egypt has launched an ambitious Irrigation Improvement Program (IIP) "later called Integrated Irrigation Improvement Management Project (IIIMP)," which includes the improvement of water delivery system, on farm water management, irrigation methods, and associated agronomic practices [41]. The extension of these programs in the Delta will affect the generation and distribution of drainage water in the region. During 1989–1997, Egypt has implemented these programs on over 350,000 feddans. These programs will be extended to an area of 3.5 million feddans in the Delta [41].

Pilot areas indicated that irrigation efficiency could be improved by 10%. Therefore, it is expected that the expansion of IIP over the 3.5 million feddans in the Delta will eventually result in a reduction of 2.6 billion m^3 drainage generations from the 1995–1996 level of 19.5 billion m^3 (12.4 billion m^3 outflow, 4.3 billion m^3 official reuse, and a Ministry's estimate of 2.8 billion m^3 unofficial reuse). This 2.6 billion m^3 drainage reduction will affect the volumes of drainage outflow as well as official reuse and unofficial reuse [52].

If the ambitious IIP extension plan is implemented, then the currently scheduled drainage reuse expansion will become partially unnecessary, since there would be less drain water available for reuse [53]. It should also be noted that with increased irrigation efficiency, decreased drain water will be accompanied by deteriorated water quality and at the same time increased availability of freshwater.

10 Outward Agriculture Horizontal Expansion

10.1 Al-Salam Canal Project

Al-Salam Canal is to be fed from the Damietta Branch upstream of Farskour Dam with freshwater while supplemented with drainage water from the Lower Serw pumping station and Bahr Hadous drain near the outfall. The drain currently contains a collection of drainage water from all the catchments served, namely, Nizam, Beni-Ebeid, and Erad [54].

The average yearly discharge of the Lower Serw pumping station is about 600 million m^3, and that of Bahr Hadous drain is about 2 billion m^3, bringing the total to 2.6 billion m^3/year.

The average salinity measured at the Lower Serw pumping station is around 1,000 ppm, and that measured at Bahr Hadous outfall is about 1,400 ppm. The weighted average of both waters is 1,300 ppm. When this is mixed with freshwater at a ratio of 1:1 the salinity of the mixture is expected to be in the neighborhood of 800 ppm which is reasonable, given that the water is going to be used for the irrigation of sandy soils.

It is planned to use 1.50 billion m^3/year of this quantity in the first and second phases of the project in addition to a similar quantity of fresh Nile water. The mixed water will be used to irrigate the reclamation lands in Port-Said Plateau, South Husseinia, and South Salhia, the total area of which is about 165,000 feddans in the first phase. The second phase covers the irrigation of 200,000 feddans extending along the northern coast of the Sinai Peninsula from Al-Arish westward [54].

10.2 Toshka Project

Toshka Project is the largest irrigation project in Egypt after the Aswan High Dam construction. It is designed to develop about half million feddans of arable land. At a designed annual irrigation requirement of 8,000 m^3/feddan under the local climatic conditions, the project withdraws about 4 billion m^3 of water from Nasser Lake [55].

10.3 First Phase: One Million Feddan Project

After the change in political conditions that accompanied the June 30 Revolution, the Government of Egypt (GOE) embarked on applying the policy of horizontal expansion through reclaiming new lands. GOE's comprehensive development plan included reclaiming about 1 million feddans distributed in the first phase as shown in Fig. 34. The project aims to reduce the food gap and increase the populated area through the creation of new urban communities. Most of the project areas will rely on groundwater. In 2015, an official in the Irrigation and Water Resources Ministry announced that the project includes digging over 5,000 water wells for a total cost of LE 6 billion, with 600 wells to be drilled in different areas of Egypt's Western Desert, including Wadi Moghra in Munkhafad Al-Qattara (the Qattara Depression), the Toshka region, and the Farafra oasis [56].

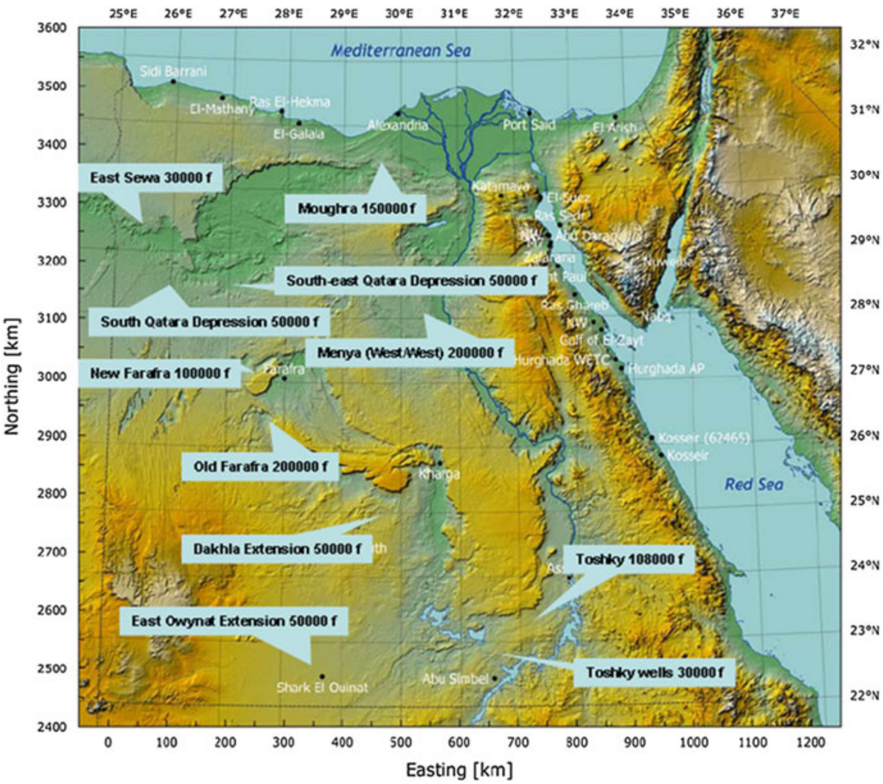


Fig. 34 First phase: one million feddans project

11 Conclusions

Egypt is facing increasing water demand to satisfy a rapid-growing population, increasing urbanization, a higher standard of living, and an increasing agricultural production in order to feed the growing population. Currently, the total agricultural land is about 12.8 million feddans, representing less than 5% of total land area. About 83.3% of water in Egypt is consumed by the agricultural sector.

In the agricultural system, fragmentation of holdings is one of the main issues that threaten the agriculture, particularly in the old land, the Nile Valley, and the Nile Delta as a result of its direct negative impact on agricultural production and water use efficiencies and marketing as well as on the income of farmers.

The Egyptian Government prepared several water policies to accommodate the dynamics of the water resources and crop productivities. The latest policy was issued in January 2005. It included several strategies to ensure satisfying the demands of all water users and expanding the existing agricultural area through reclaiming new lands. Also it gave farmers the chance to share in the different responsibilities concerning the water distribution system and the drainage water reuse besides choosing their own crop pattern.

In the agriculture sector, the agricultural, irrigation, and drainage investments have tended to increase year after year due to the launch of new land projects. Within this sector, it is clear that the private sector is playing an increasing role in agricultural investments.

To provide food for Egypt's growing population, many achievements have been made to improve the agricultural production through technological advances, better utilization of agricultural resources, using drainage water reuse, reusing of treated wastewater, improving water use efficiency, managing groundwater resources, reducing the area of rice cultivation, and developing a horizontal expansion area through reclaiming new lands.

12 Recommendations

From all the above, the following recommendation could be stated:

1. More effort should be directed to design a cropping pattern map, according to specific crop pattern suitable for the available water.
2. Activate the role of water users' associations for providing the farmers with the necessary information about water saving, crop water productivity, and technology.
3. Encourage horizontal expansion to increase cultivated lands and plant yields within the accessible amount of water resources.
4. Shifting to less water-demanding crops (e.g., rice and sugarcane areas) and gradually introducing crops consuming less water with the use of genetic engineering to produce crops with lower water requirements.
5. Improve the efficiency of the existing irrigation networks in the old and new lands to achieve maximum utilization of irrigation water by reducing losses, detecting leakage, and improving irrigation distribution and conveyance efficiency.
6. Support the role of scientific research to introduce new agricultural technologies that have high productivity and low water consumption.
7. More emphasis should be placed on the importance of selecting new strains and varieties of different crops that tolerate diseases, drought, and salinity.
8. Continuation of the policy of reuse of agricultural drainage water for irrigation.
9. Enhancement of the private sector in participation in management and operation of the water resources and to raise the public's awareness of the water scarcity problems.
10. Establish a well-coordinated information system to support decision-makers in water resources management.
11. Intensify the government's efforts to reduce the population growth rate.

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Administrative Context and the Legal Framework Governing Water Resources and Agriculture in Egypt

Mohamed Salman Tayie and Abdelazim Negm

Abstract The water resources play a vital role in the lives of nations and peoples. Water is linked to food security and the comprehensive development process in all its dimensions. Thus, water has become part of the national security of any country. Therefore, all countries are concerned with the management of their water resources and how they are distributed into different uses and sectors, including the agricultural sector, which is the largest consumer of water globally, where agriculture uses about 70% of freshwater annually according to UN estimates.

The Egyptian situation is a special case, where Egyptians rely mainly on Nile water, accounting for more than 96% of Egypt's total freshwater. Therefore, the Nile River – was and still – represents the backbone of Egyptian development in all its dimensions.

Throughout the ages, Egyptians have developed various laws, policies, mechanisms, and institutions to manage water resources and to manage agriculture in Egypt.

This study aimed to present and analyze the legal and administrative frameworks governing both water resources and agriculture in Egypt, to identify the strengths and weaknesses in the legal and administrative contexts of water resources and agriculture in Egypt and evaluate the disadvantages and reform.

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The study is based on the historical approach to present and analyze the policies and laws of water management and agriculture in Egypt. It also relied on the legal-institutional approach in presenting and analyzing the most important institutions that play a role in water management and agriculture in Egypt.

Keywords Administrative, Agriculture, Egypt, Institutional structure, Integrated water resources management, Legal framework, Policies

Contents

1 Introduction

Maintaining regular food supplies to nations and peoples – known as "food security" – is tightly connected to the ability to secure adequate amounts of clean water as far as quantity and quality are concerned. This asserts the close relationship between food security and water security, a fact that is highlighted in the sentence: "states can have no military security separate from their economic security, the peak of the latter is food, and the core of food security is water" [1].

Water – or blue gold – became a strategic supply not less in importance than oil and gas. On the contrary, it exceeds their importance since it is one of the essential development factors whether economic, social, or else. One cannot handle agricultural or industrial development away from the availability of necessary amounts of water with specific qualities.

The maximization of water usage economies and good management of water on the long run require searching for current and future resources.

In this context, it is globally acknowledged that "water resources" are "global resources," hence becoming a global public resource inclusive in the common heritage of humankind. Therefore, there is a dire need for concerted international efforts to manage this resource scientifically based on an integrated methodology to maximize the benefits of this scarce resource [2].

Consequently, the strategic relationship between water and agriculture is one of the major economic activities resulting in the emergence of many issues regarding water and agricultural domains administratively and legally, as well as in relation to the agricultural, political, and water policies adopted by concerned parties internationally.

As far as the Egyptian case is concerned, water management goes through very complicated circumstances and uncertainty since officials work under repeatedly changing circumstances which often require them to work and deal with competing demands due to the existence of a variety of different and interrelated interests regarding water. Weak points in the water management systems hindered the progress toward sustainable development, especially in the light of the profound connection between water and agriculture in Egypt. The main challenge became the possibility to attain a balance among economic, social, agricultural, and water needs – on the one hand – and the ecological sustainability on the other [3].

This paper focuses on those points [4, pp. 6–7].

2 The Administrative Context and Legal Framework Governing Water Resources in Egypt

2.1 The Administrative Context Governing Water Resources in Egypt

2.1.1 Features of the Egyptian Water Management in History

Along with history, there has been a profound interest in the management of water resources. Ancient Egyptians (Pharaohs) were concerned about the water of the Nile in the light of the floods they faced.

The "Nile" refers to the names ancient Egyptians used to name the river. They believed that the Nile is the center of the universe starting from its upstream areas. Therefore, their Mecca was the South [5]. They called it "ABBY," the god in some of their chants, which is a name, derived from the name of "NOON" the god of eternal water believed by the ancient Egyptians to be the oldest god from whose premises the Nile runs [6, 7].

The main portion of the Nile running between Cairo and Aswan was called in the hieroglyph language "ATRO-AA" meaning "The Great River." From this old word came the current Arabic "TERAA" meaning small branches of the river, while each of the numerous branches in Delta was named "ATRO" meaning river [8]. Whereas, the name Nile was introduced on a later date. It is used to be named "HAP," the god of the river, the most renowned god in those times [9].

With the dusk of the Islamic era, canal, bridges, and Nile measurement facilities were built. Moreover, during the Ottoman era, more major irrigation projects were executed including dams, canals, and reservoirs. Consequently, the agricultural spaces were expanded more than ever before. The major projects of this era included – but not limited to – El-Qanater El Khayreya reservoir (1861), drilling of Elbihairy, Eltawfiky, and Elmenoufy canals, in addition to hundreds of smaller canals, Aswan Dam (1902), Isna reservoir (1908), and Nag Hammadi reservoir (1920). As a result, the agricultural space was increased from 2 million acres in 1813 to about 5 million acres in the start of the 1950s. Then, the first mega project was executed with the arrival of the Free Officers

Movement to office, namely, the High Dam, which was a turning point in the history of the Egyptian agriculture and industry. With the start of storing water in Nasser Lake (1964), the dam helped to manage and control the water of the Nile and achieve water security for Egypt, which contributed to the plans for agricultural development projects to reach 5.8 million acres in the 1970s (5.2 million acres in 1950s). Then, the annual agricultural growth reached 2.6% (average) in the 1980s, 3.4% in the 1990s, and then 3.6% in 2006/2007. Also, the agricultural spaces were increased by 2.3 million during the same period. Thus, Egypt adopted the agricultural expansion projects which contributed to add 1.4 million acres [10].

In the same context, Egypt executed many national projects but feasibility was not achieved; the most important of those projects is Toshka. Toshka was meant to create a new delta in the south of the western desert adding about 540,000 acres that would be irrigated by the Nile water via Zayed Canal which receives annually 5.5 billion cubic meters. The investment cost of the project was about 4,014 million EGP. Moreover, in the south of the Nile valley, there is East of Oinat (Shark Eloinat) project, aspiring to add about 230,000 acres which would be irrigated by the groundwater reservoir in the region. The investment cost of the project was 3.5 billion EGP. There is also, El Salam Canal, Assiut Reservoir, and Serabioum water tunnel in Sinai. Work started in Serabioum in 2014. It is a water tunnel under the new Canal of Suez with the cost of 200 million EGP aspiring to transport the Nile waters to Sinai from the east side of the old canal to the east side of the new one [11].

2.1.2 The Most Essential Water Resources in Egypt

These resources can be summarized as [12, 13]:

- *Surface water (Nile water)*: the river extends to 6,825 km. The net quantity of the river waters reaches about 84 billion cubic meters annually, mainly used in a variety of ways. The Nile waters constitute more than 96% of the Egyptian water resources. The Egyptian quota is 55.5 billion cubic meters annually.
- *Reservoirs and tanks on the Nile*: there are 11 main reservoirs, and 17 subsidiary reservoirs on the Nile fed directly by the Nile, in addition to 37 stone reservoirs.
- *Groundwater*: which is the water reserved underground. In light of the state plan to develop the water resources (expected to be accomplished in 2017), it is planned to save 5.9 billion cubic meters of water, including 2.7 billion cubic meters of groundwater and about 3.2 billion cubic meters of the deep groundwater.
- *Rain*: Egypt is a dry country receiving minute rain quantities (20–150 m annually on the Western North coast) [14].
- *Wastewater reuse*: currently, 4.7 billion cubic meters of the agricultural wastewater are used annually. There is a plan to use 10 billion cubic meters in the next decade [10].

The Egyptian water resources in 2015 are presented in [15] which is a chapter in this volume and is not repeated here to reserve space.

2.1.3 The Institutional Hierarchy of Water Resources in Egypt

This part of the research highlights the role played by the concerned parties regarding water management in Egypt as far as use, monitoring, and planning are concerned, which is a matter related to responsibility and liability among all units. It has been noticed that there are many parties that are responsible for the management, and there are major institutions, scientific and technical support identities, etc., in addition to monitoring parties and local units which play essential roles in this context. The main line that governs the relationship among all those parties is usually connected to the Ministry of Water Resources and Irrigation as far as responsibility and accountability are concerned [16].

The Ministry of Water Resources and Irrigation works solely regarding the legal liability to plan and manage all water resources in Egypt. It is responsible for taking the appropriate steps to protect water resources and their quality. Practically, the ministry does not display major concern regarding quality. Law No. 48 stated the importance of protecting the Nile and water bodies against pollution, while "the Ministry of Water Resources and Irrigation (MWRI)" is responsible for the following duties [4, pp. 16–18]: the issuance and cancellations of drainage in the Egyptian water passages. These water passages include the Nile, canals, lakes, and groundwater aquifers. In addition to the above, the MWRI is in charge of (1) examination of the drainage water treatment facilities, (2) monitoring the feed stations of the potable water units, (3) treatment of polluted water by sewerage and industrial wastewater, (4) specification of terms and standards related to drainage in the water passages, and (5) issuance and monitoring of the necessary licenses to establish any facility that exposes wastewater directly in the water passages. In this context, the Ministry of Water Resources and Irrigation is organizationally constituted from some bodies illustrated in the Fig. 1 [17]:

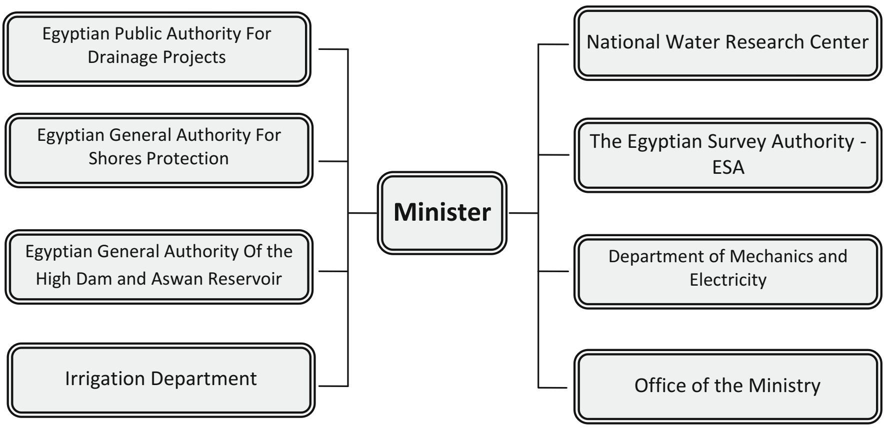

Fig. 1 The bodies that follow the Ministry of Water Resources and Irrigation [4, pp. 16–18] (source: http://www.mwri.gov.eg)

On the other hand, the ministry works to delegate most of its functions related to monitoring the quality of surface and groundwater to the National Center for Water Researches. The center and its institutions monitor the quality of water nationally and regionally in a number of strategic locations via a national monitoring network. Moreover, the ministry has the right to establish associations for water users such as water users' unions, water users' organizations, and water boards [4, pp. 16–18]. The main information center of the Ministry is the Egyptian focal point for the Euro-Mediterranean information system for knowledge in the field of water in order to improve the communication service between the Ministry and the public administrations in the governorates [18], on the other. Specialized parties assist the ministry in this domain as illustrated in Fig. 2 [20].

By integrating the bodies, units, and sectors mentioned in the previous two figures, the organizational chart of the Ministry of Water Resources and Irrigation is as shown in Fig. 3.

In this context, as a leading research institution included in the managerial hierarchy of the ministry, the National Water Research Center plays a significant role. It hosts 12 research institutes working on serving the national water resources management plan besides hosting the strategic water researches unit concerned with environmental monitoring, a geographic information systems unit, an archiving and information center, and a central library which focuses on researches publications mainly [19] (see Fig. 4):

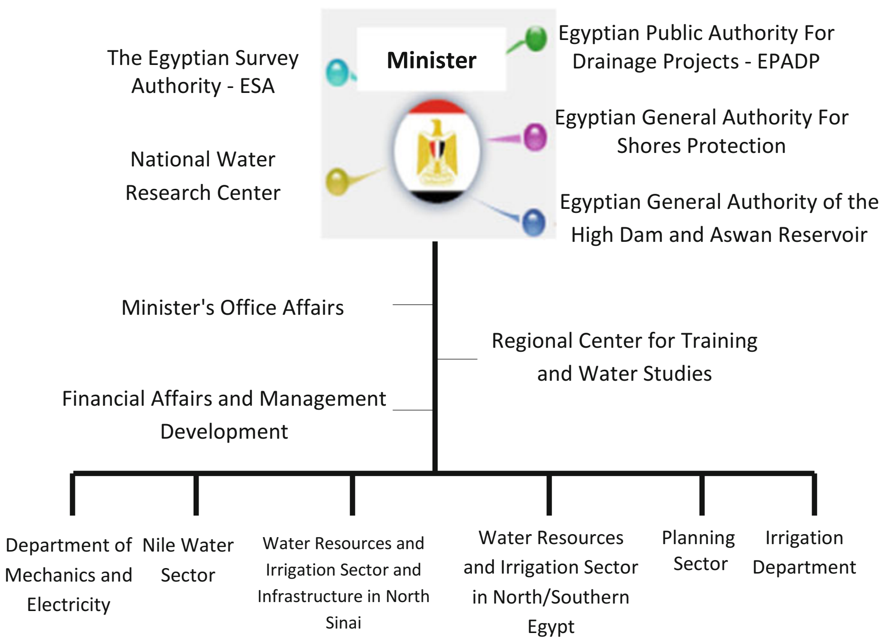

Fig. 2 Specialized parties/bodies assisting the ministry [19]

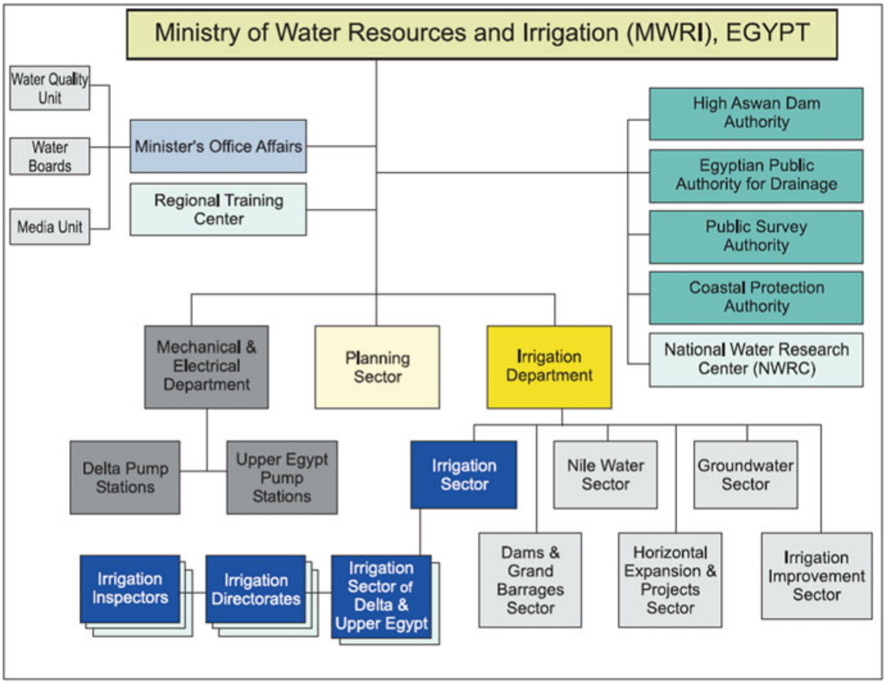

Fig. 3 Organization chart of the Ministry of Water Resources and Irrigation (MWRI), Egypt. Source: Water Policy Issues of Egypt (2005)

In addition to the National Water Research Center and its affiliated research institutes and the Central Laboratory for Environmental Quality Monitoring, there is the Egyptian–Dutch Water Consultations committee, which is a research center concerned with the strategic researches related to water scarcity and nutrition availability. It cooperates with the ministry. Also, a number of partners are also cooperating with the MWRI. These include the German federal institution which is responsible for the establishment of capabilities in the water domain in the developing countries via partnership programs such as "CEDARE," the regional center for water and environmental studies in the Mediterranean region, and the Egyptian partnership organization for water, which is a nongovernmental organization responsible for water studies and awareness [19]. The irrigation authority is one of the most critical parties which assist the ministry in achieving its goals. In turn, it includes a number of subsidiary divisions and departments as shown in Fig. 5e [22].

2.1.4 Axes of Administrative Coordination Among Concerned Institutions Dealing with Water Resources

Institutions that work in an integrated way to manage the water resources and irrigation in Egypt are presented above, with particular reference to the Ministry of

Fig. 4 Institutes of the National Water Research Center. http://www.nwrc-eg.org/introduction.html

Water Resources and Irrigation. They do not function solely. There are a number of institutions and ministries that play an essential role in the light of the national water management plan and the integrated management of this file. These ministries are [21]:

- *Ministry of Agriculture and Land Reclamation*: the closest to the Ministry of Water Resources and Irrigation since the agricultural sector is the primary consumer of water in Egypt (85% of the Egyptian quota from the Nile). Recently, the higher coordination committee (a joint committee in which both ministries take part) held its third meeting in 2017 at the premises of the Ministry of Water Resources and Irrigation to follow up and evaluate the method of growing wheat via cooling. It has been agreed that there must be a mutual coordination regarding the allocation of rice fields permanently via the concerned parties in both ministries and that modern technicality must be exploited to follow up the growing of rice in the governorates. Also, identifying the outlaw fields and to manage the cooperation in the implementation of the modern irrigation methods are among its duties [23].
- *Ministry of Environment*: responsible for setting the national environmental policy and coordination of the environmental management activities in the government according to law No. 4/1994 which is considered the most recent and general law in this context. There is also the Egyptian Environmental Affairs Agency which controls issues related to air pollution, hazardous waste, and

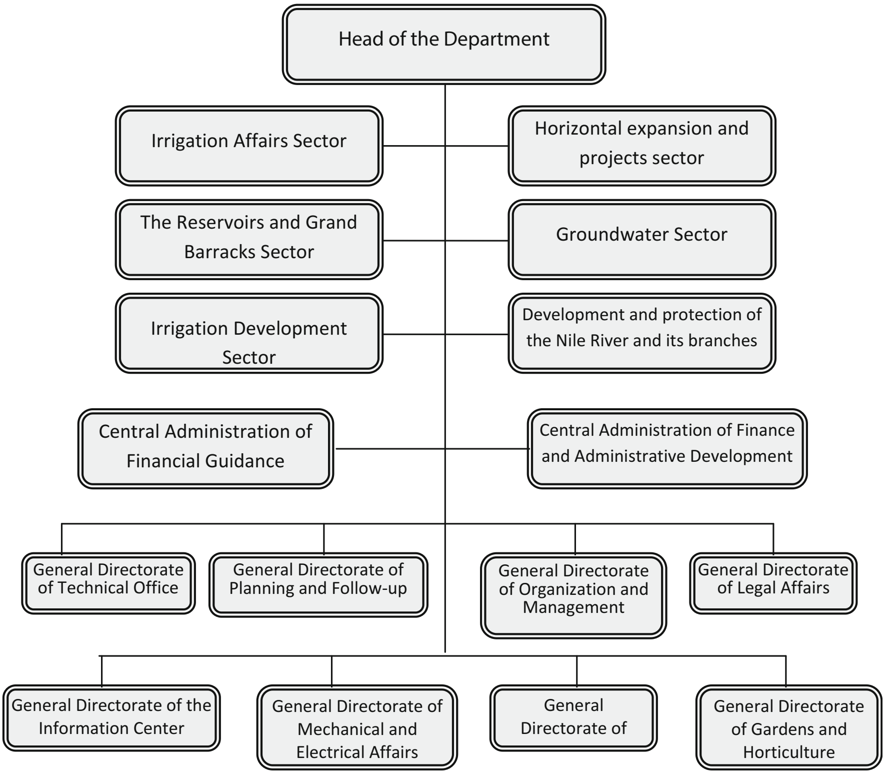

Fig. 5 The main bodies of the irrigation authority [21]

maritime drainage, besides monitoring commitments to laws, inspection, and implementation.

- *Ministry of Health and Population*: plays a vital role regarding the setting of quality standards related to water and drainage (if used for drinking). It is also responsible for acquiring samples from water and drainage stations as well as from water treatment stations for analysis. A holding company for water and drainage was established as a result of the presidential decree No. 135/2004. This company is subject to the Ministry of Housing, Utilities and Urban Development.
- *Ministry of Housing and Utilities*: it plays a role too. It manages the distribution of purified freshwater and collection of wastewater from the domestic and its disposal. The disposal of the sewage and sewerage without treatment into the surface water or to the groundwater through septic tanks pollute the freshwater leading to several problems. One major problem is the use of the untreated water in irrigation and the negative impacts of the polluted water on the ecosystems.
- *Ministry of Industry, Trade, and Small Industries*: as an affiliate to the ministry, General Organization for Industrialization supervises cases of pollution, safety, and health in factories.

- *Ministry of Interiors*: a maritime police unit is affiliated to the ministry. It is responsible for the implementation of law No. 48 and the preservation of the environment in general. Law No. 4/1994 grants extra powers to the ministry stating that the ministry is to establish a particular police unit responsible for the preservation of the environment [24].
- *Ministry of Transportation and Ministry of Tourism*: the river is used for touristic purposes and for transportation (floating hotels). Some claim that those hotels may face a catastrophic situation during the winter season when the Ministry of Water Resources reduces the water level in accordance with the preservation plan. For this purpose, the Ministry of Irrigation established reservoir locks equipped with up-to-date navigation utilities which enable a quick crossing via the reservoirs established on the Nile.
- *The Ministry of Electricity*: the ministry exploits waterfalls to generate power. In this purpose, the ministry coordinates with the Ministry of Water Resources to set the levels of water through which the highest power generation can be reached. It is also in need to use water for the thermo stations used to generate power (Alwalidia Station in Asyut – Koraimat station in Giza) [25, pp. 428–429]. On the other hand, some municipal units play supporting roles with the participation in managing water and drainage including (1) Greater Cairo Water and Drainage Facility; (2) Potable Water Facility in Alexandria; (3) Canal of Suez Authority, housing authorities in the governorates (Aswan, Menya, Beni Suef, Faiyum, Dakahlia, Sharqia, and Gharbia); (4) the New Housing Communities Authority; (5) private sector corporations in the Red Sea and South Sinai; (6) Ministry of Planning; and (7) National Investment Bank and Local Development Ministry [26].

2.1.5 Egyptian Water Management Policies

Egypt water management dates back to ancient Egyptians. There were tendencies to measure the level of the flood; then the Islamic era witnessed the rehabilitation of those policies via the integration of items specifying the quality and height of lands in the taxes system. With the French invasion of Egypt, there was a new trend related to the drawing of water policies. Napoleon introduced the “storage theory,” followed by Mohamed Ali who established summer canals and El Qanater El Khayreya reservoirs as means of surface reserves of the Nile water. 1898–1902 witnessed the first attempt to reserve water followed by the establishment of the reservoirs such as Isna and Nag Hammadi and then Delta, Zefta, Faraskour on Damietta Nile branch and Edfina canal on Rosetta branch.

Then the High Dam was established in the 1960s. On one hand, it is observed that the water management policies since 1928 started to be dealt with based on scientific methods aiming to reach 7,170 million acres in the absence of the High Dam. Then the hydro policies were directed to the “developmental base” via the allocation of potable water and industrial water while the remaining is to be allocated to agriculture [21].

With the start of the hydro policy of 1975, the Ministry of Water Resources and Irrigation commenced the evaluation of the supply and demand of water to assess the potential equivalence between supply and demand in the future. In 1981, a major hydro policy was issued aiming at introducing plans aiming to meet the agricultural water demands and study the nonagricultural demands.

Moreover, during the period from 1997 to 2017, the Egyptian hydro policies was developed depending on the "allocation base." According to this policy, water was distributed among various activities according to the needs of each one and according to the revenue of each single cubic meter of water as far as the hydro budget of the country is concerned [27].

The last hydro policy was issued in January 2000 with the title: "The Main Features of the Hydro Policies of 2017." In addition, there is the "challenge confrontation," which is the strategy the government seeks to implement to maximize the benefits of each citizen of the safe hygienic facilities to reach 60% (currently 30%) besides water availability in 2017. The National Water Council is responsible for the follow-up of the process since the strategy requires 145 billion EGP for the period from 2003 till 2017. The main stocks of projects are owned by the Ministry of Housing (63%) and the Ministry of Water Resources and Irrigation (32%), and the private sector owns 5%. The total cost of this period (2003–2017) reaches 41 billion EGP. The cost includes maintenance and operation of the hydro system, excluding the rates of the personnel who work in governmental agencies. The municipalities and maintenance receive the lion's share of the operation cost which reaches 70% to operate and maintain the water treatment units and the black water treatment units. The Ministry of Water Resources and Irrigation is responsible for 12% of the cost, while the private sector pays almost 15% [28].

In addition to the National Water Research Center, there are three committees responsible for supervising the national water resources plan, namely, high, technical, and advisory committees:

1. The counseling committee which includes the decision-makers and experts belonging to the Ministry of Water Resources and Irrigation
2. The higher joint committee of the ministries which includes the higher committee established among the ministries that are formed by the ministerial elite decision-makers in relation to the management and use of water
3. The technical common committee which includes representatives on the technical level of the ministries concerned with the management and use of water [29]

In this context, the Ministry of Water Resources and Irrigation works in cooperation with USAID to execute the project of the integrated management of the hydro resources phase II (2004–2008) after the completion of phase I of the project (2009–2012). The current project works with the integrated water management in the Ministry of Water Resources and Irrigation to provide technical support, training, equipment, and media tools to enhance the participation of water users and upgrade the integrated management of water technically. On the administrative level, the project aims to integrate the irrigation and services offices in one office to be named: "Water Resources and Irrigation Engineering" or "Integrated Water Engineering." In Phase I, the project focused on five irrigation departments in Zefta, Eastern Sharqiya in the Delta, East and West Qena, and Aswan (south of Egypt). Thus, 27 water resources and irrigation engineering departments and 600 associations for the water users to manage irrigation water for 1.5 million acres (around 15% of the Egyptian agricultural lands) were established. Therefore, 14% of the annual water needs of the departments were reserved. Six million farmers and water users benefited from the project (500,000 directly via the water users' associations) [30].

During phase II the project is expected to include eight departments: two in Damietta Governorate (Elsalam General Irrigation Department, Damietta Irrigation), two in Dakahlia Governorate (East Dakahlia and South Dakahlia General Irrigation Department), one in Ismailia Governorate (Ismailia General Irrigation Department), two in El Sharqia Governorate (East Sharqia Irrigation Department), and one in Al Qalyubia Governorate (Al Qalyubia General Irrigation Department). Moreover, 45 water resources and irrigation engineering departments and 1,200 water users' associations to manage water serving 2.2 million acres or 27% of the total Egyptian agricultural lands will be established. It is expected that 12.5 million farmers and water user will benefit from phase II of the project directly, including 900,000 of water users' association members [30].

In addition, there is a project to preserve water and develop irrigation in West Delta to support the agricultural communities via the upgrading of the surface water irrigation system by depending on allowing private contractors to recover the cost. The project scope of work is to execute a network to transport surface water from the Nile to link the farms existent in the area (covering 38,000 ha located in the southern part of the West Delta). The private sector is involved to play a role through participation in the design and construction and operating the new irrigation system and delegate some of the responsibilities related to the investment costs [4, pp. 16–18].

2.2 The Legal Framework Governing Water Resources in Egypt

The laws and legislations adopted by the state to arrange the functions of departments are an imminent issue since they are the facilitators for the developmental process and may have a diverse impact. In this sense, the water management process passed through various laws, decrees, and presidential decisions on the legislative level as a local framework, besides the bilateral and multilateral agreements on the regional level. The research focuses solely on the laws and legislations implemented on the local level.

2.2.1 Historical Development of the Legal Framework Governing Water and Actors

During the rule of Mohamed Ali, till the movement of 1952, a number of laws and regulations have been issued to manage water. Those laws and legislations were unified as one legislation in 1899 for easy access. It remained in force until the passing of the irrigation and drainage law No. 68 in 1953. The law of 1899 included the legalization of the participation of the citizens benefiting from the protection and preservation of the bridges on the Nile.

In 1953, the law of irrigation and drainage was issued, after 1952 revolution, which was called “the Overall Law” (law No 68). This law dealt with the unique measures related to irrigation. It provided the irrigation authority the complete power to distribute water all over the country. It is considered the first law which grants the judicial control power to irrigation engineers regarding irregularities committed in the irrigation and drainage sector. The law was followed by a number of amendments included in law No. 29/1956, law No. 164/1957, and law No. 116/1959.

Moreover, in 1953, the law No. 20 was adopted to arrange the fees related to irrigation and water elevating machines to protect benefactors from equipment vendors’ rapacity. In the same year, law No. 71 was adopted (rice agriculture), according to which the irrigation ministry is to specify locations of rice growing. Then law No. 250 was issued in 1956 for the same purpose and finally law No. 31/1961 which granted to the ministry the right to specify the locations where rice growing is permitted [11].

In addition, the laws organizing field drainage were adopted to be the responsibility of the owners. This was elaborated in law No. 35/1949, the law adopted in 1954 aiming to facilitate the establishments of those drainage canals, and law No. 82/1956 to facilitate the collection of the field drainage establishment fees.

In 1971, the irrigation law No. 74 was issued to unify all laws. Then law No. 12/1984 was issued to govern the irrigation, water distribution, establishment, maintenance, and groundwater process in the Nile valley and in the Delta [31].

Due to the need to establish associations for the water users to operate and maintain irrigation tools (Sawaqy), the law No. 213/1994 was issued. And in regard to the exposing of liquid wastes in the Nile, law No. 196/1953 was issued regarding the drainage of public, industrial, and commercial facilities followed by law No. 33/1954, which specifies the authority which grants permissions to expose liquid waste after the consultation of the Ministry of Health (the Ministry of Housing).

Law No. 93/1962 cancelled the abovementioned laws – related to the disposal of liquid wastes – and permissions from the ministries irrigation, health, and industry were to be obtained, and then a notification to the Ministry of Housing is to be sent to issue the final permission. For the reservation of the Nile, the canals, and the water passages against pollution, law No. 48/1982 was issued. Due to the increasing pollution problems, law No. 4/1994 for the preservation of the environment was issued specifying the powers granted to the "Egyptian Environmental Affairs Agency" [25, pp. 437–440].

One of the procedures that were adopted regarding the management and organization of water in Egypt was the ministerial decree No. 209/2005, related to the forming of a coordination committee with the task to permit the developmental activities in Nasser Lake. Moreover, in cooperation with the Ministry of Environment, the licensing standards were issued by the ministerial committee formed pursuant to the PM decree No. 203/2002 relying on allowing seasonal farming. This kind of farming depends on the humidity of the soil without the use of fertilizers and the implementation of two ministerial decrees No. 199 and No. 906/1990 issued by the Ministry of Agriculture considering that those lands are dedicated to organic farming [32, p. 6]. In cooperation with the different governorates, the Ministry of Housing are collectively responsible for drinking and wastewater supplies infrastructure [32, p. 11], besides a number of governing laws as follows [33]:

- Law No. 48/1982 regarding the protection of the Nile and water passages against pollution.
- The decree of the Minister of the Irrigation No. 92/2013 in the executive manifest of the law No. 48/1982 regarding the protection of the Nile and the water passages against pollution. The decree is connected to the issuance of permits for the disposal of the treated liquid wastes in the water passages and controlling the commitment to the requirements of the license, including taking samples and the execution of analysis.
- Decision No. 14717/1987 regarding the public properties connected to irrigations, drainage, groundwater, field drainage, irrigation tools, particular drainage canals, wastewater, and the protection of beaches.
- In addition to the above, there are a number of important decisions related to this topic, such as [34]:
  - Ministerial decree No. 402/1996 to form a committee or more on the level of the divisions to be concerned with drainage and the projects affiliated with the general Egyptian drainage projects authority [35]
  - Presidential decree No. 653/1980 for the rearrangement of the Ministry of Irrigation
  - Presidential decree No. 261/1981 for the establishment of the general authority for the protection of beaches
  - PM decree No. 918/1982 for the consideration of the Nile stream as a facility which enjoys a special status
  - Law No. 213/1994 for the purification of irrigation paths and for the arrangement of the establishment of a special fund with the name: "Irrigation Paths Development and Maintenance Fund" which is affiliated to the Ministry of Water Resources and Irrigation (then, Public Works and Water Resources Ministry) [36]

3 The Administrative Context and the Legal Framework Governing Agriculture in Egypt

Most of the Egyptian agricultural activity is concentrated in the Nile valley and the Delta due to the existence of fertile soil in those regions (a space covering 2.4 million hectares). The Delta region – alone – hosts 80% of the agricultural lands. In spite of that, the crawling population to the Delta resulted in a rapid loss of the agricultural lands [4, pp. 16–18]. On the other hand, the Egyptian agricultural exports did not achieve the presumed targets. So, prices soared raising the importation bill in 2011 to be around 3,964 million USD, which had a negative impact on the Egyptian economy. The agricultural, commercial balance deficit reached 2,552 million in the same year. Furthermore, Egypt is among the states in which citizens get a tiny portion of the agricultural spaces, which does not satisfy the requirements of food security for the Egyptian citizen [37] (0.12 acre per citizen).

3.1 The Administrative Context Governing Agriculture in Egypt

3.1.1 Features of the Egyptian Agriculture Management in History

In 1875, a high decree was issued to establish "Nezaret Elzeraa" (Agriculture Ministry). The top official was a French citizen. It supervised councils named "Agriculture Inspection Councils." The objective of which was the improvement and development of agriculture to reach 5 million acres (was 4 million acres). With ups and downs in the agriculture status in Egypt, the agricultural affairs were awarded to "Nezaret Alashghal" (Ministry of Public Works) in 1880. They were awarded to a council with the name "Agriculture Council." With the British occupation of Egypt (1882), there was an increase of the agricultural expansion and the availing of irrigation water through the establishment of the El Qanater El Khayreya reservoirs, digging of canals, and the establishment of Aswan reservoir and Zefta reservoirs (1902) and Isna reservoirs (1909). In 1910, the Egyptian government issued decree No. 34 for the establishment of the first agriculture authority, which was to be affiliated to the Nezaret Al Ashghal, and in 1913 a higher decree was issued for the establishment of the first Agriculture Ministry. In 1938, Egyptian staff was first employed in the ministry after the British staff has occupied the top offices for long. In 1944, the ministry's first department was established under ministerial decree No. 774, the so-called Livestock Department. Furthermore, in 1949, a royal decree was issued to divide the ministry into (6) departments. The decree was followed by the issuance of the ministerial decree No. 993/1950, according to which the departments were established as follows: (1) authority to protect plantations, (2) agriculture authority, (3) gardening authority, (4) agricultural economy and legislation authority, and (5) agricultural culture and veterinary authority [38].

In the second half of the twentieth century – in specific – after the movement of 1952, mega irrigation projects were executed in Egypt. The High Dam works started in 1960, contributing to the achievement of water security for Egypt allowing the execution of horizontal development and agricultural expansion projects [39]. Development continued via the development of the research capabilities in the technical departments of the Ministry of Agriculture framework. They came into force in the start of the 1990s, symbolized in the establishment of the "Agricultural Research Center" [40].

3.1.2 The Institutional Hierarchy of Agriculture in Egypt

The Ministry of Agriculture went through a multiple changing processes (integration and separation) more than other ministries since it was integrated with the agricultural cultivation ministries and others. It is worth mentioning that the Ministry of Agriculture had a separate management since 1875 – Riyadh Pasha Government – and was affiliated to the PM with business focusing on agricultural affairs. It was presided by a French citizen called "De Bellino" and was concerned with irrigation and water distribution. In 1882, its tasks were awarded to a council called "the Agricultural Council" in the Ministry of Public Works. With time, it was clear that Egypt is in need for an official authority that can handle all the agricultural affairs. Hence, the Egyptian government adopted law No. 34/ Nov. 1910 regarding the establishment of the first agricultural authority inside the Ministry of Public Works. On November 20, 1913, the higher decree was issued for the established of the Ministry of Agriculture located in El-Falaky street in Cairo, and Mohamed Mohaeb Pasha was the first agriculture minister. It was an independent ministry till 23rd of July revolution. Since then it got the name the Ministry of Agriculture. The managerial hierarchy of the ministry consisted of a number of authorities and departments affiliated to the ministry assisting in the execution of its function [41].

3.1.3 Axes of Administrative Coordination Among Concerned Institutions Dealing with Agriculture in Egypt

The higher joint committee between the Ministry of Water Resources and Irrigation and the Ministry of Agriculture and Land Reclamation in its third meeting was held at the premises of the former minister in 2017 to discuss a number of common topics. These topics include the discussion of (1) the necessary mechanisms to overcome obstacles, (2) how to confront challenges and eradicate any obstacles hindering implementation of common work in addition to the continuation of the fruitful cooperation with the target to serve the policies of the state aiming to preserve the available water resources, and (3) how to maximize the benefits of the water unity and the unity of lands, besides meeting the needs of the new plantations [42]. Moreover, the abovementioned ministries are the same concern with the cooperation with the Ministry of Agriculture to achieve the agricultural development in the framework of the management of the hydro file.

3.1.4 Agriculture Management Policies in Egypt

Some researchers and monitors see that the agricultural affairs in Egypt are governed by the same policies that were applicable before the 25th Revolution. There are no policies supporting agricultural products especially fertilizers, pesticides, and seeds. In addition, the policies governing supply are the same in the Egyptian agricultural policies because they are governed by the international prices especially regarding wheat, cotton, corn, and rice. Moreover, the role of the private sector did not change; it is still the chief financier and marketer of the agricultural production needs which are sold at high prices. Also, the role of the agricultural institutions did not change (Agriculture Development and Credit Bank is still a commercial bank seeking profits). The same applies to cooperative associations and the agricultural cooperative laws whether in relation to cultivation or other such as marketing or agricultural production needs associations.

Likewise, there is the policy of the agricultural cycle, which refers to a specific region where a specific crop grows. The farmer is obliged to grow a particular agricultural crop due to the need of the society for this crop. They are called the strategic crops such as [43] wheat, rice, cotton, corn, and sugarcane plus others, in addition to the policy of exportation priority on which the Egyptian agricultural policy is based and the policy of rice exportation [44].

3.2 The Legal Framework Governing Agriculture in Egypt

3.2.1 The Legal Framework Governing Agriculture in Egypt Along History and the Concerned Parties

In 1957, the Ministry of Agriculture went through a new organization process, according to which new monitoring sections and departments were established such as the monitor of the external agricultural relations, which has been amended in 1958. In July 1974, the presidential decree was adopted to organize the ministry so that it could include six integrated work and services sectors. These are (1) the minister bureau sector (includes the secretariat, the consultation offices, technical affairs); (2) the planning, follow-up, evaluation, financial analysis, and cost sector; (3) cattle breeding and vet. sector; (4) land reclamation sector; (5) municipal services of the governorate sector; and (6) the general secretariat sector including the financial, administrative, and legal divisions of the ministry.

On October 17, 1979, ministerial decree No. 578 was issued concerning the composition of the organizational structure of the Ministry of Agriculture, specifying the general hierarchy of the ministry to consist of 12 agencies with a technical bureau affiliated to each besides the general secretariat. Those agencies include the minister office agency, external agricultural relations agency, agricultural guidance agency, agricultural cooperation and services agency, engineering affairs agency, shopping and agricultural economy agency, pesticide agency, vegetation and gardening agency, administrative development agency, cattle breeding agency, hydro and fishery production agency, and animal health agency [45].

On April 28, 1980, decree No. 199 was promulgated by forming public administrations and sections of each department.

In 1996, the presidential decree No. 31 was adopted for the integration of the general bureau of the Agriculture Ministry with that of the cultivation general bureau under the name "the Ministry of Agriculture and Land Reclamation" governed and organized by presidential decree No. 162/1996 [46]. There are a number of presidential and ministerial decrees connected to the process of managing and organizing of agriculture in Egypt; the most important ones are [47]:

- Decree No. 31/1966 and its amendments for the establishment of the agricultural professions syndicate.
- Decree No. 53/1966 and its amendments for the issuance of agricultural law.
- The decision of the central laboratory for the analysis of foodstuffs.
- The decision of the agriculture minister No. 48/1977 for the implementations of safety measures when handling and consuming pesticides.
- Presidential decree No. 264/1978 for the arrangement of the Ministry of Agriculture and Land Reclamation.
- Ministerial decree No. 9/1980 for the specification of tasks assigned to agricultural engineers.
- Ministerial decree No. 554/1984 for the arrangement of fodders manufacture and quality assurance.
- Ministerial decree No. 590/1984 for agricultural fertilizers.
- Ministerial decree No. 59/1986.
- Ministerial decree No. 518/1986 for the arrangement of fertilizers, food, and fodders.
- Presidential decree No. 31/1996 for the rearrangements of certain ministries [46, 48].
- Recently, an amendment was issued by the legislation department in the State Council to include item No. 156 of the agricultural law No. 53/1966 which grants the Minister of Agriculture the authority to halt unauthorized construction processes. It states that "The violation of any provision of Article 152 of this law shall be punishable by imprisonment for a period of not less than two years and not exceeding five years and a fine not less than one hundred thousand pounds and not exceeding five million pounds." Whereas the second item states: "Minister of Agriculture has the right – before the judgment in the case to order – to stop the causes of the violation and remove the violation in an administrative way at the expense of the violator" [49].

– Decree No. 587/2017 was adopted, establishing a Higher Coordination Committee to manage the project of inventorying and mechanization of agricultural properties and supporting farmers (Farm Card), headed by the Deputy Minister of Agriculture for Agricultural Services and Follow-up.

3.2.2 A Bird's Eye View on the Impact of Political Changes on Water Resources and Agriculture Management

The Nile water crisis is one of the most affected by the political turmoil that followed the revolution of January 25, 2011. The Egyptian efforts failed in many joint summits through the Kinshasa Summit in May 2009; the Alexandria meeting in July 2009; the Sharm el-Sheikh meeting in April 2010; the signing of five Nile states in Entebbe, May 14, 2010, of the framework agreement for cooperation in the Nile Basin (CFA); and the accession of Burundi as a sixth country to this agreement in February 2011, which led to references to the failure of the Egyptian negotiator during the rule of former Egyptian President "Mubarak" in the management of this file.

Following the eruption of the revolution and the internal turmoil, Ethiopia took advantage of the fragile and unstable internal situation in Egypt and announced, in April 2011, the construction of the "Renaissance Dam" on the Blue Nile with technical specifications affecting the quantitative and qualitative flow of blue Nile water to the downstream countries of the Nile [50, 51].

The internal political situation in Egypt was exacerbated during the reign of President Dr. Mohamed Morsi; the water file was not adequately controlled, resulting in Ethiopia announcing the diversion of the Blue Nile for the construction of the Grand Ethiopian Renaissance Dam (GERD) [52].

Since 2011, the process of negotiating the Renaissance dam has been ongoing between the three parties: Egypt, Sudan, and Ethiopia, without achieving a development that guarantees Egypt its natural rights in the Nile waters. This is despite the signing of the Framework Agreement between the three countries on the Renaissance Dam in March 2015, which resulted in agreement on the selection of a technical office to conduct the required water and environmental studies. However, all this goes according to the Ethiopian plan, which insisted on refusing to carry out the engineering study, which is the crux of the case in the judgment on the safety of the dam from the structural point of view. Ethiopia continued to pursue a time-consuming approach in its favor to continue the construction of the dam, regardless of Egyptian water interests and concerns [53].

When talking about the Egyptian agriculture and of fluctuations, it is necessary to invoke the issues of corruption, as the encroachment on agricultural land increased significantly. Before the January 2011 revolution, the average annual agricultural area encroached exceeded 30,000 acres annually, but it reached more than 100,000 acres during the year of the revolution. However, there have been attempts to improve economic and political relations with the upstream countries, particularly with Ethiopia, but such attempts have not been reflected in the upgrading of water efficiency and the productivity of the unit of water [44].

The reactions to the Nile River crisis are undoubtedly the result of an unstable and economically turbulent political environment. As is well known, the determinants of domestic politics are a powerful component of the state's international movements through which it gains weight politically and diplomatically. This is what Egypt lacked in the period 2011–2014. During that period, corruption issues increased day by day, mainly land encroachment, which was referred to by the Accountability State Authority in one of its reports.

However, the water and agricultural situation in Egypt is witnessing relative improvement with the completion and stability of the pillars of the state politically and institutionally, through the promulgation of the Constitution of 2014, the election of the head of state, and the formation of the Parliament in 2015.

4 Conclusion

In light of the preceding, the management of water resources and agriculture has legally and administratively passed through many stages. This necessitated severe attention to the management of water resources, which has developed over different periods of time up to the present moment.

The Ministry of Water Resources and Irrigation plays a nearly sole role in terms of legal responsibility for the planning and management of all water resources in Egypt. It is responsible for taking appropriate measures to protect both quantity and quality of water resources in Egypt while delegating most of its tasks regarding the quality of surface and groundwater to the National Water Research Center, as well as to a number of other scientific and technical bodies. However, there are also a number of institutions and ministries that play an important role in light of the National Water Management Plan and the Integrated Water Management.

On the other hand, there are some local units that play complementary roles; they participate in one form or another in the regulation of drinking water and sanitation.

Water management policies are due to the era of the pharaohs when the measurements of the level of the Nile flood and the prediction of the hydraulic behavior of the river started. Then with the Islamic era, there was an interest in developing these policies via the introduction of the quality of the land and its height in the taxation equation. With the French occupation, water policies were drawn up when Napoleon introduced the theory of storage, followed by Muhammad Ali till the movement of the Free Officers in 1952.

Beginning with the water policy of 1975, the Ministry of Water Resources and Irrigation started to assess the water supply and demand situation to assess the likely parity between supply and demand in the future. In 1981, a major water plan was issued to develop plans to meet water requirements for the agricultural development and to study nonagricultural water requirements. The most recent water policies, entitled "Key Features of the 2017 Water Policy," were issued in January 2000. On the other hand, the process of water management at the legislative level has passed many laws and ministerial and presidential decisions.

Regarding agriculture, most of the agricultural activities in Egypt are concentrated in the Nile valley and Delta areas which are characterized by fertile soil. The area is 2.4 million hectares. The delta alone contains about 80% of all agricultural land in the country. In 1875, a higher decree was issued for the establishment of the first Agriculture Nezarra (ministry), followed by many developments during the British occupation of Egypt. In the second half of the twentieth century, after the Free Officers Movement in 1952, the interest in the agriculture sector increased.

On the other hand, there is an extensive set of legislations and legal procedures governing agriculture in Egypt, where most agricultural laws such as the Agrarian Reform Law and the Agriculture Law No. 53 of 1966 have been issued as mentioned above.

However, there are many legislative limitations and legal challenges facing the agricultural sector in Egypt. The agricultural policies that were applied before the revolution of January 25, 2011, are still the same.

As for the reflection of political and economic events on the water and agriculture issue, the strong and cohesive state at the domestic level has a stable capacity and effectiveness at the external (international and regional) level and vice versa which is the main issues Egypt suffered from during the period 2011–2014.

Consequently, the administrative and legal framework governing the water resources system, as well as the agriculture system in Egypt, requires comprehensive development. In particular, the water and agricultural conditions and developments require a comprehensive amendment of the legal framework for water and agriculture. Also, they need to reform the administrative system related to water and agriculture. Consequently, this is contributing to the achievement of comprehensive and sustainable development and to achieve Egypt's water, agricultural, and food security, which is a central pillar of the Egyptian national security.

Political and institutional stability in Egypt since July 2014 with the achievement of political entitlements and the completion of democratic institutions (constitution, president, parliament) is an incentive for comprehensive reform of the administrative and legal framework of water and agriculture in Egypt.

5 Recommendations and Prospects

Because the agriculture irrigation consumes about 85% of the water resources in Egypt, the authors highly do recommend to combine both the Ministry of Water Resources and Irrigation and the Ministry of Agriculture and Land Reclamation into one with one minister and two vice ministers. This new proposed structures could enable better integration between the two sectors (water resources and agriculture and land reclamation). An important entity should be developed to collect all data from both sectors and share them with all research institutes and universities. Also, sharing the strategic plan of the proposed new ministry (or of the existing ones) with the universities and research institutes/universities enables these institutes to include the research needs of the ministry into their research plan. This integration between the ministry and the research institutes/universities overall Egypt is a good step toward sustainable development of water resources and agriculture in Egypt.

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Part III
Land Resources for Agriculture Development

A Synopsis on Egypt's Digital Land Resources Database Serving Agricultural Development Plans

A. Gad

Abstract Soil conservation practices, in the Egyptian Nile Valley and Delta, in addition to raising agricultural productivity are considered main objectives of the National sustainable plans. They are aiding in filling in the gap between agricultural production and needs required to feed the increasing population. Availability of detailed accurate land resources information is quite necessary to support land reclamation, conservation and management. The current study is aimed to explain previous investments in Egyptian land resources mapping, using recent technologies of multi-temporal satellite images and geographic information systems. Moreover, a digital information platform will be opened to store further future expected resources information.

A GIS database was created, where previously produced analogue soil maps, covering the whole inhabited areas at the Egyptian Nile basin, Northern coast and desert oases, were input in digital format. Available topographic survey maps, at a scale of 1:100,000 were also used to extract different thematic layers (i.e. roads, rail ways, irrigation and drainage canals and infrastructure networks). Multi-temporal LANDSAT, SPOT and SRTM satellite images were processed and classified to produce land use and DEM GIS layers and to detect temporal changes.

It was found that 45% of the Nile Delta and 15.5% of the valley are characterized by high production capability. Urban encroachment was found often occurring at the expense of most fertile soils, classified as *Typic Torrifluvents* and *Vertic Torrifluvents*. The imbalance between irrigation and drain network lengths, of some areas, refers to its impact on accelerating land degradation, water logging and salinization. Creation of the database saved previous major projects outcome data and will still be opened to add further future expected georeferenced

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information. Its accurate integration nature makes it rather important for decision support and management of sustainable development plans.

Keywords Agriculture, Database, Egypt, GIS, Land resources, Nile Delta, Remote sensing, Satellite images

Contents

1 Introduction

The increasing Egyptian population rate, with the decrease in natural land resources, threatens the balance with available food resources. The main objectives of the Egyptian agriculture development plans (MALR 2010) target the increase and conservation of productivity, in addition to desert land reclamation. Implementation of successful sustainable agriculture requires the availability of accurately documented data for soil resources [1]. Integrated remote sensing – GIS techniques are the most suitable means for inventory monitoring and documentation of natural resources, as they are characterized by high resolution and multi-spectrally. Also, distribution of the natural resources and detection of their changes are accessible by the multi-temporal nature of remote sensing data [2].

The Egyptian academy of scientific research and technology, in cooperation with international organizations, has invested funds to produce the soil maps of Egypt.

Three major projects funded include the High Dam Soil Survey [3], the Soil Map of Egypt [4] and the Land Master Plan (LMP) of Egypt [5]. The LMP is an international collaboration between the Arab Republic of Egypt (ARE) and Kingdom of the Netherlands. Moreover, many M.Sc. and Ph.D. theses and research papers, dealing with mapping soil resources are available in the academic libraries. The nature of the past available data, in analogue format, makes it difficult to manipulate and upgrade their information. Following different land classification and mapping schemes led to a contradiction in estimating the cultivated areas and crop acreages.

This chapter is based on the results obtained through the project "Preparation of Land Data Base for Agriculture Use" [6]. The project was expanded by the National Authority for Remote Sensing & Space Sciences (NARSS) and funded by the Academy of Scientific Research and Technology (ASRT). Thus, the main objective of the presented work is to create a digital land resources database, on the basis of remote sensing and GIS capabilities. The original study extends geographically covering the Nile Valley and Delta, in addition to cultivable lands in the northwestern coastal area and the western desert oases, at the scale of 1:100,000. The current chapter is a synopsis, highlighting an example of Nile Delta and Valley, in addition to Al Fayoum depression database creation and some applications.

The detailed outline of the objectives is as follows:

1. Establishing a basic reference database including the previous studies and research works related to the Egyptian agricultural land resources at the scale of 1:100,000.
2. Using the previous studies as a base for establishing the GIS land resources numerical database for the agricultural use of sustained arable land.
3. Usage of remote sensing for updating the existing data and detecting multitemporal environmental changes.
4. Usage of GIS technology in storing, documenting, retrieving and analysing land resources data, including the tabulated geographic attributes (e.g. physical and chemical soil properties).
5. Employing the created database in mathematical modelling for the purpose of assessing land capability, land degradation hazard and urban sprawl on account of cultivable land.

2 Materials Used

2.1 Bibliography

A survey of bibliography related to the studied areas and topics was performed through available national and international publishers. This resulted in collecting satisfactory information concerning soil, geology, land use/cover, human resources and hydrogeology of the studied areas. The collected review materials include theses, reports and scientific papers available in web sites and libraries housed in universities and research centers.

2.2 Soil Maps

The soil maps of Egypt [4] are the main materials collected and converted to the digital format. A total of 42 soil maps (scale 1:100,000) covering the arable land of the Egyptian Nile basin (Valley and Delta), desert fringes as well as the western desert oases and northwestern coastal region were collected.

2.3 Topographic Maps

Topographic maps, at scale 1:50,000, covering the whole course of the Nile Valley and Delta, produced by the Egyptian General Survey Authority (EGSA) in 1992 and converted to digital format by NARSS 2001, were used in developing some GIS thematic layers (e.g. infrastructure, roads and irrigation – drainage networks). The maps are available in mosaics covering different Governorates of the Nile Valley and Delta and amounts to 202 maps.

2.4 Geologic Map

The geological map, at scale 1:500,000 produced by CONOCO [7], is available in digital format (Fig. 1). This map is added to the created GIS database layers of Egyptian land resources.

2.5 Satellite Images

ETM images from 2004 cover the whole territory of Egypt and amount to 57 scenes. These scenes, covering the Nile valley and Delta, were collected and processed to be included in the GIS land resources database and thematic mapping processes. The recent SPOT images of 2006 were obtained from NARSS receiving station, and processed for updating different thematic maps and detecting changes in land use/land cover.

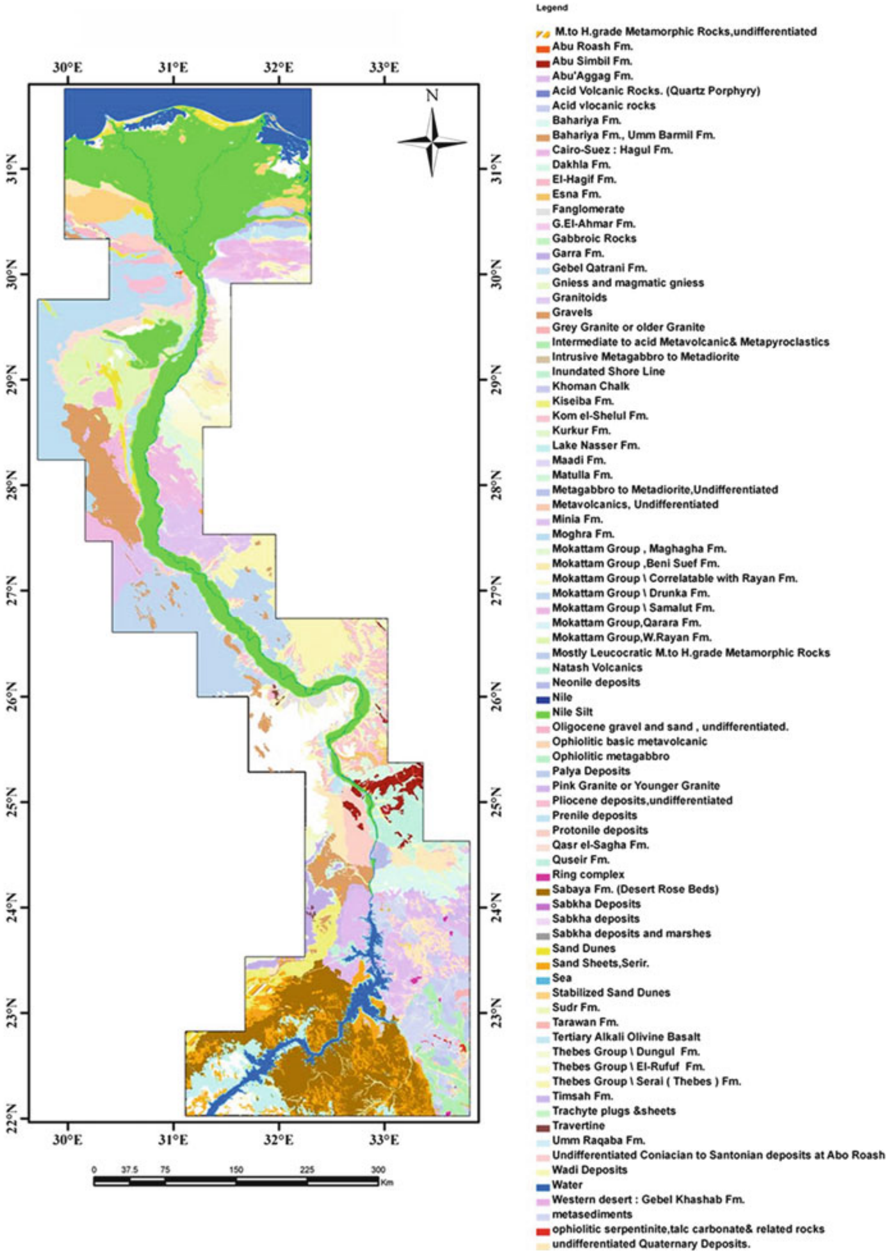

Fig. 1 The geologic map of the whole study regions [7]

2.6 Meteorological Data

FAO [8] identified four principal factors, which determine the climate along the Mediterranean Coastal tract of Egypt: (1) the situation of the region with regard to the general circulation of the atmosphere; (2) the adjacency of the Mediterranean sea; (3) the orientation of the coast and (4) the topography. The collected data include the geographical coordinates and altitudes of metrological stations. Also, different climatic parameters summarizing the characteristics of rainfall, temperature, humidity, wind velocity and solar radiation factors were collected.

3 Methodology

3.1 Coding the Soil Units

In order to input the soil maps in the geographic information database, it was necessary to codify the mapping units. It was found that the number of soil sub-great groups identified in the soil map of Egypt [4] amounts to 20. These units belong to three soil orders (i.e. *Entisoil*, *Vertisols* and *Aridisols*). Table 1

Table 1 Orders, sub-orders, great groups and sub-great groups of Egyptian soils, Egypt [4], based on [9] of soil taxonomy

Soil order	Sub-order	Great group	Sub-great group
Entisols (E)	*Fluvents (f)*	*Torrifluvents (t)*	*Typic Torrifluvents (Eftt)*
			Vertic Torrifluvents (Efvt)
		Ustifluvents (u)	*Typic Ustifluvents (Efut)*
			Vertic Ustifluvents (Efuv)
	Orthents (o)	*Torrioethents (t)*	*Typic Torriorthents (Eott)*
			Calcic Torrioethents (Eotca)
	Aquents (a)	*Haplaquents (h)*	*Typic Haplaquents (Eaht)*
	Psamments (p)	*Quartzipsammets (q)*	*Typic Quartzipsammets (Epqt)*
		Torripsamments (t)	*Typic Torripsamments (Eptt)*
			Lithic Torripsamments (Eptl)
		Calcipsamments (ca)	*Oolitic Calcipsamments (Epcao)*
Vertisols (V)	*Torrerts (t)*	*Torrerts (t)*	*Typic Torrerts (Vtt)*
			Paleustollic Torrerts (Vtp)
		Chromusterts (ucr)	*Paleustollic Chromusterts (Vucrpl)*
Aridisols (A)	*Orthids (o)*	*Calciorthids (ca)*	*Typic Calciorthids (Aocat)*
		Gypsyorthids (g)	*Typic Gypsyorthids (Aogt)*
			Calcic Gypsyorthids (Aogca)
			Petrogypsic Gypsyorthids (Aogp)
		Salorthids (s)	*Typic Salorthids (Aost)*
			Aqualic Salorthids (Aosa)

shows the different categories of classified soils on the basis of USDA [9] including soil order, soil sub-order, soil great group and soil sub-great group.

Coding the soil units ought to be indicative to the following;

1. Soil properties (surface and sub-surface texture, soil salinity, calcium carbonate content).
2. Landscape properties, indicated by slope percentage.

The considered coding system is based on the following soil formula, adopted to represent the different parameters.

Soil formula:

$$\{\text{Soil sub great group (Surface soil texture/sub-surface soil texture), slope,}$$
$$\text{salinity and calcium carbonate content}\}.$$

The surface and sub-surface soil texture range from course to fine. The slope was considered as an indication of the landscape. Codes were assigned according to Table 2. Salinity and calcium carbonate content classes were input in the GIS database by their ranges. Example (*Eftv3/4a3*) refers to *Vertic Torrifluvents*, medium-fine surface soil texture, fine sub-surface soil texture, level landscape and highly saline. Codes of different parameters are explained in the following paragraphs. Areas of "non-soils" are shown on the sheets as miscellaneous land units.

3.1.1 Textural Classes

Soil texture is one of the most important and permanent features. It is directly related to other soil characteristics; namely, consistency, soil-moisture constants, structure, porosity and cation exchange capacity (CEC). The texture of the upper layer is of overriding importance for tillage and water holding. Sub-surface texture also governs the drainage conditions and root spreading. Therefore, both surface and sub-surface soil texture are included in coding the soil units. The different textural classes are coded as 1, 2, 3, 4 and 5 for very fine, fine, medium-fine, medium and coarse respectively.

Table 2 Assigned codes for the soil texture and slope classes

Soil texture class	Soil texture code	Slope class	Slope code	Salinity class	Salinity code
Coarse	1	Level	a	Slightly saline	1
Medium	2	Sloping	b	Moderately saline	2
Medium-fine	3	Moderately steep	c	Highly saline	3
Fine	4	Steep	d		

3.1.2 Slopes

The topography, particularly slope influences runoff and erosion. Slope classes are coded in the created land resources database as a, b, c and d indicating level, sloping, moderately steep and steep landscape, respectively.

3.1.3 The Phases

Phases are considered as subdivisions of the soil units based on the characteristics significant to land use and/or management. They are, however, not diagnostic to separate the soil units themselves. The phases that were recognized on the soil Map of Egypt are salinity and calcium carbonate content. The saline phase, on the map, defines soils that contain, in some horizons within 100 cm of the surface, electrical conductivity values higher than 16 mmhos/cm in the saturation extract. It should be noted that the salinity is not shown for the *salorthids* great soil group as their definition implies a high salt content. Subdivision of the salinity degree is introduced on the Soil Map of Egypt as follows:

– Slightly saline <8 dS/m
– Moderately saline 8–16 dS/m
– Highly saline >16 dS/m

Calcium carbonate content has been introduced on the Soil Map of Egypt, 1982 and subdivided into the following:

– *Crypto* contains $<4\%$ $CaCo_3$
– *Hypo* contains 4–8% $CaCo_3$
– *Hyper* contains 8–12% $CaCo_3$

Soils containing higher calcium carbonate are classified as *calciorthids* by definition. Coding soil phase was done by assigning a number indicating both salinity and calcium carbonate content.

3.2 Digital Satellite Image Pre-processing and Processing

3.2.1 Pre-processing of Satellite Images

Satellite images are basically a set of pixels that are often less than a perfect image representation [10]. By pre-processing, some undesired variations/noises can be reduced or eliminated and desired features are enhanced. The sources of image variation/noise can be attributed to certain conditions. Sun et al. [11] stated that pre-processing of satellite images prior to image classification and change detection is essential. It commonly comprises a series of sequential operations, including radiometric correction or normalization, image registration, geometric correction, masking and image enhancement (e.g., for clouds, water, irrelevant features) [12]. In the current work, different functions of ERDAS IMAGINE (Ver. 8.6) are used for all processing steps.

Raw remotely sensed data gathered by satellite or aircraft are representations of the irregular surface of the Earth. Remotely sensed images are distorted by both the curvatures of the Earth and the sensor being used. The process of shifting pixel locations to remove distortion is known as rectification or geo-rectification.

Geometric rectification of the imagery resamples or changes the pixel grid to fit that of a map projection or another reference image. This becomes especially important when the scene to scene comparisons of individual pixels in applications such as change detection are being sought [13]. A map projection system is any system designed to represent the surface of a sphere or spheroid on a plane (e.g. UTM, State Plane, Geographic, etc.). The process of assigning geographic coordinates to an image is known as *georeferencing*. Often the process of rectification includes georeferencing, because one can both shift the pixels to remove distortion and assign coordinates to those pixels at the same time. It is usually necessary to *preprocess* remotely sensed data and remove geometric distortion so that individual pixels are in their proper planimetric (x, y) map locations. *Geometrically corrected imagery* can be used to extract accurate distance, polygon area, and direction information. This allows remote sensing-derived information to be related to other thematic information in GIS or spatial decision support systems, SDSS [13].

Registered vectors (road, canals and drains network) were overlaid upon the 2001 un-registered imagery. Image identifiable points were selected and matched to vectors until a semi-regular grid of GCP's covered the entire scene. Those GCP's were then used to project the uncorrected imagery to an ETM coordinate system. Each GCP was ordered by the residual error it contributed to the polynomial fit. Points with high error were discarded before registration. Image fit was considered acceptable if the RMS error was <15 m or one-half pixel wide (RMS $= 0.5$). Overall, RMS errors of less than 0.5 pixels were achieved for each transformation. RMS error is the distance between the input (source) location of a GCP, and the resample location of the same GCP [13].

3.2.2 Radiometric Correction or Normalization

The normalization of satellite imagery takes into account the combined, measurable reflectance of the atmosphere, aerosol scattering and absorption, and the earth's surface [14]. The goal, stated by Hall et al. [15], should be that following image preprocessing, all images should appear as if they were acquired from the same sensor.

3.2.3 Geometric Correction

Geometric rectification of the imagery resamples or changes the pixel grid to fit that of a map projection or another reference image. This becomes especially important when the scene to scene comparisons of individual pixels in applications, such as when change detection is being sought [13].

To confirm the pixel grids and remove any geometric distortions in the satellite imagery, the separate images were registered to the Egyptian Transverse Mercator (ETM) system. GCP collection, first order transformation, and nearest neighbour resembling of the uncorrected imagery were performed. First order transformation is also known as a linear transformation that applies the standard linear equation ($y = ax + b$) to the X and Y coordinates of the GCPs.

3.2.4 Satellite Image Enhancement

"The goal of image enhancement is to improve the visual interpretability of an image by increasing the apparent distinction between the features" [16]. There are different enhancement techniques which can be applied to the image for that purpose (e.g. contrast stretching, Gray-level threshold, Level slicing and spatial stretch).

3.3 Building GIS Database

3.3.1 Defining Maps Digitizing Specifications

The digitizing specifications of the maps were defined according to the available themes. A number of 12 thematic layers were decided to be included in the geographic land resources database. Each theme was subdivided into sub-themes, which were coded for the purpose of GIS modeling.

3.3.2 Editing Base Maps

This work aims to edit the topographic digital maps (scale 1:50,000) that cover the whole study regions. The different digital maps were corrected for different errors and edge-matched after the geo-referencing processes.

3.3.3 Edge Matching

Edge matching, also known as "rubber sheeting," is the spatial adjustment process that "aligns features along the edge of one layer to features of an adjoining layer"

[17, 18]. The layer with the least accurate features is adjusted, and the adjoining layer is used as the control. Edge matching aimed to link the base maps (scale 1:50,000) of the Nile Valley and Delta Governorates, in addition to the northwestern coast which was produced by the Egyptian General Survey Authority. The same edge matching technique was performed on all thematic layers included in the 42 soil map sheets covering the study regions (scale 1:100,000). This process resulted in obtaining mosaic maps covering the whole study area.

3.3.4 Editing and Refining Mosaic Maps

In order to maintain a valid database, another editing session has taken place after edge-matching of the thematic maps covering the whole study regions. The powerful integrated functionalities (i.e. topology rules, networks and relations) in ArcGIS system enabled accurate refinement. Editing during this stage was to modify the geometry of the features and/or their attributes without affecting the spatial context of the map neither the previously stored attribute data [19].

3.3.5 Input of the Digital Geological Map

The geologic map (Fig. 1) of the whole study regions and their surroundings was driven from CONOCO [7]. The surface geology includes sedimentary rocks belonging to the Tertiary and Quaternary groups. The cultivable soils in the study area are originated from the sedimentary rocks, formed mainly by fluvial activity (i.e. sediments of alluvial fans and flood plains). Aeolian processes have contributed to the soil formation processes in some locations (coastal and inland dunes). The subsurface soil layers of the fans are related to their calcareous origin. Soil types differ according to their texture, depth, calcium carbonate contents, salt contents and secondary formations.

3.3.6 Spatial Adjustment on the Basis of LANDSAT Images and Topographic Maps

"It was noticed, after edge matching, that there is a kind of deviation (constant in many places in its direction and magnitude) between the produced maps and the well registered topographic maps as well as the satellite images of the study area. It was possible to attribute the deviation to two reasons; lack of coordinate system in some original map sheets and the rubber-sheeting accompanied the edge-matching task" [20]. In order to overcome this problem another spatial adjustment (transformation) has been performed. Well-registered topographic maps and accurately georeferenced satellite image have been used to perform the transformation process. "The transformation tools of ArcGIS systems were found to be very effective in performing the spatial adjustment of the soil maps" [18, 21].

3.3.7 Compilation of Laboratory Analysis Results

The collected soil samples, representing the different soil units of the studied regions have been analysed in the lab for soil chemical and physical characteristics. The results of these analyses have been compiled in database tables and then incorporated into the attribute table of the digital GIS ready soil maps in order to be used later in different applications.

3.4 Developing Digital Elevation Model (DEM)

The DEM of the Nile Delta, Nile Valley, northwestern coastal region and western desert oases have been generated from the elevation points (Spot heights) and the vector contour lines, using *Topo to Raster* function of ArcGIS system. The produced DEM did not give the significant variability within the Delta and along the Nile flood plain due to the low variation in altitudes. On the other hand the variation in topography was obvious at the rocky fringes of the Nile valley. For this reason another source (i.e. Shuttle Radar Terrain Mission “SRTM”) of terrain topography has been consulted in order to represent the area landscape. The images of the whole territory of Egypt, acquired in 2001, were processed to generate the digital Elevation model for the whole country [22, 23]. These images are provided at a resolution of 90 m, which is suitable to produce maps at a scale of 1:250,000.

The following procedures were followed using the environment of visualizing images (ENVI 4.2) software:

1. Geometric correction for 62 scenes has been carried out using the affine transformation and projection utilities.
2. Mosaicking of a number of 62 geometrically corrected scenes has been performed, using the map mosaicking function.
3. Correcting the bad values in the mosaic was carried out, by the topographic replace bad values function.
4. The topographic-hillshade function was applied to produce the surface map at scale 1:250,000.

The output was transferred to *ArcGIS 10.3* software for developing the topographic layer in the created database. A layout was produced for the classified resulted DEM subdividing the elevation values into 15 categories.

3.5 Extracting Areas of Interest

After creating one digital soil map for the Nile Delta and Valley, combined with soil laboratory analysis incorporated in the GIS attribute tables, extracting some areas of interest was performed. This step aimed to have a digital soil map for each Governorate in the Nile Delta and Valley. The *clip* function in ArcGIS system has been used to extract the soil map from the soil mosaic using the administrative boundaries of each Governorate.

3.6 Layouts

Layouts of the produced maps were done using different template sizes according to the dimensions of map sheets and included information. An important task before the laying out process is the development of a unified and standard map legend for the soil maps. The comprehensive colour pallets and renders of ArcGIS systems enabled the rendering of different mapping layers in one map sheet without creating any kind of interference between them.

3.7 Field Observation and Laboratory Soil Analyses

Field missions were carried out to study different soil-mapping units. A number of 166 soil profiles were studied according to FAO guidelines [24, 25]. Moreover, a number of 25 soil profiles, included in the "Soil Map of Egypt" project reports, were additionally studied. The soil laboratory analyses (i.e. soil texture, $CaCo_3$ content, CEC, EC, ESP, pH, soluble cations and anions and organic matter content) were carried out for 422 disturbed soil samples representing different soil profile layers using the soil survey laboratory methods manual [26]. Soil colour was defined by the Mansell Color Charts [9].

3.8 Land Capability Classification

"Land Capability classes were defined according to the rating of soil properties adapted from Stori" (1964) and Sys [27]. The influence of each land quality is determined by a set of interacting single or compound land characteristics. Each land quality is assessed qualitatively according to its contribution to the concerned constraints as shown in Table 3.

Table 3 Description of land capability classes, adapted from Sys [27]

Rating	Capability classes	Description[a]
I	Very highly capable	Very low grade of liability/absence of risk
II	Highly capable	Low grade of liability/low risk
III	Moderately capable	Medium grade of liability/medium risk
IV	Low capable	High grade of liability/high risk
V	Very low capable	Very high grade of liability/very high risk

[a]Adapted to arid condition

4 Results and Discussions

4.1 Egyptian Nile Delta and Valley Soil Taxonomy

The current study presents the land resources database of the Nile valley and Delta, however readers may be referred to Gad [28] to insinuate the whole inhabited Egyptian territories. Three soil orders could be defined at the Nile Delta soils: *Vertisols*, *Aridisols* and *Entisols*.

4.1.1 Soil Order *Vertisols*

According to USDA [29], soils classified under the *Vertisols* soil order are those soils, which have:

1. A layer of 25 cm or thicker, with an upper boundary within 100 cm of the mineral soil surface, has either slickensides close enough to intersect or wedge-shaped aggregates which have their long axes tiled 10–60° from the horizontal; and
2. A weighted average of 30% or more clay, in the fine-earth fraction either between the mineral soil surface and a depth of 18 cm or in Ap horizon, whichever is thicker, and
3. A weighted of 30% or more clay, in the fine-earth fraction of all horizons between a depth of 18 cm and either depth of 50 cm, or a densic, lithic, or paralithic contact, duripan, or petrocalcic horizon if shallower; and
4. Cracks that open and close periodically.

All previous characteristics cannot be generalized in the Nile Delta and Valley alluvial soils, mainly due to irrigation. *Vertisols,* however, could be found in limited spots that wouldn't be possible indicated in the handled map scale (1:100,000). The soil map sheets of the Nile Delta produced through the project of "Soil Map of Egypt" [4] showed that the majority of the soils were classified under the order *Vertisols*. However, revising the required characteristics of this soil order, on the basis of USDA [29] revealed that these soils were generally classified under the sub-great group *Vertic Torrifluvents*, which will be highlighted under the *Entisols* soil order.

4.1.2 Soil Order *Aridisols*

The characteristics of this soil order refer that these soils are characterized as follows:

1. Having the following conditions:
   (a) Aridic soil moisture regime,
   (b) An ochric or anthropic epipedon and
   (c) One or more of the following with the upper boundary within 100 cm of the soil surface,
      - A *cambic* horizon with a lower depth of 25 cm or more;
      - A *cryic* temperature regime and a *cambic* horizon;
      - A *calcic, Gypsic, Petrocalcic, Petrogypsic* or *Salic* horizon; or a *duripan*; or
      - An *argillic* or *natric* horizon; or
      - Have a *Salic* horizon and Saturation with water in one or more layers within 100 cm of the soil surface for 1 month or more during a normal year; and a moisture control section that is dry in some or all parts at some time during normal years; and no sulfuric horizon that has its upper boundary within 150 cm of the mineral soil surface.

Three sub-orders were found under this soil order (i.e. *Calcids*, *Gypsids* and *Salids*). Table 4 summarizes the areas of different great groups included in those suborders (Figs. 2 and 3).

The *Calcids* are *Aridisols* that have a *calcic* or *petrocalcic* horizon having its upper boundary within 100 cm of the soil surface. Only *Haplocalcids* soil great group, under which *Typic Haplocalcids* sub-great group is found, covering an area of 1,012.6 km^2 representing 23.7% of the Nile Delta's *Aridisols* whereas 36.3% at the valley. The *Haplocalcids* are *Calsids* soils that have no *petrocaclic* horizon, where the *Typic Haplocalcids* includes soils having no *lithic*, *ustic*, *vertic*, *aquic*, *duric*, *sodic* properties.

Table 4 Areas of great groups, belonging to *Aridisols*, in the Nile Delta and Valley region

	Nile Delta		Nile Valley	
Type (Great group)	Area (km^2)	%	Area (km^2)	%
Aquisalids	1,928.8	45.2	–	–
Calcigypsids	4.1	0.1	1.9	4.0
Haplocalcids	1,012.6	23.7	17.4	36.6
Haplogypsids	1,007.5	23.6	–	–
Haplosalids	166.9	3.9	3.9	8.2
Petrogypsids	145.9	3.4	24.4	51.2
Total	**4,265.7**	**100.0**	**47.5**	**100.0**

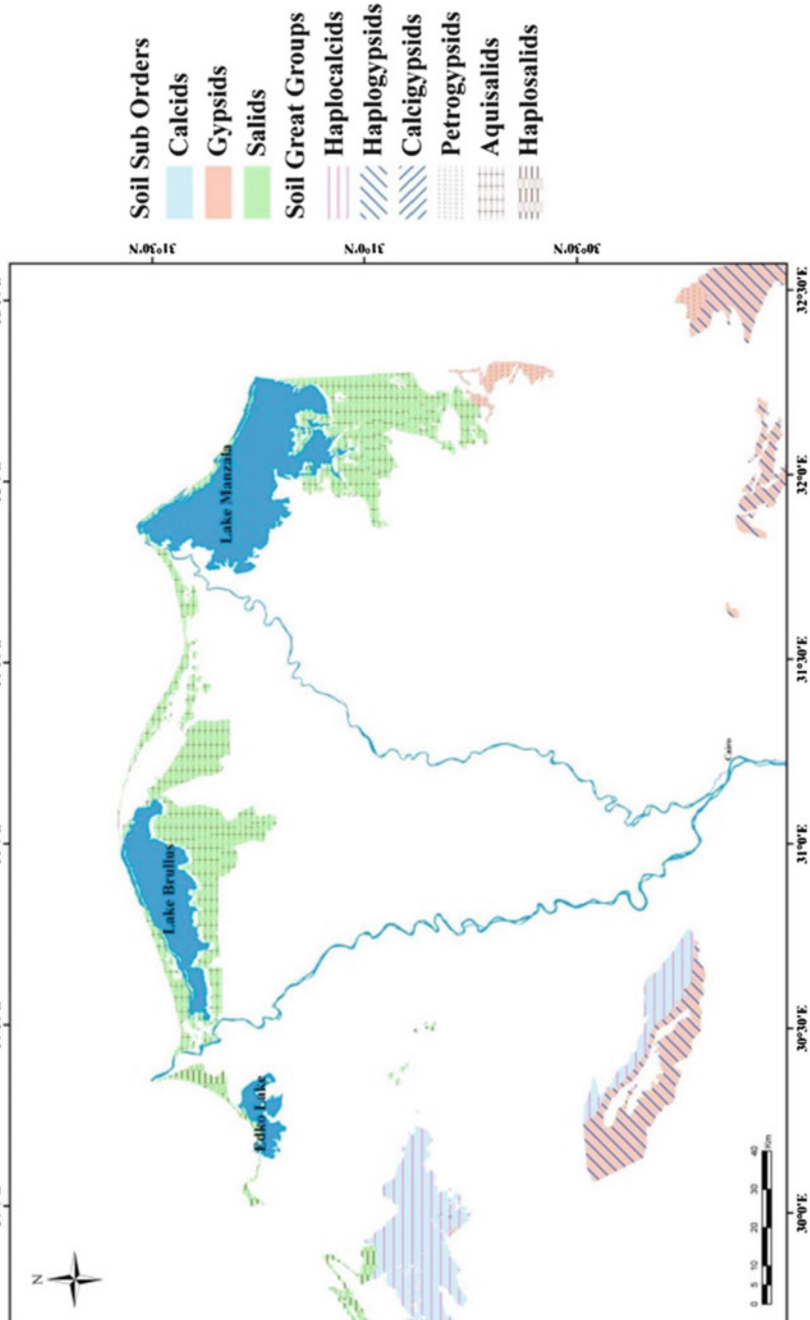

Fig. 2 Geographical distribution of the sub-orders under *Aridisols* in the Nile Delta

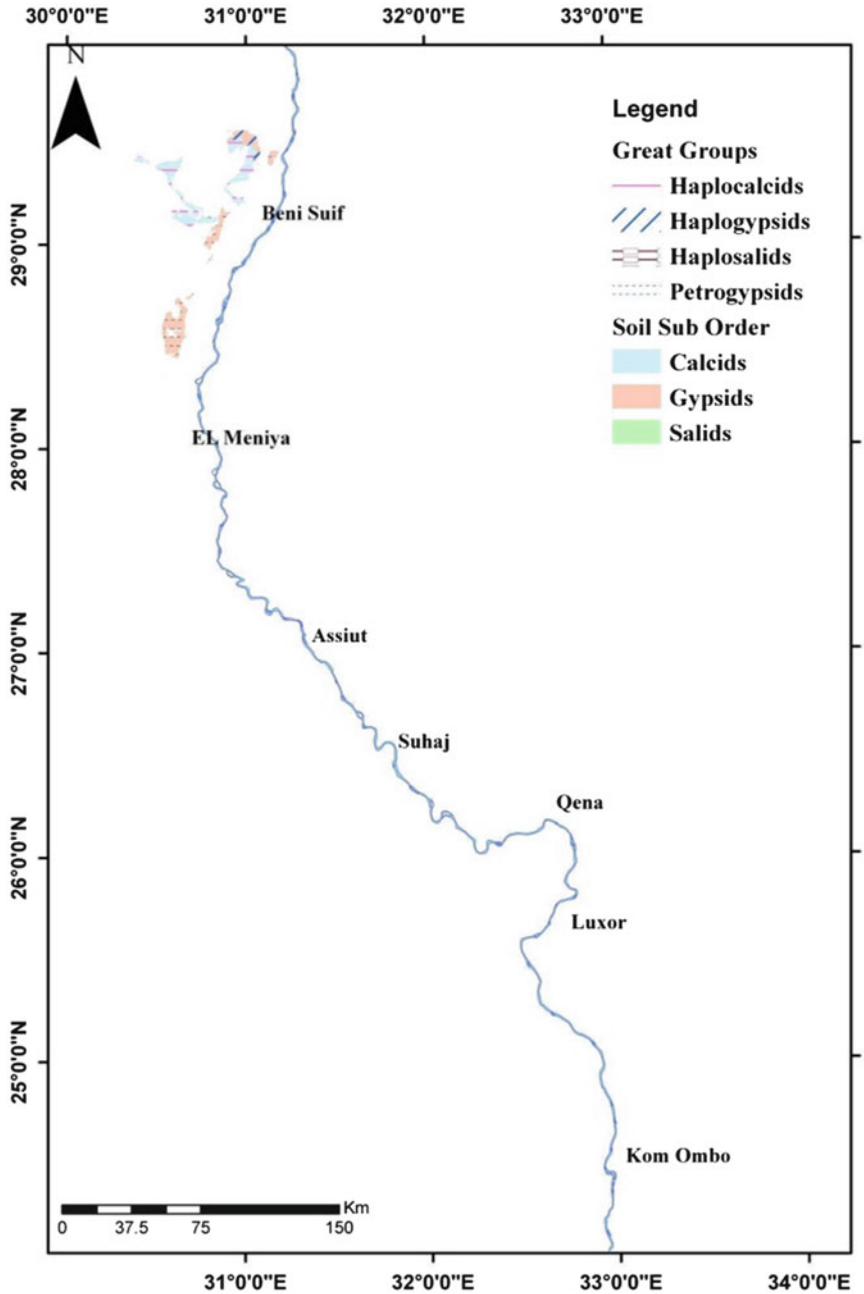

Fig. 3 Geographical distribution of *Aridisols* order in the Nile Valley region

The Gypsids are Aridisols that have a gypsic or petrogypsic horizon have "its upper boundary within 100 cm of the soil surface. They do not have neither a petrocalcic horizon overlying these horizons" nor having cryic, salic, duripan properties.

Three great groups are found belonging to this sub-order (i.e. *Calcigypsids*, *Petrogypsids* and *Haplogypsids*). The *Calcigypsids* great group soils are *Gypsids* having a calcic horizon with its upper boundary within 100 cm of the soil surface.

These soils exhibit an area of 4.1 and 1.9 km^2 representing 0.1% and 4% of Nile Delta's and Nile Valley's *Aridisols,* respectively. The *Petrogypsids* are *Gypsids* having a *petrogypsic* or *petrocalcic* horizon having its upper boundary within 100 cm of the soil surface.

The *Petrogypsids* great group covers an area of 145.9 and 24.3 km^2 representing 3.4% and 51.2% of Nile Delta's and Valley's *Aridisols*, respectively. The *Haplogypsids* are *Gypsids* that do not have a calcic, argillic, natric, petrogypsic or petrocalcic horizons exhibit an area of 166.9 and 3.9 km^2 representing 3.9% and 8.2% of Nile Delta's and Valley's Aridisols, respectively.

2. The *Salids* are *Aridisols* that have a *salic* horizon with its upper boundary within 100 cm of the soil surface and do not have a cryic soil temperature regime. Two great groups are found in the north of the Nile Delta region under this sub-order (i.e. *Aquisalids* and *Haplosalids*). The *Aquisalids are* salids that are saturated with water in one or more layers within 100 cm of the mineral soil surface for 1 month or more in normal years. They cover an area of 1,928.8 km^2 representing 45.2% of *Aridisols* of the Nile Delta region. The *Haplosalids* are other *salids*, which are not qualified for *Aquisalids* great group. These cover an area of 166.9 km^2 representing 3.9% of Nile Delta *Aridisols*. Only the *Typic* sub-great group of the previous great groups is found within the Nile Delta soils.

4.1.3 Soil Order *Entisols*

The USDA soil taxonomy [29] defines *Entisols* as "This soil order includes recently developed soils, which do not have the requirements of the other soil orders". The *Entisols* soil order dominates the study area representing 85.5% of studied Nile basin soils, including three sub-orders (i.e. *Psamments*, *Fluvents* and *Orthents*). The most pronounced great group is the *Torrifluvents* covering areas of 15,893.3 and 910.2 km^2 representing 66.9 and 53.6% of all Nile Delta and Valley's *Entisols* soils, respectively. Figures 4, 5 and Table 5 demonstrate the geographical distribution and areas of different great groups, belonging to the *Entisols* of the Nile Delta and Valley region.

1. The Sub-Order *Psamments* is *Entisols* that:
   - have less than 35% by volume rock fragments, and
   - a texture of loamy fine sand or coarser in all layers within the profile control section.

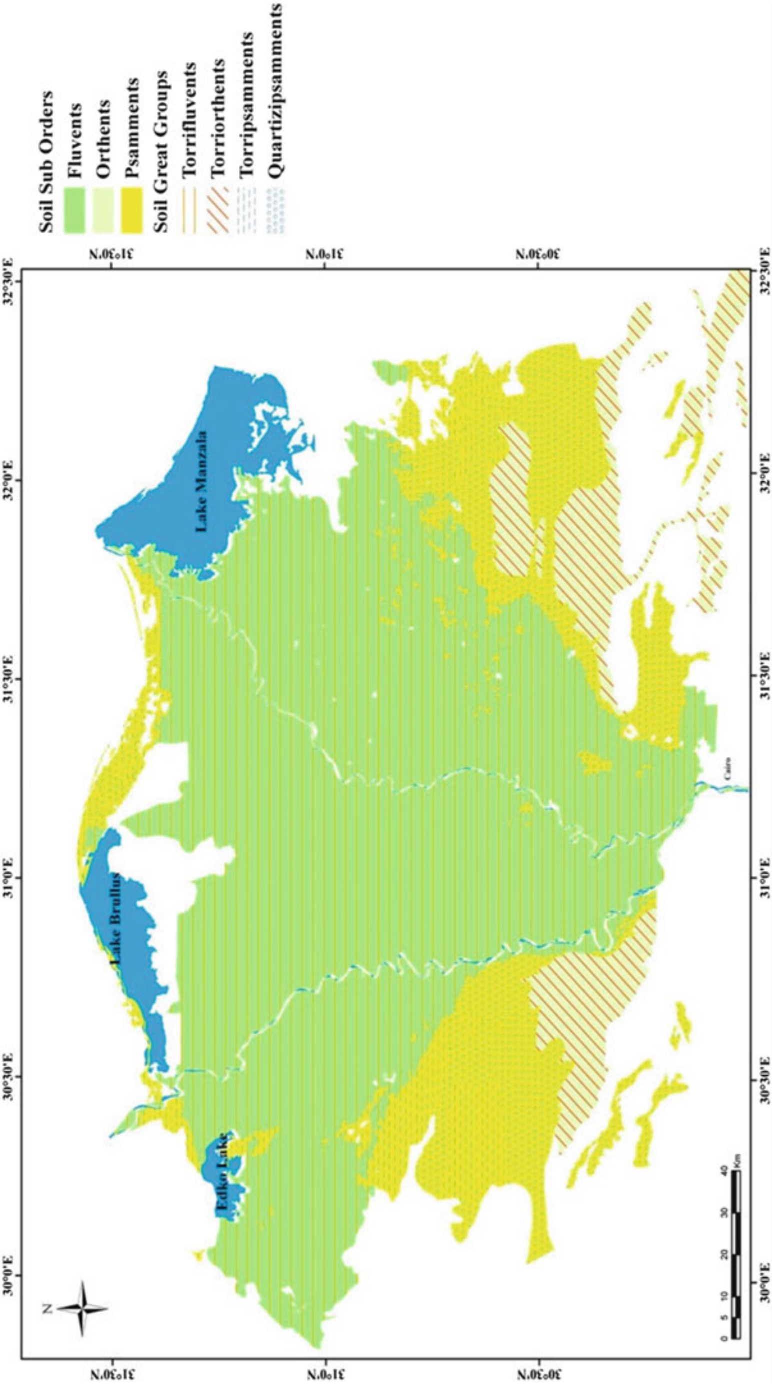

Fig. 4 Geographical distribution of the sub-orders under *Entisols* in the Nile Delta

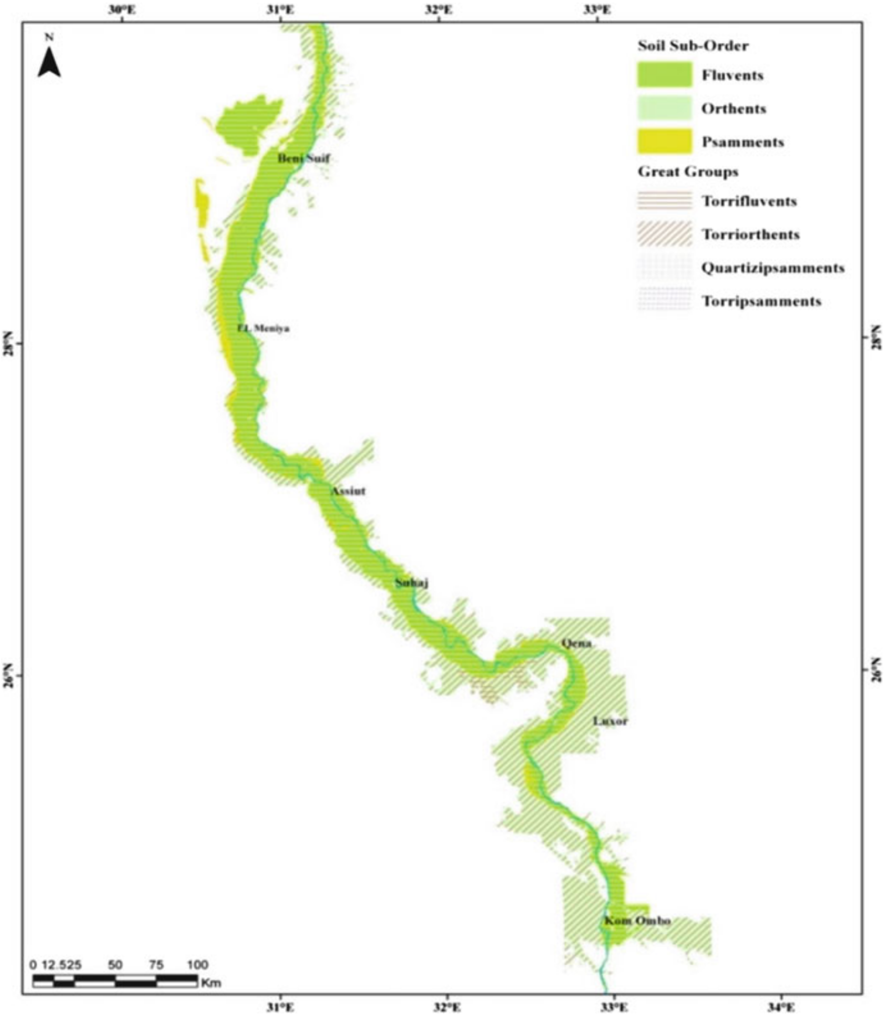

Fig. 5 Geographical distribution of the sub-orders under *Entisols* in the Nile Valley

Table 5 Areas of the great groups, belonging to *Entisols*, in the Nile Delta and Valley region

		Nile Delta		Nile Valley	
Sub-order	Type (Great group)	Area (km^2)	%	Area (km^2)	%
Fluvents	*Torrifluvents*	15,893.3	66.9	910.2	53.6
Orthents	*Torriorthents*	2,390.9	10.1	455.0	26.8
Psamments	*Torripsamments*	1,385.0	5.8	–	–
	Quartzipsamments	4,082.0	17.2	333.3	19.6
Total		**23,751.3**	**100.0**	**1,698.5**	**100.0**

Two great groups are found in the Nile basin under this sub-order (i.e. *Torripsamments* and *Quartzipsammets*) while only *Quartzipsammets* is found in the Nile Valley. The great group *Torripsamments* soils are *Psamments* that exist in *aridic* (or *torric*) moisture regime, while the *Quartzipsammets* are *Psamments* that have a sand texture within the particle size control texture consisting of more than 90% (by weight) resistant minerals. They, respectively, cover areas of 1,385 and 4,082 km^2 of Nile Delta *Entisols*, representing 5.8 and 17.2% of the Nile Delta. Only 19.6% of Nile Valley' *Entisols* is exhibited by *Quartzipsammets*.

2. The Sub-Order *Fluvents* is *Entisols* soil order, which does not have a *densic, lithic*, or *paralithic* contact within 25 cm of the mineral soil surface and has:

   - Slope of less than 25%
   - Either 0.2% or more organic carbon "at a depth of 125 cm below the mineral soil surface or an irregular decrease in organic carbon content from a depth of 25 cm to a depth of 125 cm, or to a *densic*, *lithic*, or *paralithic* contact if shallower"; and
   - A mean annual soil temperature above 0°

The *Vertic Torrifluvents* sub-great group is found dominating the alluvial Nile basin soils. They cover an area of 15,893.3 and 910.2 km^2 representing 66.9 and 53.6% of the Nile Delta and valley *Entisols,* respectively. These soils are characterized by the following:

- *Torrifluvents* that have cracks within 125 cm of the "soil surface that are 5 mm or more wide through a thickness of 30 cm or more for some time in most normal years and slickensides or wedge shaped aggregates in a layer 15 cm or more thick that has its upper boundary within 125 cm of the soil surface"; or
- A linear extensibility or 6.0 cm or more between the "soil surface and either a depth of 100 cm or a *densic*, *lithic*, or *paralithic* contact, whichever is shallower".
- The *Aquic torrifluvents* sub-great group includes "other *torrifluvents* that have in one or more horizons, within 100 cm of the soil surface, both redox depletions with chroma of 2 or less and aquic conditions for some time in normal years (or artificial drainage)".
- Also, *Typic Torrifluvents* sub-great group is found interfering in the previous one. These soils are characterized by gentle slope and texture of sandy loam or finer, they are of the arid climate and have a *torric* moisture regime.

Nevertheless, the *Typic Torrifluvents* is soils that do not have the requirements of the other *Torrifluvents* sub-great group.

3. The sub-order *Orthents* is other *Entisols* that do not have the requirements of *Aquents*, *Arents*, *Psamments* and *Fluvents*. Only the sub-great group *Torriorthents* is found exhibiting an area of 2,390.9 and 455 km^2 representing 10.1 and 26.8% of the Nile Delta and Valley *Entisols,* respectively. These soils are *orthents* that have an *aridic* or *torric* moisture regime. The existent sub-great

group *Typic Torriorthents* is identified as other *torriorthents*, which do not have the requirements of other *Torriorthents* sub-great groups.

4.2 Digital Soil Map of Nile Delta and Valley

Figures 6 and 7 show soil map mosaics of the Nile Delta and Valley regions. Table 6 demonstrates the distribution of different soil units within the regions.

It is clear that the *Vertic Torrifluvents* is the major sub-great group in the alluvial Nile Delta, covering 12,940.3 km^2, representing 41.2% of the total Delta area, while exhibiting 7.6% of the Valley. The *Typic Torriorthents* dominates the soil area of the Nile Valley, covering 33.7% of its soil area. The origin of such soil is mostly related to the colluvial deposits in wadi mouths and plains, thus mostly located in both western and eastern desert fringes, characterized by a gently sloping landscape. The soils are medium to coarse textured, deep soil profile, massive or weak sub-angular blocky structure. It is noticed that the coverage of these soils has a significant occurrence in the southern area of Al-Minya Governorate, where the major wadis, such as Wadi Al-Assiuty and Wadi Qena, are found. Patches of sub-great groups *Typic Torrifluvents* are included in the alluvial soils.

The sub-great group *Typic Quartzipsamments* dominates the eastern and western desert fringes of the Nile basin of Egypt, covering an area of 5,361.3 km^2 in addition to an area of 375.2 km^2 interfered with the *Typic Torriorthents* sub-great group. Representative soil profiles and laboratory analyses were carefully studied to verify different soil classes.

4.3 Land Capability of Nile Delta and Valley

Fourteen soil profiles were selected from a total of forty-two studied profiles representing different soils of the Nile Delta. Also, a number of 9 soil profiles were selected from a total of 40 studied profiles representing different sub-great groups of the Nile Valley. Field investigation and soil laboratory data were input in the GIS attribute tables and used to assess the land capability for each soil unit (i.e. sub-great groups). The assessment of land quality was based on several factors (i.e. drainage condition, texture and structure, % coarse fragments, soil depth, % $CaCo_3$, CEC, soil salinity-EC and exchangeable sodium percentage-ESP). The classification categories were adapted to include the capability classes highly capable (Class I), moderately capable (Class II); low capability (Class III) and very Low (Class IV).

The results indicated that the soil salinity, soil depth, soil texture, Cation Exchange Capacity (CEC) and coarse fragments content are the main limiting factors for land capability classification of the Nile basin and its desert fringes. Figures 8 and 9 show the land capability classification maps and the main land

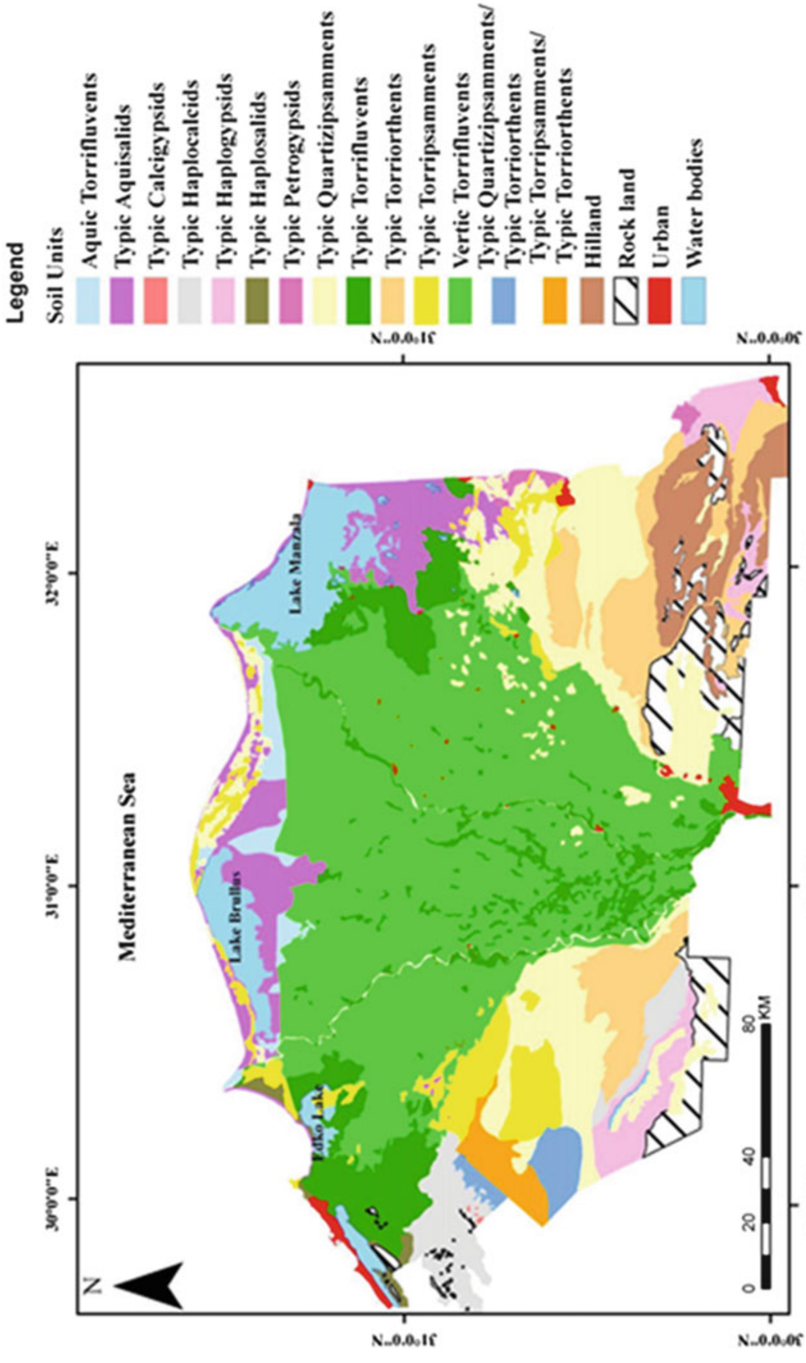

Fig. 6 Soil map of the Nile Delta region, Egypt

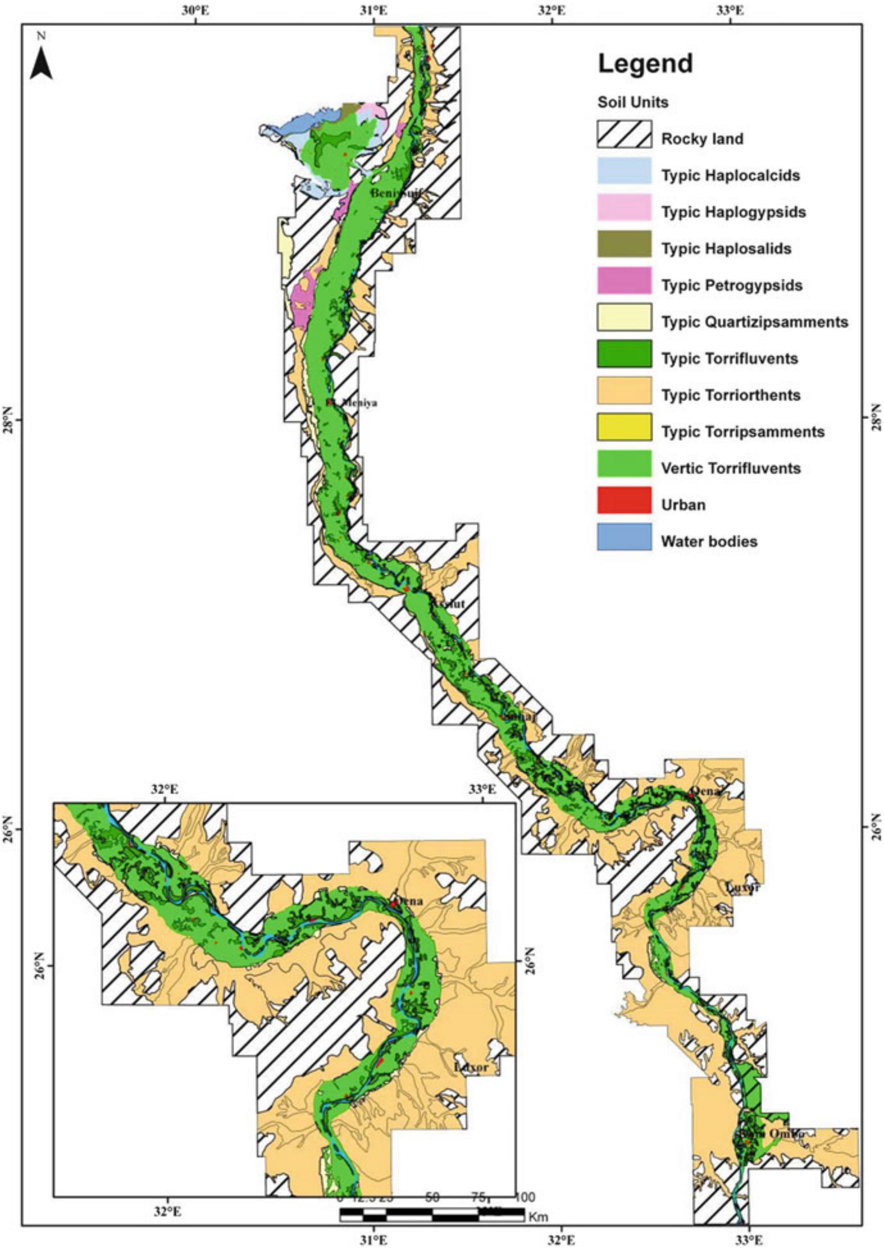

Fig. 7 Soil map of the Nile Valley region

Table 6 Distribution of different soil units within the Nile Delta and Valley region

	Nile Delta		Nile Valley	
Type (Sub great group)	Area (km^2)	%	Area (km^2)	%
Aquic Torrifluvents	437.9	1.4	–	–
Typic Aquisalids	1,928.8	6.1	–	–
Typic Calcigypsids	4.1	0.0	–	–
Typic Haplocalcids	1,012.6	3.2	446.3	1.1
Typic Haplosalids	166.9	0.5	3.6	0.0
Typic Haplogypsids	1,007.5	3.2	103.6	0.2
Typic Petrogypsids	145.9	0.5	363.9	0.9
Typic Quartzipsamments	4,082.0	12.9	1,279.3	3.0
Typic Quartzipsamments /Typic Torriorthents	375.2	1.2	–	–
Typic Torripsamments/Typic Torriorthents	399.1	1.3	–	–
Typic Torrifluvents	2,514.9	8.0	2,026.4	4.8
Typic Torriorthents	2,390.9	7.6	14,303.7	33.7
Typic Torripsamments	1,385.0	4.4	23.4	0.1
Vertic Torrifluvents	12,940.3	41.2	8,313.6	19.6
Hilland	1,223.2	3.9	–	–
Rock land	1,426.9	4.5	15,527.3	36.6
Total	**28,791.3**	**100.0**	**42,390.9**	**100.0**

qualities of the Nile Delta and Valley, the different classes and their areas are shown in Table 7. It is clear that the very highly capable soils (Class I) represent about 45.1 and 10.38% of the total area of Nile Delta and Valley, respectively, it is associated with the *Vertic Torrifluvents* sub-great group, and dominates the middle parts of the Nile Delta.

The moderately capable soils (Class II) represent 8.9 and 5.13% of the total area of Nile Delta and Valley respectively, they are found in scattered parts at the middle, northwest and northeast of the Nile Delta and along the Nile Valley. These soils are associated with soils sub-great group *Typic Torrifluvents*.

Low capability class (Class III) represents 15.0 and 55.8% of total area of Nile Delta and Valley respectively, they are also found around the Northern Lakes and limited parts of the desert fringes. These soils coincide with the soil sub-great groups *Typic Quartzipsamments*, *Typic Haplocalsids*, *Typic Torriorthents* and *Typic haplogypsids*.

The very low soil capability class (Class IV) covers 20.7 and 1.7% of total Nile Delta and Valley respectively, soil areas spread in the latitudes between Al-Fayoum and Beni Sweif Governorates. These soils correspond to the sub-great groups *Typic Petrogypsids*, *Typic Haplosalids* and *Typic Torripsamments*. It can be noticed that the low capability class is mostly associated with the soil great groups *Calcids*, *Gypsids* and *Salids* soils.

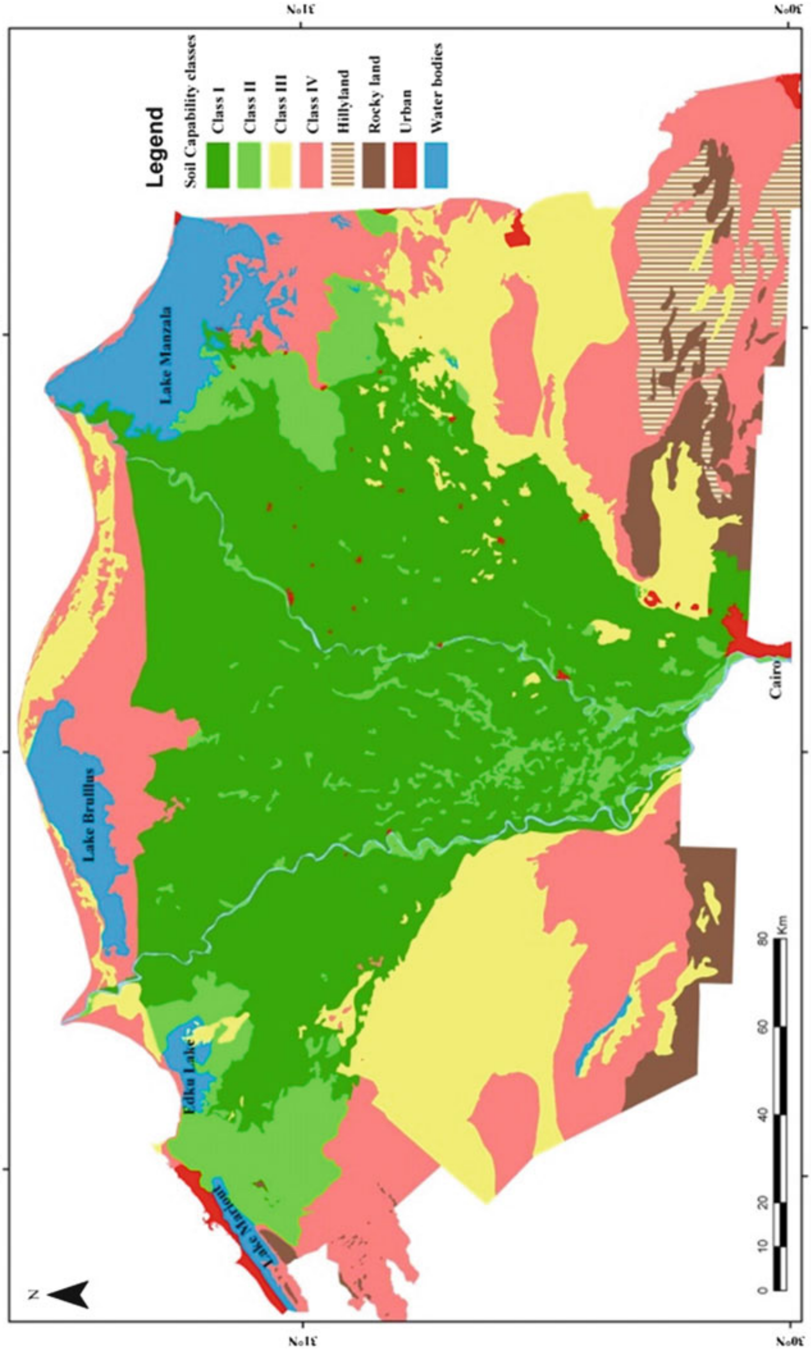

Fig. 8 Land capability classes and limiting factors of the Nile D region

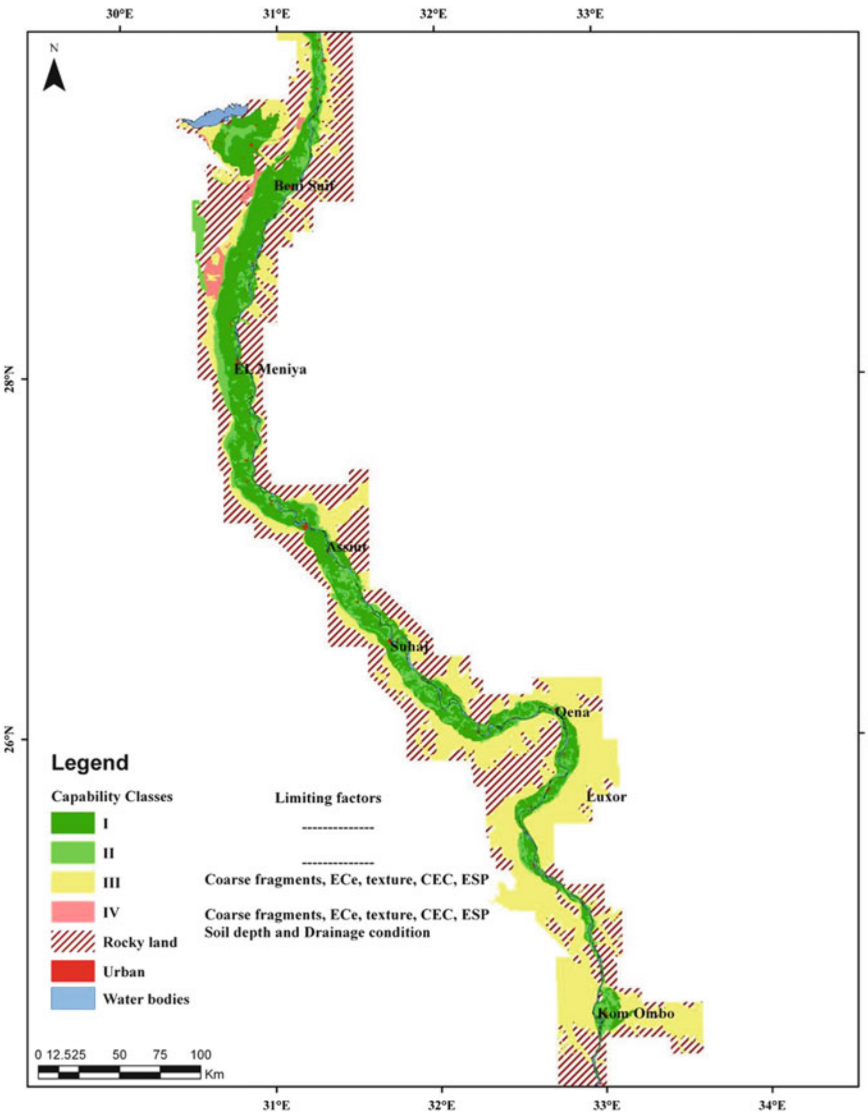

Fig. 9 Land capability classes and limiting factors of the Nile Valley region. The rocky areas and water bodies represent about 10.3 and 26.9% of the total area of Nile Delta and Valley, respectively

Table 7 Areas of the Nile Delta land capability classes

Capability class	Area Nile Delta		Nile Valley	
	km^2	%	km^2	%
I	12,794.4	45.1	3,058.3	10.4
II	2,510.8	8.9	1,510.9	5.1
III	4,251.6	15.0	16,432.6	55.8
IV	5,880.4	20.7	3,058.3	1.7
Other features				
R	573.8	2.0	7,506.3	25.5
U	208.1	0.7	190.3	0.7
W	2,143.9	7.6	239.3	0.8
Total	28,362.9	100.0	29,451.7	100.0

4.4 Creation of Land Resources Database (Case Study of Al-Fayoum Governorate)

4.4.1 Environmental Setting of Al-Fayoum

The Governorate is located, in a depression, at the southwest of Cairo, where the distance to the Fayoum town is 90 km (see Fig. 10). It is connected to the Nile Valley by the Hawara canal, through which Bahr Yussef is transporting the Nile water. The Fayoum Governorate was chosen for this study as an example representing the alluvial soils of the Nile Valley (Table 8).

Al-Fayoum Governorate is administratively sub-divided into five districts, Table 6. The areas of the districts can be arranged as follows: Atsa > Al-Fayoum > Ibsheway > Tamyah > Senouris districts having areas of 395.9, 454.6, 388.3, 304.1 and 232.0 km^2, respectively.

4.4.2 Layers of Al-Faioum Land Resources Database

Figures 11 and 12 show the main elements included in the database of Al-Fayoum Governorate. Field survey data, LANDSAT ETM+ and SPOT images and digital elevation model (DEM) were used to define the physiographic units in Al-Fayoum Governorate The soil layer demonstrates that the sub-great group *Vertic Torrifluvents* is the dominant soil sub-great group, it covers an area of 792.6 km^2 representing 37.7% of the mapped soils.

The inclusion of *Typic Torrifluvents* occurs within the depression, covering an area of 148.0 km^2 representing 7.0% of the mapped soils. These soils are associated with the recent terraces of the flood plain. The sub-great group of *Typic Haplocalcids* covers an area of 444.1 km^2 representing 21.1% of soil units area. Its geographic distribution is located on the edges of the depression exhibiting the old river terraces.

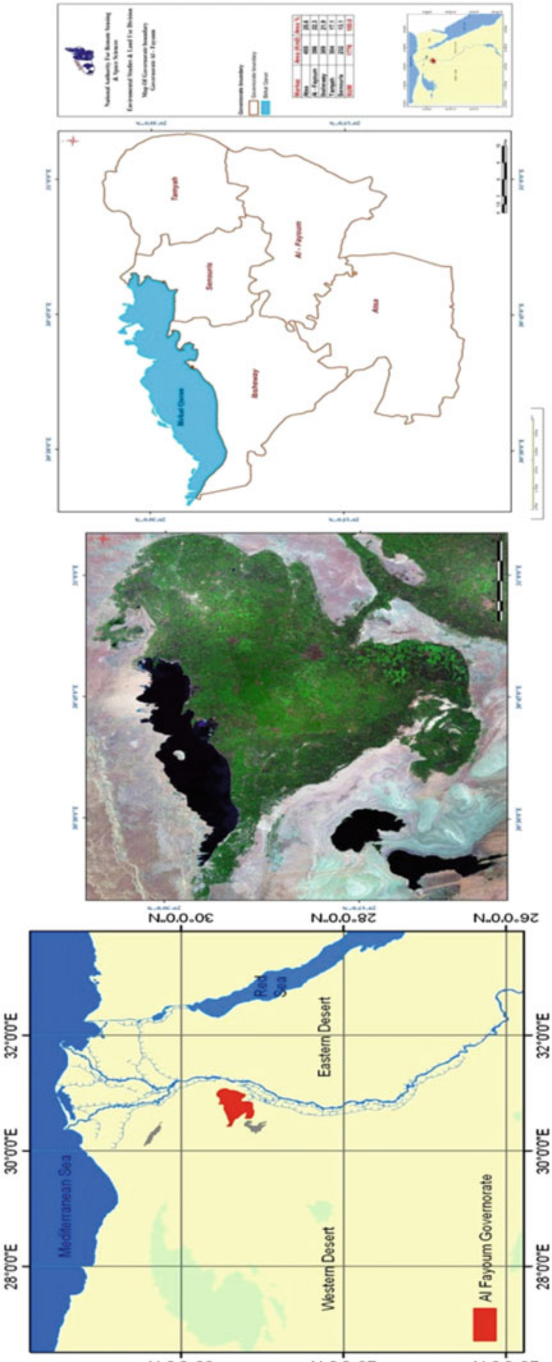

Fig. 10 Location map of Al-Fayoum Governorate

Table 8 Areas and frequencies of Al-Fayoum Governorate administrative districts

District name	Area (km^2)	%
Al-Fayoum	395.9	22.3
Atsa	454.6	25.6
Ibsheway	388.3	21.9
Senouris	232.0	13.1
Tamyah	304.1	17.1
Total	1,775.0	100.0

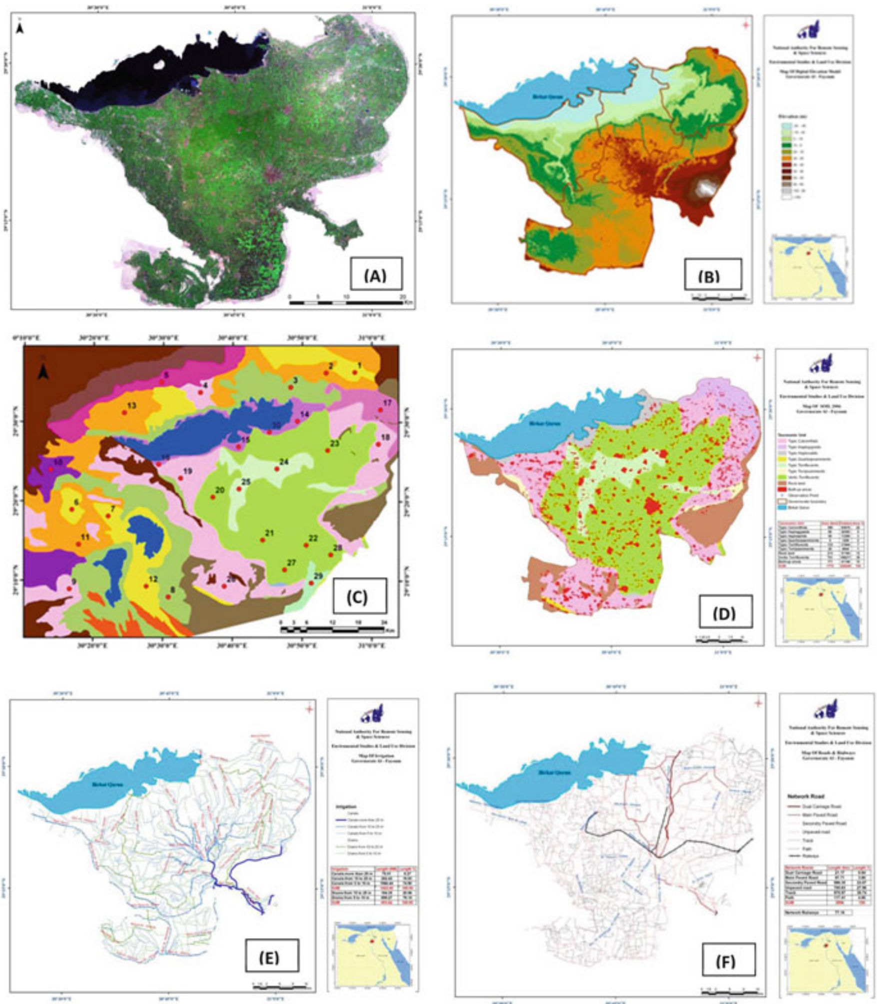

Fig. 11 Some GIS thematic layers of Al-Faioum land resources database. (**a**) LANDSAT ETM, (**b**) Digital Elevation Model – DEM (**c**) Physiography (**d**) Soil great groups (**e**) Irrigation and drains network (**f**) Road network

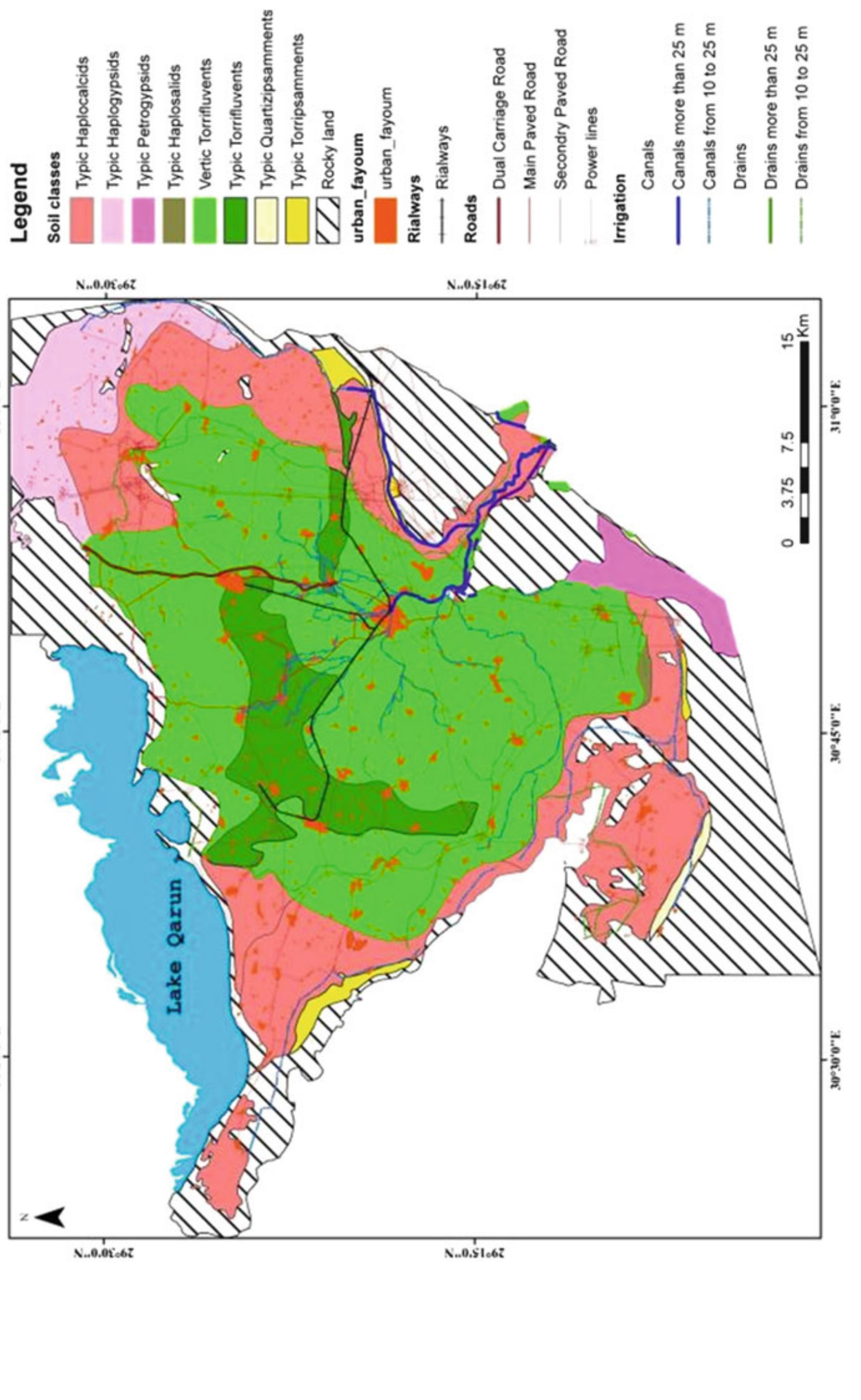

Fig. 12 Database layers of Al-Fayoum Governorate

The Gypsic soils (i.e. *Typic Haplogypsids and Typic Pertrogypsids*) exist on the eastern borders of Al- Fayoum depression covering areas of 103.6 and 37.8 km^2 representing 4.9 and 1.8%, respectively. The geographic location of these soil units may be explained by the transgression of Qaroun Lake to the northwest of the depression [30]. Both *Typic Quartzipsamments* and *Typic Torripsamments* cover small spots in the south of Al-Fayoum depression, covering areas of 10.7 and 23.4 km^2 representing 0.5 and 1.1% of the area, respectively. A very small patch of the sub-great group *Typic Haplosalids* exists in the southeast of the depression exhibiting an area of 3.6 km^2 representing 0.2% of the mapped soils.

It should be highlighted that such variability of sub-great groups is unique for Al-Fayoum Governorate due to its location, altitude, and formation processes pattern and agricultural practices (Table 9).

Two main irrigation and drain canals are shown in the database layout of Al-Fayoum Governorate, lengths of each canal are presented in Table 10. The irrigation canals of more than 25 m width have a total length of 75.2 km, while those of 10–25 m width attain a total length of 282.4 km. The drainage canals of more than 25 m width have a total length of 184.4 km, while those having 10–25 m width attain 135.7 km length.

Table 11 reveals that a number of three roads categories exist within the Governorate. Total lengths of dual carriage, main paved and secondary paved roads are 21.2, 97.7 and 598.4 km, respectively.

Table 9 Areas and frequencies of soil sub-great groups in Al-Fayoum Governorate

Soil class	Area (km^2)	%
Vertic Torrifluvents	792.6	37.7
Typic Haplocalcids	444.1	21.1
Typic Torrifluvents	148.0	7.0
Typic Haplogypsids	103.5	4.9
Typic Petrogypsids	37.8	1.8
Typic Torripsamments	23.4	1.1
Typic Quartzipsamments	10.7	0.5
Typic Haplosalids	3.6	0.2
Rock land	539.8	25.7
Total	**2,103.4**	**100.0**

Table 10 Lengths of the main irrigation and drain canals in Al-Fayoum Governorate

Type	Length (km)
Canals more than 25 m	75.2
Canals from 10 to 25 m	282.4
Drains more than 25 m	184.4
Drains from 10 to 25 m	135.7

Table 11 Total lengths of main road categories in Al-Fayoum Governorate

Type	Length (km)
Dual carriage road	21.2
Main Paved Road	97.7
Secondary Paved Road	598.4

4.4.3 Urban Sprawl in Al-Fayoum Governorate

Urban areas, utilities and railways are included in the land resources database of Al-Fayoum Governorate. The urban area covers 46.2 km^2, while the length of utilities and railways are 532.8 and 77.2 km, respectively.

Change detection technique resulted in presenting the evolution of urban areas and its implication on soil and land capability units. The built-up areas (see Fig. 13) in the governorate increased from 64 km^2 (i.e. 4%) in the year 1992 to 107 km^2 (i.e. 6%) in 2001 and to 171 km^2 (i.e. 10%) in the year 2006.

Studying the urban expansion from 1992 to 2006 revealed that urbanization mainly occurs on the most fertile soils of Al-Fayoum depression (Fig. 14).

GIS Spatial analyst showed that the remained cultivable land exhibited by the soil sub-great group *Vertic Torrifluvents* decreased from 760 to 701 km^2, where the area of *Typic Torrifluvents* soils decreased from 141 to 133 km^2 and *Haplocalcids* area decreased from 421 to 390 km^2 during the period of 1992–2006.

In terms of land capability classification (Fig. 12, the high capable soils-Class I) decreased from 761 km^2 in 1992 to 701 km^2 in 2006. The moderately capable soils decreased from 141 to 133 km^2 from 1992 to 2006, while the marginally capable soils decreased from 513 to 480 km^2 during the same period.

5 Conclusion and Recommendations

It can be concluded that the digital mapping of land resources is encouraged by the "progress of Geographic Information System (GIS) and data provided by satellite images". Such approaches may preserve investment spent in cataloguing soil and another thematic mapping, as the digital maps are more granted. Updating and manipulating the digital thematic maps to be more accessible is also economically effective. Usage of the digital maps and their attribute tables assist in decision support systems and may result in sustainable development project planning. The digital format of the soil map facilitates the linkage with the different software; this allows the integration of data for defining the optimum land uses of a studied region. The obtained results, extracted from the created digital Egyptian land resources database, recommend testing land capability and realizing the optimal land usage.

Al Fayoum depression, as a case study in the current publication, may support integrated sustainable development. The establishment of basic infrastructure in surrounding open desert areas may decrease the urban sprawl against most fertile alluvial soils. The critical status of sustainability issues should be considered in order to maintain sustainable development. Remote sensing and GIS proved to be satisfactory tools to collect information for assessing the potentiality for sustainable development issues and hazards.

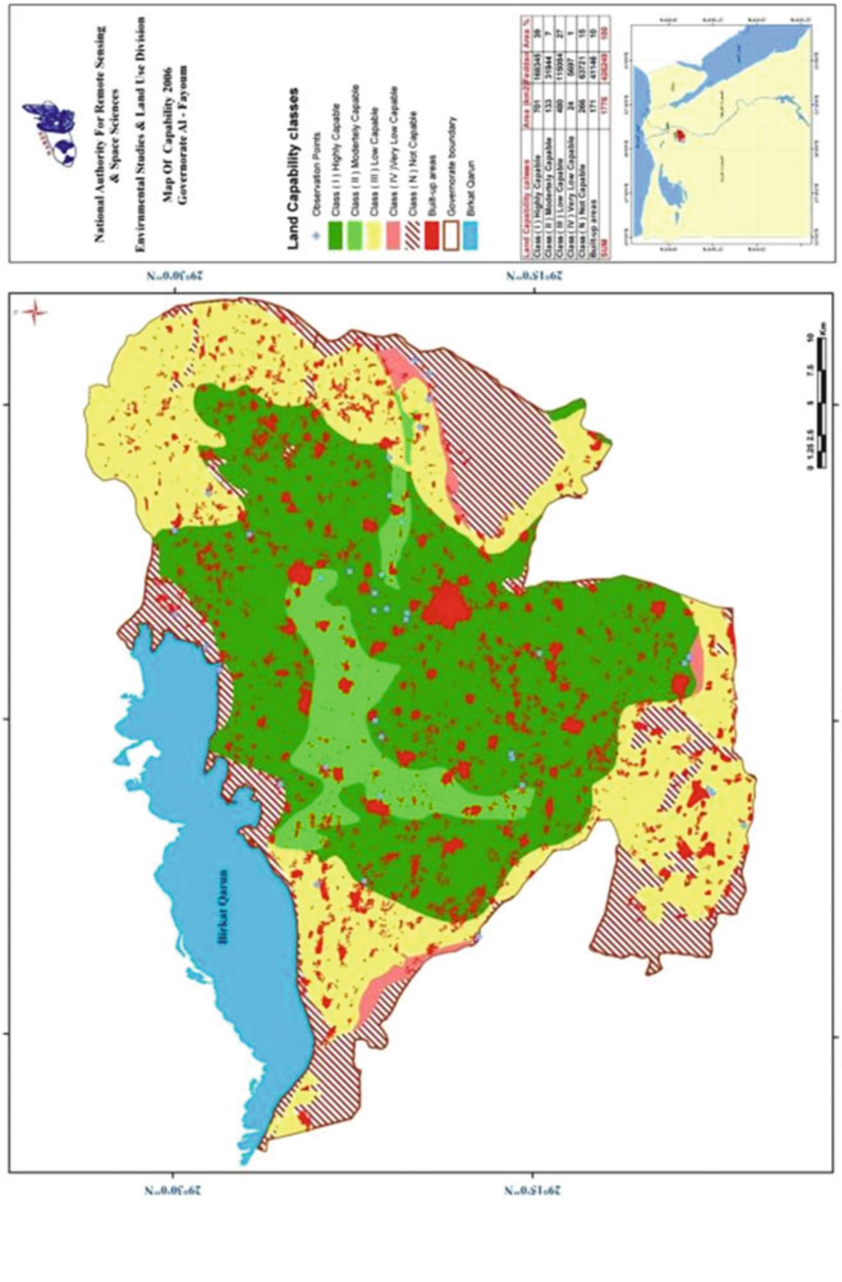

Fig. 13 Land capability classes of Al Fayoum Governorate, based on LANDSAT ETM and GIS land resources database

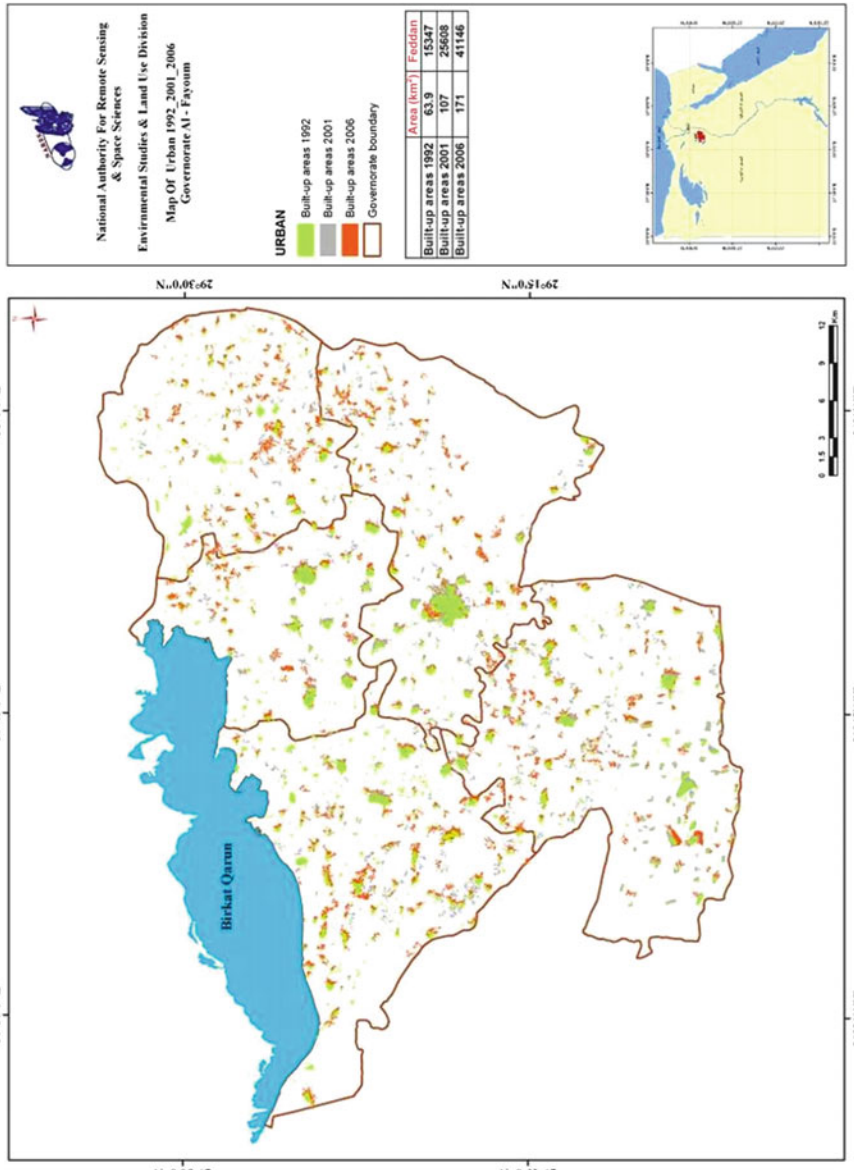

Fig. 14 Changes in the Built-up areas, Al Fayoum Governorate, 1992, 2001 and 2006

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Land and Groundwater Assessment for Agricultural Development in the Sinai Peninsula, Egypt

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Abstract Management of land and water resources in arid regions is vital and opens the way for new agricultural activities and growth of residential communities. The Sinai Peninsula suffers from water scarcity, limiting these types of development in a substantial way. This chapter seeks to evaluate the conventional land and water resources of Sinai, Egypt, using remote sensing (RS) and geographic information system (GIS) techniques. The future of land reclamation in Sinai will depend largely on its groundwater potential.

For major portions of Sinai, however, information on soil resources is limited. Generally, Sinai soils lack pedological features that indicate the soil development under arid conditions. El-Tina plain soils are derived from fluvial-lacustrine deposits with poorly drained, shallow water tables, with clayey or loamy texture and a salic horizon. Sandy soils extend through southern El-Qantara East and the surrounding areas of Lake El-Bardawil; these are considered Aeolian deposits without horizon differentiation. Wadi El-Arish soils are developed from fluvial deposits as influenced from limestone in the upstream. The Wadi El-Arish cultivated area extends from the confluence of Wadi Abu Gidi north to Wadi El-Bruk. The good agricultural land is located along the Wadi E1-Arish main channel and its tributary. Wadi Al-Aqabah is also a good agricultural area but is smaller and narrower than the Wadi El-Bruk area.

The assessment of suitable agricultural lands must be associated with an evaluation of water availability. The availability of water is usually the most limiting factor when planning development in Sinai. In this study, areas with the most (soil and groundwater) potential for agricultural development are identified and mapped to inform decision-makers. The best locations for drilling groundwater wells were selected from the decision map, which was produced by utilizing the GIS technique.

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The iso-salinity contour map of the Lower Cretaceous (LC) aquifer shows a general increase of groundwater salinity toward the west and the north, with four salinity zones recognized. The importance of LC groundwater development is essentially related to the necessity of providing basic extension services (mainly water supply for domestic purposes and for small-scale irrigation agriculture) to the existing nomad tribes in central and South Sinai. Moreover, as the groundwater in the LC aquifer is moving down the gradient across the eastern border toward the aquifer discharge area along the Dead Sea-Gulf of Aqaba rift valley, it is desirable to use this water in Sinai before it gets naturally lost in the rift discharge areas. The salinity of the Upper Cretaceous (UC) carbonate aquifer is rather high in most of Sinai (3,200–10,870 ppm) with the exception of its central part along the El-Tih, El-Egma, and Shaira zone, where the groundwater salinity of the UC ranges between 1,100 and 1,500 ppm. Consequently, it is not recommended to rely on exploiting this aquifer for future development projects in Sinai. Favorable areas for groundwater development from the Eocene aquifer include the area between El-Hasana and El-Quseima and the area north of Nakhl and El-Thamad, where the aquifer hydrogeological setting is similar to the northeastern Sinai at Ain El-Guderrate and Ain Qedees. The groundwater quality in South Sinai is better and has more potential than that in the North Sinai.

Keywords Assessment, GIS, Groundwater, Land resources, RS, Sinai, Soil mapping

Contents

1 Introduction

Egypt's land and water resources are finite and under pressure from a growing population as well as climate change. These resources are central to agricultural development, as well as degradation of quality and quantity [1]. After the creation of the El-Salam Canal and six new tunnels under the Suez Canal to connect the Sinai Peninsula to the Egyptian homeland, Sinai has received great attention in respect to future agricultural development. Management of land and water resources in Sinai is vital and will open the way for new residential communities and agricultural activities. However, water scarcity in Sinai is a major socioeconomic crisis. Accordingly, many researchers have undertaken studies in Sinai.

Geofizika [2] carried out geophysical, hydrogeological, and soil investigations in the northern, central, and southwestern parts of Sinai to assess the water and soil resources for agricultural development plans. Issar et al. [3] estimated the Nubia sandstone aquifer storage capacity to be several hundred billion cubic meters, although only a small fraction of this water can be pumped. A large part of the water in this aquifer is fossil (paleowater), and dating using ^{14}C indicates an age range from 13,000 to more than 30,000 years old. Dames and Moore [4] carried out a comprehensive study of the water resources of Sinai based on the existing stratigraphic data from 69 wells and 57 columnar sections and hydrogeological data from 716 water points (wells and springs). However, the use of conventional techniques for land and groundwater management is often severely restricted by the lack of adequate data. Frequent and long-term monitoring by these traditional methods is expensive, laborious, time-consuming, and destructive [5].

Innovative technologies, such as remote sensing (RS) and geographic information systems (GISs), have an immense role to play [5–8]. RS techniques were used for land and water assessments over large and inaccessible areas. Visual image interpretation [9] can be used in monitoring the geographic distribution of land and water resources. Vegetation varieties can serve as an indication of approximate groundwater depth [10]. Robinson [11] used seven Radarsat-1 data images to outline the drainage systems, which permitted the definition of passageways and intermediate holding areas. According to Meijerink [12], microwave or radar images have several hydrogeological applications, which are associated with groundwater. Sultan et al. [13] incorporated optical and radar RS and geophysical data for groundwater exploration in the El-Qaa Plain, South Sinai, Egypt. AbuBakr et al. [14] utilized space-borne radar data to define the structurally controlled paleolakes along Wadi El-Arish. The former main channel course of Wadi El-Arish was depicted west with a length of 109 km of Gabal El-Halal. Three major paleolakes were defined in which the largest lake occupied an area of at least 337 km^2 and contained approximately 10.7 km^3 of water when filled during pluvial phases. Kotb et al. [15] utilized the geophysical investigation procedures (magnetic, geo-electrical resistivity, and shallow refraction seismic) to recognize the groundwater aquifers in the southwestern Sinai. Khalil et al. [16] integrated geophysics, RS, and GIS for groundwater assessment, using a direct-current resistivity electrical technique. Mohamed [17] integrated diverse methods such as field geology, geophysics, and RS and GIS technologies for investigating groundwater potential at locations associated with major shear zones in the area. Abuzied [18] took a holistic approach to assessing groundwater locations in the Wadi Watir area, Egypt, based on RS (e.g., Radarsat 2000 and ground-penetrating radar) to define the favorable zones of groundwater occurrences.

It is argued that satellite data can be used if ancillary analysis is used to infer groundwater from surface expressions [19]. Therefore, the objectives of this chapter were to review previous investigations, to assess the land and groundwater information for Sinai, and to identify potential soil and groundwater resources for agriculture development. This assessment is based on information obtained from the following sources:

1. Literature review of documents, reports, and previous studies.
2. Hydrogeologic database of the 2,110 groundwater wells previously drilled in Sinai.
3. Data collected during field visits to several development sites in Sinai.

2 Description of the Sinai Peninsula

The Sinai Peninsula covers an area of approximately 61,000 km^2 [20]. The length of the Sinai coast is about 700 km; however, the total length of the Egypt's coast is about 2,400 km. Therefore, the ratio of the length of the coast of Sinai is about 29.1% of the total length of the coast of Egypt, or about one-third of the Egyptian coast. This spatial feature of Sinai is unique among the deserts of Egypt; it has three coasts surrounding it. It is triangular with its apex found by the junction of the Gulf of Aqaba and the Gulf of Suez in the south and its base by the Mediterranean Sea coastline between Port Said in the west and Rafah in the east (Fig. 1). The topography of Sinai has an elevation difference of 2,640 m between its highest point and its lowest point. The elevation of the northern part of Sinai ranges from 1,626 m above sea level to the lowest level at the Mediterranean Sea. The elevation of the southern part of Sinai ranges from 2,640 m above sea level to the lowest level at the Gulf of Suez and Gulf of Aqaba. Three-dimensional elevation of the ground is shown in Fig. 1 (left) as extracted from a digital elevation model (DEM) with point data at 30 m intervals.

Climate and soil are the two most important factors that determine the ultimate sustainability of rain-fed areas. In some cases, soil and climate factors will seriously limit the feasibility and practicability of soil reclamation. Fig. 1 (right) shows the average annual precipitation (mm) extracted from TRMM 3B42.v7A 3-hourly data acquired (1998–2013) over Egypt [17]. The annual rainfall falling over Sinai is for the most part under 200 mm in the far northern zone of Rafah and El-Arish and is less than 20 mm in the lower south of the area of Ras Mohammed. High mid-southern zones (the mountain region) have the yearly precipitation sums on range from 50 to 150 mm [17]. Meanwhile, the amount of annual rainfall falling on the southern Sinai heights between 50 and 75 mm. The central Sinai is viewed as the driest zone in the Peninsula, where the greatest yearly precipitation adds up to only approximately 30 mm. The average precipitation sum annually ranges from 80 to 100 mm. Despite the lack of rain in Sinai, in general, it is the most abundant rain compared with the eastern and western desert. Sinai receives a great deal of solar radiation and wind. However, the risk of sand dunes creeping in Sinai is much lower than in the Western Desert, which has the Great Sand Sea.

Sinai in relation to national security has the highest priority over all other deserts of Egypt, including the Western Desert. A special project for national security of any state that does not bear in mind the physical cost and thus development and reconstruction of Sinai is underway. Most of the Egyptian petroleum exist in the Gulf of Suez. It is also rich in mineral wealth, such as manganese, kaolin, marble,

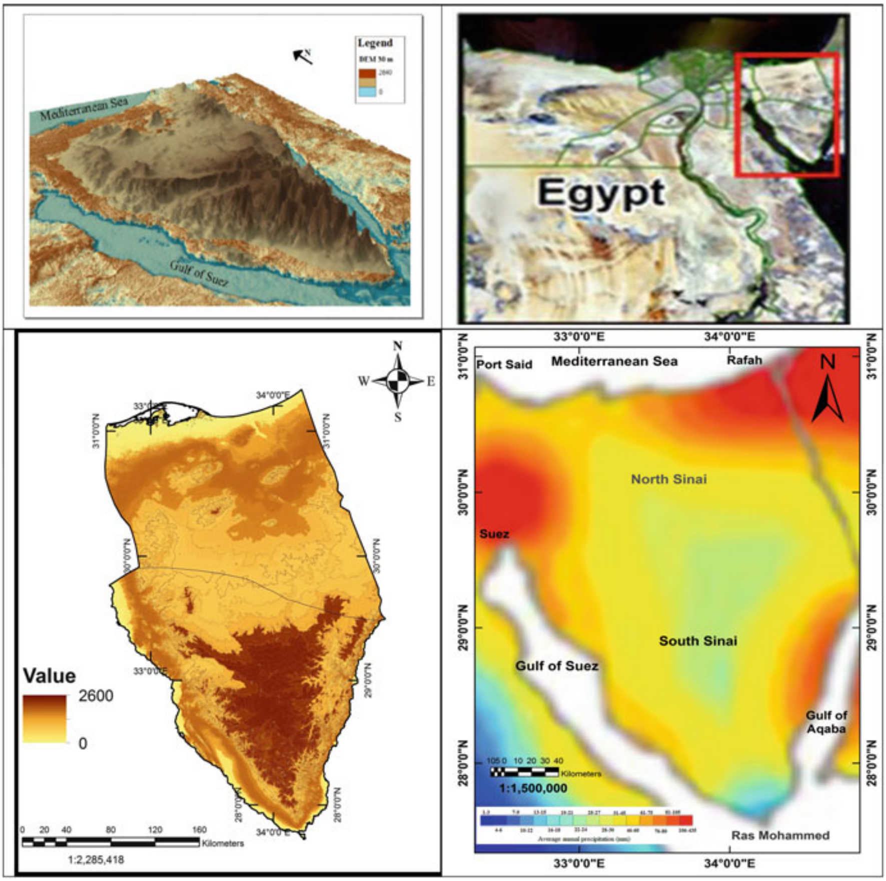

Fig. 1 3D view map created from a digital elevation model representing Sinai topography (*left*). Average annual precipitation, mm (*right*) extracted from TRMM 3B42 (v7). A 3-hourly data acquired (1998–2013) over Sinai [17]

copper, gypsum, black sand, and white sand. Since Sinai is close to urban centers of the Delta and the Suez Canal cities, it is a prime area for development. Also, the existence of a global navigation channel of the Suez passageway, on the eastern bank of the Canal and East Port Said, and the consequent ease the export of agricultural and industrial products. Drilling of the new Suez Canal will contribute to the economic sector as well as open the way for many investments. Six new tunnels under the Suez Canal to allow cars and trains to pass are additionally planned. Development in the region will include the El-Salam Canal project, which will increase irrigation by roughly 400,000 acres in northern Sinai [21]. Additionally, there already exists the presence of large tracts of agriculturally suitable land.

3 Geological and Geomorphologic Features

Groundwater resources and watershed areas of Sinai are greatly controlled by the associated geological formations. Therefore, it is necessary to provide general foundation knowledge about these formations. The general geology of Sinai was outlined by Said [22] and Shata [23]. Geologically, the Peninsula is divided into a number of distinct zones. In the north, a strip of loose sand and dunes run inland from the coast for 16–32 km and afterward level off to a flat, barren plain. This gravel and limestone plain proceeds for almost 241 km, ascending at its southern extremity to the El-Tih plateau. From this level toward the southern tip of Sinai, it is intercepted by a jagged system of mountains and wadis. Figure 2 (left) demonstrates the fundamental geology for Sinai.

Paleozoic rocks overlay the Precambrian basement in the southwestern Sinai [25, 26]. Mesozoic strata crops in the northern Sinai, where an almost complete sequence from Triassic to Cretaceous is known [27], create a subsurface section achieving an exceptionally gigantic thickness (955 m for Jurassic rocks) at Ayun Musa. A standout among the most imperative Mesozoic rocks is the Nubian sandstone of LC, which represents the main water-bearing unit in the region. It achieves the highest thickness at around 500 m, while at central Sinai it has a thickness of 70–130 m [26]. Sinai was classified geologically into 15 formations, e.g., basalt, carbonate rocks, granite rocks, limestone and phosphate rocks, metamorphic rocks, and sand dune volcanic rocks (Fig. 2).

Soil resources of Sinai are greatly affected by the associated landform types. Sinai was classified into six landform units [28], which are highlands (southern mountains, central tableland, El-Egma tableland, and northern folded blocks); northern Piedmont plain; western outwash plain (Feiran, Sidri-Baba, and Sudr-Abu Suweira plains); morphotectonic depressions (El-Qaa Plain, Wadi Araba, El-Saghir, Bitter Lakes, Lake Timsah, the area between El-Maghara and Risan Aneiza, and the area between Gabal Yelleq and El-Halal); northern coastal plain; and sand dunes. Geomorphologically, the Peninsula includes seven regions (Fig. 2, right). The southern elevated mountain district involves the southern part of Sinai assuming a triangular shape with its apex at Ras Mohammed to the south. The central plateau district involves the central part of Sinai as two principle quests: El-Egma to the southwest and El-Tih to the north [29]. A hilly region lies to the northeast of Sinai. It is gently sloping toward the northeast and is characterized by local isolated hills. Likewise, a coastal district of gently undulated surface is set apart by sand ridges of thick sandstones. Muddy and marshy land districts occupy the shorelines and some lakes (e.g., Lake El-Bardawil, Timsah Lake, and Bitter Lakes). The southern part of Sinai is occupied by the high mountain complex, such as the Gabal Catherina (2,641 m above mean sea level – amsl), Um Shomar (2,586 m amsl), and Serbal (2,070 m amsl). Toward the north of this mountain mass occurs the great El-Egma limestone plateau, which inclines from more than 1,000 m downward the Mediterranean Sea. The southern mountains are highly dissected by watersheds draining either to the Gulf of Suez or to the Gulf of Aqaba,

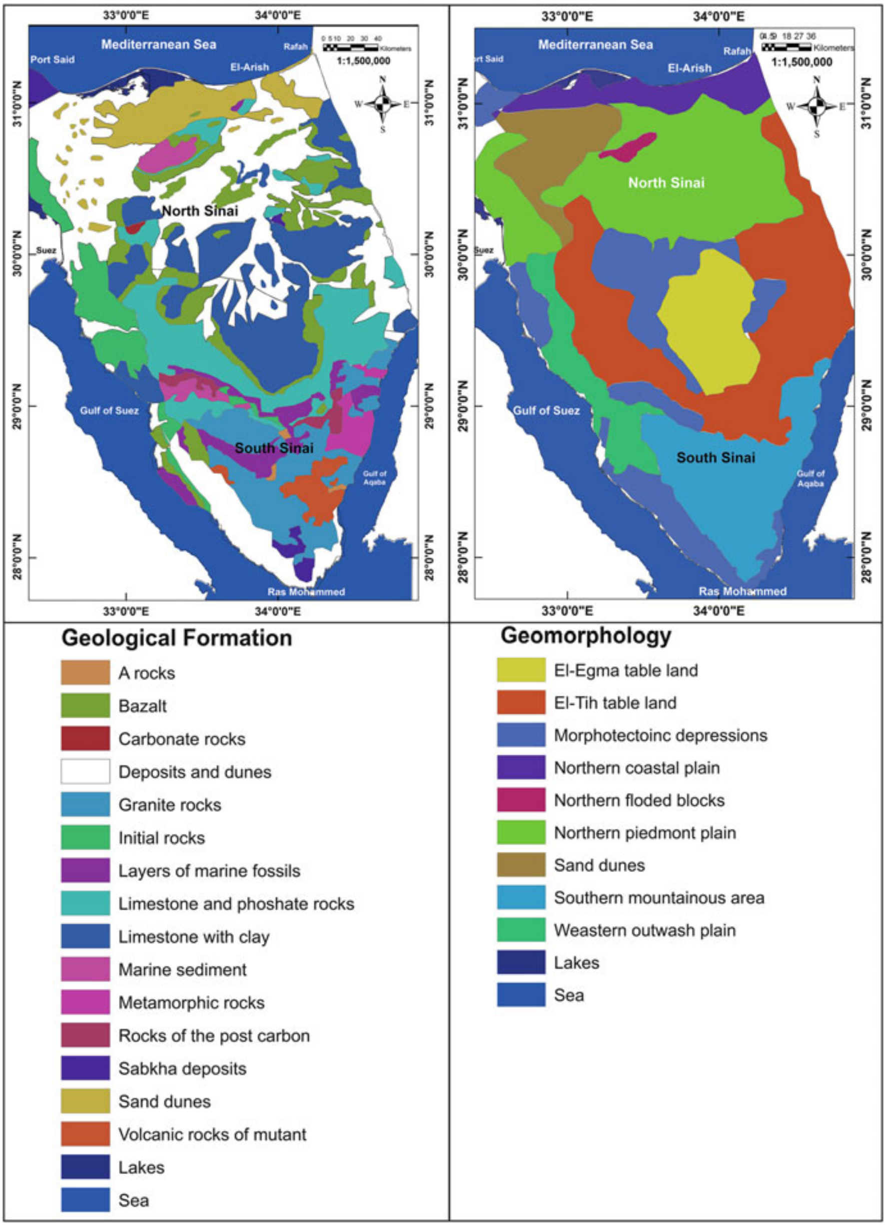

Fig. 2 The main geological (*left*) and geomorphological units (*right*) of Sinai [24]

though the majority of the drainage basins of the northern plateau are debouching northward to the Mediterranean Sea (Fig. 2). Two gulfs represent two grabens, which continue along the Suez Canal and Wadi Araba.

4 Case of Studies

4.1 Groundwater Resources in the Sinai Peninsula

Water resources in Sinai are dependent on the following:

– Rainfall: The northern strip of Sinai receives the maximum amount of rainfall during winter time (200–300 mm/year), and this amount decreases southward (25 mm/year).
– Springs: Few springs were discovered in North and central Sinai, and only two springs are of particular importance (Ain El Gedeirat and Ain Qedees).
– Nile water mixing with drainage water, conveyed by the El-Salam Canal.
– Existing groundwater supplies.

4.1.1 Large-Scale Groundwater Mapping

The existing deep aquifer systems in Sinai derive their characteristics from past geological events and structural movements and from regional and local recharge conditions occurring over the past centuries. The results of 2,110 deep drilling wells (Fig. 3) for oil and groundwater investigation in the different parts of Sinai show that seven deep lithostrategic units serve as the primary deep aquifers in Sinai. These include Pleistocene coastal, Quaternary alluvial, Middle Cretaceous, Eocene, Miocene sandstone, crystalline, LC sandstone, and Nubian sandstone.

Miocene units serving as aquifers are sandstone, belonging to the Lower Miocene Gharandal Group, and sandstone and grits forming a thin basal Miocene unit. These units occur on the west side, along the Gulf of Suez, in the Bitter Lakes area, Wadi Feiran, and the coastal foreshore area (south of Rafah and El-Magdaba). The results of testing the Miocene sandstone in the northern coastal foreshore area at well Misri-1 (well no. 2022) showed that its groundwater is of poor quality (salinity of 10,000 ppm). At the Habashi oil exploration well (well no. 2045), east of the Bitter Lakes, Miocene sandstone units produced water with a salinity of 1,020 ppm. South at Ras Misalla, wells tapping basal Miocene yielded water with a total salinity ranging from 2,600 to 5,000 ppm. Further south, aquifer groundwater salinity progressively increases to reach 380,000 ppm at well Lagia-2 Downstream of Wadi Feiran. At the Petropel Co. well-field, wells tapping Miocene sandstone units (well no. 2103) yield water with salinity ranging from 3,900 to 5,300 ppm [4].

The Eocene fractured carbonate aquifer is represented by limestone and marl. It extends outcropping from El-Tih and El-Egma plateaus in central Sinai to cover

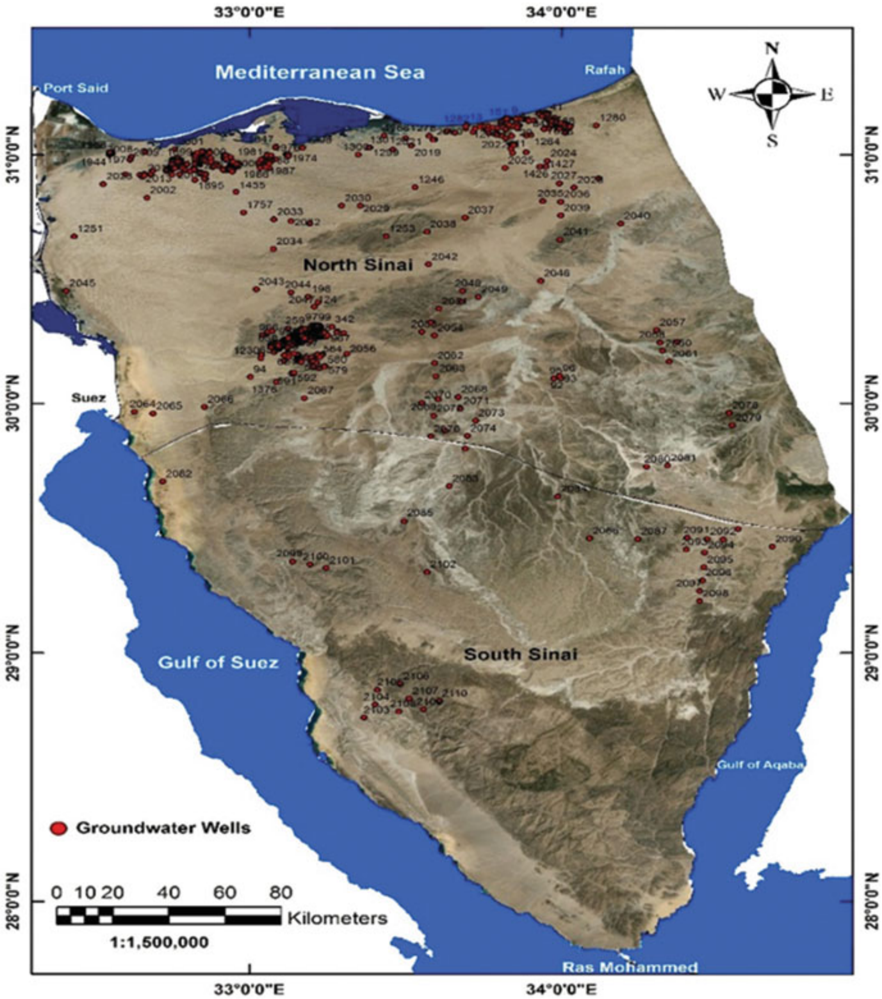

Fig. 3 Locations map of 2,110 groundwater wells in Sinai

vast areas northward to the line between Risan Aneiza and Gabal El-Maghara and attains a thickness of 200–360 m. A characteristic of the Eocene aquifer, developed in the limestone, is the shortage of groundwater at the basal part of the limestone underlain by the impervious Paleocene Esna shales. This is clearly demonstrated at Ain El-Guderrate and Ain Qedees in El-Quseima area, which issues from the Eocene limestone and discharge water at daily rates of 1,500 and 480 m^3 with a total salinity of 1,440 and 1,200 ppm, respectively. Well located northeast of Ras Sudr (well Abu Qiteifa 1) yielded water from the Eocene rocks with a salinity of 1,990 ppm, which increases progressively to reach 310,000 ppm at Lagia area south of Ras Sudr [4]. All other wells tapping the Eocene aquifer north of the zone between Gifgafa and El-Quseima yielded water with a total salinity ranging from

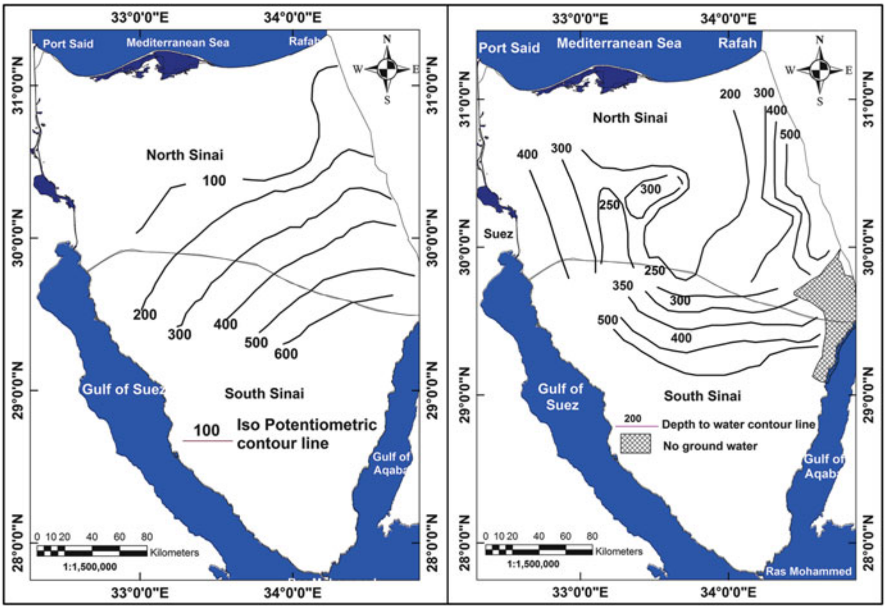

Fig. 4 Potentiometric surface map of the Upper Cretaceous aquifer (*left*) and depth to groundwater in the Lower Cretaceous aquifer (*right*) in Sinai [30]

8,500 ppm to reach 19,000 ppm at El-Mowaleh well (well no 2040). Favorable areas for groundwater development from the Eocene aquifer include the area between El-Hasana and El-Quseima and the area north of Nakhl and El-Thamad, where the aquifer hydrogeologic setting is similar to that prevails in northeastern Sinai at Ain El-Guderrate and Ain Qedees.

Data obtained from test wells tapping the Upper Cretaceous (UC) carbonate aquifer in Sinai indicate that the depth to water ranges from 85 m at well Shaira-2 (well no. 2092) and 180 m at El-Hasana well (well no. 2050) to 40–90 m at Wadi El-Amro/El-Magdaba areas in the North Sinai [30]. Figure 4 shows the potentiometric surface map of the UC aquifer. The recharge of the UC aquifer occurs through the direct infiltration of rainfall or from surface flow on its exposed areas. The estimated rate of recharge to the UC aquifer is expected to be 190,000 m^3/day [4]. However, the LC aquifer was recharged in the South Sinai area approximately 20,000 years ago and the groundwater quality in South Sinai is better and has more potential than that in northern Sinai. The LC sandstone aquifer is the most promising aquifer in terms of its potential capacity and water quality. The storage capacity of the aquifer is estimated to be 320 bcm. Figure 4 shows the depth to water from the groundwater surface in the LC aquifers. It indicates that at the north of the Ragabat El-Naam fault, the depth to water is about 200 m below the ground (mbg) around the Nakhl- El-Hasana road and gets deeper eastward and westward to reach 300–400 mbg. South of the fault, the depth to water in the LC aquifer in

El-Tih-El-Egma plateau areas ranges between 300 mbg in the northern part and 400 mbg near the southern outcrops of the Malhah formation.

According to El Osta and ElKashouty [31, 32], the groundwater in the southern Lake El-Bardawil (northern Sinai) is tapped from different water-bearing formations, which are Holocene and Pleistocene. The Quaternary aquifer (Holocene and Pleistocene) thickness varies from 150 m (Bir El-Abd well) to 330 m (Qatia-1 well) and rests directly on the Pliocene clay. The Holocene sand aquifer is developed along the coastal plain from Gilbana to El-Massaid along a distance of about 150 km with an average width of 20 km in the form of elongated sand dunes (coastal) or sand sheet (inland) or saline sand (sabkhas). This aquifer wedges out at El-Tina plain until it vanished. Groundwater of the Holocene aquifer exists under a free water table condition, where depth to water ranges from 2 to 9.92 m below ground surface. However, this depth is very near to the ground surface and close to the seashore. In El-Tina plain, the groundwater comes very near to the ground surface. The depth to water varies from less than 1 m in the north to about 2 m in the south because of the presence of cap rock (30 m clay). To the southern part of El-Tina Plain (East El-Qantara), the Pleistocene aquifer is about 170 m thick, and it rests directly on the Pliocene aquiclude, where both the Holocene and Pleistocene aquifers are partially hydrogeologically interconnected [31]. In the Qatia area, the Pleistocene aquifer attains about 300 m in thickness due to the presence of a graben structure.

4.1.2 Small-Scale Groundwater Mapping

The area of El-Sheikh Zuweid-Rafah was studied by many authors [33–35]. It received many of the studies since the 1950s and so far in the fields of geology, hydrology, geochemistry, and soil. It was found that the aquifer capacity of El-Sheikh Zuweid-Rafah area is limited and depends mainly on two sources. First is the direct rainfall, which ranges between 200 and 300 mm/year, and second is the water leakage from the floods that hit the region from the south via the streams of some valleys. The sand dunes stretching along the coastline are considered a major source to feed the aquifers in the area through vertical leakage. The drilled wells are concentrated in the narrow coastal strip and noted a high density of wells around the towns of El-Sheikh Zuweid and Rafah. The groundwater levels in the El-Sheikh Zuweid-Rafah area ranged from 0.5–1.5 to 4.5–6 m (Fig. 5). The winter crops are important to avoid groundwater salinity in the summer, which is due to seawater intrusion in the area affected by falling groundwater levels. This is illustrated in the southern dune areas and to the existence of underground water with salinity up to 7 g/l, which invades region from the south via the main fault of Lehefin. All of this has an adverse impact on the environment, which leads to soil salinity.

At the El-Qaa Plain area, the flow direction of the main channels was determined using integrated optical and radar RS and geophysical data for exploring groundwater [13]. The hydrological investigations of the digital elevation model (DEM) extracted the drainage network pattern to elude the relationship between

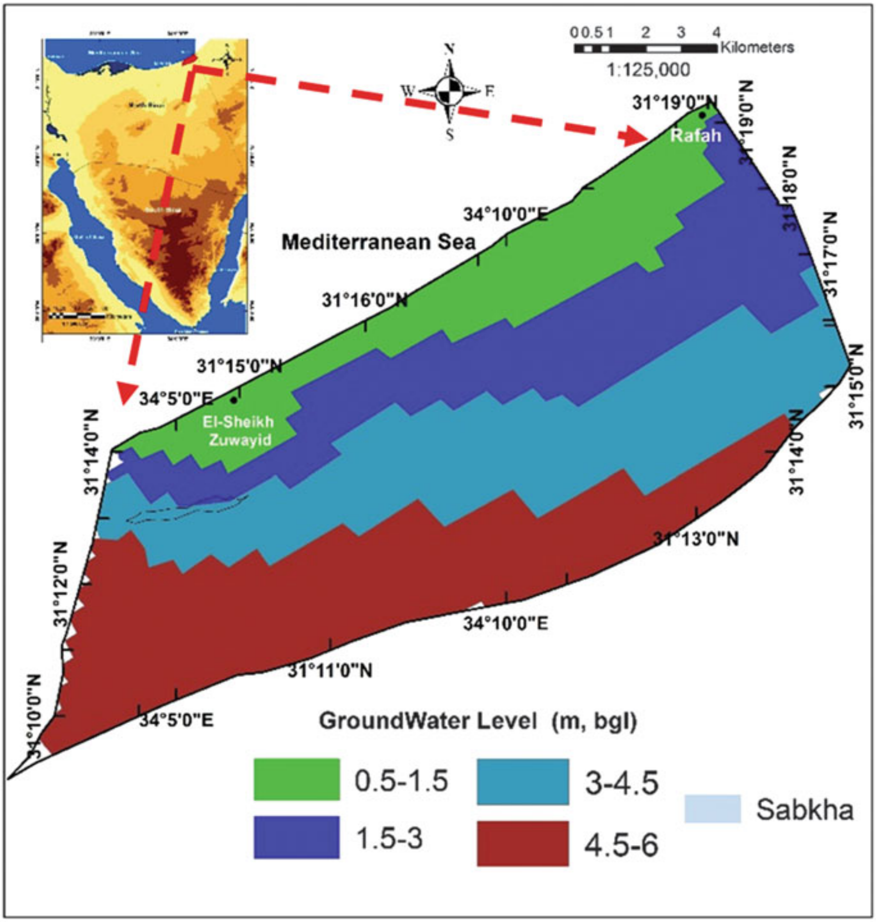

Fig. 5 Groundwater level map for the El-Sheikh Zuweid-Rafah area

paleochannels and structural elements. The water table maps developed from interpreted geo-electrical data show that the elevation of the water table declines from the east and north toward the west. In the El-Qaa Plain, Sultan et al. [36] report an investigation of the Quaternary aquifer utilizing gravity, magnetic, and geo-electric surveys. One hundred twelve gravity and magnetic stations have been measured and interpreted. The region is dissected by faults with orientations consistent with the gulfs of Suez and Aqaba and the Nile valley. Groundwater data demonstrated an E–W flow and an increase in salinity toward the Gulf of Suez. The variation of resistivity with depth below the ground surface was derived utilizing the vertical electrical soundings (VES) and associated with the access to geological information. The VES interpretation results were utilized to build iso-resistivity, depth maps, and isopach maps for the upper part of the Quaternary aquifer. The iso-resistivity map (Fig. 6a, left) demonstrates that the true resistivity decreases from east to west.

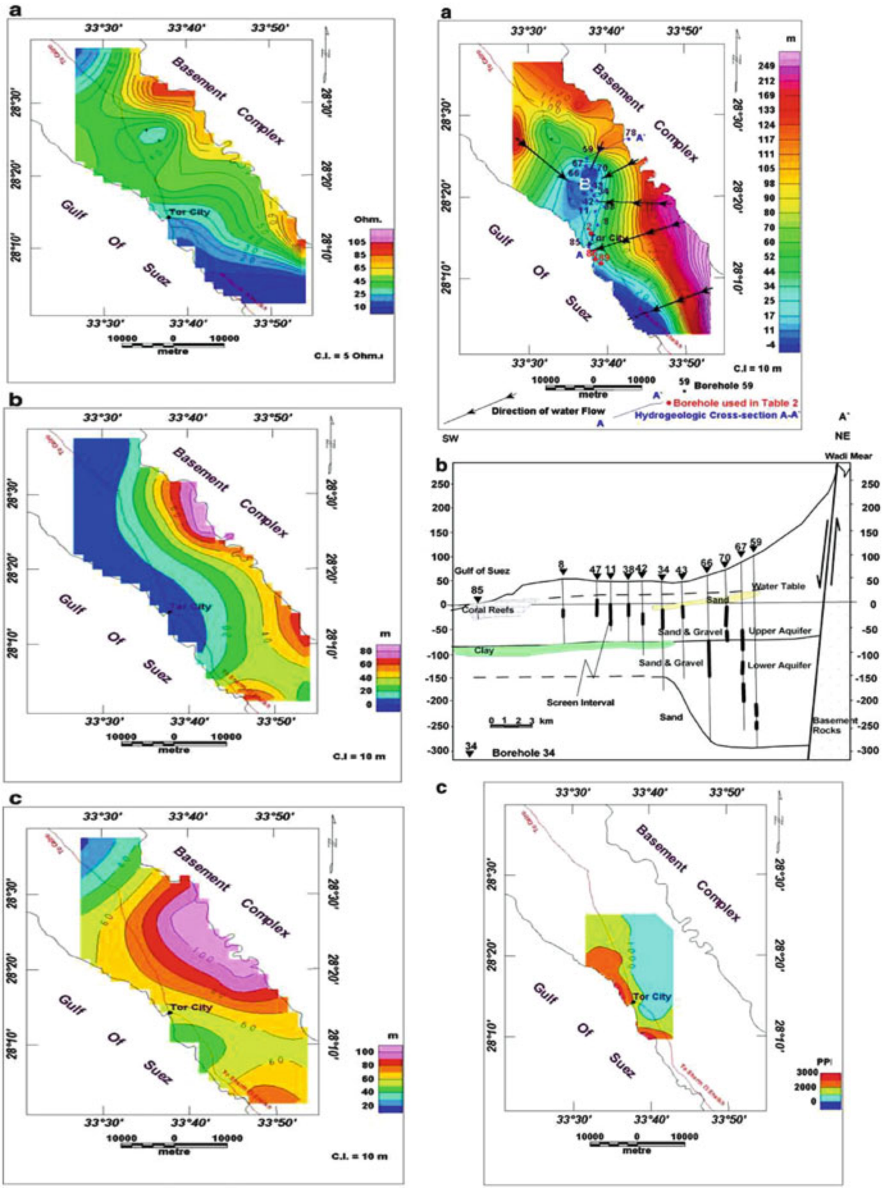

Fig. 6 (*Left*) (**a**) an iso resistivity map, (**b**) depth map of the aquifer, (**c**) isopach map of the upper unit of El-Qaa aquifer; and (*right*) (**a**) water table map, (**b**) Hydrogeological cross-section A–A′ [37], (**c**) salinity map [38]

The eastern part is close to the wadis, which dissects the basement rocks and represents the recharge zone. This is reflected in the increased resistivity (55–90 Ω m) at the freshwater-bearing zone compared with the higher resistivity because of salinization of groundwater toward the west and south. Figure 6b shows that the depth of the aquifer increases gradually eastward from a few meters to 80 m. The isopach map (Fig. 6c) indicates the thickness of the upper unit of the aquifer (the freshwater component consisting of gravel and sand), which increases gradually from 20 m in the north to 100 m in the eastern part of the central area.

The water table map (Fig. 6a, right) indicates that the elevation of the water table decreases from the east and north toward the west. The water table is at around 10 m depth at zone B. The water flow direction is southwest, toward the Gulf of Suez. Hydrogeological cross section A–A′ incorporates a group of boreholes situated in the central part of the area and begins from A at the Gulf of Suez to A′ at Wadi Mear (Fig. 6b). The aquifer comprises of an upper and lower horizon, with thicknesses diminishing from east to west. An ordinary fault is apparent between the basement rocks and the Quaternary aquifer. The central part of the region (Fig. 6c) has fresh and brackish water with salinity values ranging from 500 to 3,000 ppm.

Abu Zenima groundwater was studied through an integrated geophysics, remote sensing, and GIS assessment [16]. A direct-current (DC) resistivity electrical technique was applied in Abu Zenima area to determine and evaluate the main aquifer. The first surface layer was characterized by variable apparent resistivities (70–955 Ω m) and corresponds to Plio-Pleistocene and recent surficial deposits: silt, sand, and gravel sediments. The resistivity value variations could be attributed to areal variations in the grain size distribution and variation in the gravel-sand-silt-clay ratios. The thickness of this layer ranges between 1 and 8 m. A second layer represents the fresh to slightly brackish water-bearing formation. The layer resistivity reaches between 36 and 71 Ω m corresponding to Plio-Pleistocene and recent silt and sandstone. The layer thickness ranges between 10 and 66 m (Fig. 7). A third layer is characterized by very low resistivity (2.2–5 Ω m). Comparing to Miocene evaporites (marl, gypsum, and anhydrite), the low-resistivity estimations of this layer are because of the salt seawater intrusion and in addition to the dissolution of the Miocene evaporites. The thickness of this layer ranges from 162 to 405 m. A base layer was characterized by very low resistivity extending between 3.1 and 3.8 Ω m and is most likely Miocene limestone.

At El-Tor area, Kotb et al. [15] distinguish the groundwater aquifers between latitudes 27°52′ and 28°05′ N and longitudes 33°55′ and 34°05′ E in southwestern Sinai utilizing the distinctive geophysical exploration methods (magnetic, geo-electrical resistivity, and shallow refraction seismic). The outcomes demonstrate that the maximum depth to the basement surface is 180 m. The structure elements, which are influenced in this area by various typical faults, have different patterns and directions, which make two grabens confined by one horst. Tariff Sandstone bed recorded as water-bearing formation and the basement ridge gates in the Gulf direction are not capable to pass the groundwater from the area to the Gulf of Suez. The basement ridge gates in the Gulf direction are not capable to pass the groundwater from the area to the Gulf of Suez. This region must be created by

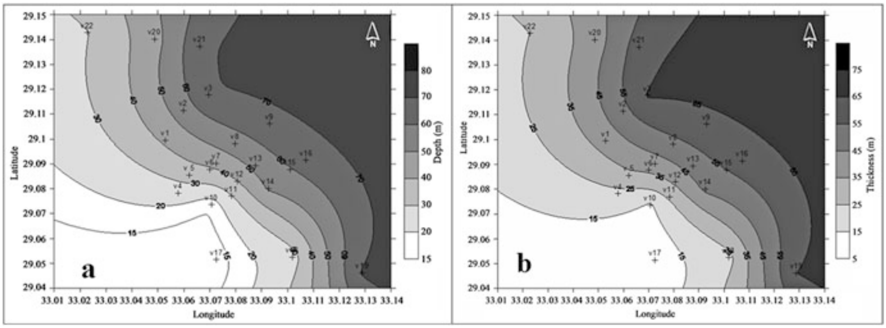

Fig. 7 Contour maps showing (**a**) the depth (m), (**b**) the thickness (m) maps of the fresh water-bearing layer. The thickness of fresh to slightly brackish aquifer ranged from 10 and 66 m. The aquifer thickness increased toward the northeastern part of the area with resistivity ranges from 36 to 71 (Ω m), which increased toward the northeastern part

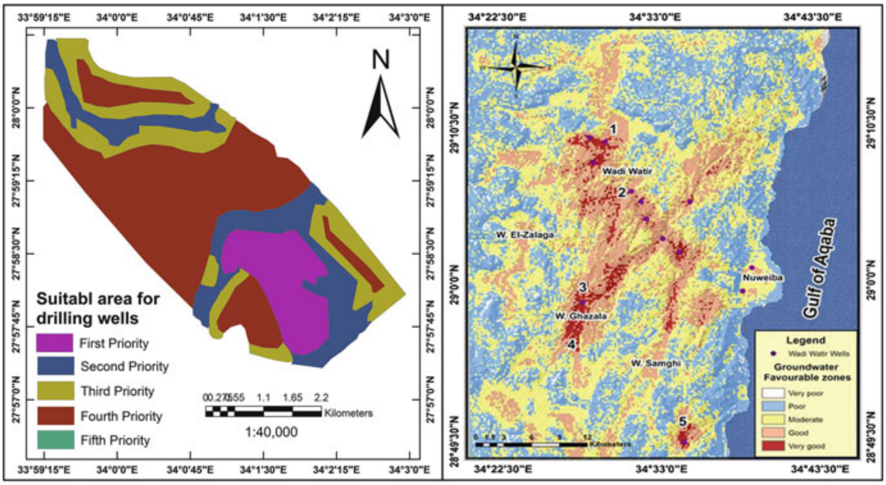

Fig. 8 Reliable and less cost decision map for drilling water wells in El-Tor area (*left*). The groundwater potential map of the Wadi Watir area (*right*)

establishing farms and foundations, which are suitable since it is located strategically between El-Tor city (capital of South Sinai) and Sharm El-Sheikh (the first touristic city in the region). The suitability map for drilling water wells (Fig. 8) outlines five priority classes. These classes are based on depth to water, which defines the reliability, and are less costly for drilling water well. The first and second priorities are concentrated mostly in the southwestern depression (graben).

In Wadi Watir area, Abuzied [18] took a holistic approach to assessing groundwater locations based on topographical, geomorphological, and geological factors to define the favorable zone of groundwater occurrences. These layers include lithology, lineaments, faults, landforms, elevation, and slopes, which were prepared from different data sources including SPOT5, Radarsat 2000, Alos PALSAR, SRTM, and ground-penetrating radar. Multisource data are the most suitable technique to extract the structural elements and textural characteristics of the alluvial deposits. The final groundwater potential map (Fig. 8) points to the promising localities for groundwater accumulations, which are mostly located at highly permeable areas, which are found at the downstream of Wadi Watir, Wadi El-Zalaga, Wadi Ghazala, Wadi Samghi, Wadi Nekhil, and Wadi Sada El-Beida. Most of the wells in the downstream area of Wadi Watir are found in the low to moderate elevated zones tapping alluvial aquifers. Low elevation, low drainage density, high lineament density, and gentle slope nominate highly probable good groundwater source. The generated map was checked using different sources including field investigations, previous work, and high spatial resolution satellite images. Hence, the generated map can be used in the future as a preliminary reference map to select sites of promising wells and in land-use planning for groundwater exploration.

In the Saint Catherine and Wadi Feiran area, Mohamed [17] integrated different methods such as field geology, geophysics, remote sensing, and cost-effective GIS for investigating groundwater potential locations that are associated with major shear zones (Fig. 9). The shear zones within the basement complex were delineated using false color images that were generated from Landsat-8 band, high spatial 1 m resolution Orb-view3 image, Google Earth images, hillshade, and band ratio images. The spatial and temporal precipitation events over the basement complex were then identified from TRMM data. Observations extracted from temporal change in backscattering values in radar (Envisat ASAR radar scenes) were used to identify the water-bearing shear zones. Finally, field observations and very low frequency (VLF) investigations were then applied to test the validity of the satellite-based methodologies for locating targeted aquifer types and for refining the satellite-based selections. Many wells in the Saint Catherine area were found along the shear zones especially at the intersection of two or more shear zones or at the intersection of the shear zone and fault system. The area is generally affected by two main sets of shears: NNW-SSE and NE-SW. Groundwater in the Saint Catherine area exists in both the shared basement rocks and the Quaternary alluvial deposits.

4.1.3 Priority Areas for Groundwater Development in Sinai

The future of land reclamation in Sinai will depend largely on its groundwater potential. The best locations for drilling groundwater wells were chosen from the decision map, which was produced by utilizing the GIS technique.

The iso-salinity contour map (Fig. 10, left) of the UC aquifer indicates a general trend of salinity, which increases toward the north, with the lowest values of 1,100 and 1,500 ppm observed at Shaira well (well no 2092) and Yerqa Spring (located in the western part of El-Tih), respectively. The highest salinity (5,628 ppm) was observed at the El-Bruk well (well no 2062) and 10,870 ppm at El-Magdaba well

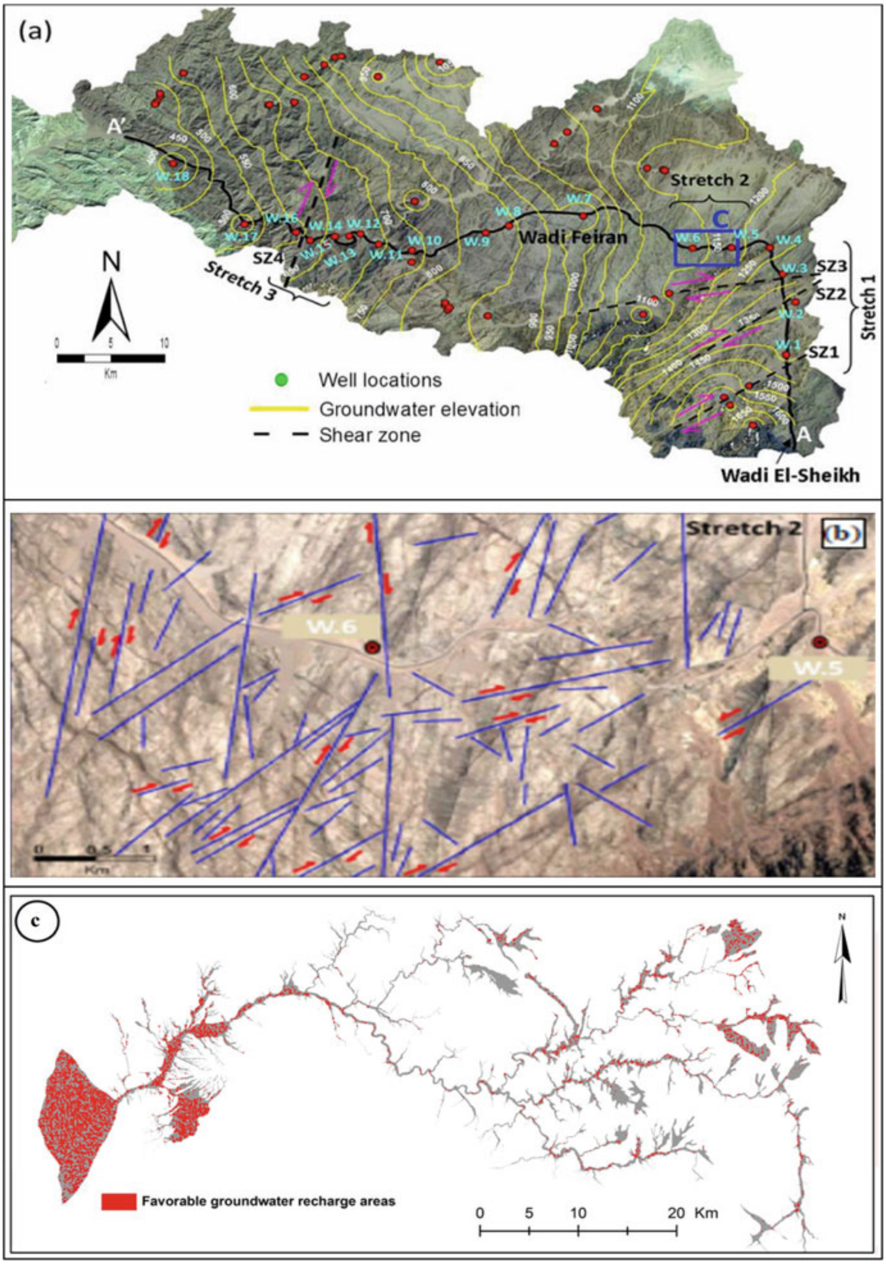

Fig. 9 Change in groundwater flow direction related to the structural control of Wadi Feiran. (**a**) Landsat TM image over the Feiran watershed showing the approximate groundwater levels (*yellow contours*), and the regional groundwater flow direction; also shown are locations of traverse A–A′ along Wadi El-Sheikh and Wadi Feiran, sections (stretch 1, 2, and 3) along traverse A–A′ where shallow groundwater levels were reported, well locations along traverse A–A′, and

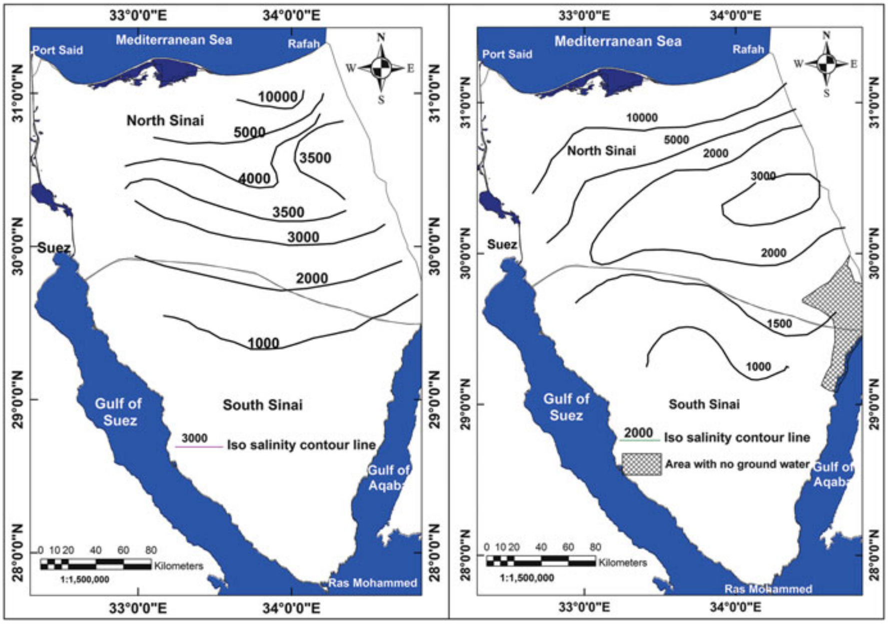

Fig. 10 Iso-salinity contour map of Upper Cretaceous aquifer (*left*) and of Lower Cretaceous aquifer (*right*) in Sinai [30]

(well no 2025). Although the UC aquifer contains relatively low groundwater salinity in the El-Tih-El-Egma plateau area, the observed salinity at Wadi Gharandal well (well no 2099, same aquifer) was reported to be about 5,000 ppm. The reason may be attributed to the fact that the Cretaceous aquifer in Wadi Gharandal is hydraulically separated from the other part of the aquifer in El-Tih-El-Egma plateau. Figure 10 (right) represents the iso-salinity contour map of the LC aquifer. It shows a general increase of groundwater salinity toward the west and the north, with four salinity zones.

Zone I has a groundwater salinity of <1,500 ppm. It occupies the area of the aquifer located south of the main road Joining Sudr El-Heitan, Nakhl, and Ras El-Naqb. The recorded aquifer salinities of the Sudr El-Heitan, Nakhl, Wadi Feiran, Shmra and the Gharandal wells are 1,246, 1,600, 800, 1,500 and 1,330 ppm, respectively. Test drilling in the LC aquifer in the southwestern part of the El-Egma plateau (well no 2102) indicated a salinity of 500 ppm. Zone II occurs to the east of the line joining Sudr El-Heitan – Nakhl – El-Bruk – El-Menashereh – El-Hassana – El-Quseima, where the aquifer salinity ranges between 1,500 and

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Fig. 9 (continued) the distribution of shear zones (SZ1, SZ2, SZ3, and SZ4). (**b**) Enlargement of area covered by *blue box* in (**a**) (stretch 2) showing the distribution of dike swarms (*dark streaks*) that are intensively displaced by dextral faults (outlined by *blue lines*). (**c**) Map showing groundwater recharge areas

2,000 ppm within this zone and in the vicinity of the folded structures at El-Bruk, Gabal El-Menashereh and Gabal Arif El-Naga. Salinity appears to be high due to the possible groundwater stagnancy around these highly elevated structures allowing for more dissolution of salts. This occurs at El-Menashereh well number 2054 (2,973 ppm) and Arif El-Naga well number 2061 (3,008 ppm). Zone III is characterized by salinities ranging between 2,000 and 5,000 ppm. It occupies a narrow area surrounding Zone I and extends to Ayun Musa area in the west and Gifgafa north of Gabal El-Halal in the north. Zone IV occurs to the north of Zone III and has salinities in the LC aquifer ranging between 5,000 and 10,000 ppm. Zone V occupies the northern and western parts of Sinai where the LC aquifer has been deeply buried by faulting. The rather high salinity values in this zone (14,000 ppm at well no 2024, 19,000 ppm at well number 2023) may be due to the ineffective flushing of the formation's saline water by the recharging meteoric water due to the interruption of the groundwater flow paths by block faulting.

Along the eastern coast of the Gulf of Suez, the salinity of the LC aquifer is high (227,000 ppm at Ras Sudr well no 2082) because it is deeply down-faulted and the formation water has not been diluted or flushed by groundwater inflow from the east. The exception to this is the aquifer discharging area at Ayun Musa where groundwater salinities of 2,536–3,180 ppm were observed at wells numbers 2064 and 2065. This could be attributed to the fact that the aquifer occurs at a shallow uplifted block and it is possible that hydraulic continuity occurs with the aquifer in the east. Because of its wide extension, considerable storage and good water quality, the Cretaceous aquifers are considered to be of high potential, and therefore it has the priority areas for deep groundwater development. The salinity of the UC Carbonate aquifer is rather high in most of Sinai (3,200–10,870 ppm) with the exception of its central part along Gabal El-Tih, El-Egma, and Shaira zone, where the reported groundwater salinity of the UC ranges between 1,100 and 1,500 ppm in this zone [30].

Although the recorded depth to water is relatively shallow (85 m below ground level, bgl, at well Shaira-1), the aquifer productivity proved to be very poor (well specific capacity 0 08 m^3/h/m). Consequently, it is not recommended to rely on exploiting this aquifer for future development projects in Sinai. The priority areas for the development and utilization of groundwater of the LC aquifer based on its potentiality are shown in Fig. 11 and as follow: first priority is found in Western Sinai (Downstream of Wadi Feiran and Wadi Gharandal) and in Central and South Sinai (El-Minshera Nakhl, El-Burk, Wadi Watir). Second priority is found in El-Quseima Arif El-Naga El-Kuntilla, El-Thamad, Sudr El-Heitan. Third priority is found in El-Tih plateau, south of Sudr El-Heitan, El-Thamad road, Shaira. Fourth priority is found in Ayun Mosa, Gifgafa, El-Hasana, Talat El-Badan, El-Hala, Um Shitan, Wadi El-Amro, El-Kherim.

The areas located north of Gabal El-Maghara, Gabal EI-Halal and EI-Ouga, and along the eastern coastal zone of the Gulf of Suez between Ras Sudr and Ras Mohamed, where groundwater salinity ranges from 5,000 ppm to more than 200,000 ppm, are not recommended for the development of the LC groundwater. The identified deep groundwater development priority areas should be considered

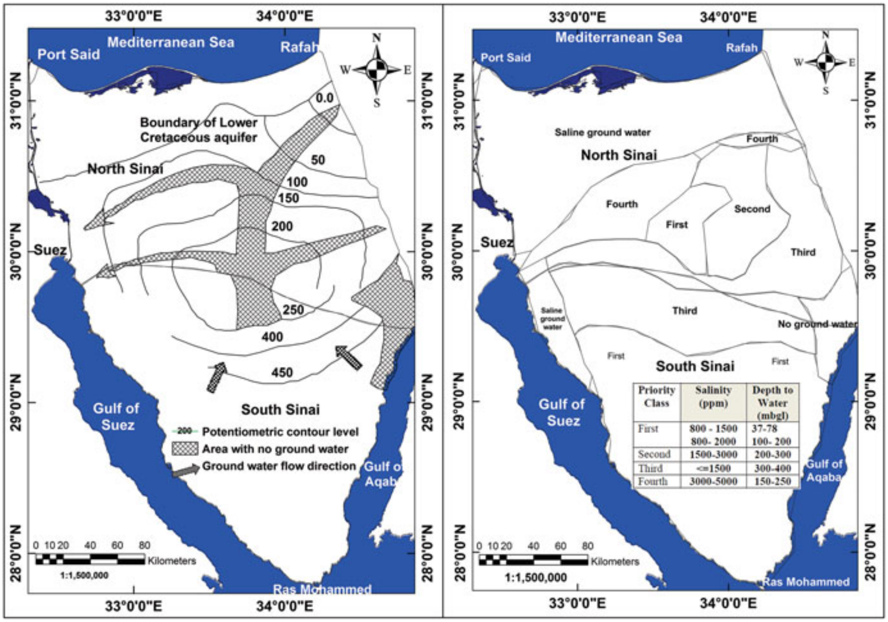

Fig. 11 Potentiality surface map of Lower Cretaceous aquifer (*left*) and a map of development priority areas of Lower Cretaceous aquifer (*right*) in Sinai [30]

in the evaluation of their sustainab1e potentials, applying groundwater modeling and an assessment of the economics of their use for different sectors should be done.

The LC Malhah water-bearing formation is considered the main aquifer system in the central and southern parts of Sinai. The importance of LC groundwater development is essentially related to the necessity of providing basic extension services (mainly water supply for domestic purposes and for small-scale irrigated agriculture) to the existing nomad tribes in central and South Sinai. Therefore, they will establish permanent settlements and not migrate north to EI-Salam Canal project development areas. Moreover, as the groundwater in the LC aquifer is moving down gradient across the eastern border toward the aquifer discharge area along the Dead Sea-Gulf of Aqaba rift valley, it is desirable to use this water in Sinai before it gets naturally lost in the rift discharge areas.

Elewa and Qaddah [39] integrated Enhanced Thematic Mapper Plus (ETM+) images, GIS, a watershed modeling system, and weighted spatial probability modeling (WSPM) to recognize the groundwater potential zones in Sinai, Egypt. Validation utilizing measured well yield data was performed to check the WSPM results. The resulting map (Fig. 12) shows that the diverse geographic locations are appropriate for groundwater storage with various magnitudes and potentialities, yet the overall groundwater potential is of the moderate class.

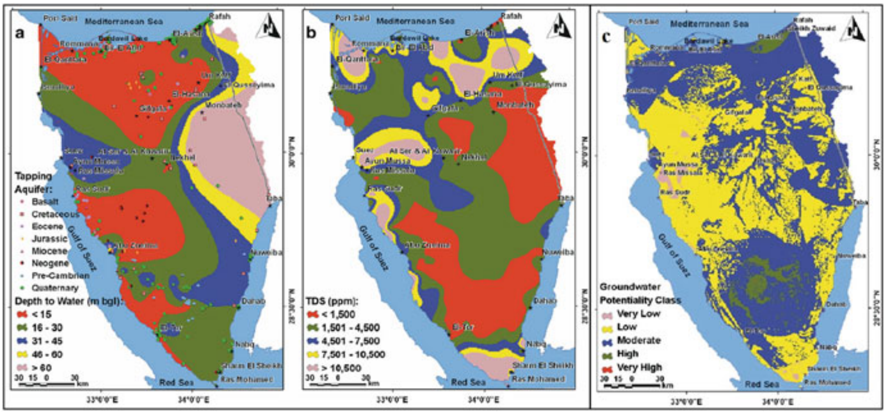

Fig. 12 Groundwater depth (**a**), salinity (**b**), and potentiality map (**c**) of Sinai [39]

4.2 Land Resources Mapping in the Sinai Peninsula

Sustainable agricultural development is an important issue in light of the increasing population and limitation of natural resources. Therefore, the assessment and mapping of land resources is of great importance for Egypt. Increasing attention has been paid since the liberation of this region in 1973 and it was decided to rehabilitate and develop the area. The northern part has wide scope potential for agriculture. However, in the southern part, the El-Qaa Plain and some other wadis (e.g., Wadi Feiran) are the areas that have agricultural potential based on the ground and rainwater amounts.

4.2.1 North Sinai Soils

Soils of El-Sheikh Zuweid-Rafah Area

The soils of El-Sheikh Zuweid-Rafah area are mostly sandy. There are few sandy loam to loamy soils; low in salinity. Most of the cultivated lands are considered fair to good lands for agriculture [40]. Soils of El-Sheikh Zuweid-Rafah area have been categorized as follows:

1. Flat to almost flat soil, loam and low salinity.
2. Undulating soil, sand over clay layers at different depths.
3. Sandy soil, subsurface loamy layers to a depth of at least 1 m from the soil surface; salinity is very low.
4. Saline soils, waterlogged, mostly concentrated in the swampy El-Sheikh Zuweid and unfit for agriculture.
5. Sandy soils of coastal dunes.

Abed El-Salaam [33] classified the soils of El-Sheikh Zuweid-Rafah area into several main units within an area of 151.23 km^2 as follows:

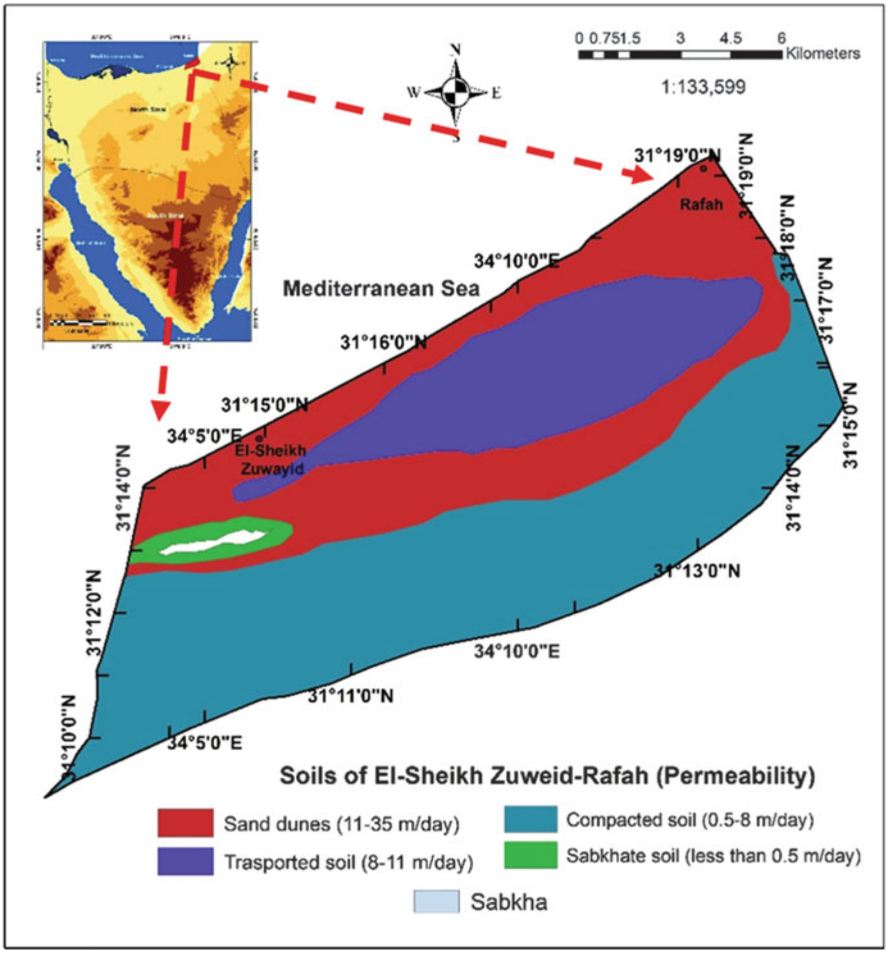

Fig. 13 Soils of El-Sheikh Zuweid-Rafah area

- Sand dunes extended along the coastline with an area of about 15,450 acres (64.9 km^2).
- Interdunal depressions also extended on the coastal strip and covers 684 acres (2.9 km^2), which planted vegetables and fruits.
- Sandy loam soil is located south of swampy El-Sheikh Zuweid with an area of 772 acres (3.2 km^2).
- Loam soils with thickness of 20 cm and occupy an area of 523 acres (2.2 km^2).
- Saline soil where the groundwater level is close to the surface and is characterized by high concentrations of salts with an area of 269 acres (1.13 km^2).
- Sandy soil with various thickness and distributed in different parts of an area of 18,300 acres (76.9 km^2).

Based on the vertical permeability coefficient of the soil, the soil was divided into four main types (Fig. 13):

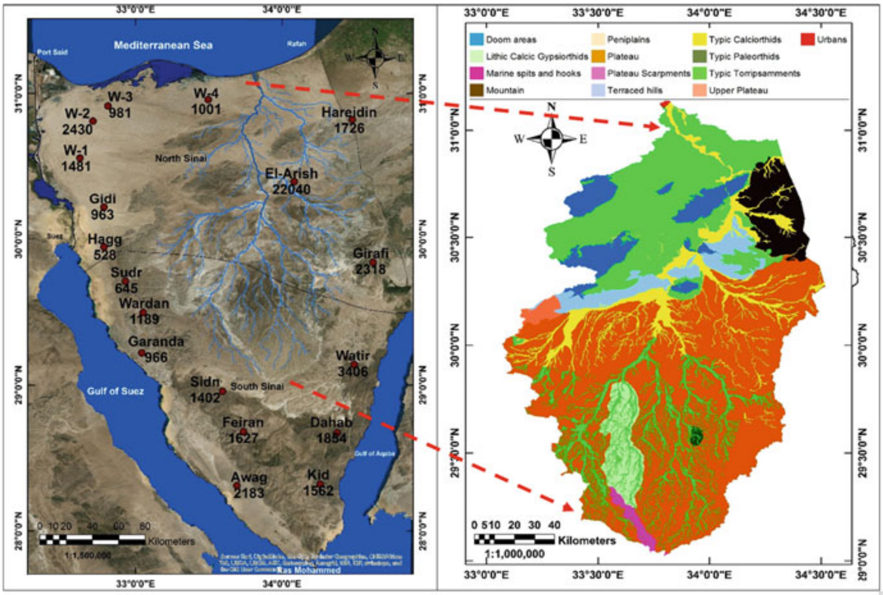

Fig. 14 (*Left*) The outlet of Wadi El-Arish and distribution of different wadis networks in the Sinai. Also shown are the areas (in Km^2) covered by the identified watersheds. (*Right*) The soil dominant in the Wadi El-Arish basin

– Soil sand dunes along the coastline, where the permeability coefficient ranged between large permeability (11 m/day) and a very large permeability (35 m/day).
– Transported soil in the middle of El-Sheikh Zuweid-Rafah area where the permeability coefficient ranged between a medium permeability (8 m/day) and large permeability (11 m/day).
– Consolidated soil, which extended south the El-Arish-Rafah road where the permeability coefficient ranged between low permeability (0.5 m/day) and medium permeability (8 m/day).
– Sabkha soils, which are located in the area where the swampy Sheikh Zuweid with permeability coefficient very few (<0.5 m/day).

Soils of Wadi El-Arish Basin

Soils of the Wadi El-Arish basin consist of the area between the Mediterranean Sea and Bir Lehefin, El-Qseama, El-Ser and El-Qawarir, Wadi El-Brouk, Gifgafa, El-Gidi, and Nakhl area. Wadi El-Arish basin is situated in Sinai where it flows toward the Mediterranean Sea, and its downstream part is located in El-Arish City (Fig. 14, left). Wadi El-Arish is bound on both sides by three terraces, namely, upper terraces (33 m above the Wadi floor), middle terraces (20 m), and the lower terraces (10 m) [41]. The Wadi infrequently receives flash floods from much of southern and central Sinai, which are a great threat to the life and to the properties located in El-Arish City. Wadi El-Arish (250 km distance from the drainage basin to El-Arish town) is one of the largest drainage basins in Egypt and comprises about one third of the whole Sinai area (20,000 km^2). It is located between latitudes 29°00′ and 31°10′ N and longitudes 33°05′ and 34°40′ E (Fig. 14). The Wadi has two main tributaries, Wadi El-Aqaba on the eastern side and Wadi El-Bruk on the western side. The Wadi is associated with many secondary tributaries: Wadi Hareidin, Wadi El-Azarq, Wadi El-Hadeira, Wadi El-Hassana, Wadi El-Geraf, and other wadis. These wadis pour into Wadi El-Arish, which receives rainfall from different regions of El-Egma and El-Tih plateaus. The soil dominant in the Wadi El-Arish basin could be categorized under the following subgroups, namely (Fig. 14, right), *Typic Torripsamments*, *Typic Calciorthids*, and *Salorthic Calciorthids*, and could be categorized under two orders, namely, Entisols and Aridisols.

The sustainable development of the Wadi El-Arish watershed depends mainly on soil and water resources for agriculture and other purposes. Mohamed et al. [42] classified Wadi El-Arish soils to the following classes:

– The high suitability class is represented by wadi deposits (2617.5 km^2) especially in the north and middle of the El-Arish basin, reflecting their higher capability for agricultural use. It can contribute to the storage of floodwaters to raise the soil moisture needed for agriculture, which is indicated by the distribution of natural vegetation along the wadis. These soils are characterized by very gently sloping, deep soil profile (>120 cm), loamy to gravelly sand texture, and mostly non-saline soils (<4 dS/m).
– The moderate suitability class is represented by sand sheet (1884.0 km^2), which is characterized by nearly leveled topography, deep soil profile (>120 cm), sand texture, and mostly non-saline soils (<4 dS/m).
– The low suitability class for land use is represented by alluvial plains, terraces, and footslope deposits having gently to strongly sloping surfaces (3316.3 km^2) and consisting mainly of loamy sand to very gravelly sand texture. The depth of soil profiles is more than 80 cm and mostly moderate to high saline soils (>4–16 dS/m).
– The non-suitable class is represented by the hill and plateau unit.

The area between El-Arish and Lefhen is covered by beach soils, Aeolian soils, and alluvial soils. Soils of Wadi El-Brouk are classified as an outwash plain, flood plain, and wadi bottom. Soils of Wadi El-Brouk range from sand to sandy clay loam, and $CaCO_3$ content ranges between 34.5 and 71.5%. Organic matter content ranges between 0.1 and 0.9%. The soil is neutral to moderately alkaline as pH values range between 7.0 and 7.9. Soils of gullied and isolated remnants were extremely saline as the EC values exceeded 17.0 dS/m, while soils of the wadi are non-saline to slightly saline. Gypsum content is varied and exists between 6.6 and 10.1% with an irregular distribution pattern with depth. Soils of Wadi Sabha at El-Quseima are highly calcareous as they are derived from calcareous rocks.

Alluvial deposits of Wadi Sabha are surrounded by the gravelly plains and cultivated olive trees and other plants. Soils are sandy to sandy loam texture and have high calcium carbonate and low salinity, with soft and hard lime segregation. These soils are similar to some extent to the soils of Wadi El-Geifa (El-Quseima). Alluvial soils of Gifgafa are sandy to sandy loam texture and have low $CaCO_3$ and low salinity. Aeolian sandy soils are present as isolated patches within the wadis with dense natural vegetation, and a sand sheet covers a relatively large area. Soils of gravelly plain occupy a large area of Gifgafa, including sandy soils, gravelly soils, and heavy-textured soils.

Mahmoud [43] carried out studies on some soils along El-Salam Canal, northeast of Egypt. Sand sheets, hummocks, and dunes of both of the deflated old deltaic plain and El-Gifgafa-El-Maqdaba depression reflect the prevailing aridity, while the wet soil materials of the lacustrine plain refer to the effect of both Nile and seawater on soil climate. Due to the climatic conditions of the study area, chemical weathering and soil development are weak, and there exists mostly physical weathering due to the variation in temperature, scarcity of rainfall, and wind erosion in most parts of the area. Salinization, gypsification, and calcification are the main processes in some parts of the area. They are quite common in soils of the El-Gifgafa-El-Maqdaba depression and small spots of the lacustrine plain. The accumulation of salts occurred because of capillary rise of the saline water table. The soluble salts, gypsum, and carbonates are formed in these soils as evaporates, which are formed by the evaporation of water. In addition, features related to the previous climatic conditions occur because of changes in climate during the Pleistocene period, which had an effect on soil formation, and numerous dry drainage lines, i.e., Wadi El-Arish. From the geological history of the deposits covering different geomorphic units of east of delta and northern Sinai, the lacustrine plain and the deflated old deltaic plain are recent deposits of Holocene period. These deposits have a young pedological age, resulting in very weak pedological processes. The deposits of the El-Gifgafa-El-Maqdaba depression belong to the Pleistocene period; therefore, they show a certain degree of development reflected in the presence of lime segregations, gypsum, and salt crystals. The statistical size parameters indicate that the soils are generally formed of homogenous well-sorted sediments, which means that the soil parent materials were transported from a source, which is not far from the soil site, and/or by currents (wind in most cases) with moderate energy. Smectite and kaolinite are the dominant clay minerals, whereas quartz and feldspars dominate the silt fraction. The dominance of smectite in soils of the lacustrine plain can be attributed to the poorly drained environment. Kaolinite, on the other hand, is expected to be formed in a marine environment. Predominance of feldspars in the silt fraction indicates that a part of soil materials is derived from Nile sediments.

El-Ser and El-Qawarir are plains in the eastern part of North Sinai. The area is located between latitudes 30°47′ and 30°56′ N and longitudes 33°40′ and 34°00′ E (Fig. 15). The area (135,000 feddan) is classified according to their elevation to three categories: 66,000 feddan less than 90 m (48.9%); 54,400 feddan, 90–100 m (40.3%); and 14,600 feddan (10.8%), 100–110 m above sea

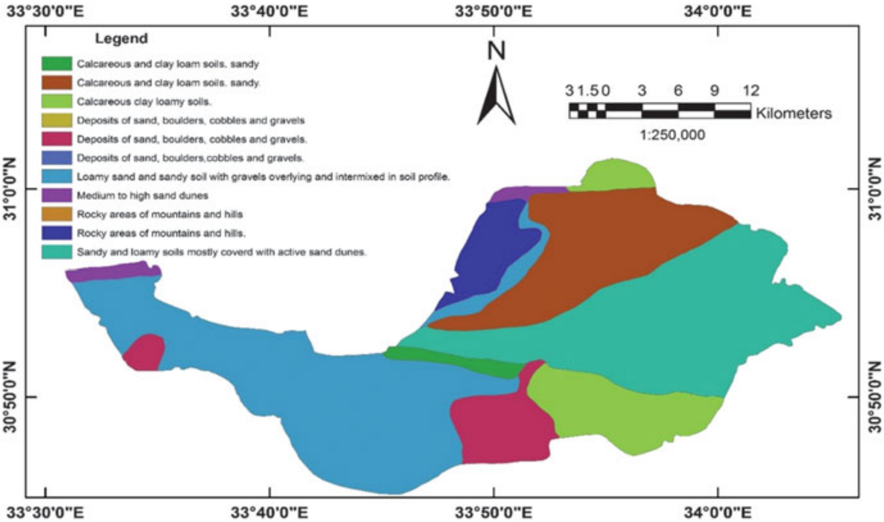

Fig. 15 El-Ser-El-Qawarir area in the eastern part of North Sinai

level [44]. Sand sheet occupies the majority of the northeastern district of the area, which represents many landforms, i.e., sand sheets, sabkhas, plains covered with desert pavement, and wadi bottom and terraces. The area of El-Ser and El-Qawarir is characterized by its irregular shape, bounded by Risan Aneiza at the north, the foothills of Gabal Lobna at the south, and on the east by Wadi El-Arish. Sandy to sandy loam soils are dominant in the north. The sand sheet and the sand dunes in the central and western part and gravelly sand are found in other parts [44]. These soils contain the highest values of calcium carbonate (11–30%) and gravels. The drainage water flows toward the main channel of Wadi El-Arish with a gradient. The water drain could be used for cultivation of forests of different trees, which could have many benefits such as wood supplies, positive changes in the ecosystem, and fixation of sand dunes. An opinion exists which suggests that it is better to exclude the area because of the high cost of raising the water (60–110 m). This opinion is reasonable from the economic point of view. Nevertheless, the development of central Sinai is an urgent initiative for the national security regardless of economic cost.

Soils of El-Ser and El-Qawarir are generally sandy in texture, non- to strongly saline, and slightly to strongly calcareous. These soils display no signs of presence of any secondary formation or any diagnostic horizon. Therefore, they are classified as *Typic Torripsamments*. Sabkha is located in the southern part of the depression. Soils vary between coarse and moderately fine textured, strongly to extremely saline, slightly to strongly calcareous, and gypsum content from slightly to moderately in fine crystals form. Some soils have weakly developed gypsic horizon though other soils have salic horizon accompanied with weakly developed calcic one. Therefore, these soils belong to *Typic Haplogypsids* and *Calcic Aquisalids*.

Soils of the plains extend over different districts covering a relatively large area and cover a wide range from fine to coarse textured, strongly to extremely saline, slightly to strongly calcareous, and gypsum content from slightly to moderately. These soils can be distinguished into soils with weakly developed calcic or gypsic horizons and soils that have no secondary formation. Therefore, these soils belong to *Calcic Haplosalids*, *Typic Haplogypsids*, and *Typic Haplocalcids*. Soils of wadi terraces are moderately fine textured, extremely saline and calcareous, and located in *Calcic Haplosalids* and *Typic Torrifluvents*.

Soils of El-Salam Canal Basin

The land reclamation area comprises the low-lying Mediterranean foreshore strip between the Suez Canal and the El-Arish and the area lying along the eastern bank of the Suez Canal. The 400,000 feddan scheduled for irrigation on the eastern side are marginal lands. Studies on the coastal area located on the North Sinai were performed by Ibrahim [45]. Soils of South El-Qantara East (70,000 feddan), Rabaa (70,000 feddan), Bir El-Abd, and South El-Bardaweil (70,000 feddan) differ in their properties according to the mode of formation, parent material, and geographic position. Most soils of the coastal strip are located at low elevations. Sandy soils constitute most of the sandy terrain at south El-Qantara East, Rabaa-Qattia, Bir El-Abd, and south El-Bardawil. The area extends south to the El-Tina plain, parallel to the Suez Canal, with almost sandy soils (75,000 feddan), and about 20,000 feddan need drainage [44]. The northern part (10,000 feddan) at an elevation of 1 m above sea level consists of clay to clay loam surface soil. The rest of the area, at elevations ranging from 5 to 40 m above sea level (65,000 feddan), is sandy soils. Soils of El-Qantara East are mostly sandy and have a shallow to deep soil profile and shallow water table at many sites [6]. Many sabkhas with shallow (50–75 cm) to moderately shallow water tables (75–100 cm) are scattered throughout the area especially on the northern part. Salinity is low in most of the soils except some sites are highly saline. El-Salam Canal basin in North Sinai is subdivided into El-Tina plain area, south El-Bardawil area, and El-Ser and El-Qawarir area (these are similar to those mentioned in soils of the Wadi El-Arish basin).

Reda and Ragab [46] studied the area (70,000 feddan), which occupies a part of Bir El-Abd district (Fig. 16). The area is bound by the Mediterranean Sea and the Lake El-Bardawil to the north and Rabaa to the west and adjoins the sand dunes zone of the southern and the eastern edges. The area is covered with the sandy terrain of Aeolian origin. The salinity was very high (4.5–6.5 dS/m), which may be attributed to the mixing ratio or the high evaporation. Soil mapping units identified are as follows: soils of flat sandy terrain of the coastal strip, soil of the flat sandy terrain, soils of the undulating sandy terrain, and soils of the interdunal sandy terrain. Soil potentiality is poor arable land to moderate arable land (Fig. 16).

The area located between Rabaa-Qattia and Bir-El-Abd has elevations ranging from 20 to 30 m above sea level. The undulating sandy terrain cover the areas of El-Maraibah, Rabaa-Qattia, and north El-Nasr, while the rolling sandy terrain

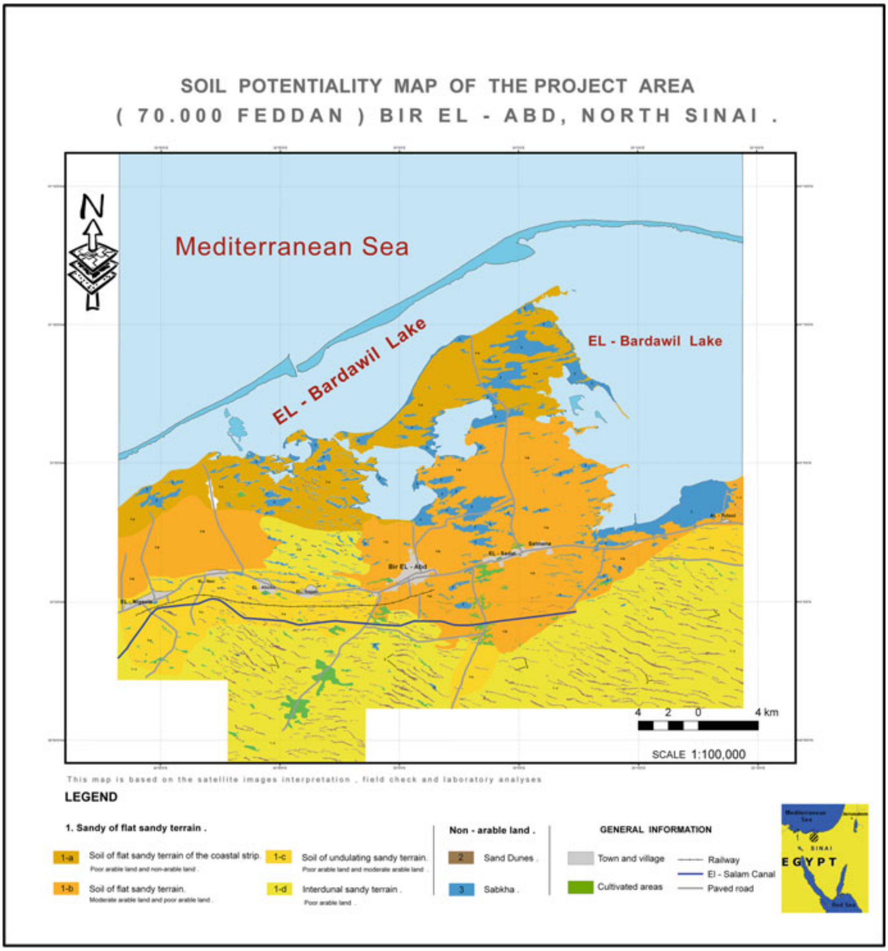

Fig. 16 Land suitability map of Bir El-Abd area [46]

covers the area of north Balouza and 6th of October [41]. Many sabkhas are present especially near Rommana, Rabaa-Qattia, 6th of October, and south El-Bardawil. The sand dunes are common especially at Bir El-Abd and south El-Bardawil. Soils are mostly sandy and very poor in calcium carbonate, with a variable amount of soluble salts. Salinity is mostly low while at some sites can be very high. Most of sandy soils are surrounded by shifting sand dune especially at Bir El-Abd and south El-Bardawil. South El-Bardawil basin is located south El-Bardawil from El-Khriba in the east and extends to the western side of El-Arish. Most of the soils are sandy and surrounded by shifting sand dunes. The water table is generally high, and the water quality is brackish or saline [44]. Therefore, without Nile water from El-Salam Canal for irrigation and subsurface drainage, little can be done for crop production. $CaCO_3$ is very low (0.5–2%).

Abd-Allah et al. [47] studied the soils along El-Salam Canal territory in the North Sinai Peninsula. The effect of erosion by wind is obviously noticed in the formation of desert pavement where coarse materials such as gravels and pebbles are left behind as well as the presence of ventifacts. However, the wind erosion effect was observed in the soils southeast of El-Qantara, Bir El-Abd, El-Ser, and El-Qawarir. These soils have been developed under arid conditions. The prevailing arid climate, different in the parent materials, and the age of the area are the dominant factors affecting the formation and nature of the soils. Soils of south El-Qantara, Rabaa, and Bir El-Abd are classified into Torripsamments and Psammaquents.

Soils of salinized lacustrine plains occupy the low-lying flat clay flat El-Tina plain (50,000 feddan). El-Tina plain is located in the northwestern corner of Sinai between latitudes 30°50′ and 31°15′ N and longitudes 32°20′ and 32°40′ E. The elevation is at mean sea level or just above or below and varies between 0 and 2 m a.s.l. [48]. El-Tina plain consists mainly of a mud flat of young lacustrine and deltaic deposits (fluviomarine clay). Nile sediments were transported to the area through the old branch of the Nile (Pelusiac). Low sandy spots have very high salinity (sabkhas), without external drainage. Level terrain of Aeolian deposits with hummocky surfaces is common. The soils of El-Tina plain have been formed from three different origins, old deltaic, lacustrine, and Aeolian deposits. Soils of El-Tina plain have severe limitations, such as extremely high salt content (sometimes 200 dS/m or more), thin to thick salt crust, waterlogging, alkalinity, claypans, and very shallow saline and hypersaline water table [41]. Soil texture varies between sandy loam to clay. Calcium carbonate (0.5–3%) is very low, and exchangeable sodium is relatively high at many sites. The soils developed in the ancient Nile Delta have medium to fine and moderately to strongly salinity. The lacustrine soils are weakly developed or undeveloped and of medium texture. Salt crust, gypsum crystals, mottles, decomposed organic materials, and anhydrite segregations were the main pedo-feature in these soils. Aeolian deposit soils are coarse textured, moderately saline, and slightly to strongly calcareous. The presence of a high water table level with high salt content and the dominant aridic condition in El-Tina plain have led to the accumulation of salts on the soil surface. The differences of salt crust forms in El-Tina plain may be due to different degrees of salinization, heterogeneity of parent materials, texture, and soil depth [49]. Abou E-Hag [50] studied the soils of the northern coastal area of the Sinai Peninsula. The study indicated that these soils are strongly to non-saline and the texture ranged from clay to gravelly sand. Soils of El-Tina plain contain a saline horizon; therefore, these soils are classified into Haplocalcids.

Nawar [51] utilized satellite images, geographic information systems, and geo-statistical analysis to produce soil maps for El-Tina plain. The soil map (Fig. 17) shows that soils of the area consist of 18 soil mapping units. Calcium carbonate content ranged between 0.1 and 6.3%. Organic matter content ranges between 0.1 and 2.1%. The total soluble salts ranged from 4.5 to 164.4 dS/m. Cation exchange capacity ranged between 3.4 and 64.4 cmol (+)/kg soil. Gypsum content ranges between 0.1 and 7.9%. The studied soils were classified to eight subgreat groups, i.e., *typic aquisalids*, *typic haplosalids*, *aquic torriorthents*, *typic torriorthents*, *aquic torripsamments*, *typic torripsamments*, *gypsic aquisalids*, and *gypsic haplosdlids*.

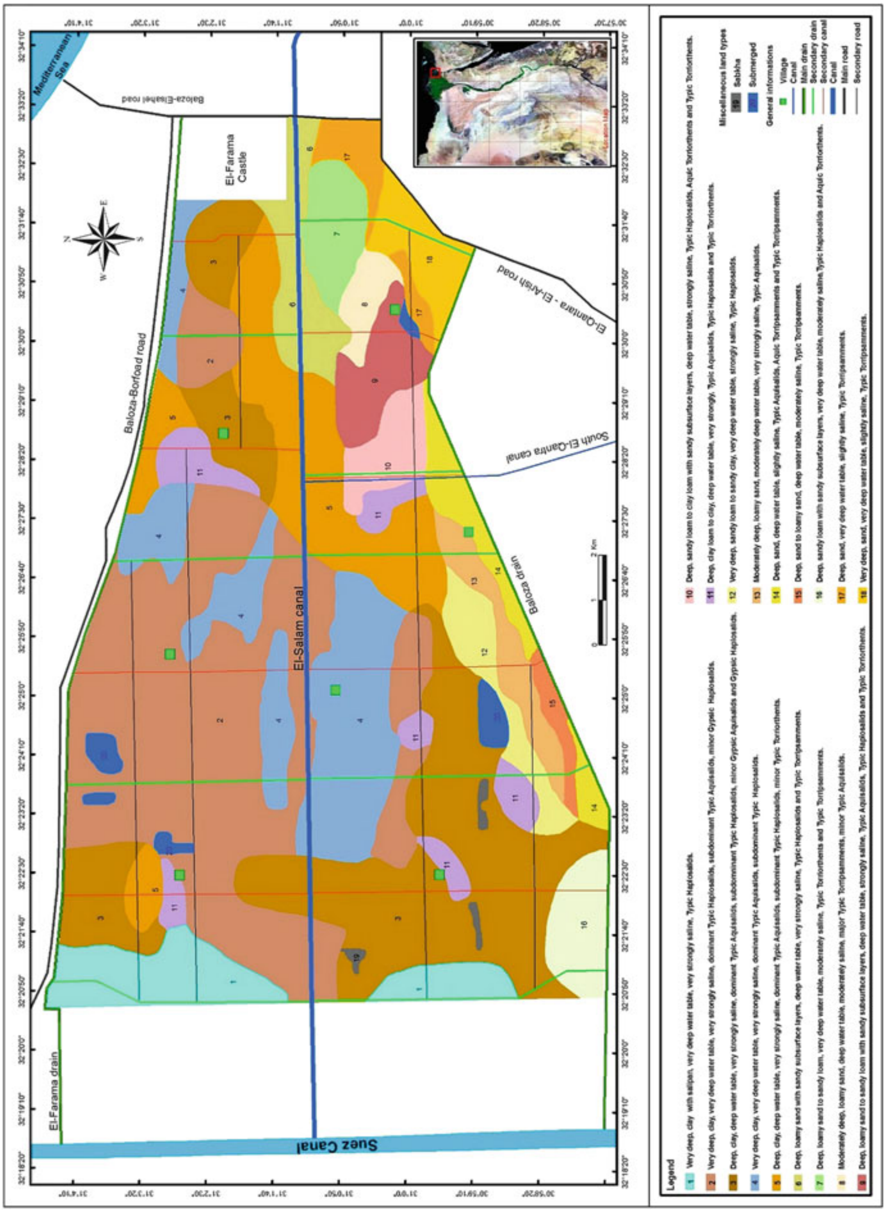

Fig. 17 Soil map of El-Tina plain [51]

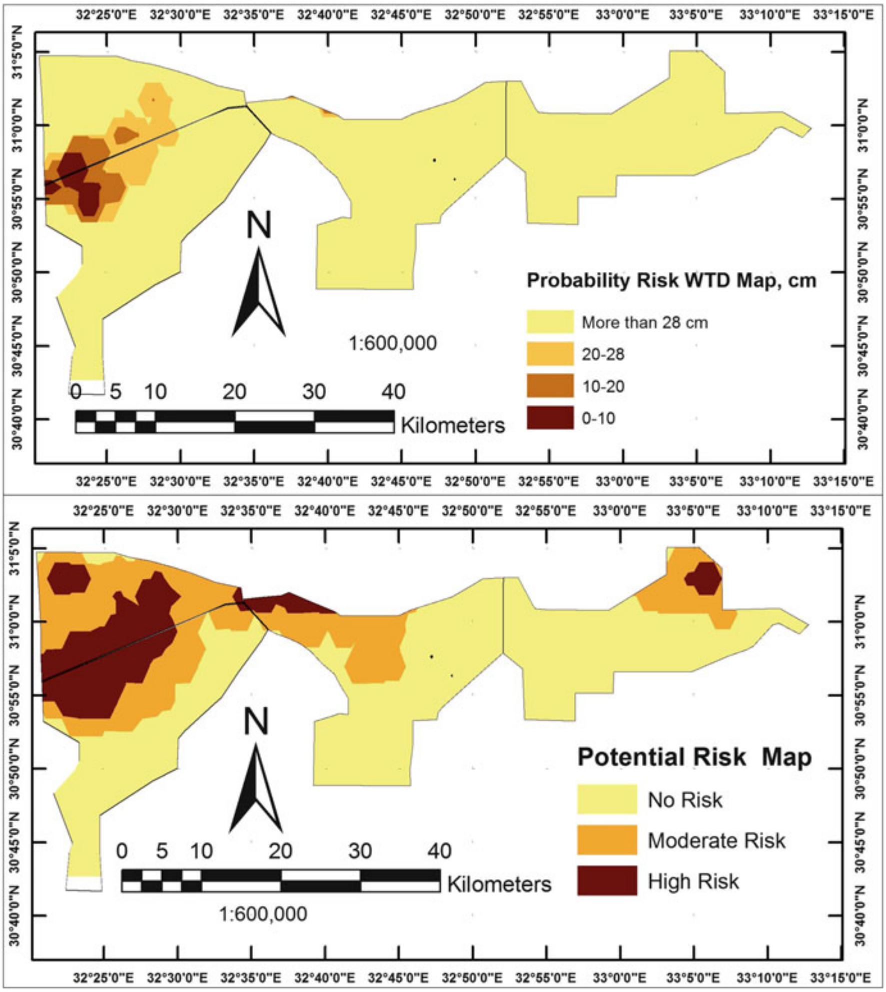

Fig. 18 Expected risk map that at April 1st (*upper*) in a future year, WTD will be shallower than 50 cm, and areas with risk of WTDs deeper than 50 cm on October 1st (*lower*). Three small susceptible areas were detected with potential risk of shallow WTDs at April 1st and four areas were detected on October 1st

Omran [6] developed a potential risk map for water table depth (WTD) in North Sinai using an early warning technique incorporated in GIS, simulation model, and stochastic methods (Fig. 18). A stochastic model is useful for estimations of WTDs because uncertainties can be quantified. Utilizing a time series model is conceivable to simulate over periods that do not have observations, as long as data on explanatory series are available. The uncertainty about the true WTD can be perceived in stochastic methods by creating large numbers of possible realizations utilizing simulations. The results indicate that on the chosen date, April 1, 2016, there is a negligible risk of shallow WTDs that could influence agriculture. The maximum prediction of WTD level in the

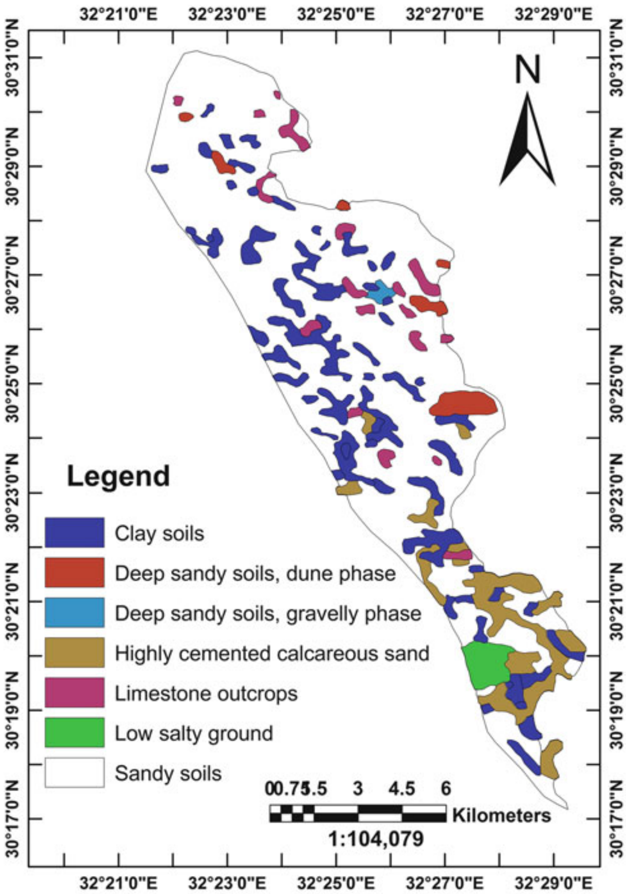

Fig. 19 East Bitter Lakes soils

following 20 years will increase from 145 cm depth to 100 cm depth. However, the minimum future WTD level will increase from 60 cm depth to 30 cm depth. This implies the future high water level will be about 0.30–0.45 m higher than the present level.

Soils of East Bitter Lakes

Soils of East Bitter Lakes (Fig. 19) were studied [52–55]. The area is relatively flat to undulating, and the elevation increases toward the east. Many depressions are located at low elevations and at water table at less than 2 m from the soil surface. The soils were found to vary greatly with respect to the sequence of layers and intrinsic properties of each layer. The main soil groups are the deep sandy soils, the clay soils, and the miscellaneous land types. Analysis indicated the presence of alkalinity and high-salinity conditions. Permeability and infiltration tests produced high values for sandy soils, while clay soils were impermeable. X-ray analysis revealed the presence of clay type "hectorite," which is a magnesium-rich member of montmorillonite. Regarding the classification for land use, the soil could meet the criteria given for class 4, with priority given for sandy soils. Miscellaneous land types are class 5, which includes the nonagricultural land. Most of the soils are sandy soils except some clay soils present as patches in between sandy terrain. Soils mostly have a high salt content, very low $CaCO_3$, high gypsum, and very low organic matter. Many severe soil limitations such as pan layers at various depths, salinity, wet depressions, sand dunes, and rocky outcrops exist [55]. Large areas of cultivated land are degraded and became unsuitable for agriculture because of the occurrence of the pan layers (claypan, gypsipan, and calcipan). Induration and hardness of pan layers could limit the chances for agricultural use. Their presence leads to the formation of shallow water table, poor drainage, and high salinity.

4.2.2 South Sinai Soils

Soils of South Sinai consist of three areas: Suez basin, El-Qaa Plain, and Feiran basin.

Soils of Suez Basin

Soils of Suez basin (Wadi Sidri, Wadi Wardan, Wadi Sudr, Wadi Kahali, and Wadi El-Hage) have sand, sandy loam, and loamy sand textures. $CaCO_3$ content ranged from 13.77 to 65.61% without any specific pattern with depth throughout the soil profiles at Kahali and El-Hage wadis. Organic matter content did not exceed 0.52%. The soils are neutral to moderately alkaline as pH values varied between 7.3 and 8.3. The soils are non-saline to extremely saline, and salinity increases with depth. Gypsum content ranged from 0.06 to 38.17%. Sudr outwash plain has many cultivated areas in patches particularly in the Delta of the Wadi, which is being irrigated from the present wells. Soils of Wadi Sudr are variable according to the sites in the main channel or the Delta. These soils are considered poor agricultural lands. Sudr-Abu-Rudies area is located east of the Gulf of Suez and extends along the coastal plain from Sudr at the north to Abu-Rudies at the south [40]. Sandy soils occupy the coastal plain from Abu Zenima at the north to Abu-Rudies at the south, while sandy peneplain with igneous and metamorphic mountain is located westward. This sandy soil was derived from the igneous and metamorphic rocks through wadis: Wadi Wither, Wadi Sidri, Wadi Naga, Wadi Babda, Wadi Dafori, Wadi Beida, Wadi Mattuia, Wadi Daft, and others. Soil salinity is low and $CaCO_3$ is very low. Under good soil-water management, these soils could be suitable for cultivation. Stoney sandy carbonatic soils are common within the area between Wadi Lahata and Wadi Kahali on the east of slopes of El-Tih plateau and hilly landscape. Loamy alluvium deposits are found in few areas mainly at Ras Malab (outlet of Wadi Gharandal) and Abu-Suwaira (outlet of Wadi Wardan).

Gobran and Osman [56] investigated the soils of the main wadis, i.e., Wadi El-Murr, Wadi Wardan, and Wadi Gharandal in south of Sinai. These wadis are situated between latitudes 27°35′ and 305°06′ N and longitudes 32°15′ and 35°6′ E. The parent material of the soils belonging to sedimentary deposits and soil surface is covered with little gravel and stones. Generally, soils have gravelly sand to sandy clay loam texture in surface layers and sometimes become finer in deeper layers. The profiles of Wadi Gharandal have the lowest ratings, indicating slight horizontation or differences between the horizons compared with the profiles representing Wadis El-Murr and Wardan. This indicates that the soils of Wadi Gharandal are lower in pedological development than other studied soils in other wadis. The ratios of resistant minerals have different values in most profiles representing studied soils in these wadis [57]. The differences are relatively clear between the layers of the same profiles, which indicate the stratification of these profiles. The majority-studied profiles are considered young from the pedological point of view. The high resistance of quartz to weathering and the presence of feldspars could be taken as indication of weathering during soil formation and evolution, which were not drastic enough to cause a complete decay of feldspars. In addition, the soils located in Wadi Gharandal and some soils located in other wadis are relatively weathered based on the distribution of resistant minerals and weathering ratios. The relative dominance of both weatherable and ultra-stable minerals compared with opaque minerals in the soils of the studied wadis can be considered an indication of the occurrence of active physical weathering for soil sediments. In addition, some transformation of iron minerals and the immature conditions prevail in the studied soils.

Soils of Feiran Basin

Sediments of Quaternary age are preserved in lowland settings as wadi floor alluvium; as terrace remnants of older, higher wadi floors; as alluvial fans variably dissected to suggest terraces; as colluvial spreads; and as badland terrain developed in the Pleistocene beds. Under present conditions, wadi floors are awash with aperiodic floods. In higher order wadis, such as the Wadi El-Sheikh, catastrophic discharge is sufficiently competent to transport small boulders. Prehistoric artifacts occasionally were found on the surface of wadi alluvium. Since these are active channels, none was in primary sedimentary contexts, and cultural material buried in these sediments should be expected to be derived. Wadi Feiran is considered as the main important valley in southern Sinai, where it stems from mountainous areas and flows into the Gulf of Suez. The upper part of the valley has three main tributaries: Wadi Solaf, Wadi El-Sheikh, and Wadi El-Akhadar. Most of Wadi El-Sheikh, Wadi El-Akhadar, St Catherine, Wadi El-Raha, and Nuweiba-Dahab are initially of tectonic origin modified later by the drainage courses, which lead to either Gulf of Aqaba or Gulf of Suez.

Erosion and sedimentation cycles appear to be strongly affected by the grading of stream beds according to the level of the Red Sea during Pleistocene times. Although the area is now experiencing a severe arid cycle, heavy rainstorms occur once or twice every year in winter and are responsible for bringing rock debris and weathering products from the mountain slopes to be deposited along the wadi bottoms (Fig. 20). These sediments are hardly affected by pedogenic processes. Soils of Wadi Feiran (Wadi El-sheikh, Wadi El-Tarfa, El-Watti Pass, Wadi

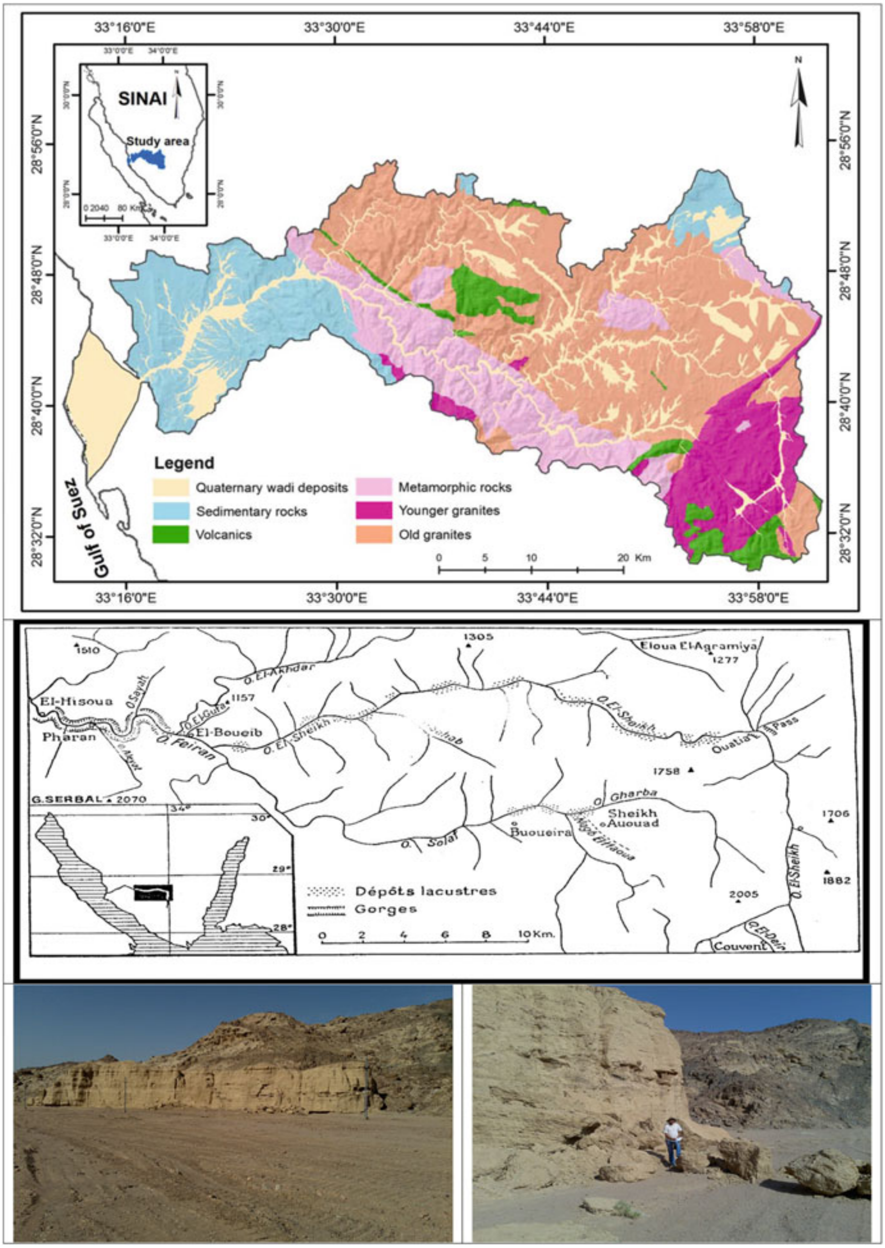

Fig. 20 Simplified geologic map of the Wadi Feiran Basin (*upper*) [60]. A map showing the locations of the sediment basin (*middle*), and field photo of lacustrine deposits (*lower*)

El-Akhadar, and other wadis) are formed because of water action, and their materials are mainly poorly sorted. Soils are formed then, with minor and negligible symptoms of horizon differentiation. Soils of Wadi Feiran are mostly sandy to skeletal sands with many boulder and cobble in the main channel of the wadi, except some loamy soils on the remnants of some terraces on both sides of the wadi. These soils are characterized by very low content of salts and calcium carbonate. Soils of Wadi El-Sheikh are similar to the soils of Feiran except of the absence of stones on the soil surface. The soils are mainly poor on agricultural land. Rocks are regarded as weathered under conditions leading to the physical breakdown of various rock fragments. Transformations of primary minerals into secondary minerals are highly predictable most probably at the rock surfaces before and during breaking down of rock bodies.

Lacustrine deposits are scattered in different locations in the Wadi Feiran, Wadi Solaf, Wadi El-Sheikh, Wadi El-Akhadar, Wadi Sahab, Wadi El-Tarfa, and Wattia Pass at levels ranging between 600 and 1,250 m, with a thickness ranging between 3 and 30 m (Fig. 20). These deposits are made of sand with moderate amounts of silt and small amounts of clay and calcium carbonate and with a few gravel and rocks. The main drainage channels of wadis Feiran and El-Sheikh are filled with a series of yellowish silts and clays interbedded with minor sands and gravels. The mineral composition of the clay and sand for these sediments using X-ray and polarized microscope shows that the montmorillonite is the dominant clay minerals and is accompanied by smaller amounts of kaolinite and illite and very small amounts of chlorite and vermiculite. While the sand fraction prevails by mica and hornblende as heavy minerals, quartz and feldspars are prevailing light minerals [58].

For the formation method of these Lacustrine deposits, Issar and Eckstein [59] believe that these deposits were formed as a result of new Dykes, which have worked as barriers to water, leading to the formation of freshwater lakes, as well as barriers to the flow of groundwater, thus recharging the reservoir of Feiran Oasis. However, Reda [58] rejects this theory, where these Lacustrine deposits were formed under swampy conditions rather than separate lakes during rainy times, because the new local Dykes existed before Wadi Feiran formation, and therefore the valley and its branches have made their small wadis and canals unimpeded. In addition, the new dykes are unequivocally relatively less resistant from local rocks. There is another suggestion: El-Sherbini [61] considered the Glacial Periods as mainly responsible for the formation of lakes and sand and gravel were moved by the output water of the ice that have worked as barriers for water, which closed valley branches. The area of South Sinai is exposed to heavy floods through some valleys, especially the active ones like Wadi Feiran, Wadi Dahab, Wadi Watir, Wadi Gharandal, and Wadi Suder, which are considered hazardous and most risky areas and most vulnerable to floods, causing agricultural and infrastructure projects to be destroyed and sometimes extending damage to human life. Many cultivated areas are scattered at different sites especially at Feiran Oasis, Wadi El-Tarfa, Wadi El-Sheikh, and Wadi El-Sahab. Well water is the main source for irrigation.

Soils of El-Qaa Plain

El-Qaa Plain is an extensive longitudinal plain occupying a stretch of land trending NW–SE between latitudes 27°45′ and 28°45′ N and longitudes 33°15′ and 34°15′ E with a total area of about 1742.6 km^2. Soils of El-Qaa Plain (Wadi Mahash, Wadi Isla, El-Qaa Plain, and Wadi Feiran) are ranked as high-priority development areas in South Sinai. Soil texture is varied from sand to sandy loam. Total carbonate content ranges between 6.1 and 35.69% with an irregular distribution pattern with depth. Organic matter did not exceed 0.29% in the different layers of the soil profiles. Soluble salts indicate that soils were saline to extremely non-saline where electric conductivity (EC) ranged between 0.9 and 36.4 dS/m. The highest value was found in soils of Wadi Feiran, while the lowest value was detected in the soils of Wadi Mahash. Soil is neutral to alkaline (pH 7.0–8.7). Gypsum content varied between 0.05 and 16.0% with an irregular distribution pattern with depth.

Morphological analysis of the soils of El-Qaa Plain revealed that these soils are highly calcareous and coarse textured. The soil layers are mostly due to the sedimentation regime. All layers of these soils contain carbonate nodules. The increase of carbonates is caused by local enrichment of secondary carbonate nodules. This feature, however, does not implicitly mean considerable leaching of carbonates downward. The dissemination of lime nodules in almost all horizons would suggest the syngeneic formation (calcic and salic horizons). Since there is no extensive weathering or translocation after deposition, statistical analysis proved that these soils are of alluvial origin as they are generally poorly sorted. The obtained results indicated an alluvial origin at least from the northern part of El-Qaa Plain where several wadis descending from both eastern and western hills are depositing their loads in the plain. In the El-Qaa Plain, it appears that wind action has minimum effect probably because of the coarse nature of sediments. The characteristics of the parent materials of the area based on skewness are in general similar although the kurtosis ranges are not always the same. It is quite apparent that these soils especially at northern parts of El-Qaa Plain are derived from several common rocks of different igneous, metamorphic, and sedimentary origin. Primary, secondary, and accessory minerals are present frequently in most of the soils and could account for the origin of these soils, which is known to be alluvial. At both sides of the plain in northern extremities, wadis draining the country hills are cutting through the three types of the major common rocks [62].

Shereif [63] investigates the soils of the El-Qaa plain area using remote sensing: unsupervised classifications of ETM images. Image analysis and fieldwork show that the soils, especially in northern part of El-Qaa plain, are derived from several common rocks (igneous, metamorphic, and sedimentary). However, in northern extremities of the plain in the area of country hills, wadis are cutting through the three types of major common rocks. They identified six kinds of soils (Fig. 21, left):

1. Rocky surfaces. Soils of this unit are classified as lithic leptosols.

   Inter-ridge sand flats. Depth of soils is ≤50 cm, soil texture class is coarse sand, saturation percentage of these soils ranges between 21 and 22, pH values tend to

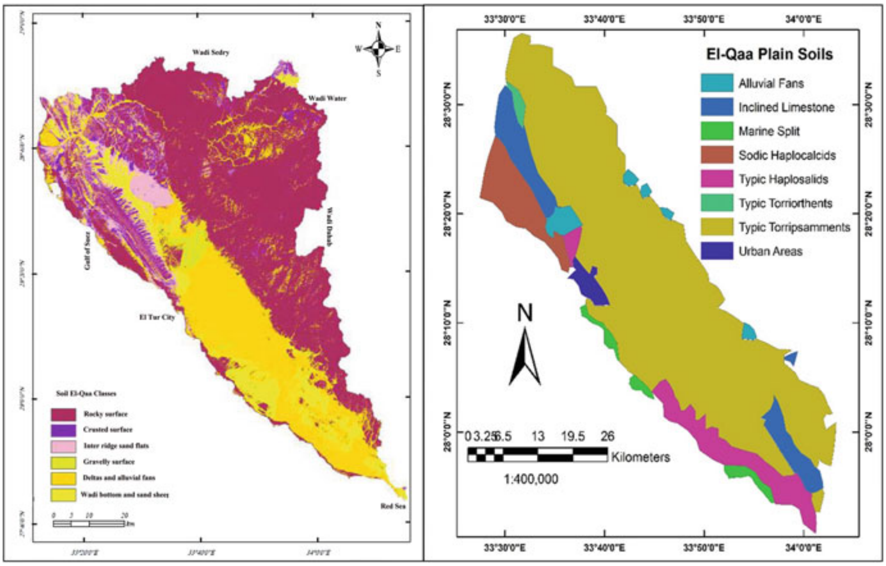

Fig. 21 Soil maps of the El-Qaa plain using remote sensing (*left*) and using analysis of 26 soil profiles (*right*)

be slightly alkaline (8.0–8.4), EC values range between 2.5 and 5.0 dS/m, and $CaCO_3$ content ranges between 7.7 and 8.7%. Lithic contact at 50 cm defines the depth of this soil profile. Soils of this unit are classified as *Lithic Torripsamments*.

2. Crusty and gravelly surface. Gypsum and/or carbonate crust covering more than 60% of the area. It is distributed mostly in the northeast of the area (Qabilyat mountain area), in the northwest of El-Qaa plain, and in the lower part of Wadi Feiran basin.
3. Gravelly surface. These deposits were found at the wadi mouth and mostly coarser than the other deposits that built up fans. Soils of this unit are classified as *Typic Torripsamments*.
4. Deltas and alluvial fans. Soils of this unit are classified as *Typic Torripsamment*. Consecutive series of alluvial fans are forming a foot plain along the edge of a linear mountain range.
5. Wadi bottom and sand sheet. The wadi bottom is covered mostly by sandy and silty sediments. Soils of this unit are classified as *Typic Haplocalcids*.

Land resources of El-Qaa Plain were studied using a database of 26 soil profiles [64]. Soils of El-Qaa Plain area (Fig. 21, right) include sand sheet (low, moderate, and high) classified as *Typic Torripsamments* and *Typic Haplosalids*, bajada classified as *Typic Torripsamments* and *Sodic Haplocalcids*, wadis classified as *Typic Torripsamments* and *Sodic Haplocalcids*, basin classified as *Typic Torriorthents*, dry sabkhas classified as *Typic Aquisalids*, and wet sabkhas classified as *Sodic Psammaquents*.

4.2.3 Land Resources: Priority Areas for Sinai Development

For major portions of Sinai, information on land characteristics and soils was limited. Remote sensing (RS) can provide valuable and timely information about natural resources and environment as an important basis for sustainable development. Geographic information system (GIS) can provide effective tools for decision-makers. Based on an assessment of resource potentials, the areas most suitable for various land uses are identified (Fig. 22). In terms of agricultural suitability, major limitations to the development of an area include such constraints as local relief in excess of 150 m, slopes in excess of 8%, shallow rock and thin soils, stony residuum, sand dune movement, saline soils, and severe erosion and gullying. These constraints, either individually or in combination, could be potential limiting factors in determining a particular area's suitability for agricultural development. The assessment of suitable agricultural lands must be combined with an evaluation of water availability. The availability of water is generally the most limiting factor to be taken into consideration when planning development in Sinai. Areas with the most potential for development will be identified by matching the quantity, quality, and data shown on the groundwater potential map with the land resources map.

All of the good agricultural lands (Fig. 22), those having 0–8% slopes, 0–50 m of local relief, and a deep soil cover, are located in northern and central Sinai. There is suitable agricultural land located along the wadi channels. The main areas are along Wadi El-Bruk, extending from Gabal El-Kaib north to Bir El-Thamada and then east to the confluence of Wadi E1-Arish near Gabal Kherim including the Wadi E1-Arish main channel and its tributary. Wadi El-Aqabah is also a good agricultural area but a smaller and narrower one than Wadi El-Bruk. The Wadi El-Arish agricultural area extends from the confluence of Wadi Abu Gidi north to Wadi El-Bruk. The Wadi El-Aqabah branch extends south along the wadi channel to the confluence with Wadi El-Misheiti. There is also good agricultural land from the confluence of Wadi El-Bruk north to the El-Mitmetni Gorge. Feeding into this area from the east is a large area formed by the flood plain of Wadi Geraia. From the El-Mitmetni Gorge, a narrow belt of good agricultural land runs north along Wadi El-Arish to the confluence of Wadi Gayifa. This narrow strip of good land also runs eastward up Wadi Gayifa to near Ain Qedees. The other major region of good agricultural land in North Sinai includes the El-Qawarir area east of Gabal Maghara and Wadi El-Hamma, which drains the lowlands between Gabal Maghara and Gabal Yelleq. It is restricted on its eastern side by Gabal Libni. An additional area of good agricultural land runs along Wadi El-Arish from the town of El-Arish south to El-Mitmetni Gorge.

Fair agricultural areas (Fig. 22) are usually more dissected than good areas and have a slightly stonier surface. Areas are designated as fair tends to extend upstream along the wadi channels from the good areas. They may also form narrow belts along the outwash plains of the mountains. There are several significant areas of fair agricultural land in Sinai. On the western, northern, and southern sides of Wadi El-Bruk, between the wadi and the mountains, there is an irregular, narrow band of fair agricultural land. This band broadens and becomes quite extensive in the

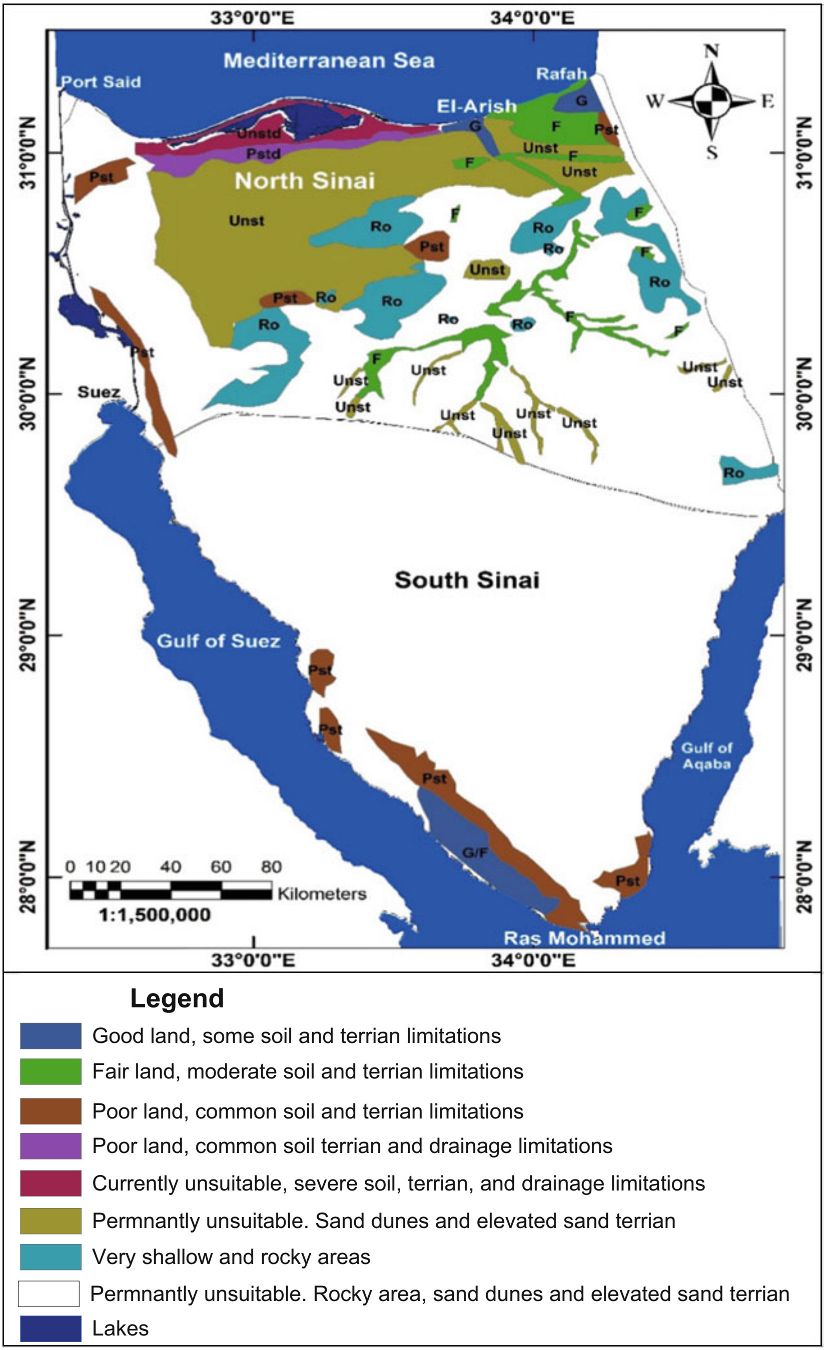

Fig. 22 Land resources priority areas in Sinai

Harabet Es Saheimi area. A large area of fair agricultural land lies around the base of Gabal Libni. It occupies most of the area between Gabal Libni and the El-Ser areas. It also extends to the west over much of the Wadi E1-Hamma flood plain. Along the northeastern coast between the town of El-Arish and the border, extending inland about 10 km is a small strip of fair agricultural land. This strip coincides roughly with the Mediterranean coastal aquifer. On the eastern side of Sinai, a narrow strip of fair agricultural land lies along the flood plains of Wadis Gerafi and Khadakhio near El-Kuntilla. Another large area of fair agricultural land in North Sinai is a 5–20 km strip that trends north–south along the Great Bitter Lake area. In South Sinai, the largest area of fair agricultural land lies in the El-Qaa Plain. This area runs north–south, encompassing most of the central stretch of the E1-Qaa plain. At its broadest point around El-Tor, it widens to about 10–15 km. Two further areas of fair agricultural land are found at Abu Rudeis and Belayim. These areas occupy alluvial fans developed by Wadis Baba and Feiran, respectively. Long narrow strips of fair agricultural land are located in most of the major wide wadis of South Sinai.

There are several extensive areas of poor agricultural land (Fig. 22) in Sinai. These areas generally occupy the colluvial deposits upslope from the fair agricultural land. One of the most extensive areas of this class practically surrounds Gabal Yelleq, except on the east where it is bounded by the flood plains and good agricultural land of Wadi El-Arish. This area covers the El-Nehaidein area between Gabal Maghara and Yelleq and extends westward to Bir Gifgafa and then south along Wadi E1-Hegayib to Bir E1-Thamada. It occupies a narrow east–west strip on the upper alluvial slopes of Gabal Yelleq. Another large and extensive area of poor agricultural land has formed in the headwater drainage basin of Wadi Geraia. This area occupies the entire region between Gabal Arif El-Naga (Shaira and El-Gunna) and the confluence of Wadi El-Baluhi and Wadi Geraia. A slim (5 km wide) 40 km-long strip of poor agricultural land is located along the Little Bitter Lake and the Gulf of Suez to about Ras Misalla. In South Sinai, the eastern flank of the El-Qaa Plain is occupied by a strip of poor agricultural land that broadens in the extreme south pinching out the fair agricultural land near Ras El-Millan. Other areas of poor agricultural land in South Sinai are along the alluvial fans bordering the Gulf of Aqabah.

By far the vast majority of Sinai's terrain is categorized as unsuitable for agricultural purposes (Fig. 22). This land has been evaluated as being unable to support any agriculture on an economic basis. Much of the land classified as unsuitable contains either no soil or a very thin veneer of soil.

5 Conclusions

The Sinai Peninsula is characterized by the occurrence of six deep aquifers. Due to the limited extension of the Miocene aquifer, low productivity, and poor groundwater quality of the Eocene/UC aquifer, the LC sandstone is considered the most important aquifer in Sinai with the highest potential quantity and quality of groundwater. Potential areas for development of the LC groundwater in Sinai were identified based on the aquifer hydrogeological characteristics and groundwater quality. The iso-salinity contour map of the LC aquifer shows a general increase of groundwater salinity toward the west and the north, with five salinity zones recognized as follows:

Zone I has groundwater salinity $<$1,500 ppm. It occupies the area of the aquifer located south of the main road joining Sudr El-Heitan, Nakhl, and Ras El-Naqb within this zone.

Zone II occurs to the east of the line joining Sudr El-Heitan, Nakhl, El-Bruk, El-Menashereh, El-Hassana, and El-Quseima, where the aquifer salinity ranged between 1,500 and 2,000 ppm within this zone and near the folded structures at El-Bruk, Gabal El-Menashereh, and Gabal Arif El-Naga. Salinity appears to be high due to the possible groundwater stagnancy around these highly elevated structures allowing for more dissolution of salts.

Zone III is characterized by salinities ranging between 2,000 and 5,000 ppm. It occupies a narrow zone surrounding Zone I and extends to Ayun Musa area in the west and Gifgafa north of Gabal El-Halal in the north.

Zone IV occurs to the north of Zone III and has salinities in the LC aquifer ranging between 5,000 and 10,000 ppm.

Zone V occupies the northern and western parts of Sinai where the LC aquifer has been deeply buried by faulting. The rather high salinity values in this zone (14,000 ppm at well no. 2024, 19,000 ppm at well no. 2023) may be due to the ineffective flushing of the formation's saline water by the recharging meteoric water due to the interruption of the groundwater flow paths by block faulting.

For major portions of Sinai, however, information on land and soil resources was limited. Generally, Sinai soils lack pedagogical features indicating the soil development, under arid condition. El-Tina plain is clay flat consisting of fluvio-lacustrine deposits of loamy and clayey texture. Flat sandy terrain is formed of Aeolian sand deposits and is very gently undulating. The soils are non-saline and deep sandy textured, and water table is moderately shallow. Undulating sandy terrain are susceptible to wind erosion. The water table is expected to be very deep, and the drainage is excessive. The soils of the Wadi El-Arish bed have been formed of calcareous fluviomarine deposits and are loamy texture with moderate drainage. Calcareous sandy terraces are located between Rafah and El-Sheik Zuweid. The soils are fine sand or loamy sand in texture and have moderately deep water table. Factors restricting land reclamation are lowland sabkhas and mobile sand dunes. All of the good agricultural lands, those having 0–8% slopes, 0–50 m of local relief, and a deep soil cover, are located in northern and central Sinai. The good agricultural land is located along the wadi channels. The main areas are along Wadi El-Bruk, extending from Gabal El-Kaib north to Bir El-Thamada and then east to the confluence of Wadi E1-Arish near Gabal Kherim and the Wadi El-Arish main channel and its tributary. Wadi El-Aqabah also forms a good agricultural area but a smaller and narrower one than the Wadi El-Bruk area. The Wadi El-Arish agricultural area extends from the confluence of Wadi Abu Gidi north to Wadi El-Bruk. There are several significant areas of fair agricultural land in

Sinai. On the western, northern, and southern sides of Wadi El-Bruk, between the wadi and the mountains, there is an irregular, narrow band of fair agricultural land. A large area of fair agricultural land lies around the base of Gabal Libni. Another large area of fair agricultural land in North Sinai is a 5–20 km strip that trends north–south along the Great Bitter Lake area. In South Sinai, the largest area of fair agricultural land lies in the El-Qaa Plain. Two additional areas of fair agricultural land are found at Abu Rudeis and Belayim. These areas occupy alluvial fans developed by Wadis Baba and Feiran, respectively. Long narrow strips of fair agricultural land are located in most of the major wide wadis of South Sinai.

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Part IV
Food insecurity due to Water Shortage and Climate Change

Impact of Climate Change on the Agricultural Sector in Egypt

M.A. Mahmoud

Abstract The complex interrelationship between environmental change and agricultural production will become one of the most significant policy debates, in both developed and developing countries particularly in the coming decades of the twenty-first century. Global and regional climate changes will modify both agricultural production capacity and locations of production. Also, the increasing intensity of agricultural production will contribute to environmental change at both the regional and global scale. Agricultural production in Egypt depends on irrigation, using surface water coming from the River Nile. Groundwater also contributes with very low amounts. Generally, the agricultural sector is considered the largest consumer of water (80% from total water budgets).

Climate change can have several kinds of impacts on the agricultural sector and stability of food security in Egypt. Crop production will be affected negatively due to the expected increases in temperature, extreme weather events, drought, plant diseases, and pests. Also, the land use will change due to flooding from sea level raising, seawater intrusion, and secondary salinization. Water resources may be affected due to global warming and decreases in precipitation. Moreover, crop water requirements are expected to increase. The confounding effect of all these components represents the main challenge for researchers.

The current infrastructure and cropping systems have to be changed to comply with future demands with regard to the growing population and the threat of climate change. The negative impacts of climate change on agricultural crops can be reduced by the implementation of integrated farm-level adaptation strategies, for instance, changes in the date of planting, cultivars, use of extra fertilization, and changing irrigation intervals. The author will present in this chapter the impact of

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climate change on agriculture in Egypt and some adaptation strategies to reduce these impacts.

Keywords Adaptation, Agriculture, Climate change, Egypt, Greenhouse gases

Contents

1 Introduction

Globally, food demand is expected to increase two- to fivefold from 1990 to 2030; however, agricultural land dedicated to crop production is shrinking due to population growth, urbanization, and soil degradation [1]. Climate change will increase food security problems facing many countries [2]. Direct negative impacts on food security are related to changes in water availability, soil characteristics, and crop productivity. Adverse impacts on soil quality may occur as a result of the depletion of soil organic matter, the decrease in soil fertility, the decline in available water capacity, and degradation in soil structure, crusting, erosion, and salinization. Water resources could be impacted through alterations in the hydrological balance (runoff and evaporation), and high soil erosion may exacerbate nonpoint source pollution. There are numerous indirect impacts of climate change such as a change in farming/cropping systems. For example, the land currently suited for paddy rice in northwestern India may be converted to corn, cotton, soybean, vegetables, or aerobic rice similarly, and corn in the savannah region of Africa may change to sorghum [3].

Climate change impacts on the agricultural sector include production (in terms of quantity and quality), species types, environment, and land use changes. The integration of all these confounding components represents the main challenge for researchers [4]. Africa is likely to be highly impacted by these adverse direct effects due to their high agricultural dependency, and limited capacity to adapt [5]. Egypt is also vulnerable to climate change because of its large traditional agricultural practices, and the limited source of water from the Nile River as the main water source. Also, the coastline of the Nile is already suffering from erosion and intensifying development [6, 7]. Climate change may affect agricultural production in Egypt especially the Nile Delta region. This region is characterized as one of the mostly vulnerable regions in the world to climate change in particularly soil and water degradation, sea level rise, undiversified crop patterns, pests and disease severity, yield reduction, irrigation, and drainage management.

Agriculture plays a vital role in Egypt's economy contributing roughly 15% of the Gross Domestic Product (GDP) and employing about 30% of the national workforce. Smallholder farmers represent the majority of Egypt's farming sector [8]. Thus, adaptation strategies to climate change are vital for sustainable agriculture and food security in Egypt.

2 The Impact of Global Warming on the Agricultural Sector in Egypt

2.1 Increase Evapotranspiration and Crops Water Requirements

Increased evaporation due to warmer temperatures anticipated with climate change will increase potential evapotranspiration [9]. Climate change will affect crops production indirectly by increasing crops water requirements. Climate change could increase summer crops water requirements 16%; on the other hand, decreases winter crops requirements 2% by the year 2050 [10]. By 2100, water requirements for strategic crops in Egypt are expected to increase by 5–13% [11, 12]. The gross irrigation requirements may increase by 4–18% in all Mediterranean zones due to climate change only [13]. By 2030, water requirements for rice, soybean, tomato, cotton, corn, sunflower, sorghum, wheat, and sugarcane crops will increase 16%, 15%, 14%, 10%, 8%, 8%, 8%, 2.5%, and 2.5%, respectively. However, water requirements for barley crop will decrease 2% under climate change conditions compared with the current situation [14].

2.2 Reduction of Crops Yield

Climate change may cause earlier crops growth and a squeeze of growing season. These responses may help some crops like winter crops to escape summer drought stress, but at the same time an increase in the frequency of extreme weather events like heat waves and frost at sensitive phonological stages may cause bud breaks that will affect the final quality and quantity of the yield [15]. Increasing the number of days of extreme heat may cause large drops in crop yields, especially when they occur during vital stages of plant growth such as flowering and grain filling

[16]. Crops photosynthetic, multiplicative cells, plant growth, grain quality, and crop yields will be affected negatively by extreme heat [16–19].

Many studies were conducted to investigate the impact of climate change on crop production in Egypt; general consensus indicated that the productivity of most crops would be affected negatively. The projected decline in agricultural activities due to increased temperature ranges from 10 to 60% [20]. Higher temperatures due to anticipated climate change will directly affect yields of many crops causing a potential reduction of 10–30% for crop yields such as rice, wheat, barley, maize, soybeans, and sunflower [21, 22]. By 2050, if temperature rises by 2°C, the expected wheat yield will be decreased by 15% [23], rice production will be reduced by 11% [24, 25], maize yields will be reduced by 19% [25, 26], soybean yields will be decreased by 28% [24], and barley yield will be decreased by 20% [27]. Egyptian clover declines as fodder production would be an important challenge for farmers providing to livestock [12]. The predicted productivity of wheat, barley, corn, sorghum, rice, soybean, sunflower, and sugarcane will be decreased by 18%, 18%, 18%, 19%, 11%, 28%, 27%, and 25%, respectively, when temperature increases by 3.5°C. Tomato yield will decrease by 14% and 50% when the temperature rose by 1.5°C and 3.5°C, respectively [14]. However, cotton yield would be increased by 17% and 31% if the temperature increased by 2°C and 4°C, respectively [14, 26]. Cotton and potato yields are expected to be increased 15–40% particularly if it grew in the main seasons [21, 22]. Cotton yield is expected to increase from 15 to 17% in three main agroclimatological regions of Egypt [28].

In Egypt, the projected wheat yield was to be above the baseline of 1970–2000 in 2020 and 2050 by six and five emission scenarios, respectively. However, in 2080 wheat yield expected to be below the baseline level under all emission scenarios. Rice yield reduction was simulated from 2020 up to 2080. Maize yield is expected to decrease with climate change under all emission scenarios [29]. The productivity of wheat and maize will be declined 15–20%, respectively. Seawater intrusion is expected to reduce land productivity in the Nile Delta region. Declines in fish catches resulting from changes in the ecosystem in the northern lakes are also projected [28]. Wheat yield on rainfed areas in Egypt would be decreased by 50% if rainfall were decreased by 20% under the SRES B2 scenario. While, increasing rainfall by 20% will reflect an increase of wheat yield by less than 5% [30].

The direct impacts of climate change that are expected to cause a reduction of crop yields include storms, flooding, heavy rains, eroding soils, rising sea levels, salting soils, and higher ozone levels. In addition, increasing severe, frequent, longer-lasting heat waves, large-scale drought, changing river flows, and thriving plant diseases and pests will also have an impact.

2.3 Plant Disease and Pests

The expected temperature increases in Egypt may cause changes in agroclimatic zones with implications for diseases, pests, and crop suitability. There are many crop pests that can grow and survive in a wide range of higher CO_2 environments and warmer temperatures such as weevils and aphids. Ecological stresses may cause mutations in crop diseases which could potentially increase their volatility. The earlier onset of warm temperatures could result in an earlier threat from disease with the potential for more severe epidemics and increases in the number of fungicide applications needed for control [31].

3 Drought and Decrease Precipitation

The overall climate trend is a decrease in rainfall, and subsequently an increase in drought frequency and intensity [9]. This may impact the amount of water resources available for agriculture, reducing amounts available for irrigation [32]. However, in Egypt most studies showed that the expected change of climate "will not significantly affect water resources in the Nile River as higher evaporation from drier weather will be compensated by wetter East Africa," but water requirements of crops will be increased [22, 33, 34].

4 Sea Level Rising and Changing Land Use

The global average of sea level rise rate was around 1.8 mm/year from 1961 to 2003 and about 3.1 mm/year from 1993 to 2003 [35]. It is unclear if the increased rate observed between 1993 and 2003 will reflect in increases in the underlying long-term trend. By 2100, if the mean global temperature increases by 2°C, the mean global sea level will increase to 0.49 m above the present levels. If the mean global temperature increases 4°C, the mean global sea level will increase by 0.71 m above the present levels [36].The Intergovernmental Panel for Climate Change (IPCC) estimated that the mean increase of global seawater levels was between 10 and 20 cm during the last century. It is expected that during the twenty-first century sea levels will rise by 11–88 cm [37, 38].

Rising sea levels will cause the submergence of many parts of the coastal area. With progressively severe, frequent storms and wave demolition, the shoreline retreat will be accelerated. In addition, it is expected that there will be disastrous flooding events caused by high tides, heavy flooding, and windstorms in combination with higher seas [39]. Large parts of the coastal areas of the Nile Delta in Egypt might be flooded by seawater and the coastline might change to land for several kilometers in the western and eastern borders of the delta [40]. Particularly vulnerable areas include Alexandria, Port Said, Damietta, and Beheira governorates. Over this century, if sea level rises from 0.5 to 1.0 m and no action is taken, an area of about 30% of the Alexandria will be lost due to flooding [41]. Alexandria is the second largest city in Egypt, it is revealing a land subsidence of about 2 mm/year, and it is highly vulnerable to erosion and flooding because 35% of the land area is below mean sea level [42]. Increasing sea level by 1 m, an estimated area of about 68% of its land could be inundated [43]. If sea level rises by half a meter, the loss of the agricultural land would be more than 1,800 km^2, affecting about 3.8 million people [44]. A 0.5 m rise in sea level would cause a loss of 19%, and 32% for a 1 m rise, of the total area of the Nile Delta. Although about 33% of the groundwater resources will be lost when sea level rises by 1.0 m, the available volume of the freshwater will be decreased by about 15% assuming that the current pumping rates will be maintained [45]. About 12–15% of the high-quality agricultural land area in the Nile Delta region will be lost as a result of sinking or salinization with a rise of sea level by about 0.5 m [14]. But, if it is increased by 1 m, more than 6 million of people would need to leave their land [46].

Rising sea level is expected to damage weak parts of the sand belts, that are vital for the protection of reclaimed lowlands and lakes. It will affect water quality, freshwater fish, salinization of groundwater resources, and flood valuable agricultural land [47]. It may cause damage to the best productive agricultural lands along the Mediterranean coast with consequences on fish production since 33% of Egypt's fish catches are from Mediterranean lagoons [22, 48].

Rising sea level will have the highest impacts on groundwater resources in coastal aquifers. First, the shoreline will become more exposed and become land (depending on the topography of the area); this movement may be significantly affected by the groundwater in the affected zone. Second, seawater level rising would cause extra pressure at the seaside and hence the seawater would move more inland. Third, decreased precipitation may affect the natural groundwater replenishment [45].

5 Seawater Intrusion and Secondary Salinization

Seawater intrusion means the movement of saltwater from the sea into coastal aquifers due to over pumping of groundwater and it is a dynamic equilibrium of groundwater movement [49]. It is a natural phenomenon that occurs in virtually all coastal aquifers connected to the sea as a consequence of the higher density of the seawater compared to the water in the aquifer. Seawater intrusion is considered one of the chief processes that reduces water quality by increasing salinity. This damage may occur due to human activities like overpumping from the aquifers and/or by natural events as sea level rise, seasonal changes in natural groundwater flow, barometric pressure changes, tidal effects, and seismic waves [50]. Because of the higher density of seawater, it moves inland into freshwater aquifers without any pumping actions [51].

Seawater intrusion is the main problem in coastal aquifers. Seawater intrusion in the Nile Delta aquifer has expanded inland more than 100 km from the Mediterranean coast [52, 53]. This may be due to the abstraction from wells that were initially in fresh groundwater may then become located in brackish water or saline water [54]. Intrusion might be affected by external factors such as irrigation and recharge practices, increase or decrease in groundwater pumping, land use practices, and possible rising in seawater [45]. The excessive and random pumping from the Nile Delta aquifer would quicken seawater intrusion [51, 55].

Increasing seawater level by 1 m as a global mean by 2100 would cause 0.37 m rising in seawater level at the Nile Delta [56]. An increase in sea level of 0.38 m would result in the movement of the shoreline to the current 0.75 m contour and loss a 5% of the Nile Delta agricultural land by 2060. Agricultural areas which are below 1 m are susceptible to seawater intrusion and salinization, and moreover require water management planning. Rising seawater level by 0.5 m in the Mediterranean Sea under steady-state conditions would cause the equitable concentration lines 35, 5, and 1 g/L to move inland by distances of 1.5, 4.5, and 9 km, respectively [57]. Sea level rise will move the saltwater interface further inland [54]. The continued rise in sea level increases the risk of coastal erosion and intrusion of saline water [58]. Such effects become more obvious in lowland, flat, and coastal alluvial plans where wide areas might be flooded with seawater due to seawater rise [55].

Seawater intrusion has a direct impact on soil salinity, the groundwater resources, quality in the coastal zone, and agricultural productivity [59]. A combination of increased salinity of the soil due to increased evaporation and seawater intrusion resulting from rising sea level is predicted to decrease the quality of shallow groundwater supplies in the coastal regions [60]. The expected increases of sea level by 1 m might cause the worst situation, in which the freshwater might be reduced to about 513 billion m^3 [53]. Rising seawater level has a significant effect on the location of the transition zone [51].

Seawater intrusion can be controlled by injection of freshwater, subsurface barriers, and saltwater extraction [50, 61]. Injection of freshwater by about 10% of the usage rate can successfully push the interface toward the shoreline and keep reducing salinity [61]. Javadi et al. [28] found that using artificial surface recharge that is based on a mixture of saline water near shoreline and recharge of aquifer using surface ponds has good results to control seawater intrusion. Decreasing the groundwater pumping by 50% would mostly sustain the freshwater resources when seawater level rises by 0.5 m [45].

6 Economic Impacts of Climate Change

Egypt is classified as the fifth in the world in relation to the impact of climate change on the total urban areas, GDP, and natural resources such as water resources, coastal zone, water quality, agricultural land, livestock, and fisheries. Also, Egypt may face environmental crises such as saltwater intrusion, shoreline erosion, and soil salinity issues [41]. The coastal areas of Egypt suffer from a number of serious problems, including rapid population growth, extreme erosion rates, land subsidence, water logging, salinization of the soil, lack of management systems, and land contamination and degradation are the main serious problems in coastal areas [62]. A sea level rise of 0.5 m could result in a loss of 8% of the urban area, 13% of the industrial area, 1.6% of the beach area, and other physical and socioeconomic losses in Port Said governorate, costing more than US $2.2 billion [62, 63]. A sea level increase of 1 m could reduce the Egyptian GDP by 6.44% due to the loss of 28,000 km^2 of agricultural land (>13% from all nation), 24,000 km^2 of wetland (>6% of total Egypt area), and 25,000 km^2 of urban area (>5% from total) [46]. A sea level increase of 0.25 m would devastate Alexandria which has 40% of Egyptian industry and drives Egypt's economy. When sea level increases by 0.25 m, 60% and 56.1% of Alexandria's population and Alexandria's industrial sector, respectively, would be below sea level. However, a sea level increase of 0.5 m would be more disastrous, placing 67% of the population, 65.9% of the industrial sector, and 75.9% of the service sector below sea level [25]. Alexandria is one of the most vulnerable cities in the world to the adverse impacts of climate change, such as rising sea level or losing parts of the Nile Delta, reflected in all social and economic damage [64, 65]. By 2030, floods and sea level rise of the Mediterranean may cause displacement of about 6 million citizens in the northern Nile Delta by the expected loss of the agricultural lands, which would lead millions of persons to migrate to new places. Rising sea level by 0.30 m, about 70.4 thousand jobs of the agricultural sector in North Delta would be lost. The Nile Delta is already subsiding about 3–5 mm/year, and rising of 1.0 m would flood about 25% of the Nile Delta, compelling about 10.5% of Egypt's population to leave their homes [20, 66]. The total agricultural output and food security in Egypt will be impacted due to climate change via loss of agricultural land, declining productivity of the agriculture workers, decreased yield of most crops, and labor shortages as a result of displacement [14].

The estimated impact of climate change on Egypt's GDP exceeds 6% for 1 m rise and 16% for 5 m [7]. "In turn, this will affect the management and access to archaeological sites, reduce tourism, and result in socio-economic impacts on the people who live in these parts" [60]. Climate change could cause a decline in fish catches in the Northern lakes and lagoons in Egypt, which would lead to fishermen seeking new occupations and the consequent decline in Egyptian GDP [60]. Egypt is spending US $300 million to construct concrete sea walls to defend beaches from seas level rising [41]. Seawater level rise by 0.5 m would cost more than $2 billion and eliminate over 33% of the jobs located in Rosetta as another city in the delta [25]. By 2060, the estimated decrease in agricultural production could reach 8–47% and also, the reduction in agriculture related jobs could reach up to 39%. The projected losses in agriculture could range from 40 to 234 billion Egyptian pounds (EGP) in 2060. The economic impact of sea level rising in the Nile River Delta could be 7–16 billion EGP. Increased heat stress and concentration of particular matter could result in about 2,000–5,000 more deaths/year, with an equal loss of 20–48 billion EGP/year. Climate change could cause loss of about 2–6% of future GDP. This loss may be due to their impacts on agriculture, water resources, coastal resources, and tourism. Moreover, thousands of people could die from heat stress and air pollution. Also, millions of people could lose their jobs in agriculture [20].

7 Effect of the Agricultural Sector on Climate Change

The atmospheric emissions of carbon (C) increased globally since 1970s. Some increase were due to soil cultivation and changing land use practices. Changing land use practices include burning biomass, deforestation, drainage of wetlands, conversion from natural to agricultural ecosystems, and soil organic content (SOC) depletion under cultivation. The depletion of soil C is accentuated by soil degradation and by soil mismanagement and land misuse [67]. Agriculture contributed in increasing greenhouse gas emissions through the draining of wetlands, ploughing of rangelands, and clearing of forests which had a significant role in increasing the atmospheric CO_2, as organic carbon was decomposed. Nitrous oxide (N_2O) is created as a by-product from the application of nitrogen fertilizer in waterlogged soils. In high latitudes, spring emissions of N_2O exist with rapid snowmelt and also low-lying areas which have heavy rains cause N_2O emissions. Methane (CH_4) is emitted in the digestive system of cattle and from the microbial breakdown of plant material [4]. Additional anthropogenic disturbances such as overgrazing in rangelands, deforestation, non-sustainable irrigation practices, and extractive farming practices, which produce depletion of stored soil carbon and reduced fertility, may be expediting desertification in North Africa [68].

Agriculture can both mitigate and worsen global warming. Lowering of the soil water content leads to a decrease of methane emissions or even to a small uptake of methane (CH_4) from the atmosphere [69]. Rice fields are sources of the greenhouse gases methane (CH_4) and nitrous oxide (N_2O). CH_4 and N_2O budgets of rice fields were affected by structure and dynamics of anaerobic/aerobic conditions in the soil. CH_4 emissions increase under continuous flooding while N_2O is primarily emitted in pulses after fertilization and strong rainfalls [70]. Moreover, drainage may result in the release of high amounts of organically fixed N and N_2O (nitrous oxide) may emerge as a result of the nitrification and denitrification processes [71]. "Some of the increase in CO_2 in the atmosphere comes from the decomposition of organic matter in the soil, and much of the methane emitted into the atmosphere is caused by the decomposition of organic matter in wet soils such as rice" paddies [22]. Net CO_2 emissions at the cropland and grassland sites were similarly high, taking into account changes in management and the change from corn for silage to corncob mix led transiently to rather small greenhouse gas emissions [72].

8 Adaption Strategies of Climate Change

Egypt is one of the most highly vulnerable countries in the world to climate change impacts, especially in coastal areas; thus, adaptation strategies are imperative. However, the slow economic growth and the high population growth, etc. are reducing Egypt's adaptive capacity. Adaptation is important for reducing the impacts of climate change on food production [73]. In Egypt, climate change adaptation is a main issue from the perspectives of food production, water resources development, and stabilization of the rural population [41]. Egypt, without enough adaptation measures, will likely suffer from negative impacts on several main crops which are important for large food security. Adaptation strategies for Egypt face many limitations and barriers such as information and policy perceptions, the weak adaptive capacity of the rural societies, limited existing scientific data, lack of financial support, and deficient institutional frameworks [34]. The vital sectors for climate change adaptation in Egypt include agriculture, water resources, health, tourism, and coastal resources. Egypt should develop a national plan for adaptation [20].

Eitzinger et al. [74] suggested some adaptation actions to face the rise of sea level which include intensification of planting salinity tolerant crops and shifting cropping activates to aquaculture gradual and establishing a field drainage system supported with a suction pumping unit to control water table level. The adaptation techniques for impacts of climate change on coastal areas in Egypt include: tightening legal regulations, construction of groins and breakwaters, integrated management of the coastal zone, and changing land use [41]. Climate change adaptation strategies in the Nile Delta region include changing cropping patterns, growing salinity tolerant crops in areas close to Mediterranean Sea, preparing plans for integrated management of coastal areas considering natural coastal protection (sand dunes, the coastal highway, and other structures such as seawalls), and developing policies for coastal protection. Such policies should identify a distance from the coast where the danger is predictable [75]. The expansion of planting rice in saline areas and cultivating salt tolerant crops are suitable in Egypt to face groundwater salinization [76].

Increasing nitrogen fertilizers, increasing the amount of applied irrigation water, and delaying sowing dates could be used as adaptation strategies to climate change for crops [10, 24, 27, 77]. The highest benefits will likely result from more expensive methods including the improvement of new crop varieties and the expansion of irrigation [21]. Crop phenology changes and their relationship with the environmental changes were a basis for expressing reliable adaptation policies [15]. Improvement of wheat yield and saving irrigation water could be attained using the proposed adaptation strategies in the year 2038 [78].

9 Future Vision

A study of the dynamic interactions of land and water regionally and globally is necessary to offer more reasonable predictions of both irrigation water efficiency and cost as a function of water scarcity; these studies should include challenges faced by other sectors [79]. There is a need for a parallel implementation of adaptation strategies and mitigation actions in order to diminish the negative effects of climate change on human activities and ecosystems. Society must learn to respond to climate change pressures over the approaching decades [80].

Collecting regular information about the ecosystem (phonological observations, inventories of land use per species, production statistics, etc.), and their development over the precedent few decades on a large scale is needed to understand the effects of climate change on cultivation and forestry and also to improve our understanding of certain mechanisms. Analyzing the comprehensive series of climatic data on national territories over a period extending from the end of the nineteenth century to the present day is an important thing. It is necessary to complement these data by phonological series coming either from observations of the natural vegetation or forest species, or from the cultured species, especially the perennial species (fruit trees, vines, etc.) [4]. There must be a quick adaptation of cultivation to meet the challenge of maintaining food security. Although there is a countless number of strategies for doing so, one of these strategies is taking the benefit of the extra CO_2 put into the Earth's atmosphere [81].

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Challenges and Issues in Water, Climate Change, and Food Security in Egypt

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Abstract Climate change is a real and growing problem and a complex phenomenon that alters the whole environment in which humans live. The impacts of climate change on freshwater systems and their management are mainly due to the observed and projected increases in temperature and precipitation variability. Developing countries, such as Egypt, are the most threatened by drastic impact of climatic changes on agriculture and food security. Several studies reported that Egypt is one of the most vulnerable countries to the potential impacts and risks of climate change, even though it produces less than 1% of the world total emissions of GHG, with a vulnerability of all sectors of development and a low resilience of the majority of stakeholders. One of the main challenges facing water management in Egypt is the expected impacts of climate change on the Nile flows and the different demands of the water sector. This in turn will directly affect the agricultural sector which is a key sector for the socio-economic development in Egypt, and plays a significant role in the Egyptian national economy. Climate change, population growth, and economic development will likely affect the future availability of water resources for agriculture in Egypt. The demand and supply of water for irrigation is expected to be influenced not only by changing hydrological regimes (through changes in precipitation, potential and actual evaporation, and runoff at the watershed and river basin scales), but also by concomitant increases in future competition for water due to population and economic growth. Egypt is therefore in a situation where it must plan for several different future scenarios, mostly negative, if climate change results in increased temperatures and decreased precipitation levels. Egypt's negative environmental consequences of climate warming represent rise of sea level, water scarcity, agriculture and food insufficiency, and pressures on human health and national economy. Even in the absence of any negative effects of

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climate change, Egypt is dealing with a steady growth in population, increased urbanization, and riparian neighbors with their own plans for securing future water needs. All of these will require Egypt to put water resource planning as a top national security priority. The future impact of the above negative environmental consequences of climate change scenarios, the adaptation measures, and mitigation polices are the main points of concern in this chapter.

Keywords Climate change, Food security, Freshwater in Egypt, Population increase, Sustainable planning

Contents

1 Introduction

Climate change is a real and growing problem for the world [1]. It is a complex phenomenon that alters the whole environment in which humans live. A change in climate state can be identified by detecting changes in the mean and/or the variability of its properties, and that continues for an extended period of time, typically decades or longer [2]. Changes in the atmospheric profusion of greenhouse gases and aerosols, in both solar radiation and in land surface properties alter the energy balance of the climate system. These progressions are communicated regarding radiative forcing, which is utilized to think about how a scope of human and natural factors drives cooling or warming influences on global climate. Since the IPCC third assessment report, new records and related modelling of greenhouse gases, solar activity, land surface characteristics, and some aspects of aerosols have increased the performance of the quantitative estimation of radiative forcing [3]. Global climate change will have profound implications for the quality of life of hundreds of millions of people [4]. In the last few years, climate change has become one of the most heavily researched subjects in science. There is no doubt about the increase in mean global surface temperature by $0.6 \pm 0.2°C$ over the twentieth century [5, 6] is a consequence of climate variability as well as of enhanced emission of greenhouse gases due to human activities [7]. From the recent Intergovernmental Panel on Climate Change fourth assessment report [8], little doubt remains that the climate system has warmed in recent decade [9].

Developing countries – such as Egypt – are the most threatened by drastic impact of climatic changes on agriculture and food security, as their economic base is linked to agriculture and a large proportion of their populations depends directly on agriculture and agriculture related business. The first and second Egyptian communications reports [10, 11], which were prepared by the Egyptian Environmental Affairs Agency (EEAA), reported that Egypt is one of the most vulnerable countries to the potential impacts and risks of climate change, with a vulnerability of all sectors of development and a low resilience of the majority of stakeholders.

Climate change is likely to increase the stress on currently stressed resources, especially in the developing world [12]. Studies have shown that most systems are sensitive to both the magnitude and the rate of climate change [13]. However, the vulnerability of a system to the expected change depends on economic strength and existing infrastructure as well as overall country resilience to cope with different risks. Most developing countries, such as Egypt, are generally more vulnerable and less able to adapt [14, 15]. In order to reduce the expected impacts of climate change, it is necessary to both reduce (mitigate) emissions of heat-trapping pollution and build resilience (adapt) to the impacts of climate change. However, even with strong programs to reduce greenhouse gas emissions (which proved to be a very difficult process), the effects of climate change will persist due to the longevity of certain greenhouse gases in the atmosphere and the absorption of heat by the oceans. Therefore, adaptation has a major role to play in reducing the impacts of climate change on people, businesses, and society.

Several sectors such as water resources, agricultural and food security, coastal, tourism, and health are highly vulnerable sectors with serious socioeconomic implications. Egypt is considered as limited water resources country and the available water for irrigation varies due to changes in freshwater availability and to competition among various water users [16, 17]. Main challenges facing water managers regarding water issues in Egypt, are climate change impacts on the Nile flow and the increasing demands of the water sector. This in turn will directly affect the agricultural sector, which is a key sector for the socio-economic development in Egypt, and plays a significant role in the Egyptian national economy [18]. In Egypt, agriculture consumes the biggest amount of the available water with a sharing exceeds 85% of the total demand for water. In the Egyptian economy, the agricultural sector contributes about 20% to Gross Domestic Product (GDP) and provides about 40% of total employment [16]. In view of the expected increase in demand from other sectors, such as municipal and industrial water supply, the development of Egypt's economy strongly depends on its ability to conserve and manage its water resources. Climate change, furthermore, may cause salinity challenges, where high extraction levels and declining inflows provide less dilution. Saline environments tend to hinder agricultural production by lowering crop yields, often quite substantially.

Climate change, population growth, and economic development will likely affect the future availability of water resources for agriculture in Egypt. The demand and supply of water for irrigation is expected to be influenced not only by changing hydrological regimes (through changes in precipitation, potential and actual evaporation, and runoff at the watershed and river basin scales), but also by concomitant increases in future competition for water due to population and economic growth [19]. So, an integrated study is essential to examine cropping systems, crop water demand, and water availability for irrigation under changing climate, population growth, and economic development conditions. This study should include an assessment of adaptation strategies for the water resources and agriculture sectors to achieve resilient agricultural production, which is a necessary element to achieve food security.

2 Country Background

Egypt is located on the northeastern side of Africa with an area of 1,001,449 km^2, has coastlines on the Mediterranean Sea and the Red Sea (Fig. 1). Geological history of Egypt has produced four major physical regions, as follows: Nile valley and Nile delta about 4% of the total; Eastern desert (from the Nile Valley all the way to the Red Sea coast) about 22%; Western desert (from the Nile west to the Libyan border) about 68%, and the Sinai Peninsula with about 6%. Egypt is located

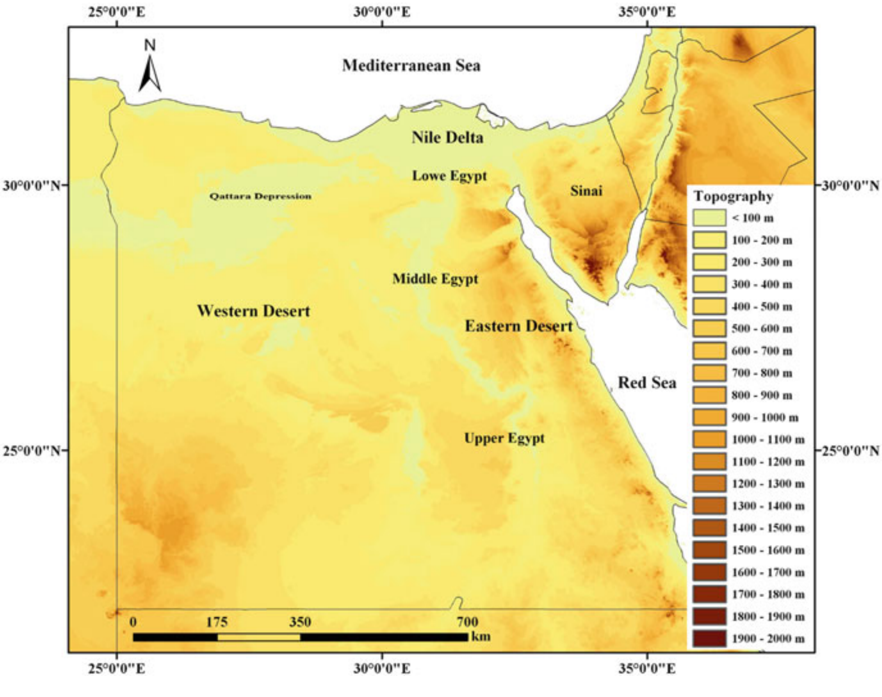

Fig. 1 Egypt's topography [20]

in a semi-arid zone and its climate is characterized by hot dry summers, moderate winters with very little rainfall. Egypt relies on the Nile River as its main resource of freshwater to meet the requirements of increasing demands in agricultural, industrial, and domestic sectors. With about 95% of the population (84 million in 2012) living along the Nile Delta, any changes in water supply due to climate change, with the certainty of increased demographic pressure, would pose a serious risk to the whole country. In addition, sea level rise (SLR) threatens settlements and agriculture in the Nile Delta as well as in the Red Sea. Besides, higher temperatures alone would evaporate more water, increase the need for water supplies, create more heat stress, exacerbate already high levels of air pollution, and may drive away tourists. The delta has been formed through annual supply of nutrients and sediment deposits for thousands of years by the Nile, forming a topsoil of about 20 m in depth over the original shallow sea bed. Intensive farming has been going on in the delta for 5,000–6,000 years.

With the construction of the High Aswan Dam, the delta no longer receives nutrients and sediments, and heavy fertilization is used instead. In addition to that, the outer edges of the delta are eroding in some places as much as 90–100 m a year. Besides, some coastal lagoons have seen increasing salinity levels. Most of the Nile delta is used for agriculture, where perennial irrigation allows two or three crops a year. Industry is another important activity distributed over the whole area. Water is provided to the intensive agriculture in the Delta across a complicated system of irrigation canals. The irrigation and drainage system in Egypt is complicated, moreover a large portion of the agricultural drainage water is reused to supplement shortage of the freshwater requirements especially in the low reaches of the canals. Water quality in the irrigation and drainage canals is getting worse as we move downstream due to the intensive pollution load from the heavy agricultural activities and high population density.

3 Present Status of Water Resources

Egypt, like any other country lies in arid region, faces the serious challenge of minimizing the gap between its limited water resources and the increasing water demand. Egypt considers the River Nile its “main artery of life,” being the exclusive source that covers nearly about 95% of the requirements [21, 22]. The other riparian countries depend on the Nile water in various ways according to each country’s precipitation and water use patterns. These riparian countries, compared with Egypt, are less vulnerable to fluctuations of the Nile flows and being mostly humid and/or less populated than Egypt [23, 24]. The main water management issues in Egypt arise mainly from quality of supply and demand management responses to water shortage. Although the fact that decreasing Nile water availability with respect to increasing in both populations and requirements for development is an alarming issue, Egypt has not yet reached the situation of a crisis. In Egypt, water resources are limited to the Nile River, rainfall and flash floods, deep groundwater, and potential desalination of sea and brackish water. Each of these resources has its limitation of usage, whether these limitations are related to quantity, quality, space, time, or exploitation cost. Table 1 and Fig. 2 present the

Table 1 Egypt water balance in 2015 – supply versus demand [27]

Water balance for the current situation			
Uses (km^3/year)	Sector	Quantity (km^3/year)	Water resources
9.50	Municipal	Traditional water resources	
4.00	Industry	55.50	Nile River
64.00	Agriculture	2.00	Deep ground water
3.20	Evaporation losses, Navigation and environment needs	1.30	Rains and torrents
		0.20	Desalination
80.70	Total	59.00	Sub-total
Industry water uses don't include electrical station cooling		Untraditional water resources (reuse)	
		6.20	Shallow ground water
Industry uses 2.0 km^3 directly from the Nile and canals network and groundwater		15.50	Drainage water reuse
		21.70	Sub-total
80.70	Total uses	80.70	Total water available

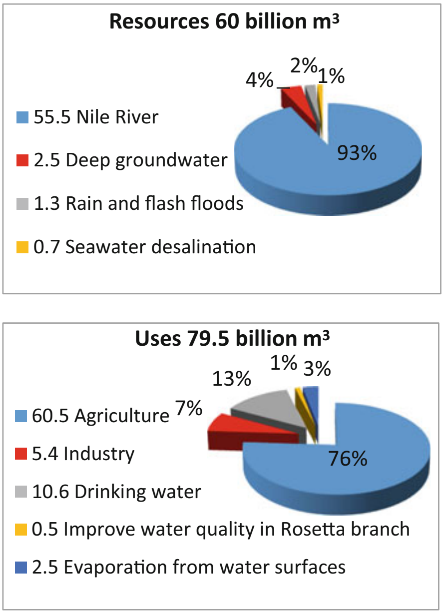

Fig. 2 Water resources of Egypt

water demand in Egypt in 2015, illustrating how these water requirements were satisfied through process of non-conventional water resources, including water savings and possibilities of reuse. The share of Nile water in Egypt is 55.5 billion m^3 per year, representing 93% of the country's available traditional water resources; desalinated seawater comprises only 0.70%. Egypt is a very arid country and the rainfall declines very rapidly from coastal to inland areas and occurs only in winter in the form of scattered showers, therefore deep groundwater plus rain and flash floods is 3.3 billion m^3 per year (6% of available water resources). Non-conventional water resources have been considered for a long time in Egypt, and the drainage water reuse in 2015 was 21.7 billion m^3 per year. It can be clearly seen in Table 1 that the Nile basin inside Egypt is a closed system and inputs (resources) and outputs (demands) are balanced. Managing water resources becomes a more complex issue because it is influenced by the potential impacts of climate change. Several studies predict that climate change will intensify and accelerate the hydrological cycle, which will result in more water and wetter weather being available in some parts of the world and less water and dry weather being available in other parts of the world. Weather patterns are predicted to be more extreme. Those regions adversely affected are expected to receive drought and/or possible flood events. Egypt is vulnerable since the Nile waters are highly sensitive to impacts of climate change on trends of both rainfall and temperature. Some studies showed that temperature changes affect rainfall, therefore it could be expected that climate change will take the form of changes in levels of rainfall and that the resulting effect on the Nile river flow will be from moderate to extreme.

4 Population

Only small communities are spreading throughout the desert areas of Egypt and these communities are clustered around oases and historic trade and transportation routes. The Egyptian government has attempted to urge migration to newly irrigated land reclaimed from the desert [25]. However, as people are moving to the cities in search of employment and a higher standard of living the proportion of the population living in rural areas has continued to decrease. Egypt is considered as the most populous country in the Arab world and the third most populous country within Africa. Most of the country is desert, therefore nearly 97% of the country's people is concentrated in a narrow strip of fertile land along the Nile River, which represents only about 5% of Egypt's land area [26]. These densely populated areas in Egypt, which occupy about 4% of the country's area, are among the world's most densely populated regions where the population density is about 1,600 inhabitants per km^2 [27]. As shown in Fig. 3, Egypt's population was about 24 million in 1955, swelling to 35 million in 1970 and reaching 93 million in 2015. Egypt's rapid population growth, 49% between 1995 and 2016 from 62 million to 93 million (Fig. 3), puts pressure on the country's natural resources, economy, and environment and is threatening the health care and well-being of its Egyptian people. The

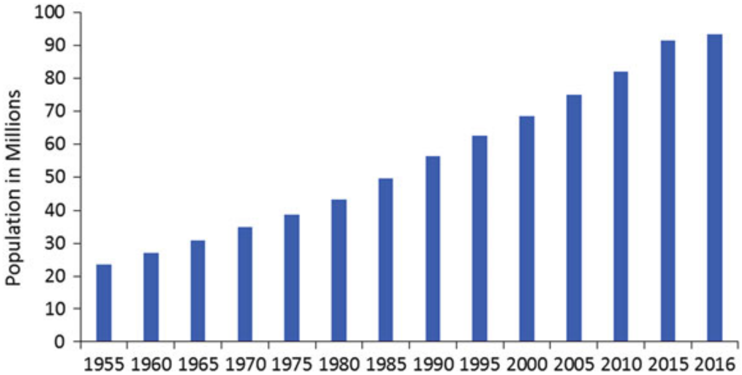

Fig. 3 Egypt's population grew by 49% between 1955 and 2016

Central Agency for Public Mobilization and Statistics (CAPMAS) indicated, in its report titled "Water Resources and Means to Rationalize their Use," that the per capita annual share of water decreased from a water excess of about 2,500 m^3 in 1947 to a sufficient level of 1,900 m^3 in 1970 then water scarcity with 660 m^3 in 2013. By 2025, an Egyptian's share in annual water will drop to 582 m^3 as forecasted by CAPMAS. The United Nations declared that a population where per capita annual water resources are below 1,000 m^3 faces water scarcity and at a level of 500 m^3 the country approaches the absolute water scarcity. With the current population growth of about 2.6% a year, the Egyptian government faces several challenges in providing for the basic requirements of its citizens, including jobs, suitable housing, sanitation, health care, and education. Moreover, Egypt is faced with shortages of freshwater resources and energy, which are necessary for sustaining health care, food production, food security, and economic development.

5 Climate and Climate Changes

The word climate refers to the representative conditions of the lower surface atmosphere of the earth at a specific location. The variables, which are mainly used by meteorologists to measure daily weather phenomena are air temperature, precipitation, atmospheric pressure and humidity, wind, and sunshine and cloud cover. Climate changes can refer to long-term changes in average weather conditions, or all changes in the climate system, including the drivers of change, or the changes themselves and their effects, or only human-induced changes in the climate system. Various evidence from records of the climate system and global climate model results have led to the conclusion that human activities are contributing to a warming of the earth's atmosphere [1].

5.1 Climate Changes and Its Impact on Water Resources of Egypt

The hydrologic system, as an integrated part of the earth's geophysical system, both affects and is affected by the climatic condition [28]. Changes in temperature affect the rates of evapotranspiration, characteristics of cloud, soil moisture, storm intensity, and both snowfall and snowmelt regimes. At the same time, changes in precipitation have an effect on the timing and magnitude of floods and droughts, shift runoff regimes, and alter groundwater recharge rates [29]. Exact information about precipitation amounts reaching the land surface is of special importance for freshwater assessment and management related to agriculture land use, hydrology and risk reduction of flood and drought [30]. There are likely more regions in the world where the frequency of heavy precipitation events has increased than where it has decreased (Fig. 4).

The Nile River basin has a drainage area more than 3 million km^2 and about 73% of the drainage basin located in Sudan and Egypt with net consumption of water (Fig. 5). The Nile River basin crosses six hydroclimatic zones, namely: (1) lake plateau territory (Burundi, Rwanda, Tanzania, Kenya, and Uganda); (2) Sudd freshwater swamp (southern Sudan); (3) Ethiopian highlands; (4) Sudan plains (central Sudan); (5) northern Sudan and Egypt (from the Atbara and Nile Rivers confluence to Cairo), and (6) Mediterranean zone (coastal region with no measurable rainfall) [33]. In the Nile River basin, the ratio of the producing watershed to consuming watershed is low. Ethiopia, with about 12% of the drainage basin, generates about 86% of the river annual-round flow, while the remaining 14%

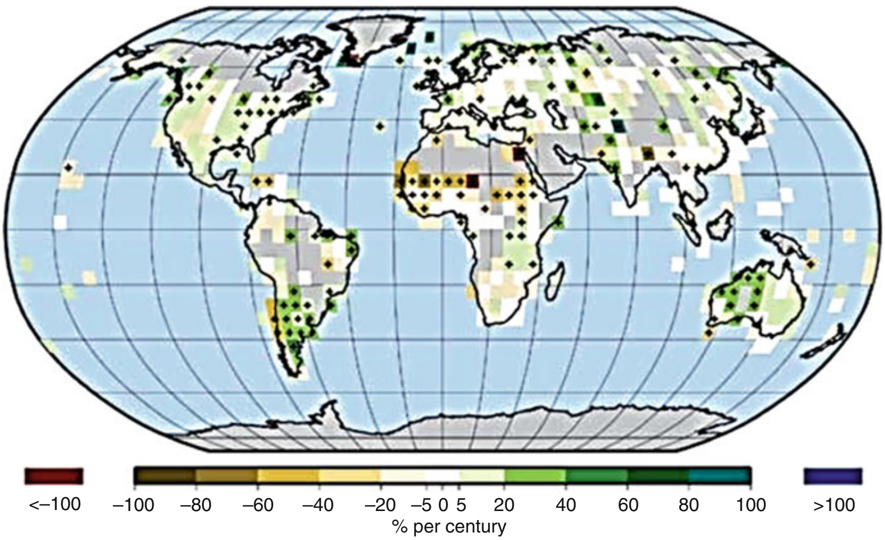

Fig. 4 Observed change in annual precipitation over land, 1901–2005 [31]

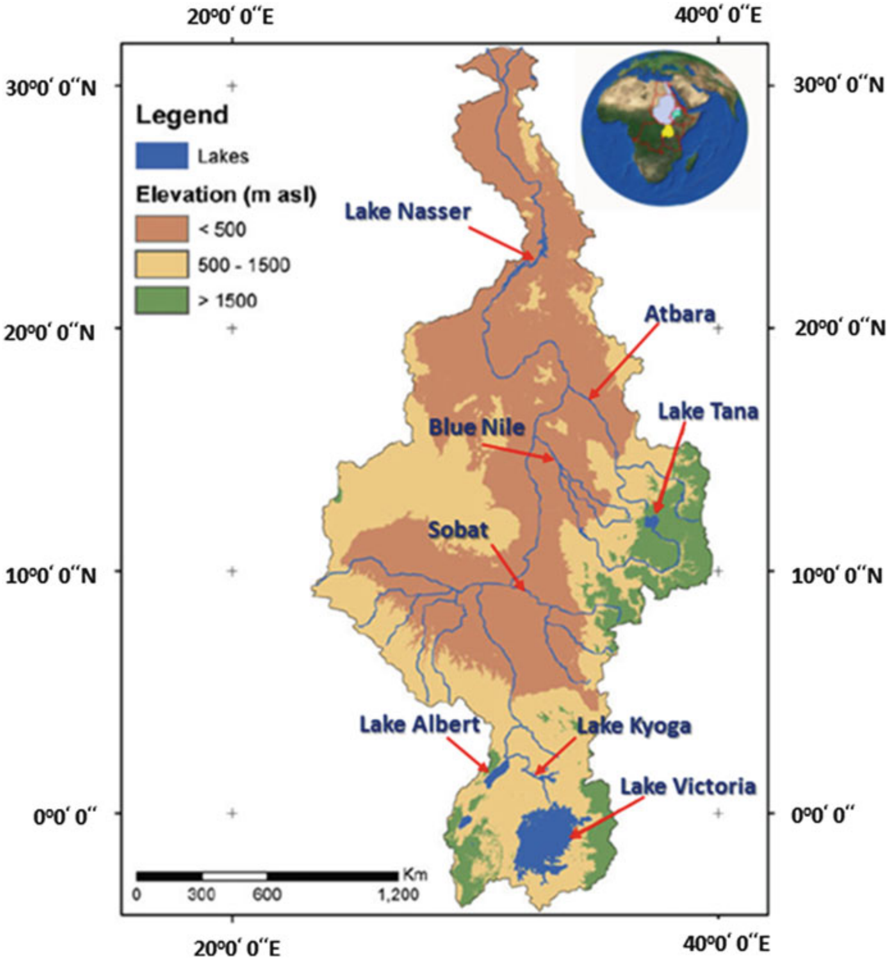

Fig. 5 Nile River basin. After [32]

comes from the White Nile, which has a larger drainage basin. The Ethiopian highlands generate a discharge of 87% of the total Nile flow at the Aswan dam in Egypt. The Blue Nile River basin, which has drainage area of 324,530 km^2, is the main source of the Nile River and contributes about 60–69% of the main Nile discharge.

A large number of studies have been carried out in the Nile River basin to investigate historical trends in rainfall. Several studies have also been conducted, using climatic model output as the input of hydrological models, in order to project future hydrological regimes [34]. Studies over the Nile basin provide conflicting evidence regarding the existence of any long-term trend in the historical rainfall. While there is generally insignificant change in the annual rainfall series in most of the Nile sub-basins, the trend appears to be decreasing seasonality in some key watersheds of the upper Nile in Ethiopia such as the southern Blue Nile and Baro-Akobo. The magnitudes (and sometimes the signs) of the trends in rainfall varied from season to season, and also from one station (or subregion) to another. Some studies also supported the idea that, except for Lake Victoria, all sub-basins of Nile experienced slightly-to-strongly decreasing trends in precipitation. The three catchments of Bahr el Ghazal, Sobat, and Central Sudan recorded significant drops in annual precipitation, whereas the observed changes in many other catchments were not significant. Regarding the future projections of rainfall in the Nile river basin, a large number of studies have been carried out to project future regimes of rainfall. Results of several studies showed that, in contrast, the rainfall changes did not suggest that there was any consensus among general circulation models (GCMs) regarding rainfall trends for the region. Most of ensembles examined in the literature did not show any statistically significant changes in median. Several studies indicated that there was no consensus among the GCMs about the sign of the rainfall change in the Nile River basin [35]. Thus, there are large uncertainties in predicting climatic change impact on rainfall trends over the Nile basin and their impacts on its flows. By nature, the future is uncertain and this is partly handled via emissions' scenarios that capture different visions of how the world will develop in the future in terms of population, technology, and energy use.

Several studies showed that projected changes in rainfall trends in different sources of the Nile as well as their impact on the Nile flow into Egypt remain considerably uncertain [36]. However, more certain is that temperatures will continue to increase because of climate change. This will likely lead to significant increase in the evaporative losses from the Nile River over Egypt and Sudan where the Nile flows with very slight flow-gradient over a semi-arid region. Moreover, higher temperatures will also increase demands for water for agriculture, domestic, and industrial uses [37]. A number of studies investigated the implications of fluctuations in Nile flows for water resources in Egypt, mainly since a prolonged period of drought during the 1970s and 1980s [38]. Table 2 shows the results of three Global Circulation Models (GCMs) used in 1996 to estimate projected Nile flows [39]. Results indicated that even with increases in the amount of rainfall, Nile flows would decrease in two of the three scenarios as a result of increase in temperature.

Table 2 Nile flows under GCM scenarios

	Base	UKMO	GISS	GFDL
Precipitation	100	122	131	105
Temperature	0	4.7	3.5	3.2
Flow (billion m^3)	84	76	112	20
% of base	100	91	113	24

6 Food Security

Food security is a concept that envelops more than just crop production, but is a complicated interaction between food accessibility and socio-economic, policy and health issues that impact access to food, utilization, and stability of food supplies. In 1996 the World Food Summit characterized food security as existing "when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs, and their food preferences are met for an active and healthy life" [40]. The food production is not the only largest consumer of water, it is also the biggest unknown with respect to future global water demand [41, 42]. In Egypt, most croplands depend basically on irrigation water from the Nile rather than on local climatic conditions.

Recent years various simulation studies report that Egypt may go through increasing pressures on food security as a result of climate change. However, socio-economic aspects may play an important role in mitigating this situation somewhat. A study by Falkenmark et al. [43] investigated the projections of available water for crops and suggested that Egypt would be a food importing country in 2050. This result was obtained based on a global analysis of food security under some scenarios of climate change, and this analysis considers the importance of water availability for ensuring global food security. Crop suitability was projected under the pattern of climate change from 21 GCMs with two emissions scenarios.

Simulation was performed for the years 2030, 2050, 2080, and 2100. Under the climate projections, only one GCM projects an increase in suitability for cultivation in current Egyptian croplands. Regarding the mitigation scenario, this single model projects about 2% of current Egyptian croplands to be more suitable by 2100. All other investigated models project no increases in suitability. By 2030, under both emissions scenarios, between 40 and 67% of current Egyptian croplands are projected to become less suitable for cultivation as defined by local climatic conditions. Therefore, for Egypt, projected changes in local climate lead to conditions, which are less suitable for cultivation over most of current cropland areas. It is worth mentioning that changes in the availability of Nile river water for irrigation have not been considered in this analysis.

7 Towards Mainstreaming Adaptation Responses

Climate change adaptation is a concept of adjusting to a changing climate in order to reduce the negative impacts already occurring and taking advantage of new opportunities. Climate change adaptation plans and strategies are essential tools to avoid disruptions to governmental operations and allow to design and implement programs that are capable of achieving their goals across the various projected future climate scenarios. Climate change adaptation plans are vital for Egypt, especially in the water sector, which affects all other sectors. Agriculture also needs to adapt to climate changes including more expected extreme weather events. There are three main pathways for agricultural development, namely: conventional agriculture, organic agriculture, and conservation agriculture. These three pathways have different approaches for addressing the above issues [26]. Agriculture production must increase to satisfy the requirements of the growing population; however, this production will have to be achieved in an environmentally friendly way. As a result of the rapid population growth, Egypt's per capita share of water is expected to be reduced by half by 2050 even in the absence of climate change. Therefore, some measures are needed to be considered such as: improvement of the irrigation system, more efficient water delivery, better control on water usage, augmented farm productivity, redesign of canal cross sections to reduce evaporation losses, change of cropping patterns, enact programs for upgrading water quality to minimize pollution, with a high priority to recycling of both industrial and sewage waste, and launch public awareness campaigns on water shortage.

8 Conclusion

Egypt faces the urgent challenge of closing the growing gap between its limited water resources and the increasing water demand. The Nile River, the sole source that covers nearly 95% of the Egyptian population requirements, is highly sensitive to climate change, both in amount of rainfall and variations in temperature. There are large uncertainties in predicting climatic change impact on rainfall trends over the Nile basin and their impacts on its flows. Climate change, furthermore, may cause salinity challenges, where high extraction levels and declining inflows provide less dilution. Saline environments tend to hinder agricultural production by lowering crop yields, often quite substantially. Continued high rate of natural population increase will result in a population of 140 million inhabitants by 2050, and Egypt's per capita share of water is expected to be reduced by half even in the absence of climate change. Agriculture production has to increase by 70% within 2050 in order to keep pace with this rapid population growth, in a way that preserves the environment, to reduce the vulnerability of agriculture to climate change. A number of climate change adaptation options are vital for Egypt, especially in the water and in agriculture sectors. Increasing water availability and increasing the reliability of water in agriculture is one of the preferred options to increase crops productivity and contribute to poverty reduction in Egypt. Developing sustainable water policies and related strategies is a must, taking into account country-specific legal, institutional, economic, social, physical, and environmental conditions. These policies and strategies must integrate the different sectors depending on water.

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Egyptian Food Insecurity Under Water Shortage and Its Socioeconomic Impacts

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Abstract Egypt is not plentiful in agriculture resources, whereby the total cultivated land is only 3.6 million ha, and total renewable freshwater is only 62 Billion Cubic Meter (BCM) for 93 million people. The water shortage in Egypt exceeds 30 BCM/year with Egypt's water share per capita being 674 m/year. This severe shortage of water resources and arable lands in addition to growing population are one of the reasons why Egypt is one of the largest food importers in the world. Egypt is the biggest importer of wheat (12 million tons/year), and fourth importer of maize at 8.5 million tons/year and the seventh biggest importer of edible oils in the world, with a gap, reached 100% of lentil, 70% of broad bean, and 32% of sugar and 60% of red meat, butter, and milk powder. There are several impacts of food and water insecurity and socioeconomic impacts such as the soaring price of food, and small and tiny farm. More than 80% of land tenure and ownership is less than 0.8 ha in addition to very low share land per capita not exceeding 0.14 acres and continuous increase in poverty rate, which reached 27.8% at the end of the year 2016. To deal with this food insecurity, Egypt counts on major reclamation projects for an addition of more than 1 million acres as an extension to the present agricultural land located in North Sinai, at Toshka in the southwest valley and the Oweinat project in the far south of the western desert near the border with Libya. Agriculture related policies in Egypt should be reformed to plan and advance increased food production especially the essential crops such as wheat, maize, sugar, lentils and broad bean, oilseed, and meat and dairy products. Moreover, Egypt should make serious efforts to find new sources of water to combat water shortage, which may include untraditional sources such as desalination of seawater, treated sewage and treated industry water, and reclaimed agricultural drainage water, and also develop and renovate the whole agricultural system.

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Contents

1 Introduction

"Food security exists when all people, at all times, have physical and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life" [1]. This definition includes the four dimensions of food security which are: availability, accessibility, utilization, and stability. What is needed is not only enough food being produced globally – enough food is produced globally now, but that everybody has access to it, in the right quantity and quality, all the time [1].

Food security can be looked at three levels – the global, national, and household levels [2]:

1. Food security on a global scale is the level to set out from for an analysis of general trends and to gain an understanding of the possible impacts of, e.g., climate change on agriculture. This is of importance since these trends have an effect on the worldwide level of agricultural prices and influence the decisions made by producers.
2. Food security on a national level is where most of the decisions on food security are taken, for example, on how much financial resources are available for the national agricultural policy. Central elements of adaptive strategies in response to crises and disasters are defined at a national level.

3. Food security at the household level: Without a detailed examination of the impacts on the household level, it would not be possible to gain an understanding of the specific needs of each individual with regard to food security. Such knowledge is key to the support of groups most threatened by food insecurity in the event of a crisis.

These distinctions show that food security for a country as a whole cannot always be equated with food security at regional level or at the household level, and this information is vital in the event of a crisis. Other regional or household information can aid in the event of a crisis. For example, food particularly rich in minerals and vitamins being handed out especially to pregnant women and infants in order to address their particular situation. Moreover, there are some groups, such as nomads, that may receive animal feed so that they can keep livestock healthy in order to earn a living. There are a number of potential risk drivers for all three levels of food security: natural hazards some of which are exacerbated by climate change on the one hand, and crises and conflicts as well as the globalization of agriculture on the other.

The fertility of the Nile Valley and Delta allowed the ancient Egyptians to build a great agricultural civilization. Nowadays, Egypt faces a high population growth raising the total population officially to 104 million capita. This will deepen the food insecurity according to the lack of both water and arable lands and weak economy which will lead to increase in poverty level. Egypt faces rising food insecurity according to the population growth which becomes 104 million in 2017. This high population will be struggling to meet its basic food and water needs. Egypt's food security issues are largely structural – rising poverty, wasteful food production and distribution systems, and exposure to price volatility. The effects of these challenges have been accumulating for over a decade and will be difficult to mend, given the country's ongoing political instability and a stagnant economy.

1.1 Food Security Background

Generally, the main and general related issues of food security include:

1. Water scarcity is emerging as a critical systemic risk worldwide. While the global population has tripled over the past century, our use of water has increased sixfold [3].
2. More than 95% of humanity's present food supply is produced from the soil.
3. About 40% of soil used for agriculture globally is classed as degraded or seriously degraded.
4. The FAO [4] has projected that for the planet, net land under crops may have to increase by about 700 million ha by 2050 to meet predicted global food needs.
5. "The loss of food security – through climate change or the loss of soil and water resources – is a major factor in people deciding to quit their homelands in search

of new life, whether as economic migrants ahead of a crisis they have foreseen or as refugees fleeing a disaster" [3].

1.2 Key Message of Food Insecurity in the World

The food insecurity in the world could be concluded as follows:

1. Nowadays, almost 795 million people are undernourished globally, even it withdrawn about 167 million over the end of last millennium, and 216 million less than 10 years before (1990–1992). Most of this decline is achieved in developing regions, despite high population growth rate [4].
2. The year 2015 marks the end of the monitoring period for the Millennium Development Goal (MDG) targets. For the developing regions as a whole, the share of undernourished people in the total population has decreased from 23.3% in 1990–1992 to 12.9%. The fast progress was in western Africa, Central, south and east Asia, Latin America, and Caucasus.
3. A total of 72 developing countries out of 129 or more than half the countries monitored have reached the MDG as one country hunger target. This was achieved under the performance of stable political conditions which improved the economic growth.
4. For the developing regions as a whole, both of the population of undernourishment and the percent of underweight children under 5 years of age declined, which is considered as a good indicator for achieving MDG.
5. Improving economy in developing countries is a key success factor for reducing poverty, but improving the livelihoods of the poor needs more efforts. Thus, the developing countries should take more efforts to enhancing the productivity and incomes of smallholder family farmers.
6. To eliminate hunger and reduce poverty, social protection systems should be applied towards the MDG. Social protection should target the reduction of poverty, hunger, and malnutrition by improving income and access to better and balanced foods, health care, and education.
7. Instability of political systems results in the failing of reaching the international hunger targets, natural and human-induced disasters. It also resulted in increases in vulnerability and food insecurity in the poor communities [1, 3–5].

2 Food Security Situation in Egypt, Water Resources and Food Production

Producing foods rely mostly on water, energy, and finally the arable lands. Thus, the next items will explain the key facts of food insecurity in Egypt.

2.1 The Key Points of Food Insecurity in Egypt

One in five Egyptians is currently experiencing food insecurity because of structural issues in the food supply system.

1. Nile is the only renewable water source in Egypt, but the conflicts between down- and upstream countries may threat its share of the Nile's flow especially under high population growth and development demands in upstream countries.
2. Population growth in Egypt under limited water resources and limited arable lands leads to increase in the deep gape of food security.
3. Water shortage (not arable lands) is a governing issue on food security, with a deep gap of more than 42 billion cubic meters (BCM) a year, where the total renewable freshwater is 62 BCM for 104 million capita while it needs water resources not less than 104 BCM/year at a rate of 1,000 m^3/capita a year to be above scarcity level [6].
4. All Egyptian renewable water is only enough to cultivate 8.8 million feddans (3.7 million ha) at a rate of 7,000 m^3/feddan to avoid salinity formation in our warm, and dry weather.
5. The limited water resources and arable lands is another limiting factor of food security. The total cultivated area does not exceed 8.6 million acres (3.6 million ha). One-third of cultivation area is new reclaimed desert lands and only 6 million feddans (2.5 million ha) are alluvial old soils suffering from salinity and water logging [7].
6. Egypt also has more than 5 million feddans as an arable land and extension area available for cultivation, but it does not have enough water resources needed to irrigate these lands.
7. Imported food will increase in the near future to meet extra food needs, but trade-based food security may not be viable in the long-term if Egypt cannot mend its struggling economy.
8. Egypt imports about 60% of their basic food, which costs more than 10 billion dollars/year.
9. Egypt is number one of the top ten list of wheat importer list since the year 2005 until now, with average imports in February 2017 of 12 million tons (the US Wheat associate) [8], as seen in Fig. 1.
10. Globally, Egypt is number four in importing maize with an average of between 8 and 8.5 million tons/year (Table 1), and number five in importing soy and soy oil; and number seven in importing sunflower oil (data from Grain Stocks, several editions), Fig. 2.
11. Egypt imports 32% of its needed sugar at a rate of 1–1.2 million tons/year, about 70% of broad bean (faba bean), and 100% of lentil and edible oil. Egypt also imports 60% of red meat, 10–15% of poultry, and 60% of dry milk and cow butter in addition to appreciable amounts in some fruits such as apple, apricot, and some others.

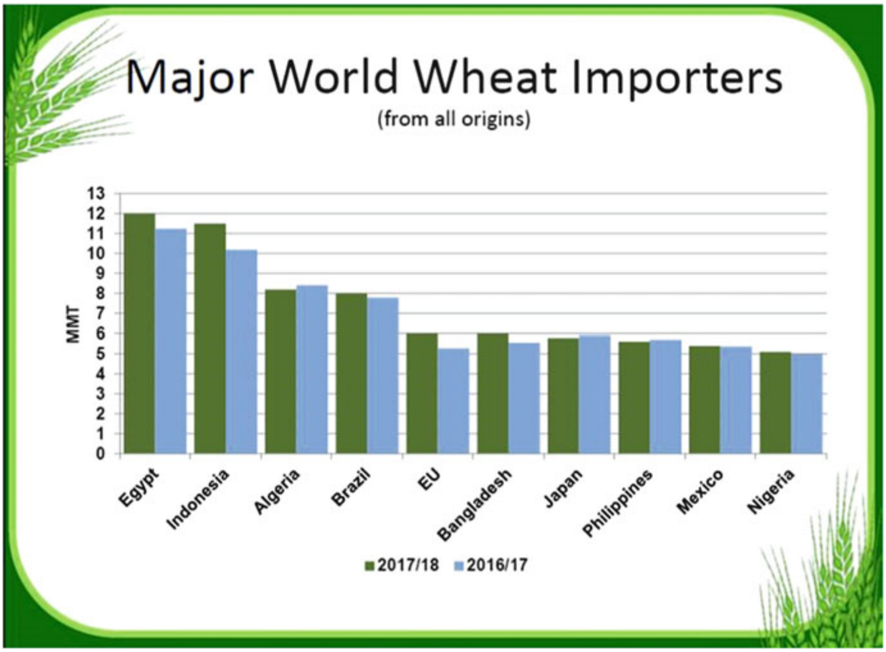

Fig. 1 The top ten wheat importers by country in December 2017 [8]

Table 1 The top five maize importing countries [9]

MMT	2009/ 2010	2010/ 2011	2011/ 2012	2012/ 2013	2013/ 2014	2014/ 2015	2015/ 2016
Egypt	5.83	5.8	7.15	5.06	8.73	7.5	8.00
EU	2.76	7.39	6.11	11.36	15.92	9.00	15.00
Japan	15.97	15.65	14.89	14.41	15.12	14.9	14.80
S Korea	8.3	8.25	11.17	5.68	10.95	10.3	10.30
Mexico	8.3	8.25	11.17	5.68	10.95	10.30	10.30

Egypt faces an even more serious and insidious long-term threat to food and water security. The population is booming, and its food needs are on the rise, but it has a declining resources base. Egypt has limited water resources because it relies mostly on Nile water by 95%; thus, it struggles with upstream countries to persuade them by the principal of “accepted rights” of water that Egypt used to receive along thousands of years. In addition Egypt also has limited arable lands whereas Egyptian people only live on 7% of all the country’s area, and the rest of country is a dry desert. Any decreases in the amounts of Egypt water share will lead to deepening of food security gap and is expected to increase to 70% instead of 60%.

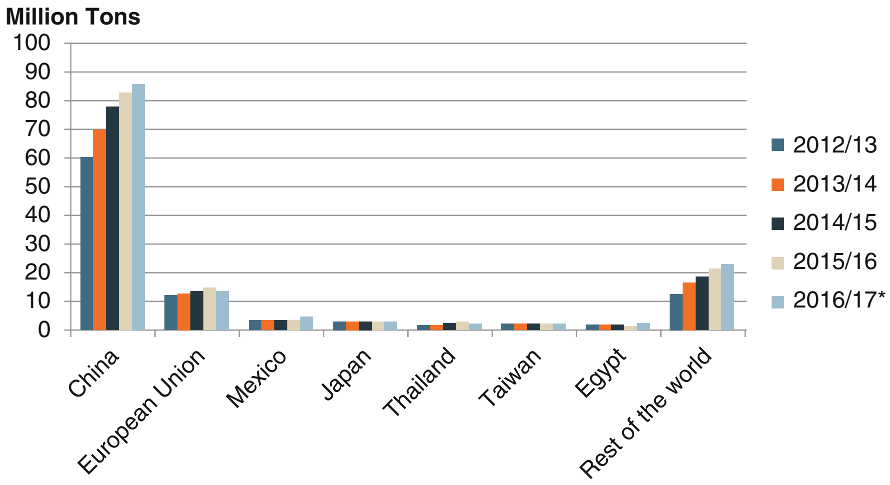

Fig. 2 Top soy oil importer countries [10]

2.2 Key Elements of Contemporary Water Scarcity

Water scarcity may cause and affect several live elements as follows:

1. The drier condition of the world's major rivers, especially in semiarid regions, and the impact of 6,000 plus dams on downstream food and water security.
2. The drying up and contamination of lakes and inland seas worldwide [4].
3. Overexploitation of groundwater in every region where it is used to grow food or support megacities and the energy sector; one-third of the world's major groundwater basins are rated as "in distress."
4. The unprecedented decline in mountain glaciers (which supply major river systems).
5. The impact of climatic fluctuations on regional water supplies.
6. Increasing frequency of drought in countries that seldom before experienced it.
7. Growing confrontation between farmers and energy corporates (coal, gas, sands, etc.) over access to and use of water around the world.

2.2.1 Key Points of the Nile River

Nile River is the love artery to Egypt according to the following:

1. The Nile River has been the center of interstate politics of the region through the years, as it is the only reliable source for renewable water supplies in the area.
2. The Entebbe Agreement aimed to shift control over the Nile away from Egypt and Sudan and canceling the accepted or historical rights [11].

3. The food and water security situation in Egypt is extremely vulnerable due to water shortage, limited arable lands (93% of Egypt area is drought desert), high population rate in addition to the threatening impacts of climate change and global warming.
4. Egypt should find a way for more cooperation with Nile upstream countries for collected works to increase the amount of water reached to the river stream and reduce the loss rates in Nile swamps and wetlands that consume about 96% of the total river resources and catchment areas. This will reduce the high worries (fears) about the future of water and food security in Egypt.

2.3 Egypt, Nile, and Food Security

Egypt's "accepted and historical rights" to the Nile have encouraged over-dependency on the river. Without the rainfall enjoyed by upstream riparian nations, Egypt relies on the Nile for 90% (55.5 Nile share water over 62.3 total water resources) of its water supply. The coping of water scarcity in Egypt is not an easy matter due to the high population growth, limited water and land resources, and the problems with upstream Nile rivers especially after the mega dams constructed in Ethiopia. Egypt's population expected to reach 150 million capita by 2050. This will need 150 BCM of water per year, but the total available water will not exceed 62 BCM/year (55.5 from the Nile share water +5.5 groundwater +1.3 from rain). Thus, the water shortage will reach 88 BCM/year, which is considered as a huge deficit (deep gape) [11].

Water shortages and limited arable lands mean that Egypt already relies heavily on food import to feed its population. Egypt's agricultural sector currently uses 86% of the nation's water supply, yet domestic production levels are considerably short of the demand and do not exceed 40% of the Egyptian needs. Two third of the 18.8 million tons of grains that Egypt consumes annually is imported, making it the world's largest grain importer. In total, Egypt imports 60% of its total food needs [5].

Egypt's current population of 104 million is growing at a rapid rate of 2.5% per annum [12] and is expected to rise to 150 million by 2050. As the population increases, water demands will grow for both household and industrial use. Also, the amount of food required to ensure the country's food security will need to increase. Egypt's reliance on food imports makes it vulnerable to global food price hikes and supply shortages. During the 2008 food crisis, Egypt was one of the largest losers from soaring food prices by more than 1% of its gross domestic product (GDP) as seen in Fig. 3 according to the World Bank.

To mitigate this security risk, Egypt was obliged (forced) to greening desert, which required that much water should come from new resource such as deep groundwater. Actually, Egypt has more than 5 million acres of arable lands but not have the water needed to cultivate these areas.

Egypt needs more water resources to face the requirements for National reclamation projects such as Toshka Depression near the south border in the southwest of western desert beside Lake Nasser, and the Al-Salam Canal system that reclaims

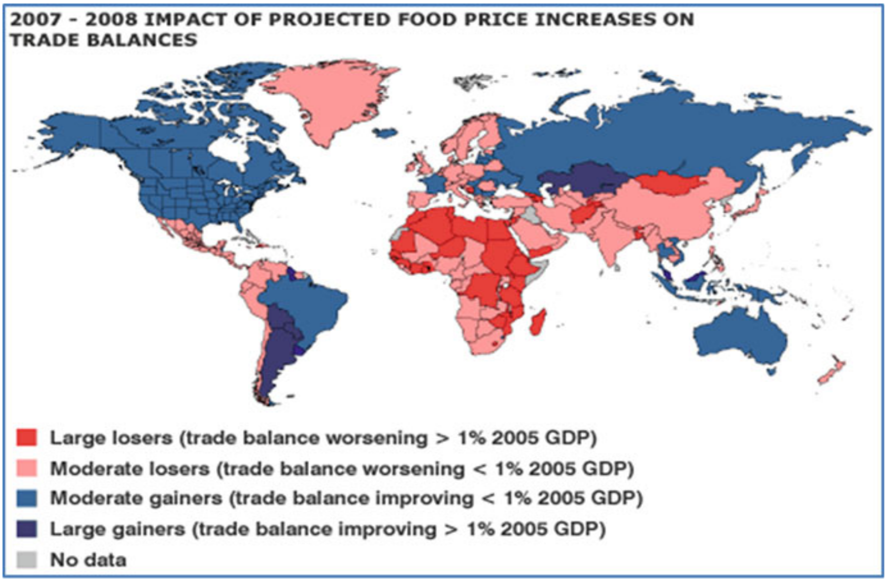

Fig. 3 Egypt is one of the largest losers during the food crisis in 2008 [13]. Source: The World Bank

land in the Sinai Desert at the northeast coast. Egypt plans to raise the efficiency of both irrigation methods and water delivery system, in addition to using more of different types of wastewater such as agricultural drainage water, and sanitary and industry wastewaters. Egypt also may oblige to decrease the areas of the high consumed water crops such as rice, sugar cane and forage, banana, and all wide leaved crops.

3 Socioeconomic Impacts of Food Insecurity

3.1 Poverty and Food Insecurity in Egypt

From my wide experiences, agriculture could lead the economic progress only in the high water resources countries such as Brazil. In contrary, the poor water resources countries should count on industry instead of agriculture due to the little water amounts needed in industrial sectors. Some other countries may rely in both of industry and agriculture for their economic developments, but that needs a minimum level of water not less than scarcity level (1,000–1,700 m^3/capita).

In Egypt, and according to the high poverty level in rural areas, agriculture may play a good rule to reduce poverty and increase incomes of the rural and countryside areas.

GDP growth generated in agriculture is four times more effective in benefiting the poorest half of the population than growth generated outside agriculture [5].

The joint report by Central Agency for Public Mobilization and Statistics (CAPMAS) and WFP [5] entitled “The Status of Poverty and Food Security in Egypt: Analysis and Policy Recommendations” is based on analysis of CAPMAS’s 2011 Household Income, Expenditure and Consumption Survey (HIECS). The report highlights an “increase in the prevalence of food insecurity to 17.2 percent (13.7 million people) in 2011 from 14 percent of the population in 2009. This increase in food insecurity has been driven largely by rising poverty rates and a succession of crises from 2005.” The report attributed this trend due to the avian influenza epidemic in 2006, the food, fuel soaring prices, and financial crises of 2007–2009. Moreover, global food price also increased in 2010 (Egypt officially imports 60% of its essential food), in addition to another internal increase after January 2011 revolution which creates instability and insecure condition. These bad circumstances have adversely affected households’ vulnerability of poorer to cope or adapt resulting to push it up twice as many people into food insecurity than those moving out of it in 2011. The report notices a similar data between 2009 and 2011, 15.2% of the population moved into poverty, twice the number who moved out of poverty (7.7% of the population), and 12.6% of the population remained in long-term poverty (chronic poor), while the highest poverty rates remain in rural Upper Egypt (51.5% of the population against a national average of 25.2%). In addition, significant pockets of poverty and food insecurity are emerging in urban areas, where poverty increased by nearly 40% between 2009 and 2011 (the national average of poverty increased to 27.8% in 2016 in addition to 5.5% of chronic poor according to CAPMAS). Figure 4 shows the national poverty in Egypt from 1995 to 2011.

In population terms, Greater Cairo (Cairo, Qualoubia, and Giza) has an even larger number of poor people (approximately, 3.8 million) than the poorest governorates in Upper Egypt.

The implications of this are significant to help target assistance programs that focus on affected areas and exert effort on making real incomes that are stable as well as reducing inequalities. For rural areas, the focus should be on structural rectification to increase the mean income level. The insecurity of food in Egypt continues to

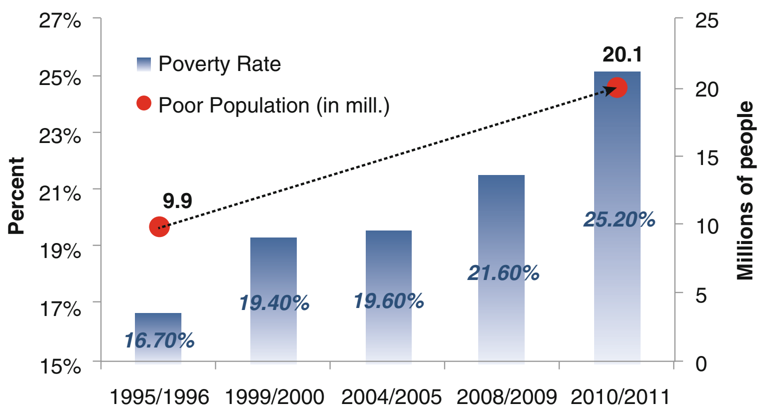

Fig. 4 National poverty rate from 1995 to 2011 [5]

be a problem for households who face difficulties towards food access that is directed by purchasing power. About 74.7% of households who were surveyed regarding shocks that affected their economic situation noted that the rise of food prices was their main shock. Therefore, the consequences of such issue included households not positively coping and a decrease in the diversity of diet (35% of Egyptians suffer from poor dietary diversity, rising to 58.3% for the poor) [5, 13]. This remains to be the biggest compelling facet of food insecurity because the poorer households decrease the purchase and consume less of the more expensive foods (e.g., meat, poultry, dairy, vegetables, and fruits) and rely heavily upon cheap foods that are dense in calories and have a lower and limited content of nutrients such as subsidized commodities that have an immense relation with obesity in adults. The poor sanitation in rural areas (reaching 65% of households) along with the scarcity of access to health services (reaching 23%) and bad living standards create a type of poverty that has many aspects and dimensions. In urban areas, the weak health services (reaching 27.4%) contribute the most which urges a need to invest in basic services. An 11.9% of the population of Egypt lives in poverty that is multidimensional. The contemporary trends of nutrition are also a big concern, with the most notorious being steady high stunting rates among children under five [5, 13]. The demographic health survey stated that the rates increased from 23% in 2005 to 29% in 2008. The HIECS using a different approach also estimated a high stunting rate for children aged between 6 and 59 months being of 31% in 2011 (where a percent between 30 and 39 is considered “high” by the WHO). Data from HIECS found that in 9 governorates anemia in children aged between 6 and 59 months was approximately 50.2% in 2011. According to a WFP study, anemia in Egypt is related with a substantial drop in future earnings. The conjunction and synchronicity of the high stunting rates, anemia, and obesity according to the HIECS points out the presence of a three-sided burden of malnutrition or a “triple burden.” The rate of obesity among women aged between 20 and 49 is considered high but decreased a little bit to 38.4% in 2011 from 39.2 in 2009 regarding people who are just overweight and from 38.9 to 34.3% regarding heavily obese people. The findings of the HIESC therefore shine a light on the need for more targeted interventions regarding and prioritizing malnutrition in the agenda of the national public health. In an optimum manner, this should include making nutrition-focused interventions mainstream in the primary health care system, to be done by the mobilizing of resources and capacity building to find and address malnutrition through careful monitoring, particularly focusing on children who are under 5 years old as well as women in the lactating process. The subsidization of food has been an essential element to the population in facing crises of food. While it relieves households from the rising prices of food, better targeting of already existing programs is required to focus on the most affected or vulnerable. About 73% of nonpoor households have ration cards for subsidies of food while 19% of poor households do not. In addition, under such economic circumstances of lacking and constrained governmental resources, improving the efficiency and effectiveness of the subsidy system can induce huge savings which can be used in creation of job opportunities, targeted food security, and nutrition interventions. All reforms taken should essentially balance between popular preferences in culture, economic

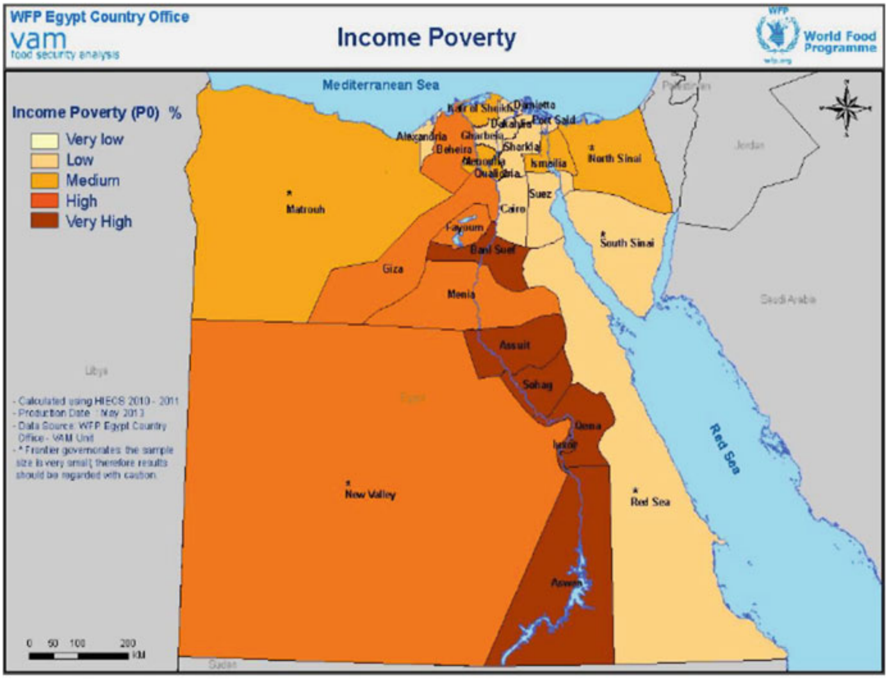

Fig. 5 Income poverty in Egypt in 2011 [5]

necessities and nutritional requirements. As part of a broader strategic development, food security and nutrition strategy, complementary livelihoods and nutrition interventions can occur alongside a gradual transition to social safety nets building on existing programs. Finally, while food availability (namely, domestic agricultural output, net food imports, and national stocks) is currently secure, macroeconomic challenges of recent times and low reserves of foreign currency point out a risk to the stable and regular supply of essential food elements such as wheat. This is amplified by the position of Egypt as a net food importer which includes more than half of its requirement of wheat. The current official policy emphasizes on increasing the production of domestic wheat and its storage capacity but this will need to be complemented by other measures in order to decrease supply chain losses and efforts to secure foreign reserves. The Figs. 5, 6, 7, and 8 show the distribution of poverty level and food insecurity in different governorates in Egypt.

3.2 *Impact of Poverty and Food Insecurity on Land Tenure*

Agriculture is not a major component of the Egyptian economy, it is only contributing 13% percent of GDP even it consumes about 85% of the total water resources.

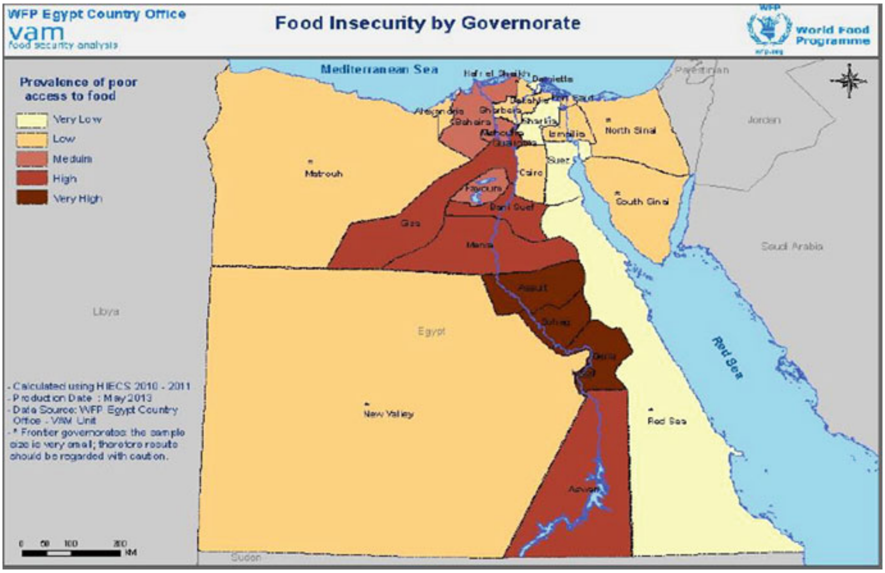

Fig. 6 Food insecurity by governorate [5]

Agriculture represents 33% percent of employment, 45% of them for women which increased in Upper Egypt to over 55% of employment [14].

One of the major problems in agriculture sector in Egypt is the small and tiny farms, whereas the farmer tends to cultivate small areas and make another fragmentation inside these small farms by cultivating more than one crop in these small areas. Another problem is the overuse of pesticides as well as not adding enough chemical fertilizers as recommended in addition to not using the modern technological tools even in land management, irrigation, harvesting and post-harvesting. (Egyptian farmers still use most of pharaoh's machines and tools). As a result, the costs of production are always high due to the high number of labor used and the yield of crops is low. The soil fertility continues to decrease due to the continuous cultivation with limited fertilizers added to the soil which leads to nutrient depletion and land degradation. There is also a lack of shading, storage infrastructure, transportation systems, and market information.

Agriculture, even though it contributes only 14.5% to GDP compared to 30% in the 1960s, it is still a major economic activity in Egypt and plays an important role for many people as sustenance farming. Nearly all agriculture depends on irrigation water [14] (https://www.usaid.gov/egypt/agriculture-and-food-security). In 2010, the total irrigated area covered 98% of the cultivated area. Even the small, more humid areas along the Mediterranean coast require water harvesting or supplementary irrigation to produce reasonable yields. Since 1993, farmers have had the ability to select the crops they grow; previously, the government selected the cropping patterns. Small holdings characterize Egyptian agriculture, with about 50% of

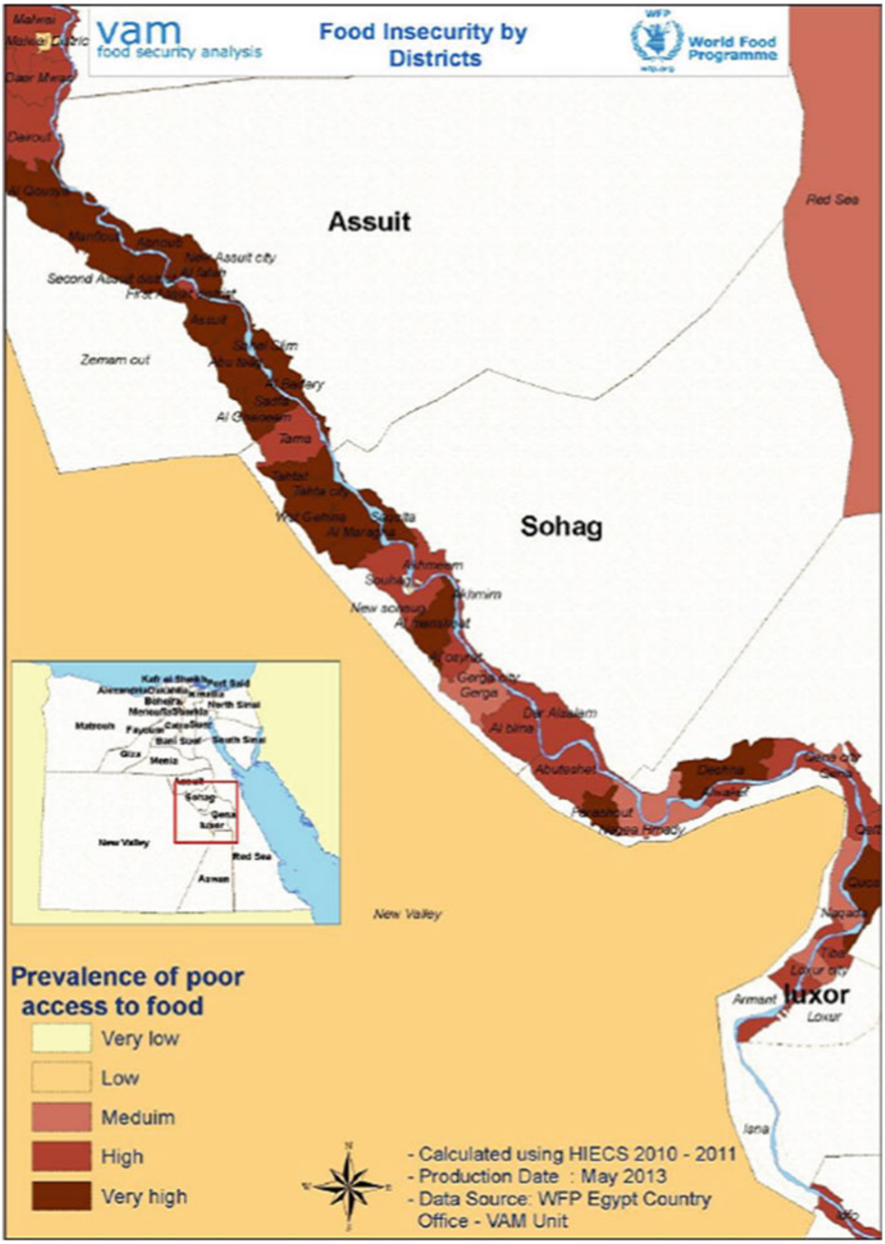

Fig. 7 Food insecurity in Egypt by district [5]

holdings having an area less than 0.42 ha (1 feddan). Urbanization represents a serious threat to agriculture in Egypt, and Tables 2 and 3 show the agriculture land tenure in Egypt and the tenure structure. It is prohibited by law to construct any

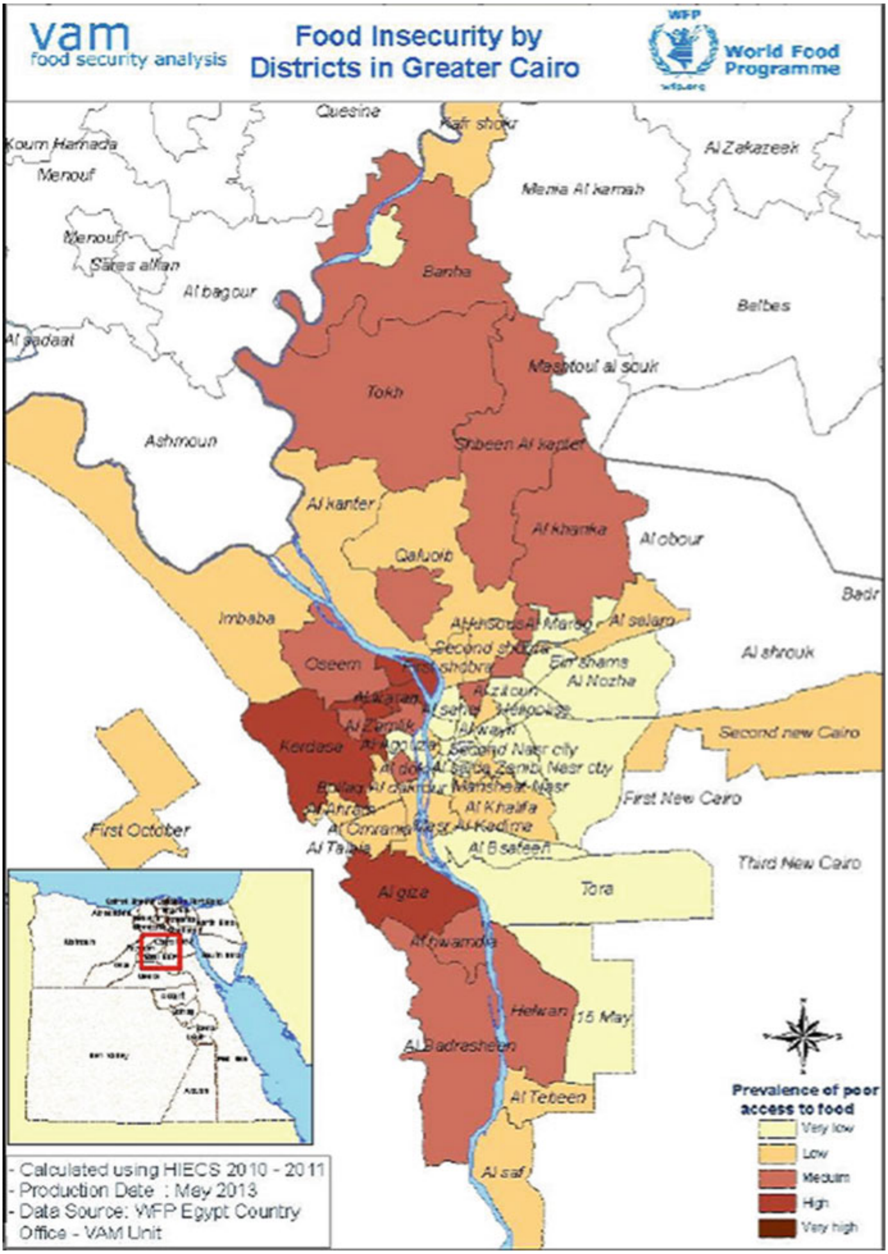

Fig. 8 Food insecurity in great Cairo [5]

Table 2 Land tenure in agriculture sector in Egypt [14]

Area class (ha)	% farms	% area
<0.42	41.12	6.0
<0.84	38.28	28.5
<2.10	15.22	17.8
From 2.1 to 4.2	3.05	22.8
From 4.2 to 8.4	0.41	7.9
From 8.4 to 42 and over	0.92	17.0
Total	100.0	100.0

Table 3 Land tenure structure according to the consensus of year 2000 [7, 15]

Ownership structure	Number of farmers (thousands)	% of total farmers
Without land	824	18.14
Less than 1 feddan	1,616	35.57
1 to less than 2	881	19.4
2–	517	11.38
3–	239	5.26
4–	107	2.36
5–	169	3.72
7–	65	1.43
10–	57	1.26
15–	24	0.54
20–	22	0.48
30–	112	2.46
50–	6	0.12
100–	3	0.06
Total	4,542	

buildings on farmland without a license from the Ministry of Agriculture and Land Reclamation, and violators are prosecuted and face serious penalties.

3.3 *Impacts on Poverty and Population Growth in Land Share Per Capita*

"In 2014, Egypt's gross domestic product (GDP) was estimated at US$ 287,000 million of which the agricultural sector accounted for 14.5 percent" [12, 16]. Food and raw agricultural products represented around 19% of exports in 2014 [17]. Egypt imported 44% of its cereals during the 2009–2011 period and exported cotton, potato, onion, tomato, and citrus. "Food represents 37 percent of Egypt's imports during the same period" [18]. "The country is one of the largest food importers. Prevalence of undernourishment remains below (or close to) 5 percent since 1990 in Egypt" [19].

National efforts to trace the drastic decline of the agricultural land share per person were materialized recently as illustrated in the shocking figures in the report entitled "Mubarak and Urbanization." This report clearly illustrated that the amount of the share of person had decreased drastically as seen in Fig. 9. Although agricultural land area, at the national level, had increased from 5.4 million in 1907 to 8.5 million in 1996, land share per person decreased from 0.48 acres to 0.14 acres [20]. Although land reclamation became one of the Egyptian policies for food self-sufficiency and horizontal expansion, it does not represent more than 25% of the

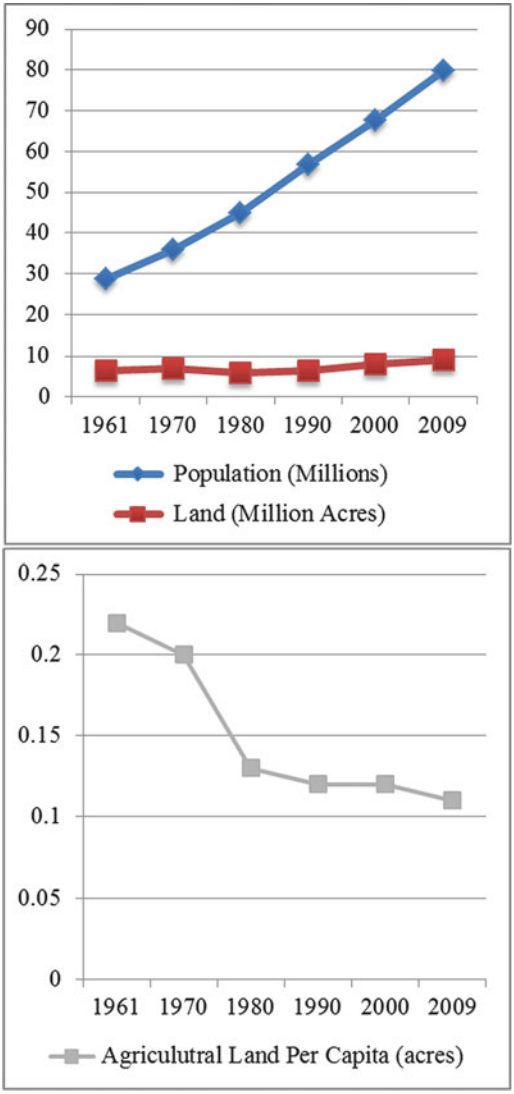

Fig. 9 Population and agriculture land share per capita in Egypt [15]

total current land cultivated outside the valley and the delta, Table 3, and hence losing agricultural land has become a greater danger.

3.4 Land Fragmentation

The land tenure system is a key factor shaping the pattern of resource allocation and the growth of the economy since it has an impact on the distribution of income in rural areas [20]. After the 1952 revolution, the government started the nationalization for the agricultural land for any ownership exceeding 200 acres to improve what they believe in social justice. The government redistributes areas between 2 and 5 acres to the poor to change the shape of land tenure system. By the time, the government decreases the maximum ownership limit to 50 feddans per family to distribute more land to the poorer and beggarly. Some researchers believe in the processes of land reforms, along with the fixed supply of agricultural land turned Egypt into a country of small farms, thus leading to the problem of land fragmentation [20]. (In fact, all the redistributed lands do not exceed 10% from the total land areas in year 1952.) The problem of land fragmentation has been increasing in severity over time. The percentage of holdings of less than 3 feddans has increased from 2.29 million feddans in 1980 to nearly 3 million feddans in 2000. Additionally, average land ownership decreased from 6.3 feddans in 1950 to 3.2 feddans in 1960 and 2.1 feddans in 2000 [7, 21, 22].

To avoid the land fragmentation in the new reclaimed land, the government allows up to a maximum of 200 acres for each family. Thus, Egypt actually has a small ownership system in old alluvial lands along with large ownership in the new reclaimed land [20]. According to Richard [23] and Shehata and Mohamed [21], land fragmentation leads to a 12% loss in the most fertile agricultural land. In addition, land fragmentation limits agricultural productivity as small peasant farms and large estates face different factor prices. Some farmers are able to adopt new technologies more readily than small peasant farmers, which has an adverse impact on the productivity of the old fertile lands [7, 20, 21]. Table 4 shows the share of agriculture land from 1907 to 1996.

3.4.1 The New Face of Land Fragmentation in Egypt

From my experience during 40 years of work in the different fields of agriculture sector in Egypt, land fragmentation in Egypt is not only the tiny and small farms but

Table 4 The share of agriculture lands in 1907–1996 [20, 21]

	1907	1917	1927	1947	1969	1970	1980	1982	1986	1996
Agriculture land in acres/million	5.4	5.2	5.28	5.76	5.60	5.75	5.88	5.9	6.02	8.5
Per capita	0.48	0.40	0.33	0.20	0.22	0.17	0.14	0.12	0.12	0.14

also the cultivation of these small areas by more than one crop. The farmers follow this trend to avoid risks from unexpected decline of crop prices for one crop. This is what we call “fragmentation inside fragmentation” or splitting of already split areas. For example, it is very common to find only one acre cultivated by tomato crop beside peas and carrots in a separate area inside the acre (not loading system). Moreover, you may find cabbage beside Taro (scientific name: *Colocasia esculenta*), or alfalfa beside wheat, and bean beside lentil, peas, and carrot, and so on. All these are considered as a kind of fragmentation or hidden or new face of fragmentation. In this trend, Egypt needs to apply crop rotation system to collect these tiny and small cultivation in one crop every season in the collected area ranged between 100 and 150 acres in the same village. We also suggested to create “Bank of Lands” to allow loans for some farmers to buy the surrounded lands to make some aggregated or collection of these tiny and small farms into a larger one unit farm.

4 Land Resources in Egypt

Land is considered the most limiting resource for agricultural production in Egypt. Officially, the total agricultural land in Egypt currently is 8.6 million feddans (9.1 million acres or 3.6 million ha), representing 3.6% of total Egypt land area (238 million feddans or million km^2), of which 3.2 million ha lies within the irrigated alluvial soils in Nile Valley and Delta.

The agricultural systems in Egypt contain three different production zones. The first one is the fertile alluvial soils in the Nile Valley and Delta with a total area ranged between 6.1 and 6.5 million acres. The second production system is the new reclaimed soils in the delta and valley fragments (edges) especially in the western and eastern delta. This area ranged between 1.5 and 2.5 million acres of low fertile soils, but it applies modern agriculture more than the old soils. The third system is the rainfed agriculture in small strip in the sandy soils in western cost from Alexandria governorate to Matrouh governorate near the border with Libya Arab Republic along with some areas in the north Sinai. This land covers about 1 million acres [7, 21].

4.1 Major National Reclamation Projects

4.1.1 The North Sinai Development Project to Reclaim 620 Thousand Feddans

The North Sinai Agricultural Development Project (NSADP) of the Egyptian Government proposes the reclamation of an estimated 400,000-feddans gross (415.2 thousand acres) of desert situated along the Mediterranean coast of the Sinai. The project aims at increasing agricultural production through agricultural and stock development, improving income distribution, and generating employment through the settlement of smallholders from the overpopulated rural areas of Egypt [24].

El-Salam Canal Project

The El Salam Canal project is being implemented in two main phases: the first covers 220,000 feddans, and the second covers 400,000 feddans. The total cost of this project is roughly 6 billion Egyptian Pounds (LE), in addition to 1.5 billion LE to establish 55 villages throughout the project area, each of which is to be built over a 23-feddan area. The intake of the Canal was chosen in this site to circumvent inhabited areas, averting, as much as possible, dismembering agriculture land, in addition to making use of the current bridges. The project consists of two phases [24]:

The first phase was implemented in the west of Suez Canal and included: the construction of the Faraskour barrage on the Damietta branch of the River Nile. This includes digging the Canal, 87-km long until west Ismailia/Port Said highway, passing through Damietta, Daqahleya, Sharqueya, and Port Said governorates. There is also the construction of three pumping stations, in addition to about 15 siphons at cross points with drains and construction of sub-outlets on the course of the Canal. The infrastructure of the first stage was completed at an estimated cost of 160 million LE.

The second phase was partially implemented in the east of Suez Canal. The work that was implemented was the construction of a siphon beneath the Suez Canal, 27-km south of Port Said. This siphon has 4 tunnels, each of which is 750-m long with an inner diameter of 5.1 m, at a depth of 45 m beneath the Canal. In addition, they were fixing a pipeline to transfer the water of the main canal to Beir Al-Abd, Al-Saroe, and Al-Quareir. To achieve this, the works need to construct five pumping and lifting stations by digging about 35 km of east Suez Canal. They are currently working on the construction of irrigation and drainage subnetwork to serve 400,000 feddans.

Water Sources of El-Salam Canal

The water of El-Salam Canal is a mixture of 2.11 billion m^3/year of the Nile fresh water from the Damietta branch mixed with 2.34 billion m^3/year of the drainage water. So, the total quantity of water is nearly 4.45 billion m^3/year with a blinder ratio almost of 1:1. This ratio was determined to make the Total Dissolved Solutes (TDSs) between 1,000 and 1,200 mg/L to be suitable for most cultivated crops [6, 25], and the Figs. 10 and 11 show the El-Salam irrigation canal route.

Fig. 10 El-Salam Canal to cross Suez Canal [25]

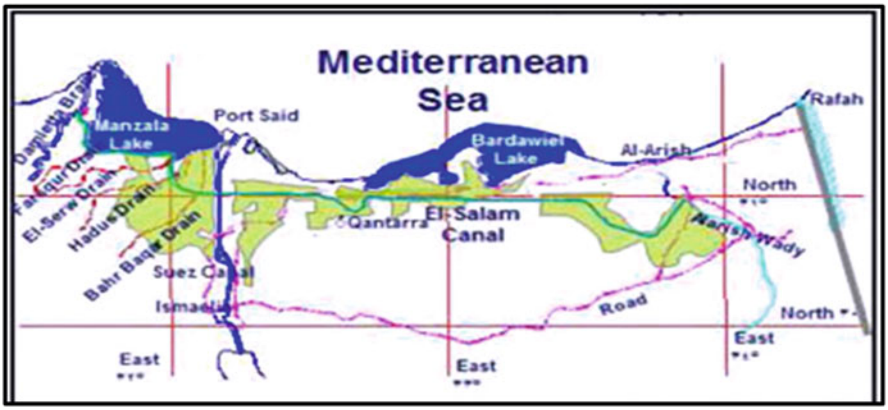

Fig. 11 El-Salam Canal North Sinai development project [25]

4.2 *Toshka Project to Reclaim 540 Thousand Feddans*

The total arable land in the south valley from lake Nasser to new Valley governorate (Wahate in Arabic or Oasis) is almost 3.3 million feddans (acre). The target in the first stage of reclamation and cultivation is only 540 thousand acres and actually it will be the first and last stage. The reason is the hot weather leads and corresponding high water consumption for agriculture which is too high under the severe water shortage in Egypt. This project costs Egypt officially almost 9 billion Egyptian pounds at a price level in 1997, but actually almost of 40 billion LE. Toshka Region is located southwest of Aswan, about 1,000 km south of Cairo, Fig. 12. The Toshka Depression has an average diameter of 22 km which could receive the overfloods that may reach the Aswan High Dam with a capacity of 120 billion m^3. Thus, Toshka

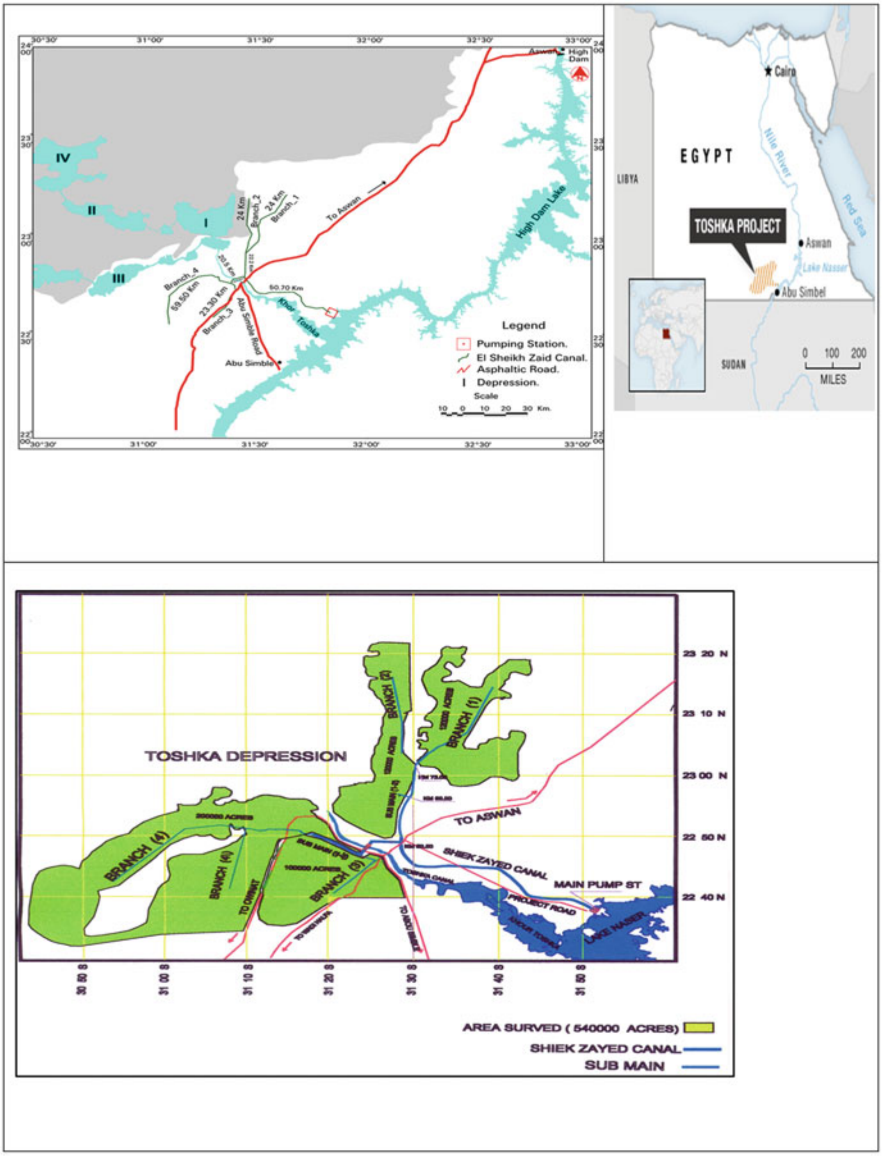

Fig. 12 Toshka project in the southwestern desert (top), the main canal, and its four branches (down) [26, 27]

Bay is a natural drain of Lake Nasser. Toshka basically is a free spillway discharging the water of Lake Nasser when it exceeds its highest storage level of 182 m. It is a 22-km long, manmade canal connecting Toshka Bay with the Toshka Depression and works as a safety valve for Lake Nasser, upstream of the High Dam. Toshka Canal is the heart and soul of the Toshka Project. It is a new canal conveying excess water from Lake Nasser through a giant pumping station that elevates the water to flow through the canal to reclaim and irrigate 540 acres. The Toshka project began with the main pumping station, also known as Mubarak pumping station (MPS), and is considered as the largest pump station in the world [6, 26–28]; Fig. 12 shows the Toshka project location and area.

4.3 East Oweinat Project to Reclaim 250 Thousand Feddans

The East Oweinat project was planned to create 250,000 acres of new farmland in the southwestern desert by exploiting underground reserves. The test study proved that the groundwater in East Oweinat is enough to cultivate this area for at least 200 years. Toshka and East Oweinat are collectively known as the South Valley Development Project. The estimated government cost is LE.3 billion to cultivate about 250,000 acres using a Nubia Sandstone aquifer system in southern Western Desert of Egypt. According to chemical analysis, the underground water is ¾ that contains low salt content. Thus, it is suitable for irrigation purposes. The East Oweinat area is one of the most important developmental areas and has drawn considerable attention from the Egyptian government in the last few decades. The soil and groundwater resources of this area meet the requirements of reclamation projects and implementation of new communities. The ongoing development of East Oweinat is largely in the southern part of the Western Desert of Egypt, located about 880 km from Cairo and 400 km to the southwest of the Kharga Oasis [29, 30] (Fig. 13). The government established an international airport in the East Oweinat to encourage farmers to export their products directly to European Union countries. Most produced crops such as cantaloupe, watermelon, sweet melon, potato, and strawberry were already being exported.

5 Water Resources

Water availability is a key challenge facing sustainable agriculture in Egypt. Egypt's water resources are highly limited, whereby total annual renewable water resources are estimated at 62 billion m^3, and the water resources include the reuse and recycled water at 73 billion m^3. Renewable water resources are estimated at 57.3 BCM per year, almost 97% of which originate from external resources [3, 15]. The Nile River is the major source of surface renewable freshwater. With an annual quota of 55.5 billion m^3, the Nile supplies 96% of renewable fresh water resources. Other sources

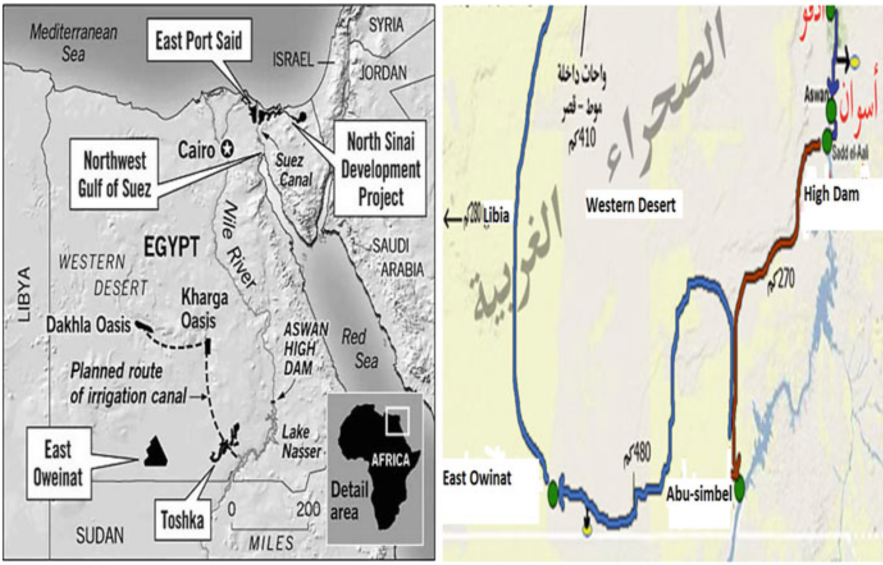

Fig. 13 East Oweinat reclamation project (left) and the road to reach it (right) [6]

of water supply in Egypt include groundwater in the Nile Valley and Delta and Western desert (5.5 BCM), and rainfalls that get useful from it in the Delta (1.3 BCM). In addition to renewable water, Egypt depends on other nonrenewable sources of water that include reusing the agricultural drainage water, recycling sewage water, in addition to small amounts of the desalination of seawater in some resorts on the Red Sea coast and south Sinai [6, 15] (http://www.fao.org/nr/water/aquastat/countries_regions/EGY/, http://www.fao.org/ag/agp/agpc/doc/counprof/egypt/egypt.html).

Water shortage affects the food security in Egypt along with limiting the processes of greening deserts. Thus, Egypt imports about 236 m^3 of water per capita annually in the form of food (virtual water) [31] to face the water shortage and food insecurity.

Water resources in Egypt are subject to inefficiency in utilization. Large amounts of irrigation water are actually being lost during water delivery from Aswan Dam to the Delta lands. According to Hamza and Mason [31] and Table 5, the loss of water from delivery systems was 20% in year 2000, increased to 31% in year 2009. This loss that ranges between 13 and 19 BCM/year from the open, and silty irrigation canals was attributed to evaporation, and deep and horizontal seepage along with the spread of water weeds along the canals [7]. This is a regular and common occurrence in the open uncemented irrigation canal which losses between 25 and 30% of its water during delivery in addition to another 10–15% loss in the field. Egyptian farmers are still using ponding irrigation system since the time of the Pharos, which results in excessive use of irrigation water and excessive loss up to 50% of its water uses in the agriculture sector. The reuse of agriculture drainage water in the Nile

Table 5 Total loss in delivery water in distribution canals of Nile valley and delta [31]

Period	Irrigation water			Total loss	
	At Aswan Dam	At canals	At fields	Amount	%
1990	56.17	50.26	42.72	13.45	23.95
1995	50.15	49.11	48.07	2.8	4.15
2000	52.50	47.25	39.38	13.12	24.99
2005	46.13	35.44	29.78	16.36	35.46
2006	59.70	47.08	40.94	18.76	31.42
2007	61.14	48.14	42.08	19.06	31.17
2008	62.10	48.85	42.85	19.25	31.00

Source: Bulletin of Water Resources and Irrigation (various issues) [31]

Table 6 Total water resources in Egypt in year 2005 and 2017 [6, 31]

	2005 (billion m^3/year)	2017 (billion m^3/year)
Nile water quota	55.5	55.5
Groundwater	0.9	4
Rain on the delta lands	1.30	1.30
Desalinated water	0.05	0.10
Reuse/increase in efficiency		
Reuse of agricultural nonreclaimed drainage water	7.5	7.4
Reused of non-treated sewage water	1.4	2.4
Nile groundwater (reused Nile water)	6.10	8.4
Improved irrigation system, and changes in crop patterns (expected and not works so far)		9.7
Total amount of water available	72.75	90.1

Valley and Delta increases the water efficiency of ponding irrigation systems to roughly 74% instead of 50% [6]; Fig. 6 shows the loss in irrigation water (Table 6).

6 Expected Impacts of Climate Changes

Climate change is already impacting food security and nutrition and will have further and larger impacts into the future effects on agroecosystems including impacts to agricultural production, the people and countries depending on this, and ultimately consumers through increased price volatility. The impacts of climate change on food security will happen due to increase of evaporation, transpiration, and contamination which means that the production of the same amounts of foods will require more water.

This leads to drawing some important observations as follows:

1. The first and the most impacted are the most vulnerable populations (poor), with livelihoods vulnerable to climate change (depending on agriculture sectors).
2. Reducing vulnerabilities by adaptation will be the key to reduce final impacts on food security.

From an agronomic perspective, favorable conditions for crops and other species will move geographically. Optimizing these conditions will thus require changing crops types and the effect of climate change on crop yields will depend on many parameters: temperature, precipitation patterns, and atmospheric CO_2 increases given the stimulatory effect of elevated atmospheric CO_2 on plant growth. This will cause an increase in the rate of leaf photosynthesis and thus improving the efficiency of water use in most cases, especially for C3 crops like wheat and rice. There are uncertainties related to the interactions between CO_2, nitrogen stress, and high-temperature effects. The response of crops is genotype-specific. Recent results also confirm the damaging effects of elevated tropospheric ozone on crop yields, with estimates of losses for soybean, wheat, and maize in 2000 ranging from 8.5 to 14%, 4 to 15%, and 2.2 to 5.5%, respectively [32].

According to Müller and Elliott [33], by 2100 the impact of climate change on crop yields for high-emission climate scenarios ranges between −20 and −45% for maize, between −5 and −50% for wheat, between −20 and −30% for rice, and between −30 and −60% for soybean. Assuming full effectiveness of CO_2 fertilization, climate change impacts would then range between −10 and −35% for maize, between +5 and −15% for wheat, between −5 and −20% for rice, and between 0 and −30% for soybean. If nitrogen limitations are explicitly considered, crops showed less profit from CO_2 fertilization [33] and amplified negative climate impacts.

A recent multimodal study using IPCC high scenario of end-of-century radiative forcing of 8.5 W/m^2 found a mean effect on yields of four crop groups. These crops are coarse grains, oilseeds, wheat, and rice, which represent about 70% of world crop cultivated area, of −17% globally by 2050 relative to a scenario with unchanging climate [34]. The hypothesis for this multimodal assessment combined the most extreme radiative forcing scenario with an assumption of limited CO_2 fertilization effects in 2050.

Wheat and maize especially in the European Union and the USA are negatively affected by climate change and global warming [33].

Maize, sorghum, and millet occupy the highest crop areas for all of Africa, but with considerable variation across regions. According to the study of International Food Policy Research Institute (IFPRI) on impacts of climate change on crop yields in Africa [35]. The report shows significant geographical variation of impacts; whereas most climate change impacts will be negative. In addition, some impacts will be positive on yield crop especially in areas that projected increases in precipitation, and in some elevated (high altitude) areas that will be able to be cultivated due to warmer temperatures.

7 Conclusion and Recommendations

Egypt is not classified as a country of plenty agricultural resources of water and arable lands; whereby, its people live in only 7% of the total area. The total agricultural lands are only 3.6 million ha, and the available renewable water is only 62 BCM, not enough for 92 million. The shared water per capita is only 674 m/year, under the global water scarcity level. Egypt imports more than 60% of its essential foods that cost more than 7 billion dollars/year and include wheat, edible oil, sugar, maize, lentil, bean, red meat, butter, and milk powder. The impacts of food insecurity cause increased poverty, which reached 27.8%, soaring of food prices, and small farm ownership of agriculture lands. Egypt needs to restructure and reform agriculture related policies to produce more food and to achieve an advanced degree of food security, which can be achieved in crops such as lentil, bean, sugar, maize, and oilseed and particularly in wheat. In 2050, the Egyptian population is projected to be 135 million and the water shortage will reach 75 BCM, thus food insecurity is expected to be more than 75% of the total essential needed food.

Even under the current situation of water shortage, Egypt could achieve good progress in food security. The restructure of agriculture policy is strongly needed. For example, in the summer crop season, Egypt suffers from the shortage of oilseed that is imported 100% of its needs. Another deep shortage is in yellow maize which is imported about 9 million tons/year, while the current agriculture lands permit to cultivate sunflower and soybean on about 1.5–2 million acres and also to replace the white maize by yellow maize in another 3 million acres. This has more feasibility because there is no need for white maize cultivation in Egypt and even no market. To achieve not less than 80% self-sufficient of the essential summer crops, the 6 million acres of the essential economic crops could be planted as follows:

1. 1.5 million acres for rice cultivation for complete food security.
2. 0.5 million acres for cotton.
3. 1.5 million acres for sunflower and soybean.
4. 2.5 million acres for yellow maize.

The winter season in Egypt is backed so much according the competition between wheat and green forage (clover) for the livestock needs, in addition to sugar beet, barley for molt industry, faba bean which represent essential food for most people, and lentil. We suggest the following crop pattern to achieve a part of food security in faba bean (70% imported) and lentil (100% imported) as follows:

1. 3 million acres for wheat.
2. 1.5 million acres for winter green forage (clover).
3. 0.5 million for sugar beet.
4. 0.5 million for faba bean (for complete food security).
5. 90 thousand acres for lentil (for complete food security).
6. 410 thousand acres for barley.

The restructure of agriculture policy in Egypt could perform a great part of food security in Egypt within a short time. Moreover, the projects of land reclamation and agriculture extension which targeted another 1.5 million acres could help so much in decreasing food gape in Egypt.

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Part V
Assessment of Water Resources

Evaluation of Water Resources Qualities for Agriculture Irrigation in Abu Madi Area, Northern Middle Nile Delta

Zenhom E. Salem, Ayman M. Al Temamy, Mohamed K. Salah, and Moamena Kassab

Abstract Twenty-six samples were collected from the shallow and the deep groundwater and surface water (agricultural drains and irrigation canal) to evaluate the water quality in Abu Madi area, middle Nile Delta. Irrigation water quality parameters were classified into individual parameters and integrated parameters. Salinity, sodium chloride MH, RSC, pH, and alkalinity hazards are considered as individual parameters. The integrated parameters include Welcox's classification, US Salinity Laboratory Staff classifications, and irrigation water quality (IQW) index. Twelve samples of the deep groundwater, two samples of the shallow groundwater, and two samples of the surface water have salinity hazards. Regarding sodium hazards, Na%, SAR, and Kelley's index calculated values mostly showed hazardous effect; however, RSC and PI values did not show hazardous effect. All the collected water samples except sample 2 have undesirable chloride concentrations (<200 mg/l) and are mostly characterized by cation–anion exchange reaction. Most of the collected samples have unsuitable MH values, corrosive CR values, alkaline pH values, and slight to moderate carbonate alkalinity hazards. The collected water samples are mostly situated in IQW moderate suitability range for irrigation and very satisfactory to satisfactory for all classes of livestock and poultry.

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Keywords Abu Madi Area, Groundwater, Irrigation water quality index, Nile Delta, Surface water, Water quality

Contents

1 Introduction

The irrigation water quality depends on the sort and the quantity of dissolved salts. These salts come from weathering of rocks and soil as natural sources and/or anthropogenic origins like industrial and domestic sources. The soil water originated from irrigation process is greatly affected by plant consumption and evaporation process. The soil salinity increases with the increase in irrigation water salinity as well as the degree of evaporation. Therefore, the quality of the irrigation water should be considered as a vital factor in the sustainable administration of the soil resources and the agricultural production [1].

It is known that the problems related to irrigation water depend on various factors including the kind of the soil and the plant type, the degree of climate aridity of the region, and also the agriculturist who uses the water. Therefore, the factors affecting the irrigation water quality could be classified into the following significant groups: (a) salinity risk, (b) invasion and permeability issues, (c) toxicity hazards, and (d) miscellaneous problems [2]. The toxicity risks can additionally be grouped into problems related with particular ion and also the existence of trace elements and heavy metals. Salinity risk happens when salts begin to gather in the root zone of the plant decreasing the quantity of water accessible to the roots. The increase in the percentage of reduction in water availability to the plants can affect the crop yield. The decreases in crop yield happen when the salt content of the root zone ranges to the degree that the plant is not any more ready to separate adequate water from the salty soil. Whenever this water stress is prolonged, plant moderates its growth, and drought-like effects begin to create [2].

Water salinity could be determined by measuring either the electrical conductivity (EC) or total dissolved solids (TDS). As a rule, the measure of water accessible to the yield gets bring down when the electrical conductivity is higher. Under such conditions, the soil is wet, but the plant is under what is called drought. Waters with EC value less than 700 μS/cm are thought to be of good quality for irrigation.

The invasion rate of water into the soil is a factor of numerous parameters including the irrigation water quality and the soil parameters. Sodium content is the major water quality parameter that affects the soil permeability, while the soil parameters are structure, compaction, and the content of organic substance. The decreased penetration rate begins to demonstrate negative effects when water can't invade to the root zone parts to the degree that the plant requires.

When soil permeability decreased, water salts accumulate on the soil surface. Higher salinity and low permeability prevent crops from adsorbing the required water quantity for growth which lead to crop yield reduction. The two most basic water quality factors that impact the ordinary rate of invasion of water are the salinity of water and the relative concentrations of sodium, magnesium, and calcium ions in water that is otherwise called the sodium adsorption ratio (SAR). The SAR estimation of irrigation water evaluates the relative extents of sodium (Na) to calcium (Ca) and magnesium (Mg). A combination between EC and SAR is utilized to evaluate the potential penetration risk that may create in a soil. While low-salinity water with high SAR content has an extreme invasion problem, high-salinity water with low SAR value does not encounter any penetration issue. As both salinity and SAR work in the meantime, the levels of sodium ion in water are the deciding parameters for potential penetration problem. It is additionally important to take into consideration that these dangers ordinarily happen in the first few centimeters of the soil and are connected to the structural stability of the surface soil and its low calcium content in respect to that of sodium [2]. It has been estimated that when soil is flooded with waters of high sodium content, a high sodium surface is accounted for to create which thus debilitates the soil structure. The high SAR esteems negatively affect soil structure because of the scattering of clay particles.

Certain ions, for example, sodium, chloride, and boron, cause poisonous quality defect for plants when they are found in raised values in water or in the soil. When these ions are taken up by the plant and gather to sufficiently high concentration to cause plant destruction or yield diminishment, they are thought to be dangerous. The level of harmfulness is particular to plant type and take-up rate. It is realized that ion toxicity is normally joined by different issues, for example, salinity and infiltration risks [2]. The soil and the groundwater are strongly impacted by the environmental and climatological variables. These variables could expand the disintegration of various minerals in water and could cause poisonous impacts [3]. The occurrence of some trace elements and different heavy metals in the used water causes soil contamination and decreases the quality of irrigation water because of its ability to resist various types of degradation in the environment [4].

In contrast to other potential contaminations that obviously develop on the soils, trace elements and heavy metals can slowly accumulate to greatly high poisonous concentrations before influencing the plant. Moreover, the concentration increase of these metals in the soil upper layers would likewise infiltrate to the down layers and in the end reach the groundwater table and fundamentally reduce the groundwater quality. It has been noticed that components, for example, cadmium, copper, lead, cobalt, manganese, nickel, and zinc, could be accumulated in plants irrigated by water affected by industrial contaminants [5]. Arsenic is thought to be among the most harmful components for crops. It has been reported that arsenic could be consumed by different yields at various rates. Especially, it could be easily gathered in the leaves of the yields and could be of great effect in humans when the leaves of such products are used [6]. It was additionally inferred that the utilization of wastewater in irrigation purposes leads to accumulation of heavy metals in the soils which could harm the human health in the long run [7].

The contamination of soils by heavy metals continues for hundreds or thousands of years even if the source of contamination was terminated. It is also important to note that these elements could exist naturally in the groundwater without human practices. In light of these contemplations, the trace element concentrations of irrigation waters should be considered when evaluating the groundwater for different uses. There are no standard levels for trace and heavy metals in irrigation water, but Ayers and Westcost [2] and Crook [8] have given concentration limits for long- and short-term utilization for irrigation water containing such elements. Recently, there are some parameters that must be evaluated well in irrigation water. These elements are called miscellaneous parameters such as pH, bicarbonate, and nitrate–nitrogen.

The primary goal of this investigation is to assess the water resource quality for irrigation purposes in Abu Madi area, northeastern middle Nile Delta, as this area suffers from surface water shortage.

2 Previous Work

Groundwater quality in the Nile Delta is highly influenced by the agricultural and the industrial activities. Taha et al. [9] assessed the quality of water resources in the southeast Nile Delta new communities. The outcomes demonstrated that the accessible water resources were grouped into various classifications given the substance of significant cations, anions, and total dissolved salts. El Arabi et al. [10] presented the spatiotemporal varieties of groundwater quality of the northern Nile Delta aquifer utilizing multivariate statistical procedures. They found that four components were controlling the groundwater quality in the examination time of 4 years (2007–2010). Two of the variables were at first allocated to normal mineralization and salinity, while the other two were identified with contamination because of industrial and agricultural practices. The ArcGIS was used to distinguish the spatial varieties of the four components. The investigation suggested a reasonable ecological treatment for the modern wastes.

Grouping of the groundwater quality or its chemical composition can offer incredible focal points particularly in groundwater regional administration and gives a short, snappy handling elucidation for many of complete hydrochemical analysis collections, understandably showing the outcomes. GIS spatial clustering system is utilized to the hydrochemical information to distinguish over land space the distinctive homogenous groundwater quality and sort classes shown in a territory north the Nile Delta [11]. Likewise, Mogren and Shehata [12] utilized GIS to exhibit the groundwater vulnerability mapping of the quaternary aquifer framework in the northeastern piece of Nile Delta. GIS layers have been made to embrace the most characteristic criteria for exploring the groundwater degradation patterns from sea level ascent and seawater interruption. Groundwater is an essential source of drinking in rural regions in Egypt. Hence, it is basic to evaluate the quality of water proposed to be utilized for drinking purposes since clean drinking water is fundamental for life.

A lot of consideration has been paid to the groundwater pollution [13–15]. Sharaky et al. [15] investigated the groundwater hydrogeochemistry in the western Nile Delta aquifers to acquire extra data on the probable pollution with different chemical components. They inferred that the freshwater in the western Nile Delta region is primarily packed in the central eastern parts, and the majority of the groundwaters are situated in the high-salinity and low-sodium risk zones. Agrama and El-Sayed [13] assessed the surface water quality in the western Nile Delta by utilizing the Canadian Council of Ministers of the Environment Water GIS-Based Spatial Distribution Quality Index (CCMEWQI). The GIS was utilized for mapping the WQI varieties in various channels. The outcomes demonstrated a range for various site areas because of the reality of mixing low-quality water of agricultural drains with waterway freshwater in the investigated region. They suggested that water use in the investigation region ought to be limited because of its quality or to enhance the water quality by expanding the freshwater release or lessening the water mixing proportion with drains.

Armanuos et al. [16] investigated the factors governing the groundwater quality in the western Nile Delta aquifer. They utilize the multivariate statistical strategy. The outcomes demonstrated that there were four factors that record for 77% of the total difference in the hydrochemical data. The first and second factors were identified with mineralization, mining, and salinity because of saltwater interruption. Alternate components were related to different human activities. They suggested that the experts should take essential activities to control the contamination of the groundwater in the area. Additionally, Armanuos et al. [17] evaluated the groundwater of the western Nile Delta, Egypt, for drinking purposes by utilizing the water quality record. They utilized the WHO and Egypt models (ES) as a kind of perspective to decide the appropriateness of groundwater for drinking purposes. The outcomes demonstrated that around 45.37 and 66.66% of groundwater wells fall in the good drinking water zone as per WHO and Egypt standards. Likewise, 37.03 and 15.07% fall in the poor drinking water zone as indicated by WHO and Egyptian standards, respectively, and 9.25 and 11.2% fall in unfit for drinking class as indicated by WHO and Egyptian standards, respectively. They presumed that human practices are the major cause for fresh groundwater quality degradation in the Nile Delta aquifer.

Negm and Asaad [18] utilized the multivariate statistical method of groundwater quality to explore the factors governing the groundwater quality in the western Nile Delta aquifers. They additionally introduced the reasonableness of groundwater in the area for drinking and irrigation. Egyptian and WHO were utilized as a reference for the appropriateness of water for drinking purposes. TDS, SAR, Na %, RSC, Mg %, PI %, KI, CRI, and CR were utilized to assess groundwater quality for irrigation. ArcGIS was used to recognize and picture the spatial characterization maps of various parameters. Multivariate examination demonstrated the presence of up to four critical elements which represent 77.0% of the total fluctuation of hydrochemistry information. The WQI (water quality index) demonstrates that 45.37 and 66.67% of GW wells fall in good drinking water classes as indicated by WHO and Egyptian standards, respectively. As indicated by estimations of TDS, RSC, SAR, and PI, over 58.83% of groundwater wells are reasonable for irrigation.

Salem et al. [19] mentioned and stated that "One hundred sixty-nine groundwater samples were collected, chemically analyzed, and classified into shallow, intermediate, and deep zones to evaluate the vertical and lateral change in groundwater quality in the central part of the middle Nile Delta. To estimate the groundwater suitability for drinking, parameter's concentrations were evaluated according to WHO drinking water guidelines to delineate the samples of desirable and undesirable range in every zone. According to the computed WQI, most of the shallow groundwater is unsuitable for drinking, intermediate groundwater zone is mostly suitable, and only 48% of the deep groundwater quality is of good quality. They also evaluated the groundwater suitability for irrigation using TDS, Na%, SAR, RSC, Cl, KI, PI, MH, CAI, CR, and irrigation water quality index (IQW). The groundwater in the central Nile Delta is mostly of medium suitability where a number of samples which fall within this class are 36 (65.5%), 29 (64%), and 34 (51%) for the shallow, intermediate, and deep groundwater. Water samples have good irrigation quality which increases downward where 15 (27.2%), 13 (29%), and 32 (48%) of the samples are recorded in this class, respectively. Samples belonging to the poor quality class are mostly located in the northern part, and its sample numbers are 4 (7.3%), 3 (7%), and 1 (1%), respectively."

Salem et al. [20] surveyed the effect of the human practices on the hydrochemistry and quality of the groundwater under Nile Delta villages. According to the WHO guidelines, the determined concentrations of the hydrochemical elements were spatially distributed, and drinking water quality index was calculated. The tested groundwater demonstrated variable quality and was grouped into three clusters. Cluster A was described by higher concentrations of TDS, electrical conductivity (EC), potassium, magnesium, sodium, calcium, sulfate, chloride, bicarbonate, Mn, Zn, P, NH4, Ba, and unfit WQI character. Low water quality of this group was caused by the impact of El Gharbia drain and seawater interruption. Cluster B included samples that had moderate mean ion concentrations and higher concentrations of Fe, Sr, and Si contrasted with the other two groups. The last group of major ion concentration order was sodium > calcium and chloride > bicarbonate. WQI of this cluster shifts from poor to very poor to unfit. Group C cluster had the lowest ion concentrations and was ruled by Ca > Na > Mg and HCO_3 > Cl. WQI of the vast majority of this sample group was good. Unwanted concentrations of arsenic and ammonia indicated coordinate penetration from septic tanks or potentially leakage from the channels. They recommended water treatment to be done before utilization of groundwater from under the Nile Delta towns as a result of human effects.

Geriesh and EL-Rayes [21] examined the pollution of the shallow groundwater under south Ismailia City villages in the eastern part of the Nile delta. They estimated that the real source of the groundwater pollution was the leakage from the ineffectively built septic tanks; therefore, the human practices were the major source of higher concentrations of nitrates and heavy metals as well as the high bacterial count in the shallow groundwater. Emara et al. [22] found that the industrial activities, wastewater drains, and fertilizers are the major sources of groundwater contamination in the water-bearing aquifer of the quaternary aquifer under some rural areas in Giza Governorate of Greater Cairo, Egypt. In the central Nile Delta region, the majority of the towns are unsewered; therefore, the used water for local reasons for existing is stored in the septic tanks and misleadingly revives the groundwater causing water logging and groundwater contamination. Salem [23] incorporated the water level, sedimentological setting, stable isotopes, subsurface temperature, and hydrochemistry information to research and assess the reasons of the groundwater contamination under Mehallet Menouf village, El Gharbia Governorate, Egypt.

3 Study Area

The study region lies in the northeastern sector of the middle Nile Delta between 31.39N and 31.51N and 31.28E and 31.51E (Fig. 1a). It is described by hot summer and warm winter. The mean yearly precipitation is around 40.4 mm, the mean relative humidity percent is 65.4%, and the evaporation rate is around 7.7 mm/d. The surface of the area was occupied by sand dunes with an average elevation about 22 m above sea level. Recently, the area was subjected to different kinds of

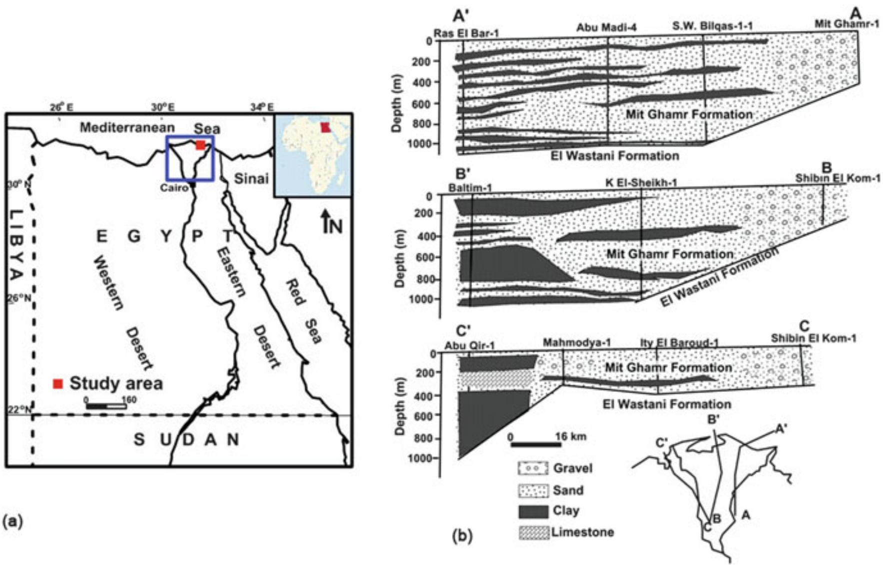

Fig. 1 Location map of the study area (**a**) and hydrogeology of the Nile delta (**b**) [24]

reclamation. Therefore, the sand dunes were removed and replaced by agricultural, industrial, and fish farming projects. Since the surface Nile water does not adequately reach to the end of the irrigation canals, groundwater could be considered as an alternative water resource. Agricultural and industrial investment projects in the region require supplementary water resources. Since groundwater is a decent option, many wells were constructed in the area. In spite of the fact that the groundwater salinity in the Nile Delta increases northward reaching hypersaline degree [25], it was astonishing to locate an artesian aquifer with brackish groundwater with levels ranging from 0.5 to 1.25 m over the ground surface in the coastal area of Abu Madi region [26].

The groundwater quality in the Nile Delta is influenced by seawater intrusion from the north and neighborhood surface contaminants (e.g., Javadi et al. [27]; Abdelaty et al. [28]; Hashish et al. [29]; Nofal et al. [30, 31]). Numerous scientists conducted their research to investigate the extent of the groundwater salinity in the northern coastal part of the Nile Delta due to seawater intrusion. On the other hand, the occurrence of low-salinity groundwater in the study area was explained by Salem et al. [24] as submarine groundwater discharge depending on hydrogeological, geophysical, and hydrogeochemical criteria. The Quaternary Nile Delta aquifer is a semi-confining characters and is the principal resource of groundwater in the Nile Delta region [32]. It occupies the entire Nile Delta with thickness range from 200 m in the southern parts to 1,000 m in the northern parts as shown in Fig. 1b [33]. The basin of the Nile Delta contains a thick succession of Neogene–Quaternary sediments. The Holocene Bilqas Formation forms the top of the aquifer and is made out of a thin layer of clays which causes the semi-confining characters of the main aquifers [34]. Bilqas Formation is a coastal lagoonal sediment composed of silt and sandy mud forming the Delta agricultural soils. This clay layer thickness fluctuates from 5 to 20 m in the south and the central parts of the Delta and achieves 50 m in the northern parts [35]. The thickness and sedimentological varieties of the mud layer greatly affect the level of the interaction between the surface and groundwaters. The principal water-bearing formation is framed of quaternary deposits and is called Mit Ghamr Formation. It is a leaky aquifer overlain by the semi-pervious Holocene clay cap of Bilqas Formation.

Salem et al. [24] used the geoelectrical resistivity survey to investigate the hydrogeological setting of the study area (see Fig. 2). The subsurface of the study area consists of a group of layers. The first layer lies close to the ground surface with a small thickness and is recharged from the surface waterways and precipitations. The second water-bearing layer is under semi-confining conditions and has low electrical resistivity because of the high water salinity. The principal aquifer in the examination territory is forming the third layer and is under confined conditions and subsequently has an artesian character where water is flowing over the ground surface. This aquifer generally has high resistivity and composed of sandy clay to water-bearing sand with a low to moderate porosity (7.5–9.6%) and with considerable thickness ranging from 72.8 to 99.8 m. These outcomes were predictable with the hydrochemical attributes demonstrating the low to moderate brackish groundwater salinity nature of the investigated groundwater. They also estimated that this

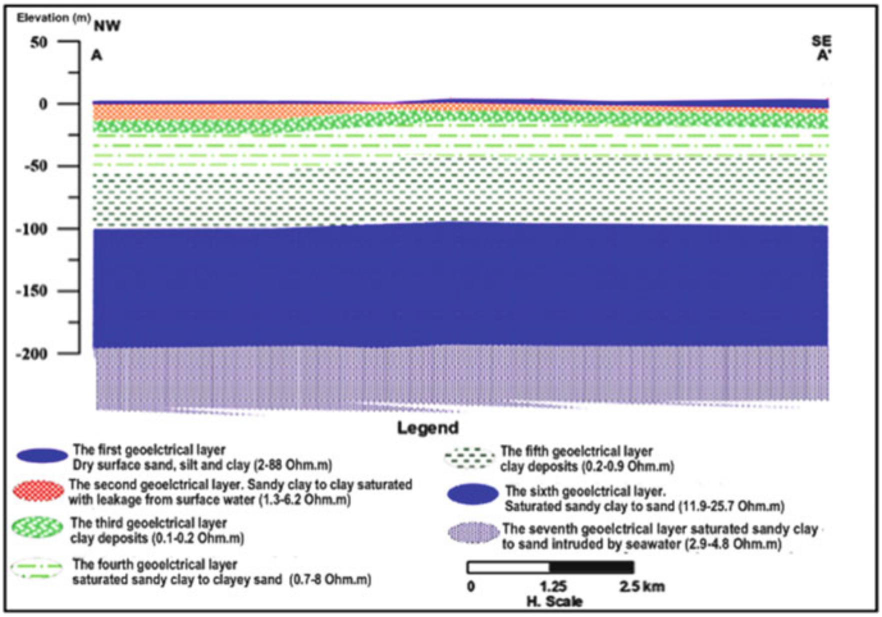

Fig. 2 Geoelectrical cross section showing the hydrogeological setting of the study area according to Salem et al. [24]

groundwater is principally made out of inland freshwater with a minor seawater content, and because of the confining conditions, the groundwater is still streaming toward the sea because of the high hydraulic head.

4 Methodology

The working procedure is illustrated as steps in the flowchart shown in Fig. 3. Twenty-six water samples were gathered from the investigated area amid 2012 for the hydrochemical examination (Fig. 4). Deep groundwater (well depth range between 130 and 180 m) and shallow groundwater (3–10 m deep) were represented by 20 and 3 water samples, respectively. Surface water including the main irrigation canal (S17) and the irrigation drainage water (S10 and S12) were also sampled. Water samples were gathered in new furthermore washed plastic bottles. Electrical conductance (mS/cm), hydrogen ion activity (pH), temperature (°C), and total dissolved solids (TDS in mg/l) were measured in the field. Hach's portable conductivity/TDS meter and portable Consort pH meter (Model P 314) were utilized [36].

The hydrochemical investigations were done in the central laboratory of Kafrelsheik University, just couple of days after sample gathering. Sulfate ion concentration was determined by spectrophotometric precipitation with barium chloride. Chloride ion was measured by titration against a standard solution of

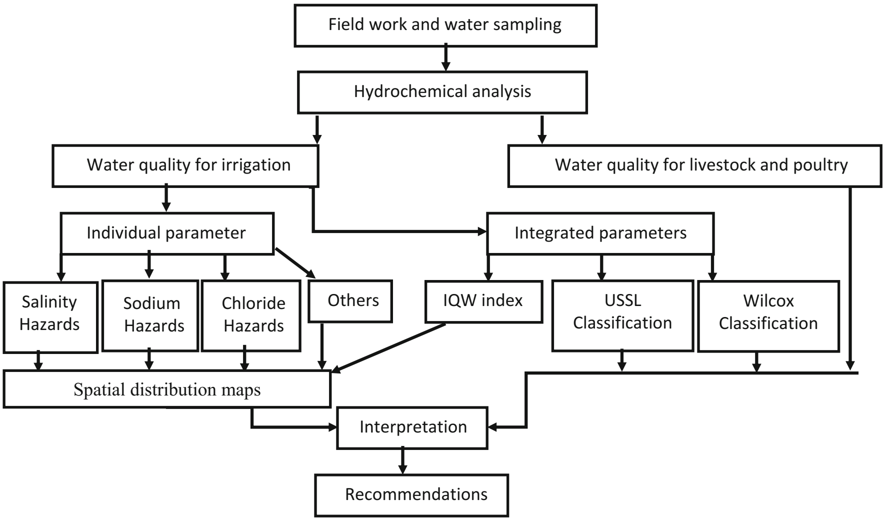

Fig. 3 Flowchart illustrates the working methodology

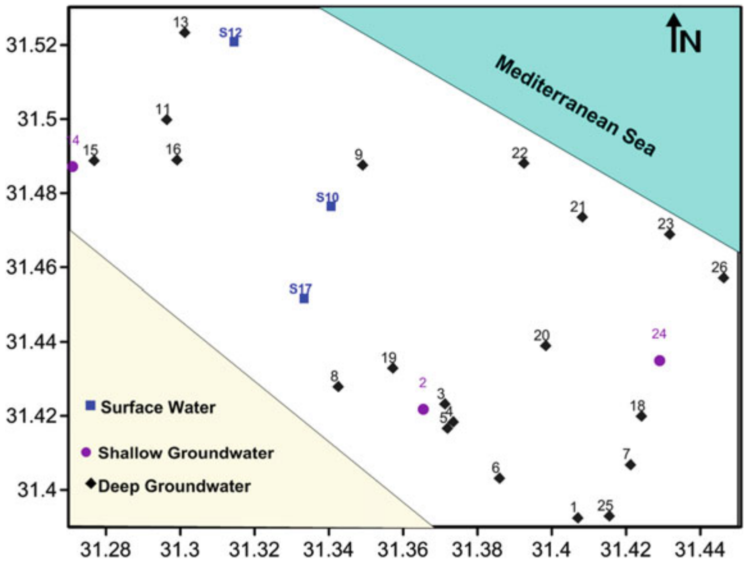

Fig. 4 Water samples location map

mercuric nitrate utilizing diphenylcarbazone reagent powder. Carbonates and bicarbonates were determined by titration against a standard sulfuric acid solution. Atomic absorption was utilized for determining concentrations of cations. The acquired hydrochemical information are recorded in Table 1. The anion–cation (charge) adjust is lower than 5%, being admirably inside the worthy range. The

Table 1 The hydrochemical analysis data of the collected water samples

	S. No	TDS (mg/l)	T (°C)	PH	EC (mS/cm)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	Cl (mg/l)	HCO_3 (mg/l)	SO_4 (mg/l)	Co (mg/l)	Pb (mg/l)	Zn (mg/l)	Fe (mg/l)	Cu (mg/l)	Mn (mg/l)	Ni (mg/l)	Cd (mg/l)
Deep groundwater	1	2,730	28.3	8.6	5.5	883.2	21.8	96.2	72.9	1,538.5	195.2	151.3	0	0.02	0	0.31	0.01	0.07	0	0
	3	2,270	28.7	8.6	4.6	660.1	17.8	84.2	46.2	1,212.3	158.6	16.8	0	0.02	0	0.26	0	0.08	0.02	0
	5	3,380	28.4	8.6	6.8	1,000.5	21.0	164.3	70.5	1,921.3	158.6	59.1	0	0.01	0.02	0.48	0	0.26	0.04	0
	6	2,950	26.3	8.7	5.9	853.3	25.1	136.3	63.2	1,637.7	158.6	45.1	0	0	0	0.11	0	0.09	0.02	0
	7	2,790	26.9	8.8	5.6	890.1	22.6	80.2	53.5	1,559.7	183.0	32.7	0	0	0	0.09	0	0.07	0	0
	8	3,440	27.3	8.8	6.9	1,106.3	24.2	164.3	99.7	2,197.8	134.2	44.2	0	0.01	0	0.39	0	0.11	0.03	0
	9	3,380	28.8	9.4	6.8	1,060.3	23.4	108.2	65.6	1,921.3	183.0	14.4	0	0.02	0	0.15	0	0.31	0.05	0
	11	4,750	28.1	9.4	9.5	1,428.3	29.1	248.5	124.0	2,906.8	158.6	40.3	0	0	0	0.12	0	0.22	0.07	0
	13	4,250	27.0	9.4	8.5	1,301.8	25.1	120.2	131.3	2,410.5	207.4	124.9	0	0	0	0	0	0.2	0.05	0
	14	2,020	28.5	9.0	4.1	595.7	17.0	80.2	34.0	1,063.5	158.6	25.5	0	0	0	0.06	0	0.24	0.04	0
	15	4,240	27.3	9.1	8.5	1,239.7	54.9	84.2	145.9	2,197.8	488.1	72.0	0	0.02	0	0	0	0.85	0.09	0
	16	4,820	26.5	9.5	9.6	1,363.9	29.9	228.5	124.0	2,800.4	134.2	22.1	0	0	0	0.05	0	0.22	0.11	0
	18	2,840	27.2	8.5	5.7	846.4	23.4	72.1	65.6	1,524.3	195.2	9.6	0	0.01	0	0.12	0	0.09	0.06	0
	19	6,150	26.0	9.2	12.3	2,574.7	29.7	400.8	194.5	3,722.1	158.6	1,976.9	0	0	0	0.53	0	1.13	0	0
	20	3,350	34.0	9.5	6.7	1,287.4	24.6	80.2	43.8	1,524.3	170.8	885.2	0	0	0.06	0.01	0	0.28	0	0
	21	3,290	28.2	9.5	6.6	1,448.3	24.6	84.2	63.2	1,630.6	195.2	1,144.6	0	0	0	0.07	0	0.11	0	0
	22	2,780	30.8	8.6	5.6	1,287.4	20.7	60.1	48.6	1,417.9	219.6	957.3	0	0	0.01	0.01	0	0.11	0	0
	23	3,860	26.7	9.6	7.7	1,609.2	24.6	100.2	87.5	2,126.9	183.0	952.4	0	0	0	0.01	0	0.43	0	0
	25	2,730	24.8	10.8	5.5	1,206.9	23.9	92.2	63.2	1,417.9	183.0	956.3	0	0	0	0.02	0	0.16	0	0
	26	5,300	24.6	9.8	10.6	2,252.9	34.8	296.6	12.2	3,013.1	146.4	1,310.8	0	0	0.01	0.03	0	0.25	0	0
Average		3,566	27.7	9.2	7.2	1,244.8	25.9	139.1	80.5	1,987.2	188.5	442.1	0.000	0.006	0.005	0.141	0.001	0.264	0.029	0.000
Sh. GW	2	270	29.2	9.1	0.6	34.5	9.7	40.1	29.2	42.5	231.8	54.8	0	0.01	0.13	0.7	0	0	0	0
	4	3,650	26.5	9.5	7.3	1,083.3	23.4	112.2	126.4	2,126.9	183.0	33.6	0	0	0	0.23	0	0.07	0	0
	24	1,550	26.1	9.9	3.2	643.7	25.4	56.1	65.6	638.1	427.1	569.2	0	0	0.89	0.46	0	0.12	0	0
Average		1,823	27.3	9.5	3.7	587.2	19.5	69.5	73.7	935.8	280.7	219.2	0.000	0.003	0.340	0.463	0.000	0.063	0.000	0.000
Surf. W	S10	5,100	33.5	8.6	10.2	1,481.2	52.5	96.2	204.2	2,765.0	524.7	35.5	0	0	0	0.15	0	0.41	0.08	0
	S12	10,320	33.1	10.4	20.9	3,985.9	137.4	104.2	196.9	6,274.4	463.7	596.5	0	0	0	0	0	0.01	0.23	0
	S17	1,760	31.2	9.9	3.5	549.7	20.2	64.1	65.6	779.9	451.5	137.4	0	0	0	0	0	0.01	0.04	0
Average		5,727	32.6	9.6	11.5	2,005.6	70.0	88.2	155.6	3,273.1	480.0	256.5	0.000	0.000	0.000	0.050	0.000	0.143	0.117	0.000

hydrochemical data used in this study were used before by Salem et al. [24] to explain the hydrogeochemical composition in the study area.

To evaluate the investigated water for irrigation purposes, the following parameters were calculated: SAR, Na%, RSC, Cl, KI, PI, TH, MH, CAI, and CR (Table 4) as well as irrigation water quality index (IQW). Calculation procedure is discussed as stated in Salem et al. [19]. Sodium is a vital element since it indicates the soluble alkali/sodium effect to soils. Since sodium decreases, soil penetrability which affects cultivation process increases. Sodium effect in soil permeability is evaluated as SAR (sodium adsorption ratio) which was calculated using the Eq. (1):

$$\mathrm{SAR} = \frac{\mathrm{Na}}{\sqrt{\frac{(\mathrm{Ca}+\mathrm{Mg})}{2}}} \tag{1}$$

where $[Na^{+}]$, $[Ca^{++}]$, and $[Mg^{++}]$ are defined as the concentrations of sodium, calcium, and magnesium ions in water, respectively [2]. In this equation, the concentrations are expressed as milli equivalents per liter. Sodium percent is a factor likewise calculated to assess the appropriateness of water for irrigation purposes [37, 38]. This factor is computed by the following equation:

$$\mathrm{Na\%} = \frac{(\mathrm{Na}+\mathrm{K})}{(\mathrm{Ca}+\mathrm{Mg}+\mathrm{Na}+\mathrm{K})} \times 100 \tag{2}$$

The relative wealth of sodium regarding alkaline earths and boron and the amount of HCO_3 and CO_3 in abundance of soluble earths additionally impact the appropriateness of water for irrigation (RSC) [39]. RSC (residual sodium carbonate) is computed as follows:

$$\mathrm{RSC} = (\mathrm{CO_3}+\mathrm{HCO_3}) - (\mathrm{Ca}+\mathrm{Mg}) \tag{3}$$

The soil penetrability is influenced by water use for a long time. Na, Mg, Ca, and HCO_3 components in the soil impact it. Permeability index (PI) was developed by Doneen [40] to evaluate the appropriateness of water for irrigation where.

$$\mathrm{PI} = \frac{\left(\mathrm{Na}+\sqrt{\mathrm{HCO_3}}\right)}{\left(\mathrm{Ca}+\mathrm{Mg}+\mathrm{Na}\right)} \times 100 \tag{4}$$

Measured Na versus Mg and Ca was used by Kelly [41] and Paliwal [42] as Kelley's index. This factor is computed as shown in this equation:

$$\mathrm{KI} = \frac{\mathrm{Na}}{(\mathrm{Ca}+\mathrm{Mg})} \tag{5}$$

Magnesium ratio (MH) was suggested by Szabolcs and Darab [43] to assess the irrigation water by the given formula:

$$\mathrm{MH} = \frac{\mathrm{Mg}}{(\mathrm{Ca} + \mathrm{Mg})} \times 100 \tag{6}$$

CAI (chloro-alkaline index) is an important factor and characterized as the ion exchange characters between the groundwater and aquifer sediments [44]. CAI is computed according to the following equation:

$$\mathrm{CAI} = \frac{\mathrm{Cl} - (\mathrm{Na} + \mathrm{K})}{\mathrm{Cl}} \tag{7}$$

CR (corrosivity ratio) is essential to assess the ability to transfer water in metallic pipes. Water with CR < 1 is safe, while >1 shows corrosive characters and thus should not to be transferred in metal pipes. The CR is computed utilizing this equation:

$$\mathrm{CR} = \frac{\frac{\mathrm{Cl}}{35.5} + 2\left(\frac{\mathrm{SO_4}}{96}\right)}{2\left(\frac{\mathrm{HCO_3} + \mathrm{CO_3}}{100}\right)} \tag{8}$$

The proposed irrigation water quality index (IWQ index) is calculated as

$$\mathrm{IWQ} = \sum\nolimits_{i=1}^{5} Gi \tag{9}$$

where i is an incremental index and G represents the contribution of each one of the five hazard categories that are important to assess the quality of an irrigation water resource (Table 2). The first category is the salinity hazard that is represented by the EC value of the water and is formulated as

$$G_1 = w_1\, r_1 \tag{10}$$

where w is the weight value of this hazard group and r is the rating value of the parameter as given in Table 2. The second category is the infiltration and permeability hazard that is represented by EC-SAR combination and is formulated as

$$G_2 = w_2\, r_2 \tag{11}$$

where w is the weight value of this hazard group and r is the rating value of the parameter as given in Tables 2 and 3. The third category is the specific ion toxicity that is represented by SAR, chloride, and boron ions in the water and is formulated as a weighted average of the three ions:

$$G3 = \frac{W3}{3} \sum\nolimits_{j=1}^{3} rj \tag{12}$$

where j is an incremental index, w is the weight value of this group as given in Table 2, and r is the rating value of each parameter. The fourth category is the trace

Table 2 Parameter classification for IWQ index

Hazard	Weight	Parameter	Range	Rating	Collected samples	Suitability
Salinity hazard	5	Electrical conductivity (μS/cm)	$EC < 700$	3	Sample 2 Sh. GW	High
			$700 \leq EC \leq 3{,}000$	2		Medium
			$EC > 3{,}000$	1	All samples except 2	Low
Infiltration and permeability hazard	4	See Table 3 for details				
Specific ion toxicity	3	Sodium adsorption ratio	$SAR < 3.0$	3	Sample 2 Sh. GW	High
			$3.0 \leq SAR \leq 9.0$	2		Medium
			$SAR > 9.0$	1	All samples except 2	Low
		Chloride (mg/l)	$CI < 140$	3	Sample 2 Sh. GW	High
			$140 \leq CI \leq 350$	2		Medium
			$CI > 350$	1	All samples except 2	Low
Trace element toxicity	2	See Table 4 for details				
Miscellaneous effects to sensitive cops	1	Bicarbonate (mg/l)	$HCO_3 < 90$	3		High
			$90 \leq HCO_3 \leq 500$	2	All samples except 10 Surf. W	Medium
			$HCO_3 > 500$	1	Sample 10 Surf. W	Low
		pH	$7.0 \leq pH \leq 8.0$	3		High
			$6.5 \leq pH < 7.0$ and $8.0 < pH \leq 8.5$	2		Medium
			$pH < 6.5$ or $pH > 8.5$	1	All samples	Low

Deep GW deep groundwater, *Sh. GW* shallow groundwater, and *Surf. W* surface water

Table 3 Classification for infiltration and permeability hazard

SAR	<3	3–6	6–12	12–20	>20	Rating	Suitability
EC	>700	>1,200	>1,900	>2,900	>5,000	3	High
	700–200	1,200–300	1,900–500	2,900–1,300	5,000–2,900	2	Medium
	<200	<300	<500	<1,300	<2,900	1	Low

element toxicity that is represented by the elements given in Tables 2 and 4 and is formulated as a weighted average of all the ions available for analysis:

$$G4 = \frac{W4}{N}\sum_{k=1}^{N} r_k \tag{13}$$

where k is an incremental index, N is the total number of trace element available for the analysis, w is the weight value of this group, and r is the rating value of each parameter as given in Table 4. The fifth and the final category is the miscellaneous effects to sensitive crops that are represented by bicarbonate ions and the pH of the water and is formulated as a weighted average:

$$G5 = \frac{W5}{3}\sum_{m=1}^{3} r_m \tag{14}$$

where m is an incremental index, w is the weight value of this group, and r is the rating value of each parameter as given in Table 2. After the total value of the index is computed, a suitability analysis is done based on the three different categories given in Table 5. The values given in this table are obtained by assigning different rating factors (i.e., 1, 2, and 3) to each parameter without changing its weighing coefficient, thus yielding three different index values (i.e., 45, 30, and 15). The medians of these values are used to set the upper and lower limits used in each category specified in Table 5. Finally, these index grids (i.e., one for each parameter of the index) are combined according to Eq. (9) to obtain the IWQ index value. The final IWQ grid map is later evaluated based on the suitability criteria given in Table 5.

5 Result and Discussion

Water quality is of equal importance as water quantity for development of any area. According to WHO [45], most of the collected water samples are unsuitable for drinking and domestic uses on account of undesirable TDS and ionic concentrations. Therefore, the water resources in the study area were evaluated according to its suitability for irrigation, livestock, and poultry uses.

Table 4 Classification for trace element toxicity

Factor	Range	Rating	Collected samples	Suitability
Cadmium (mg/l)	Cd < 0.01	3	All samples	High
	0.01 ≤ Cd ≤ 0.05	2		Medium
	Cd > 0.05	1		Low
Cobalt (mg/l)	Co < 0.05	3	All samples	High
	0.05 ≤ Co ≤ 5.0	2		Medium
	Co > 5.0	1		Low
Copper (mg/l)	Cu < 0.2	3	All samples	High
	0.2 ≤ Cu ≤ 5.0	2		Medium
	Cu > 5.0	1		Low
Iron (mg/l)	Fe < 5.0	3	All samples	High
	5.0 ≤ Fe ≤ 20.0	2		Medium
	Fe > 20.0	1		Low
Lead (mg/l)	Pb < 5.0	3	All samples	High
	5.0 ≤ Pb ≤ 10.0	2		Medium
	Pb > 10.0	1		Low
Manganese (mg/l)	Mn < 0.2	3	1, 3, 4, 6, 7, 8, 13, 18, 21, 22, and 25 as Deep GW 2 and 24 as Sh. GW and 12 and 17 as Surf. W	High
	0.2 ≤ Mn ≤ 10.0	2	5, 9, 11, 15, 16, 19, 20, 23, and 26 as DGW and 14 as Sh. GW and 10 as Surf. W	Medium
	Mn > 10.0	1		Low
Nickel (mg/l)	Ni < 0.2	3	All samples except 12 Surf. W	High
	0.2 ≤ Ni ≤ 2.0	2	Sample 12 Surf. W	Medium
	Ni > 2.0	1		Low
Zinc (mg/l)	Zn < 2	3	All samples	High
	2 ≤ Zn ≤ 10	2		Medium
	Zn > 10.0	1		Low

Deep GW deep groundwater, *Sh. GW* shallow groundwater, and *Surf. W* surface water

Table 5 Irrigation water quality (IWQ) index

IWQ index	Suitability of water for irrigation	No of sample
<22	Low	
22–37	Medium	(1, 3, 4, 5, 6, 7, 8, 9, 11, 13, 15, 16, 18, 19, 20, 21, 22, 23, 25, and 26 as Deep GW), (14, 24 as Sh. GW) and (10.12,17 as Surf. W)
>37	High	Sample 2 (Sh. GW)

Deep GW deep groundwater, *Sh. GW* shallow groundwater, and *Surf. W* surface water

5.1 Individual Parameters

The suitability classification of the collected water samples for irrigation purpose using the individual parameters is listed in Table 6.

5.1.1 Salinity Hazards (EC and TDS)

The classification of the collected water samples for irrigation purpose based upon its EC value is presented in Table 6. The value of electrical conductivity for all deep groundwater samples and the surface water samples are higher than 3,000 μS/cm except sample 2 (Fig. 5) which have low electrical resistivity value. According to Jain et al. [46], 12 samples (60%) of the deep groundwater have unfit TDS values, while 40% of the samples (8 samples) have useful TDS range less than 3,000 mg/l (Fig. 6a). Regarding the shallow groundwater, sample 2 is of desirable TDS value (less 500 mg/l), sample 24 has useful TDS range, and sample 14 has unfit TDS value (Fig. 6b). The water of the main irrigation canal (sample 17) has useful TDS value, but those of the drains (samples 10 and 12) are of unfit values (Fig. 6c).

5.1.2 Sodium Hazards

The detection of sodium toxicity is relatively difficult compared to the toxicity of other ions. Typical toxicity symptoms on the plant are leaf burn, scorch, and dead tissue along the outside edges of leafs in contrast to symptoms of chloride toxicity. The sodium ion also causes hazards in the soil structure creating reduced permeability and water infiltration problems. Also, calcium and magnesium ions are replaced by sodium ion creating an increase in soil's sodium content [47]. While EC is an assessment of all soluble salts in water, sodium hazard is defined separately due to sodium's specific detrimental effects on soil physical properties and plant survival.

Na% range of the deep groundwater is 60–80% and ranged from doubtful (11 samples, 52.38%) to unsuitable (10 samples, 47.62%) (Table 6 and Fig. 7a). The shallow groundwater ranges from good (sample 2) to doubtful (samples 14 and 24) (Fig. 7b). The surface water Na% ranges from unsuitable (sample 12) to doubtful (samples 10 and 17) (Fig. 7c). SAR is defined as the relative proportion of sodium to calcium and magnesium ions. The SAR value of the deep groundwater falls into the category of good (7 samples, 33.3%), doubtful (6 samples, 28.57%), and unsuitable (8 samples, 38.1%) for irrigation (Table 6 and Fig. 8a). SAR value for the shallow groundwater was represented in good category (samples 14 and 24, 66.6%) and excellent for irrigation (sample 2, 33.33%) (Fig. 8b). Finally, the surface water SAR values fall in three categories good (sample 7), doubtful (sample 10), and unsuitable (sample 12) for irrigation (Fig. 8c).

Table 6 Collected water sample suitability classification for irrigation

Classification pattern	Categories	Ranges	Surface water		Shallow groundwater		Deep groundwater	
			No	%	No	%	No	%
Total dissolved solids (TDS, mg/l)	Desirable	<500			1	33.3		
	Permissible	500–1,000						
	Useful for irrigation	1,000–3,000	1	33.3	1	33.3	8	40
	Unfit for irrigation	>3,000	2	66.6	1	33.3	12	60
Sodium percent sodium (Na%)	Excellent	0–20						
	Good	20–40			1	33.3		
	Permissible	40–60						
	Doubtful	60–80	2	66.6	2	66.6	11	52.38
	Unsuitable	>80	1	33.3			10	47.62
Sodium adsorption ratio (SAR)	Excellent	0–10			1	33.3		
	Good	18	1	33.3	2	66.6	7	33.3
	Doubtful	18–26	1	33.3			6	28.57
	Unsuitable	>26	1	33.3			8	38.1
Residual sodium carbonate (RSC)	Good	<1.25	3	100	3	100	20	100
	Doubtful	1.25–2.5						
	Unsuitable	>2.5						
Permeability index (PI)	Class I	>75	3	100	2	66.6	20	100
	Class II	25–75			1	33.3		
Chloro-alkaline Indices (CAI)	Base exchange	Negative	1	33.3	2	66.6	7	30
	Cation–anion	Positive	2	66.6	1	33.3	14	70
Chloride (Cl, meq/l)	Extremely fresh	<0.14						
	Very fresh	0.14–0.85						
	Fresh	0.85–4.23			1	33.3		
	Fresh–brackish	4.23–8.46						
	Brackish	8.46–28.21	1	33.3	1	33.3		
	Brackish–salt	28.21–282.06	2	66.6	1	33.3	20	100
	Salt	282.06–564.13						
	Hypersaline	>564.13						
Magnesium hazard (MH)	Unsuitable	>50%	3	100	3	100	11	52.38
	Suitable	<50%					10	47.6
Kelley's index (KI)	Unsuitable	≥1	3	100	2	66.6	20	100
	Suitable	<1			1	33.3		
Corrosive ratio (CR)	Noncorrosive	<1	3	100	1	33.33		
	Corrosive	>1			2	66.6	20	100

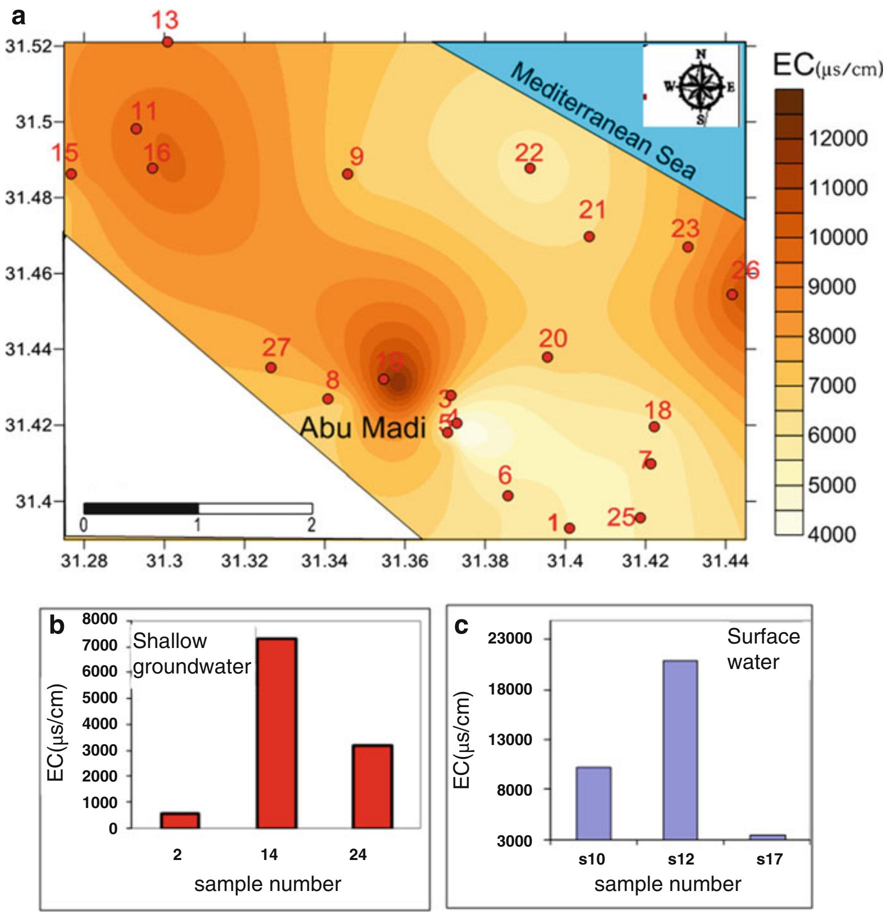

Fig. 5 EC spatial distribution of the deep groundwater (**a**) and EC graphical representation of the shallow groundwater (**b**) and surface water (**c**)

The RSC index (residual sodium carbonate) of irrigation water or soil water is utilized to show the alkalinity danger to soil. The RSC record is utilized to discover the appropriateness of the water for irrigation in clay soils which have a high cation exchange ability. When sodium concentration is higher than that of calcium and magnesium in water, clay soil swells or experiences scattering which lessens its penetration limit. In such soils, the plant roots cannot spread further into the soil because of the absence of moisture. High RSC index in water does not improve the osmotic strain to obstruct the takeoff of water by the plant roots, not at all like high-salinity water. Clay soil watering with high RSC index in water prompts to the formation of alkali soil. Calculated RSC index values of the study area reveal that all the collected water samples are low and fall within a good category for irrigation (see Table 6 and Fig. 9a–c).

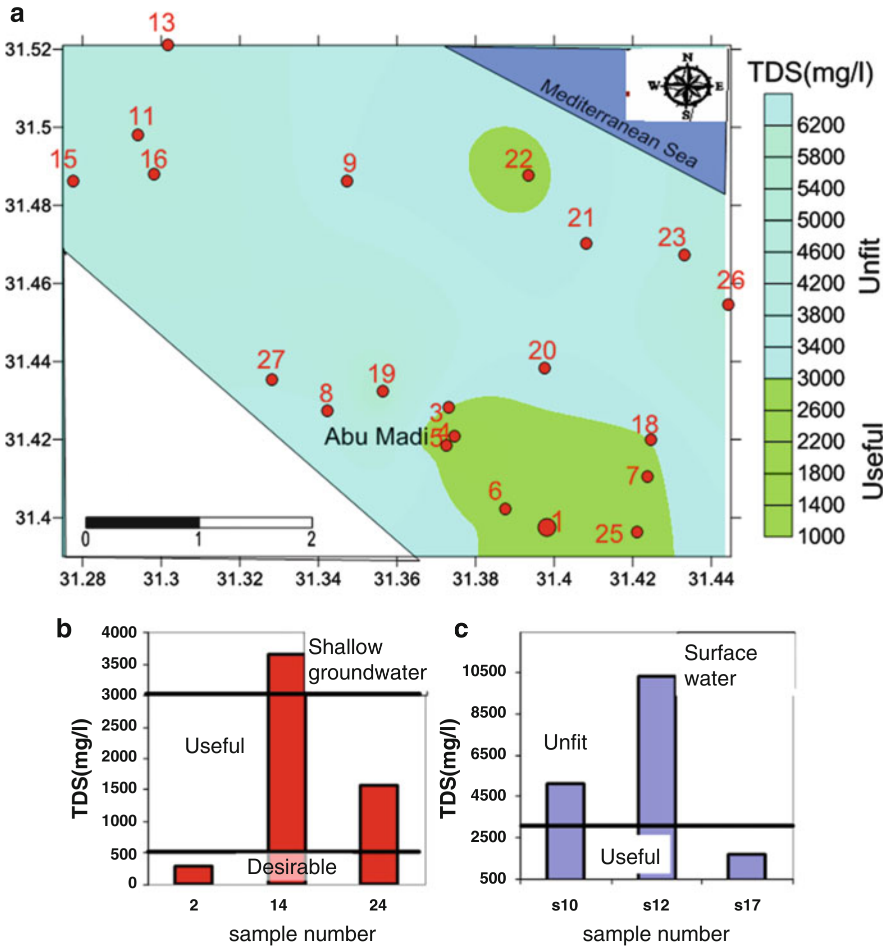

Fig. 6 TDS spatial distribution of the deep groundwater (**a**) and TDS graphical representation of the shallow groundwater (**b**) and surface water (**c**)

The PI (permeability index) classified the water in general into three classes: class I (≥75%), class II (25–75%), and class III (≤25%) orders. Water having PI values under class I and class II is categorized as good for irrigation with 75% or more of maximum permeability. Class III waters are unsuitable with 25% of maximum permeability. Calculated permeability index reveals all the collected water samples belong to class I except sample 2 (shallow groundwater) which fall within class II range (Fig. 10a–c). This means the water resources in the study area have no PI hazards. Based on Kelly's index [48], groundwater was classified for irrigation;

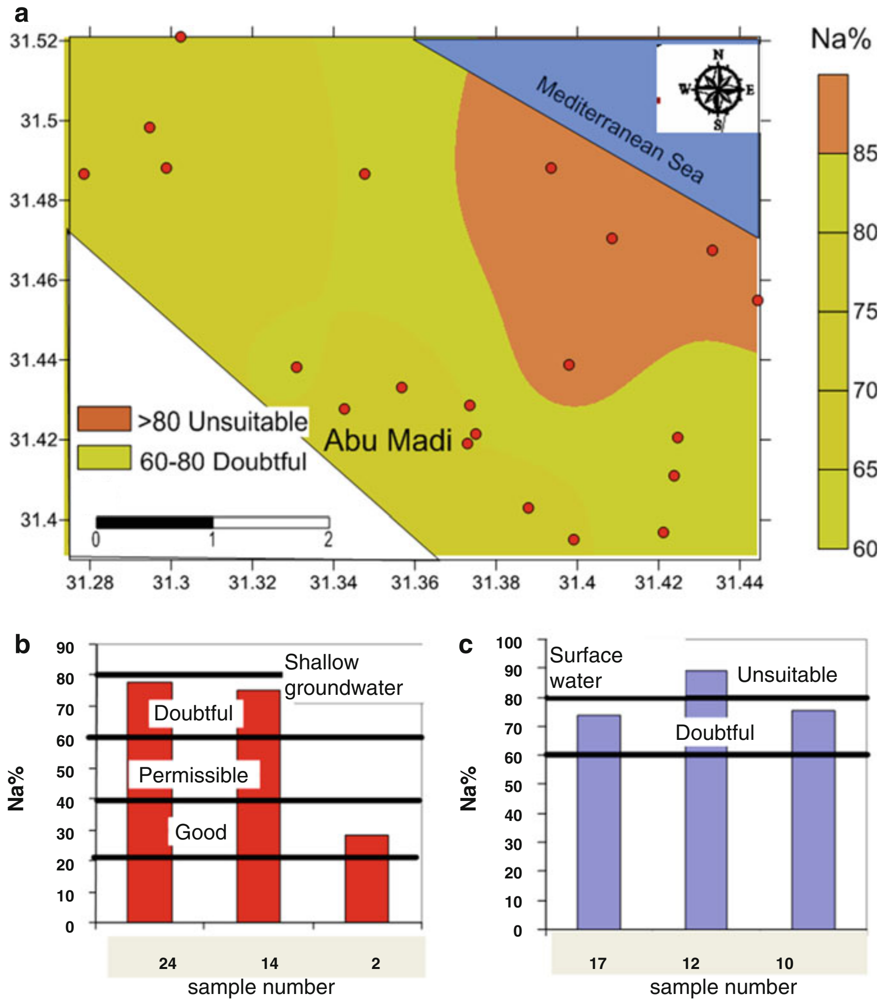

Fig. 7 Na% spatial distribution of the deep groundwater (**a**) and Na% graphical representation of the shallow groundwater (**b**) and surface water (**c**)

Kelly's index more than 1 indicates an excess level of sodium in water; therefore the water Kelly's Index of less than 1 is suitable for irrigation. Calculated Kelley's index (KI) reveals that all of the deep groundwater samples, samples 14 and 24 as shallow groundwater, and all surface water samples fall within unsuitable category (see Table 6 and Fig. 11a–c). Only sample 2 (shallow groundwater) belongs to suitable category (Fig. 11c).

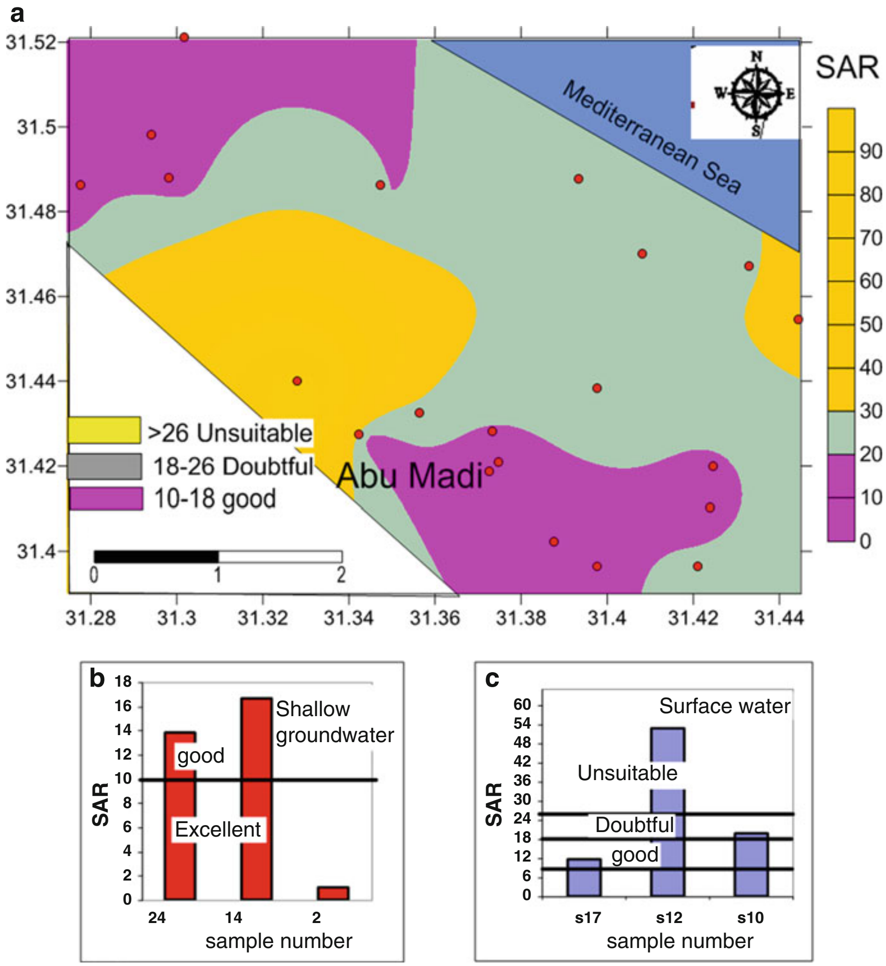

Fig. 8 SAR spatial distribution of the deep groundwater (**a**) and SAR graphical representation of the shallow groundwater (**b**) and surface water (**c**)

5.1.3 Chloride Hazards

The chloro-alkaline indices were created to indicate the evolution in the hydrochemical composition of the groundwater along its flow path. The indices are positive if Na and K from water replaced Ca and Mg from the soil, while if the exchange is reverse, then the indices are negative. Based on chloro-alkaline indices (CAI), 14 wells (70%) of deep groundwater samples have cation–anion exchange reaction characters, and 7 wells (30%) have base-exchange characters (Table 6, Fig. 12a). Samples 2 and 24 as shallow groundwater belong to the base-exchange reaction category, but sample 14 belongs to cation-anion exchange (Fig. 12b).

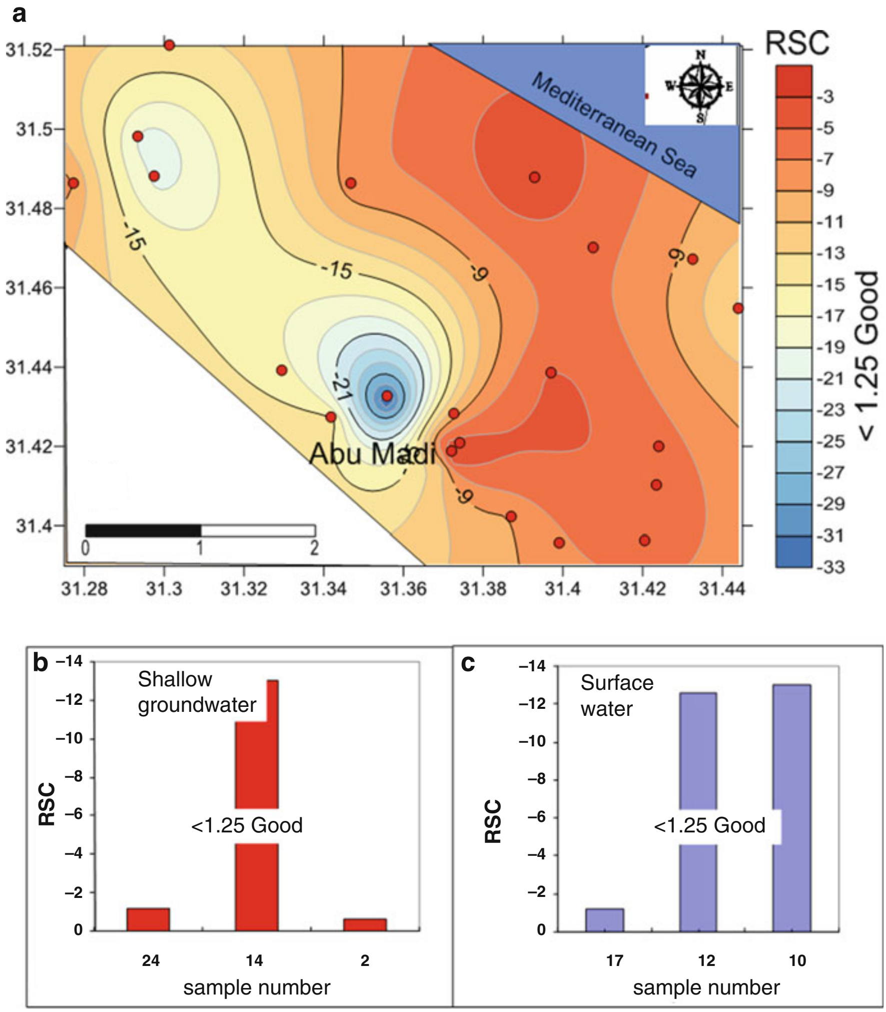

Fig. 9 RSC spatial distribution of the deep groundwater (**a**) and RSC graphical representation of the shallow groundwater (**b**) and surface water (**c**)

Samples 12 and 17 as surface water fall in cation–anion exchange category (Fig. 12c), but sample 10 has base-exchange reaction characters. The chloride content is very important for suitability of groundwater for irrigation purposes. Most plants are very sensitive to chloride ions, and certain plants have the ability to accumulate chlorides even from water of low chloride content with no harmful effect. Taylor and Oza [49] classified irrigation water according to their chloride content into four classes. It is noticed from the data distributed in Tables 6 and 7: all the deep groundwater samples, sample 14 (shallow groundwater) and samples 10 and 12 (surface water), are of highly undesirable water quality for irrigation.

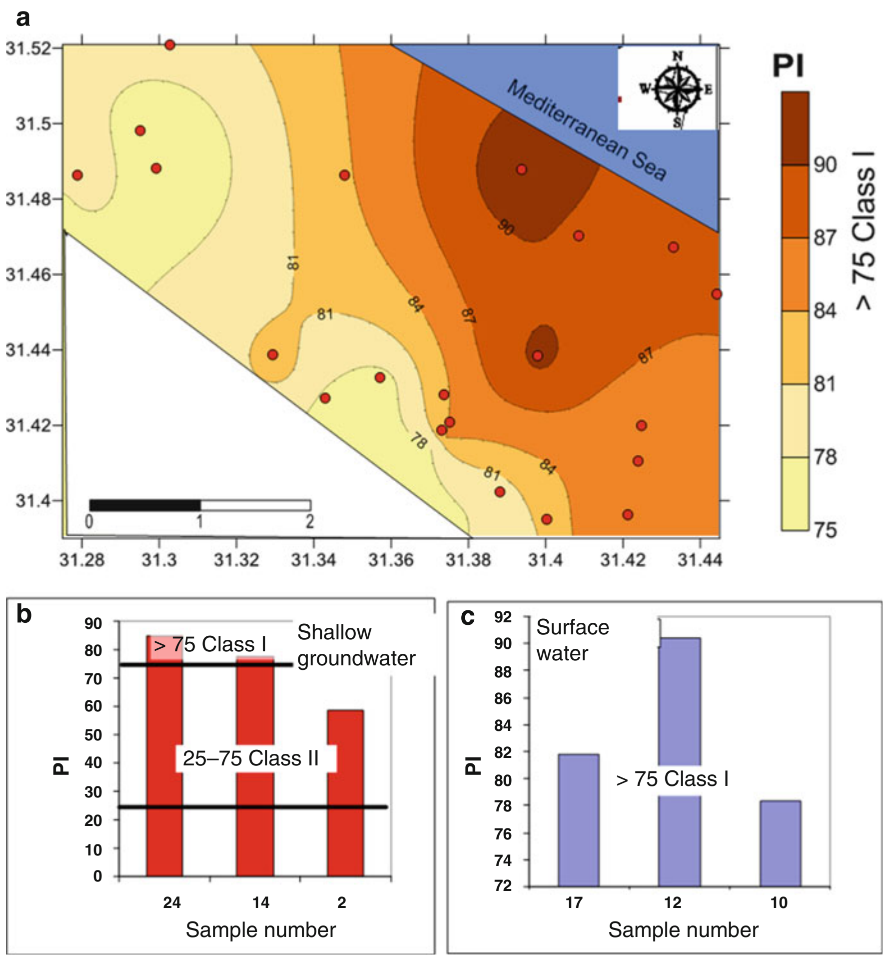

Fig. 10 PI spatial distribution of the deep groundwater (**a**) and PI graphical representation of the shallow groundwater (**b**) and surface water (**c**)

Table 7 Suitability of water according to chloride content [49]

Class no	Chloride content	Quality	Deep groundwater	Shallow GW	Surface water
1	Good-quality water	<200 mg/l		2	
2	Fair-quality water	200–500 mg/l			
3	Undesirable quality water	500–1,000 mg/l		24	17
4	Highly undesirable quality water	>1,000 mg/l	All samples	14	10, 12

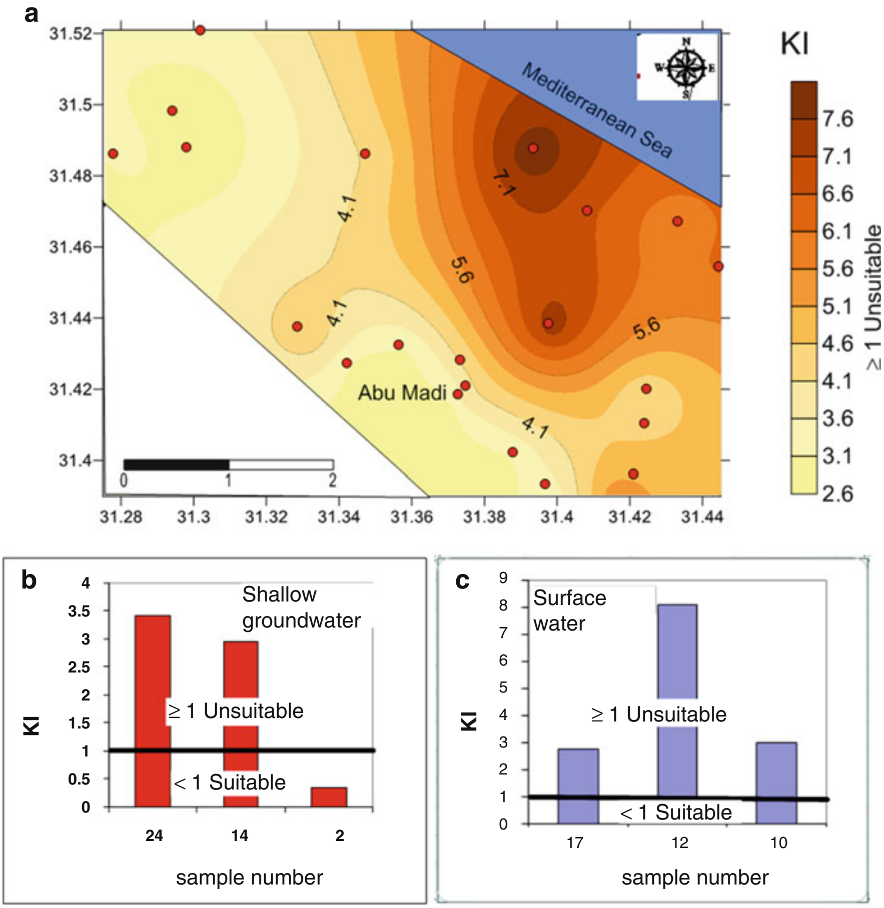

Fig. 11 KI spatial distribution of the deep groundwater (**a**) and KI graphical representation of the shallow groundwater (**b**) and surface water (**c**)

Samples 24 (shallow groundwater) and 17 (irrigation canal) are of undesirable range, while sample 2 (shallow groundwater) has chloride content less than 200 mg/l and of good quality for irrigation (see Fig. 13a–c).

5.1.4 Other Parameters

Szabolcs and Darab [43] have proposed the use of magnesium hazard (MH) for assessing the suitability of water quality for irrigation. Generally, Ca and Mg maintain a state of equilibrium in water, and they do not behave equally in the soil system. Magnesium damages soil structure, when water contains more Na and high saline. Normally, a high level of Mg is caused by exchangeable Na in irrigated soils.

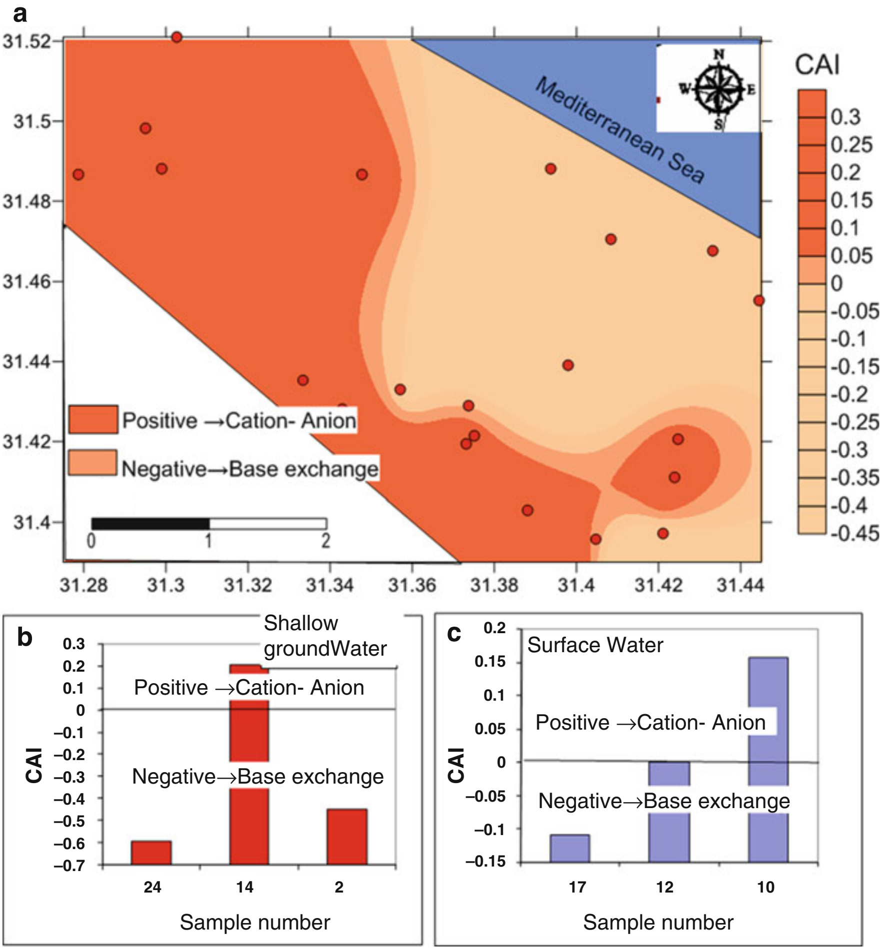

Fig. 12 CAI spatial distribution of the deep groundwater (**a**) and CAI graphical representation of the shallow groundwater (**b**) and surface water (**c**)

In equilibrium, more Mg can affect soil quality by rendering it alkaline. Thus, it affects crop yields. The MH is expressed in terms of magnesium hardness. Calculated magnesium hazard (MH) values reveal that 11 samples (52.4%) of the deep groundwater samples are of the unsuitable category but (10 samples, 47.6%) are suitable for irrigation (Table 6, Fig. 14a). All shallow groundwater and surface water are under the unsuitable category for irrigation (Fig. 14b, c).

Corrosive ratio defines the susceptibility of groundwater to corrosion and is expressed as the ratio of alkaline earth to saline salts in groundwater. The effect of corrosion is a loss in the hydraulic capacity of pipes. In groundwater which has CR values greater than 1, noncorrosive pipes (polyvinylchloride), should be used for water supply instead of metal pipes. As shown in Table 6 and Fig. 15a–c, the

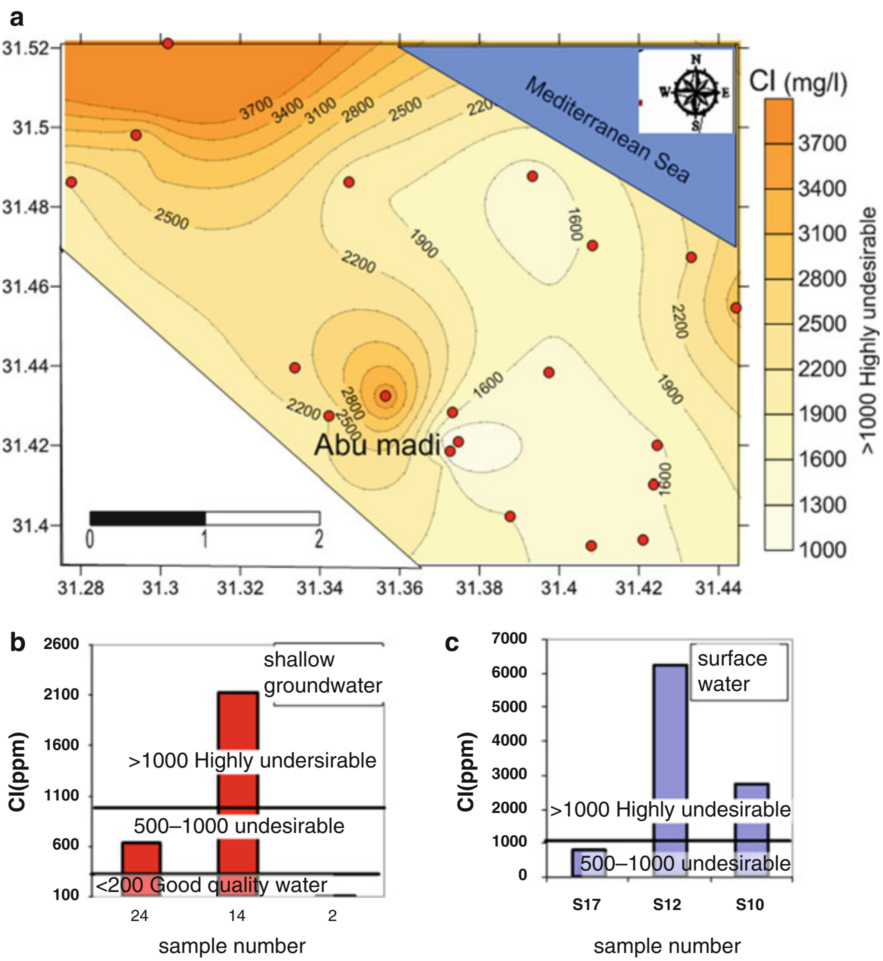

Fig. 13 Chloride content spatial distribution of the deep groundwater (**a**) and chloride content graphical representation of the shallow groundwater (**b**) and surface water (**c**)

calculated values of CR reveal that all the collected water samples fall within corrosive category except sample 2 which belongs to a noncorrosive category.

All samples whether deep groundwater, shallow groundwater, or surface water could be used for long-time irrigation without hazardous effect related to trace metals because all are of suitable concentrations for the irrigation water (Table 1). The value of pH of irrigation water changes as a component of many parameters including pollution from different contamination sources and acid precipitations. The pH degree impacts the carbonate balance, heavy metal, and the relative proportion of nitrogen components, which impacts soil quality and plant development. In acidic waters, calcium, magnesium, and aluminum are not consumed legitimately by plants. Alkaline waters give a superior domain to plant's take-up of several metals

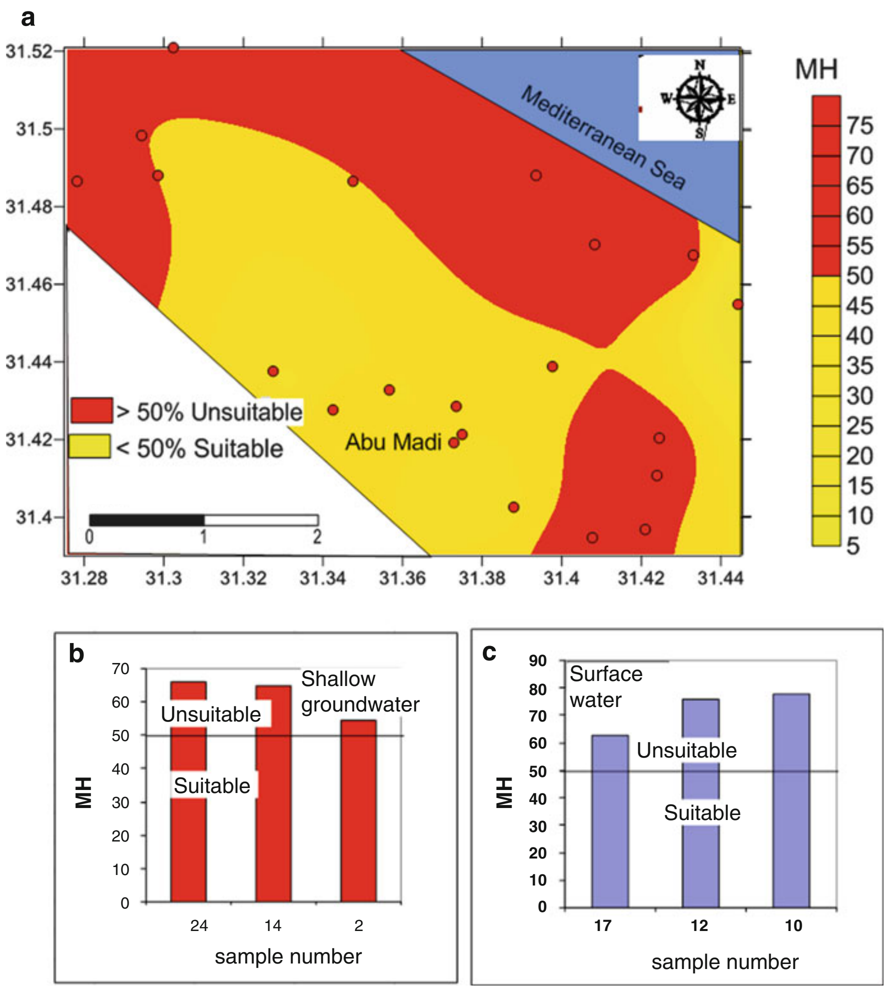

Fig. 14 MH spatial distribution of the deep groundwater (**a**) and MH graphical representation of the shallow groundwater (**b**) and surface water (**c**)

and nutrients. In any case, alkaline waters are likewise in charge of calcium carbonate gathering that impacts the physical structure of water. Generally, the perfect pH values of irrigation waters extend from 6.5 to 8.4. The order of irrigation water quality in view of its pH values is introduced in Table 2. The pH estimation values of all water samples in the investigation region demonstrate alkaline characters where they extend from 8.52 to 10.8 (Table 1) in all deep and shallow groundwaters as well as the surface water samples.

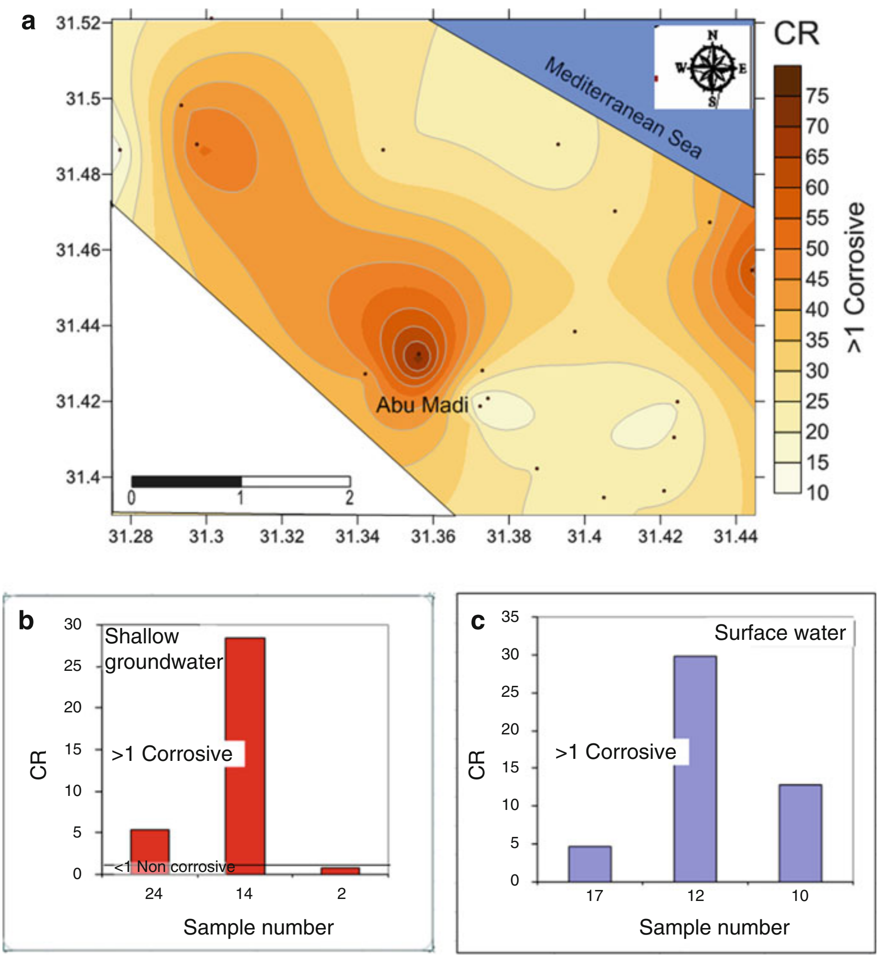

Fig. 15 CR spatial distribution of the deep groundwater (**a**) and CR graphical representation of the shallow groundwater (**b**) and surface water (**c**)

Alkalinity is an indicator of the capacity of water to neutralization acidification. Being the significant components of alkalinity, ions of carbonate and bicarbonate are for the most part in charge of high pH degree (i.e., over 8.5) of water. Raised levels of carbonates make calcium and magnesium particles frame insoluble minerals leaving sodium as the overwhelming ion in the solution. Subsequently, it is in a roundabout way in charge of the risks that high sodium concentrations cause on the watered plants and the soil. In this way, it is conceivable to infer that exceedingly alkaline irrigation waters could escalate sodic soil conditions. In such cases, it is prescribed to figure a balanced SAR to mirror the expanded sodium danger. As a rule, the bicarbonate values beneath 90 mg/l are thought to be perfect for irrigation. The characterization of the gathered water samples in light of its HCO_3 concentrations is shown in Table 2. All deep and shallow groundwater samples and samples 12 and 17 of the surface water lie between 90 and 500 mg/l range which is thought to be of slight to moderate irrigation quality (Fig. 16). Sample 10 (surface water) has bicarbonate content more than 500 mg/l which is thought to be of serious impact on irrigation water quality.

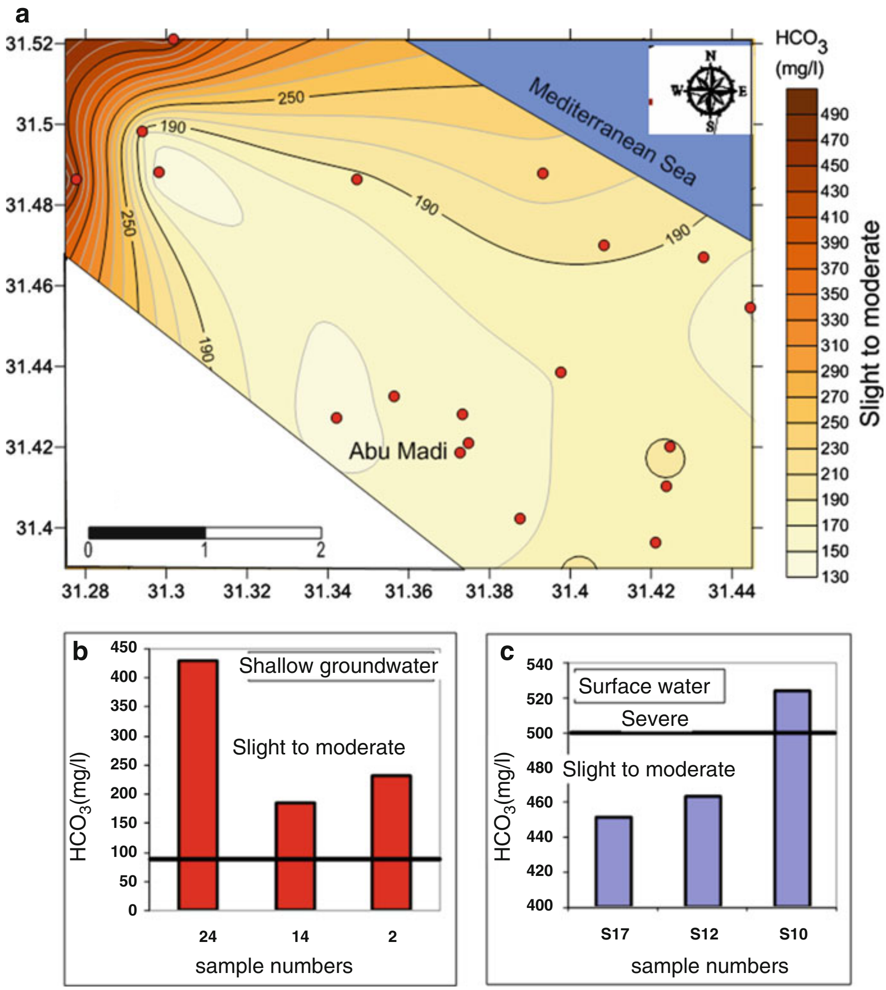

Fig. 16 Alkalinity spatial distribution of the deep groundwater (**a**) and alkalinity graphical representation of the shallow groundwater (**b**) and surface water (**c**)

5.2 *Integrated Parameters*

5.2.1 Wilcox's Classification

This classification is based on the relation between sodium percentage (Na%) and salinity governing the suitability of water for irrigation. Sodium percentage and total dissolved salt relationship is constructed by Willcox [1, 38] to illustrate the quality of water for irrigation uses. Willcox [1] designated a graph (Fig. 17) with the total dissolved solids expressed by the horizontal axis against the sodium percentage expressed by the vertical axis. This graph is subdivided into five zones (1, excellent; 2, good to permissible; 3, permissible to doubtful; 4, doubtful to unsuitable; and 5, unsuitable) to delineate water concerning its suitability for irrigation. Figure 17 shows the plotting of the collected water samples on Wilcox's diagram; the suitability of water for irrigation purposes can be summarized as follows: sample 2 is good to permissible. The remaining shallow and deep groundwater samples, as well as the surface water, are located outside the diagram of normal salinity range where they are extremely unsuitable (have a salinity which exceeds 35 meq/l).

5.2.2 The US Salinity Laboratory Staff Classification

Sodium is one of the governing specific ions owing to its effects on both soil and plants. The two principal effects of sodium are the reduction of soil permeability and the hardening of the soil. Both effects are caused by replacement of calcium and magnesium ions by sodium ions on the soil clays and colloids (base exchange) as in Eqs. (15) and (16):

$$2\text{Na}^{+} + \text{Ca}\ (\text{Clay}) \rightarrow \text{Na}\ (\text{Clay})\ \text{Na} + \text{Ca}^{+2} \tag{15}$$

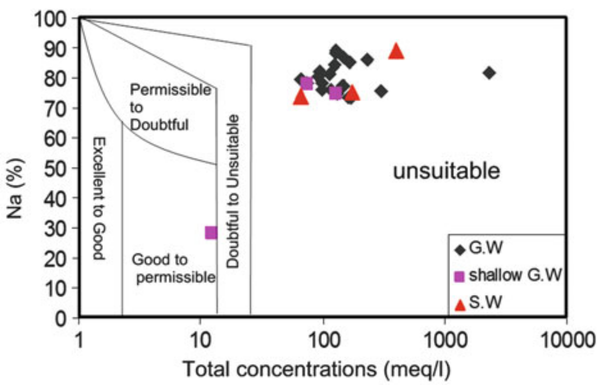

Fig. 17 Wilcox's classification of the collected water samples for irrigation

$$2Na^{+} + Mg\ (Clay) \rightarrow Na\ (Clay)\ Na + Mg^{+2} \qquad (16)$$

SAR classification system is combined with electrical conductivity (EC) classification in one graph designed by US Salinity Laboratory Staff (1954). The C1, C2, C3, and C4 classes represent the progressive increase hazard from the total salt concentration, while classes S1, S2, S3, and S4 represent the progressive increase of hazard from the exchangeable sodium. The different water types have been subdivided into 16 groups (Table 8 and Fig. 18), each having specified properties and representing a certain level of suitability for irrigation based on the combined hazard of Na/Ca + Mg and TDS expressed as EC. According to Tables 8 and 9 and Fig. 18, the collected water samples are related to the following classes:

1. *Class C1S1*: It is characterized by the water of low salinity and low sodium hazard and can be used for most soils and irrigation with most crops. Sample 2 which represents the shallow groundwater of sand dunes belongs to this zone.
2. *Class C4S1*: It is characterized by the water of high salinity and low sodium hazard. This class includes sample 24 (shallow groundwater) and 17 (surface water).
3. *Class C4S2*: It is characterized by the water of very high salinity and medium sodium hazard. Generally, this water is not suitable for irrigation under ordinary conditions, but it may occasionally be used under special conditions. This class includes samples 3, 4, 5, 6, 7, 8, 9, 11, 13, 15, 16, and 18 (deep groundwater) and 14 (shallow groundwater).
4. *Class C4S3*: It is characterized by very high salinity and high sodium hazard and satisfactory for salt tolerance crops on soils of good permeability with special leaching, good drainage, and organic matter addition; some chemical additives (gypsum) in water may help. This class includes water samples from different localities. This class includes samples 19, 20, 21, 22, 23, and 25 (deep groundwater) and 10 as surface water.
5. *Class C4S4*: It is characterized by very high salinity and high sodium hazard; it is unsuitable for irrigation purposes under normal condition. This class includes sample 26 as deep groundwater and 12 as surface water.

5.2.3 Mapping Irrigation Water Quality Index

The needed quality for irrigation water could contrast from one field to another based on the crop type, the soil type, and climate conditions. In such manner, irrigation water quality mapping is thought to be a profitable tool for the spatially conveyed appraisals of individual quality parameters. Before, index techniques were ordinarily used to evaluate water quality. One of the earliest cases of such procedures incorporated the exploration directed by Horton [50] where he built up an ordering strategy for rating the water quality. In this manner, an irrigation water quality (IWQ) index is utilized in this investigation to give a simple to utilize method that could help to estimate the general irrigation water quality. The strategy additionally

Table 8 The significance and interpretation of the water quality classes according to the US Salinity Lab (1954)

EC class	Water quality	Range micromhos/cm	Usage	SAR class	Water quality	Range	Usage
C_1	Low salinity	100–250	Can be used for irrigation with most crops on most soils; some leaching is required, but this occurs under normal irrigation practices	S_1	Low sodium	0–10	Can be used for irrigation of almost all soils
C_2	Medium salinity	250–750	Can be used if a moderate amount of leaching occurs	S_2	Medium sodium	10–18	Preferably used with good permeability
C_3	High salinity	750–2,250	Cannot be used in soil with restricted drainage; special management for salinity control may be required, and tolerance plants should be selected	S_3	High sodium	18–26	Can produce a harmful effect (good soil management essential)
C_4	Very high salinity	>2,250	Water is not suitable for irrigation under ordinary conditions but may be used occasionally under very special circumstances	S_4	Very high sodium	26–100	Unsuitable for irrigation purposes except at low and perhaps medium salinity

permits the leader to play out a spatially conveyed investigation from a more extensive point of view.

The matrix combination of this index as indicated by Eqs. (9–14) produce the IWQ index map presented in Fig. 19. This figure shows the areal distribution of the IWQ in the investigated area and could be used as a general suitability map for irrigation water in the area. Therefore, it is easy for a decision-maker to find out the most appropriate site for boring wells to extricate water for irrigation purposes. The IQW distribution map was zoned based on the IQW classification shown in Table 5. If the IQW is greater than 37, the relating region is considered to have least problems

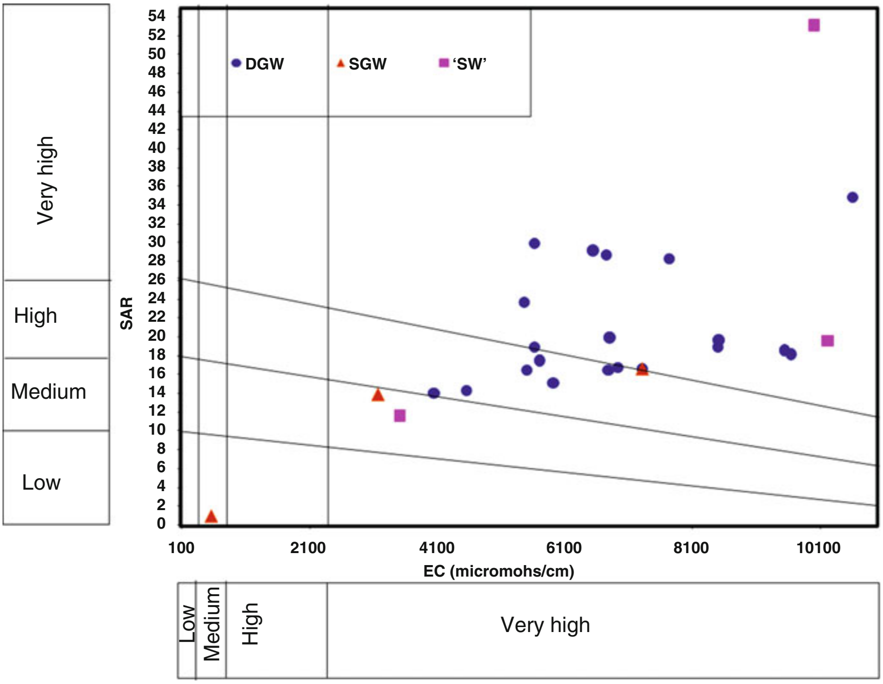

Fig. 18 The US salinity laboratory staff classification of the collected water samples for irrigation

Table 9 Classification of the collected water samples according to the US Salinity Lab (1954)

Class	Groundwater samples	Shallow GW	Surface water
C1S1		2	
C4S1		24	17
C4S2	1, 3, 4, 5, 6, 7, 8, 9, 18	14	
C4S3	11, 13, 15, 16, 20, 21, 22, 23, 25		10
C4S4	26		12

as for irrigation quality. When IQW value is in the vicinity of 22 and 37, the relating waters have moderate suitability regarding irrigation purposes. Inside this range, values higher than 30 are considered to indicate waters that could be effectively utilized on resistant plants. IQW values under 30 demonstrate waters that should just be utilized with alert and better to be avoided, especially for sensitive crops, if a superior option is available. Regions with IWQ record under 22 are thought to be low-quality irrigation waters and are not appropriate for flooding farming fields. Such waters could reduce soil quality and result in yield severe reduction. Water extraction from such territories must be avoided.

According to the constructed IQW index map and diagrams (see Fig. 19a–c and Table 5), all the deep groundwater of the study region, all surface water, and samples 14 and 24 of the shallow groundwater have IWQ values situated in the range between 22 and 37. The relating waters have moderate suitability for irrigation purposes. Sample 2 of the shallow groundwater has IWQ value more than 37 and is considered to have minimum problems regarding irrigation water quality.

5.3 *Evaluation of Water Quality for Livestock and Poultry*

Water to be used by livestock and poultry is also subjected to quality limitations of the same type as those pertaining to quality of drinking water for human consumption. The principal criteria for evaluating the water quality for purposes of livestock and poultry are shown in Table 10 as determined by the National Academy of Sciences [51]. This classification depends mainly on the total salinity values and shows the salinity limits of the different classes and the samples of the present study that fall in each class with its characteristics (Table 10). According to this classification sample, 2 (shallow groundwater) is excellent for livestock and poultry use as their salinity values are less than 1,000 mg/l. Most of the deep groundwater samples are very satisfactory to satisfactory for all classes of livestock and poultry where salinity values ranged from 1,000 to 5,000 mg/l (deep groundwater samples (1, 3, 4, 5, 6, 7, 8, 9, 11, 13, 15, 16, 18, 20, 21, 22, 23, and 25), samples 14 and 24 of the shallow groundwater, and sample 17 as surface water). It is not acceptable to use water of samples 19 and 26 as deep groundwater, and it is risky to use water of sample 12 (surface water) where salinity values are more than 10,000 mg/l.

6 Discussion and Conclusion

Twenty-six samples were collected from the shallow and deep groundwater and surface water (one for the main irrigation canal and two samples for the agricultural drains) to evaluate the water quality in the Abu Madi area which is located in the northeastern part of the middle Nile Delta. Irrigation water quality evaluation parameters were classified into two categories, individual and integrated parameters. The individual parameters include salinity, sodium, chloride, MH, RSC, pH, and alkalinity hazards. The integrated parameters include Wilcox's classification, US Salinity Laboratory Staff classifications, and irrigation water quality (IQW) index. According to EC values, all the collected samples except sample 2 are higher than 3,000 μS/cm, while the measured TDS values reveal that 12 samples of the deep groundwater, 2 samples of the shallow groundwater, and 2 samples of the surface water (drain water) have salinity hazards.

Na%, SAR, KI, RSC, and PI were used to evaluate the sodium hazards for irrigation in the study area. Na% range of the deep groundwater is 60–80% where

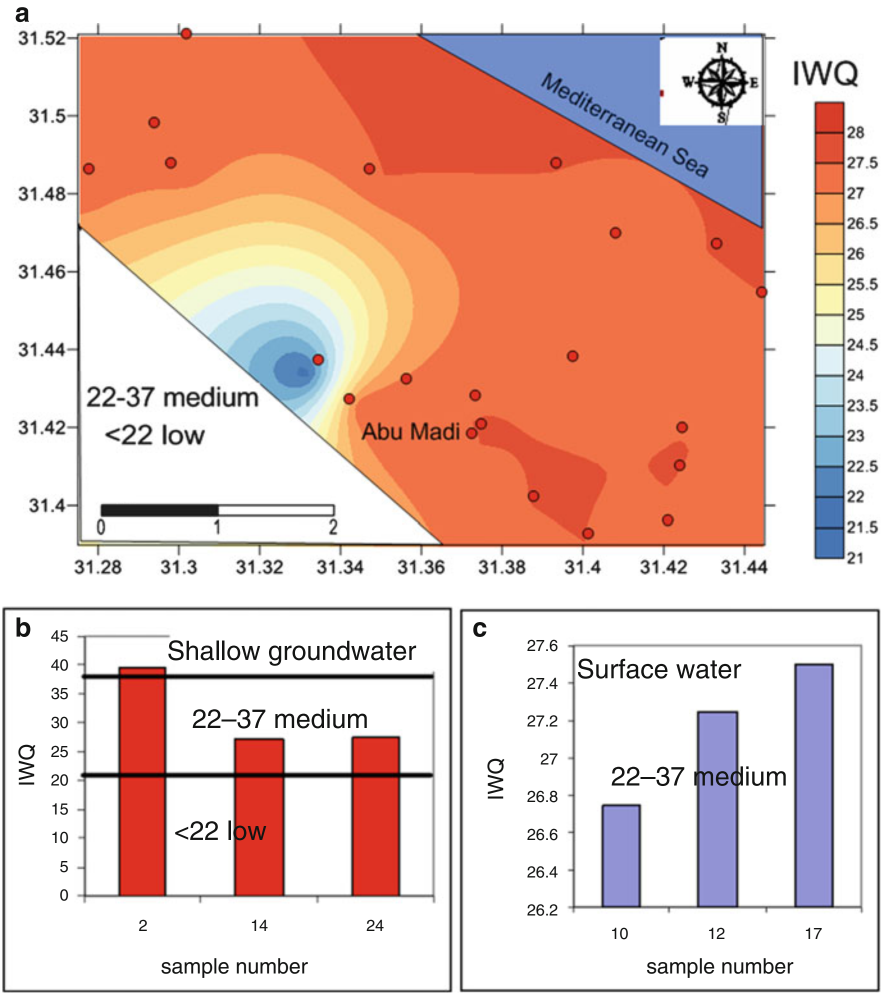

Fig. 19 IQW index spatial distribution of the deep groundwater (**a**) and IQW index graphical representation of the shallow groundwater (**b**) and surface water (**c**)

11 samples (52.38%) and 10 samples (47.62%) are situated in doubtful and unsuitable ranges, respectively. The shallow groundwater ranges from good (sample 2) to doubtful (samples 14 and 24). Na% of the surface water ranges from unsuitable (sample 12) to doubtful (samples 10 and 17). Seven (33.3%), six (28.57%), and eight (38.1%) samples of the deep groundwater are categorized based on SAR values as good, doubtful, and unsuitable, respectively. SAR value for the shallow groundwater was represented in good category (samples 14 and 24, 66.6%) and excellent for irrigation (sample 2, 33.33%). Finally, the main irrigation canal water SAR values fall in the good category, while that of the drain water were situated in doubtful (sample 10) and unsuitable (sample 12) for irrigation. Calculated RSC index values

Table 10 Guide for the use of saline water for livestock and poultry [51]

TDS mg/l	Characteristics	Deep ground water	Shallow GW	Surface water
<1,000	Relatively low level of salinity. Excellent for all classes of livestock and poultry		2	
1,000–3,000	*Very satisfactory* for all classes of livestock and poultry. May cause temporary and mild diarrhea in livestock not accustomed to them or water dropping in poultry	1, 3, 4, 6, 7, 18, 22, 25	24	17
3,000–5,000	*Satisfactory* for livestock but may cause temporary diarrhea or be refused at first by animals not accustomed to them. Poor water for poultry. Often causing water faces, increased mortality, and decreased growth, especially in Turkeys	5, 8, 9, 11, 13, 15, 16, 20, 21, 23	14	10
5,000–7,000	It can be used with reasonable safety for dairy and beef cattle and for sheep swine and horses. Avoid the use for pregnant or lactating animals. Not acceptable for poultry			
7,000–1,000	*Unfit* for poultry and probably for swine. Considerable risk in using for pregnant or lactating cows, horses, or sheep or for the young of these species. In general, use should be avoided although older ruminants, horses poultry, and swine may subsist on them under certain conditions			
>10,000	*Risk* with these highly saline water. They cannot recommended for use under any condition			12

of the study area reveal that all the collected water samples are low and fall within a good category for irrigation. All the collected water samples (except sample 2) belong to class I permeability index (PI); therefore, water resources in the study area have no permeability hazards. Calculated Kelley's index (KI) reveals that all samples of the deep groundwater, samples 14 and 24 as shallow groundwater, and all surface water samples fall within the unsuitable category.

Chloride hazards were evaluated using chloride content and CAI (chloro-alkaline index). All the collected water samples have undesirable chloride concentrations (<200 mg/l) except sample 2. CAI values showed that 14 deep groundwater samples, 1 shallow groundwater sample, and 2 surface water samples have cation–anion exchange reaction characters, while the rest of the samples have base-exchange characters. MH (magnesium hazard) values reveal that 11 samples (52.4%) of the deep groundwater samples and all the shallow groundwater and surface water samples are of the unsuitable category. The calculated values of CR (corrosive ratio) reveal that all the collected water samples except sample 2 fall within the corrosive category. The pH estimation values of all water samples in the investigation region demonstrate alkaline characters where they extend from 8.52 to

10.8 in all deep and shallow groundwater as well as the surface water samples. All deep and shallow groundwater samples and samples 12 and 17 of the surface water lie between 90 and 500 mg/l HCO_3 range which is thought to be of slight to moderate alkalinity hazards for irrigation quality.

According to Wilcox's classification, all samples (except sample 2) showed extremely unsuitable range, while in USSLS classification, all samples (except sample 2) have high to very high salinity and medium to high sodium hazards. All the deep groundwater of the study region, all surface water, and samples 14 and 24 of the shallow groundwater have IWQ values situated in the range between 22 and 37. The relating waters have moderate suitability for irrigation purposes. Sample 2 of the shallow groundwater has IWQ value more than 37 and is considered to have minimum problems regarding irrigation water quality. Most of the deep groundwater samples, two samples as shallow groundwater and one sample as surface water, are very satisfactory to satisfactory for all classes of livestock and poultry where their salinity values range from 1,000 to 5,000 mg/l. It is risky to use water of sample 12 (surface water) where salinity values are more than 5,000 mg/l.

7 Recommendations

As the studied water resources mostly have salinity, sodium, and chloride hazards, its use for irrigation should be done with caution, and selection of the appropriate crops is necessary.

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Spatiotemporal Fluctuations in Phytoplankton Communities and Their Potential Indications for the Pollution Status of the Irrigation and Drainage Water in the Middle Nile Delta Area, Egypt

Mohamed Ghobara and Zenhom E. Salem

Abstract Water pollution monitoring programs should include phytoplankton analysis to get a deep understanding of the degree of pollution and eutrophication of aquatic ecosystems. In this chapter, spatial and temporal variations of the phytoplankton composition in the Middle Nile Delta surface water were investigated. Water was sampled from two main irrigation canals (Qudaba and Mit-yazed canal) and two main drains (Janag drain and El-Gharbia main drain). A total number of 250 species and varieties belonging to 100 genera and 7 algal divisions were recorded. Bacillariophyta, Chlorophyta, Cyanophyta, and Euglenophyta were the most important and effective algal divisions in the surface water of the Nile Delta. The phytoplankton communities of the irrigation canals had a quite similar composition and so the communities of drains except in the estuary of El-Gharbia main drain. Significant differences were found between drain's phytoplankton communities and that of irrigation canals.

In general, the temperature and nutrient availability during summer seemed to give higher productivity in both irrigation and drainage water. There was evidence for heavy organic pollution through the presence of pollution-tolerant algal taxa; also there were many species that were tolerant to eutrophication. In this work, besides the observation of phytoplankton communities' fluctuations, a phytoplankton checklist

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was established for irrigation and drainage water of the Middle Nile Delta so that it can be used as environmental bioindicators and other probable applications. Palmer index was used to evaluate the organic contamination in the studied water bodies. Organic pollution in summer was higher than that of winter. In general, pollution increased along the water pathways from southern to northern direction.

Keywords Checklist, Drainage, Irrigation canals, Middle Nile Delta, Phytoplankton community, Pollution, Surface water

Contents

1 Introduction

Water resources of Egypt have serious problems including shortage and pollution, so careful water quality management and environmental protection became a necessity for sustainable development [1]. The major water requirements are mainly supplied by the River Nile, its branches, and its canals [2]. Numbers of principal and branch canals are emerging from the main body of the river, besides its two main branches: Rosetta and Damietta. Well-developed irrigation canal network system that penetrates the Delta region in addition to the west and east of the Delta delivers water to the main population centers. Also, a network of drainage systems carries industrial, domestic, and agriculture effluents away from villages and cities [3, 4]. Water pollution monitoring programs are important procedures to discover the environmental problems before turning into big threats [4]. The regular monitoring of physicochemical parameters is common but has limitations and not enough for having the complete ecological status. Biological analysis including phytoplankton monitoring is also important [5]. Sometimes, algal analysis can be used to get a deep understanding of the degree of eutrophication and pollution of aquatic ecosystems better than the instantaneous information that can be understood through regular physicochemical monitoring [6, 7].

Both phytoplankton and benthic algae showed importance during the last decades as successful environmental bioindicators as they are rapidly affected with changes of physicochemical parameters [6]. The fast and convenient phytoplankton analysis of certain suspected location along the stream of any river, canal, or drain may help to reveal the aquatic environmental crimes [8]. These crimes include the presence of illegal wastewater discharging from industry or hatcheries into the irrigation water [9]. Moreover, the blooming of certain cyanobacteria as a result of the previous high eutrophication level may lead to severe damage if the water is used directly in drinking stations without suitable treatment to remove toxins [9, 10]. Along the flow path of the irrigation canals such as Mit-yazed canal, several drinking water treatment stations providing many villages with drinking water were observed. That is why establishing a phytoplankton checklist for certain areas, especially where there is a serious pollution such as the Nile Delta region, became a task of important consideration. A phytoplankton checklist could help in using the phytoplankton as an environmental bioindicator. Moreover, the planktonic diatoms may help to solve drowning cases in forensic medicine [11].

Some studies investigated the phytoplankton communities of the irrigational and drainage water of the Nile Delta. El-sheekh et al. [12] studied the phytoplankton communities' composition and their fluctuations in response to physicochemical parameters in the River Nile, El Salam canal, and Hadous drain, Eastern Nile Delta. They found that the Bacillariophyta is the dominant group followed by Cyanophyta, Chlorophyta, Euglenophyta, and Dinophyta in the River Nile, while Cyanophyta and Chlorophyta were the predominant groups followed by Bacillariophyta and Euglenophyta in both El Salam canal and Hadous drain due to the high pollution level. The phytoplankton communities in the River Nile at Shubra El Kheima, Ismailia canal, and Belbase drain were studied by Badr El-Din et al. [13]. They found that algal community biomass increased in the warm seasons rather than in the winter; moreover, they noticed that the irrigation canal contained relatively high counts of algae compared with drainage water. They also found three dominant major algal groups (Chlorophyta, Cyanophyta, and Bacillariophyta) with the dominance of diatoms. Shaaban et al. [14] estimated that the peak periods of total chlorophyll coincided with peak periods of the stations that recorded high algal biomass. Phytoplankton in Rosetta branch of the River Nile had chloro-character particularly in summer 2007.

Shaaban et al. [15] studied the phytoplankton content of Rosetta Nile branch south and north Edfina Barrage in relation to its physicochemical properties. They found that phytoplankton population composed mainly of alkaliphilous taxa, and this is in agreement with pH mean values of water. Additionally, the most recorded algal taxa in front of (to south) Edfina Barrage had a freshwater character (oligohalobic), while those collected from the stations behind (to north) Edfina Barrage were characterized by brackish mesohalobous with tendency toward euhalobous algal forms, especially when Mediterranean water influx into Rosetta estuary increases due to the limitation of freshwater discharge from Rosetta branch.

There are many studies concerning water quality in the Nile Delta; among them are Abdel-Baky [16], Deyab [17], Shehata et al. [18], Salem [19], Abdo et al. [20], Elewa [21], Omar [7], Gemail et al. [22], Morsy and El-Fakharany [23], Salema et al. [24], Ghoraba et al. [25], Khalil et al. [26], Bennett et al. [27], Elkafoury et al. [28], Fattah and Ragab [29], El-Kowrany et al. [30], Negm and Armanuos [31], Negm and Eltarabily [32], Mohamed [10], Salem et al. [33], Sharaky et al. [34], Salem and Osman [35], Abdel-Satar et al. [36], Salem et al. [37], and El-Sheekh

[9]. These studies used physicochemical parameters or microbiological analysis as well as integrated techniques between all water quality criteria.

This work aims to prepare a checklist of the phytoplankton species and varieties for further usage as environmental bioindicators and other applications. Also, it aims to study spatial and temporal fluctuations of the phytoplankton composition of two irrigation canals and two drains as a representative for the irrigational and drainage water at the Middle Nile Delta. Finally, the current pollution status of both irrigation canals and drains was discussed based on phytoplankton fluctuations.

2 Study Area Description

Figure 1 shows the study area map with sampling stations distributed along the flow path of the selected water bodies from south to north. Mit-yazed canal is an irrigation canal, which branched from the Shubin rivulet at 30° 52′ N, 31° 08′ E. This canal penetrates the Delta to reach Kafr El Sheikh city, and then it branches into a number of smaller canals. The eastern branch was selected to complete our sampling process. Qudaba canal is a long irrigation canal. It has different names at different parts, but it is the same water body that is emerging from Rosetta branch near El Qanater El Khiria at 30° 11′ N, 31° 07′ E. Our sampling work started at Tanta city where the canal water flows to the west where Kafr El-Zayat city is located and then passed parallel to the Rosetta Nile branch to the northern direction. El-Gharbia main drain is the largest drain in the Middle Nile Delta. It collects effluents from domestic, agricultural, and industrial water by many branches in the eastern and western sides along its path. The drain finally discharges into the Mediterranean Sea (31° 34′ N, 31° 10′ E) east of Baltim city and Lake El-Burulus. Janag drain is a small drain which starts near Kafr El-Zayat city (30° 49′ N, 30° 49′ E) and then collects effluents along its path and finally discharges into the final point (31° 04′ N, 30° 47′ E).

3 Material and Methods

Surface water was sampled from 18 sites (Fig. 1b) twice from each location during 2015, once in winter and the other in summer. Sampling sites were distributed along the pathways from south to north of the two main irrigation canals (Mit-yazed canal, four sites, and Qudaba canal, five sites) and the two main drains (El-Gharbia main drain, five sites, and Janag drain, four sites).

Sample collection, preparation, and phytoplankton identifications were done as discussed in Salem et al. [37]. Phytoplankton genera and species were identified according to the following references: Prescott [38, 39], Hustedt [40], Hendey [41], Whitford and Schumacher [42], and Desikachary [43]. The counting was carried out according to methods described elsewhere [44].

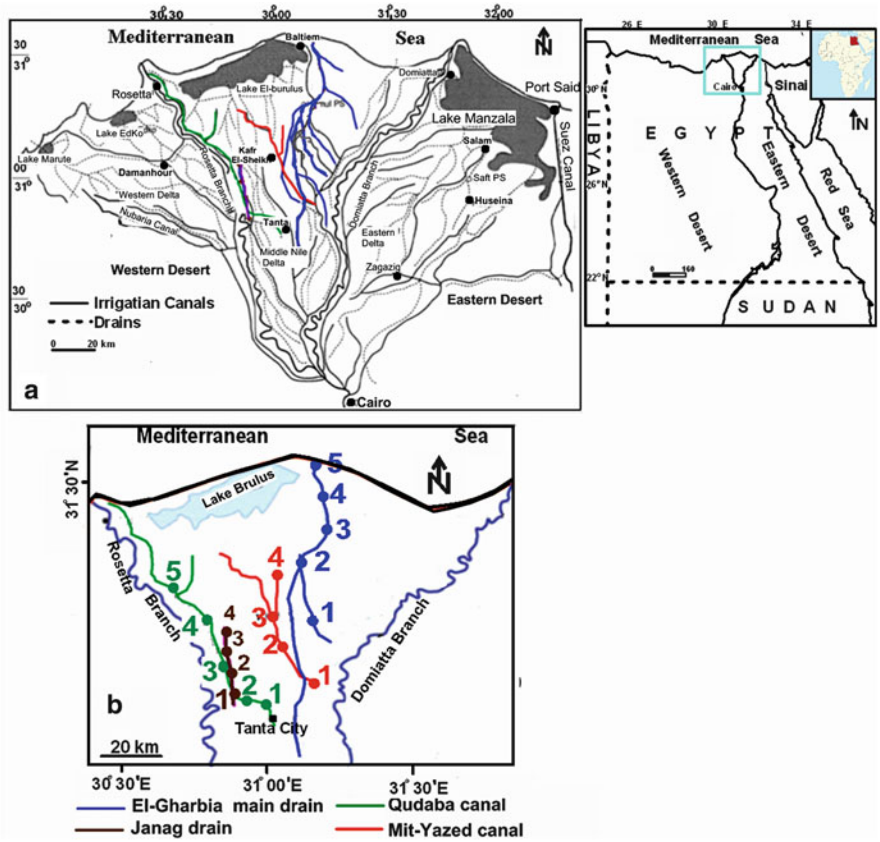


Fig. 1 Maps of the Nile Delta show the distribution of irrigation canals and drains (**a**) and sampling stations (**b**) (after [37])

The photomicrographs of the most common taxa have been taken using Carl Zeiss microscope fitted with a camera. For further identification of diatoms, the method described by Ghobara [45] was followed to clean the diatom frustules to investigate their architecture using SEM. Scanning electron microscopy (SEM) studies were carried out in the electronic microscope unit of the National Research Centre (Cairo, Egypt) using field emission scanning electron microscope (FE-SEM), Quanta FEG 250, and FEI.

4 Results and Discussion

A total number of 250 species and varieties belonging to 100 genera and 7 algal divisions were recorded, 153 taxa for Qudaba canal, 139 taxa for Mit-yazed canal, 101 taxa for El-Gharbia main drain, and 60 taxa for Janag drain (Table 1). Some of the species that are present in irrigation canals and drains were illustrated in Figs. 2, 3, and 4. The phytoplankton communities of the two irrigation canals showed similar behaviors and that of the two drains was similar except the last station of El-Gharbia main drain, where a different ecosystem (the estuary) was detected. In comparison, a great difference was detected in the phytoplankton community between irrigation canals and drains.

4.1 Phytoplankton Community in the Irrigation Canals

4.1.1 Qudaba Canal

The highest number of taxa was recorded at this canal; the number of taxa in the winter (116 taxa) was higher than that of summer (82 taxa) as shown in Table 1. The highest number of individual algal cells was 13.3 m cells per liter at station III during summer, while the lowest number was 1.7 m cells per liter at station V during winter. The total number of phytoplankton increased in the summer.

As shown in Fig. 5, Bacillariophyta, Chlorophyta, and Cyanophyta were the most representative algal divisions in this canal. Bacillariophyta was abundant in all Qudaba stations during both winter and summer. Chlorophyta was dominant over Cyanophyta during summer in all stations except station V. A reverse situation was noticed during winter. Cryptophyta appeared in Qudaba stations during winter; however, it disappeared during summer and was replaced with Dinophyta.

Most of the taxa were oligohalobus which is tolerant to slightly alkaline water. The winter was characterized by an abundance of *Cyclotella ocellata*, *Synedra ulna*, *Scenedesmus* spp., *Merismopedia* spp., *Microcystis* spp., and *Oscillatoria* spp. and rare presence of Cryptophyta and Chrysophyta, while summer was also characterized by the abundance of *Cyclotella ocellata* and *Synedra ulna*, besides the appearance and strong presence of *Pediastrum* spp., colonial cyanobacteria (such as *Aphanocapsa* spp., *Gomphosphaeria* spp., *Gloeocystis* sp., *Sphaerocystis* sp.), and *Oocystis borgei* and the rare presence of Dinophyta.

4.1.2 Mit-yazed Canal

The second highest diversity of taxa was recorded in this canal; the number of taxa in the winter (91 taxa) was higher than the summer (82 taxa) as shown in Table 1. The highest number of individual algal cells was 11.9 m cells per liter at the station I during summer, while the lowest number was 0.5 m cells per liter at the station IV

Table 1 The phytoplankton checklist of different studied water bodies (Q, Qudaba canal; M, Mit-yazed canal; K, El-Gharbia main drain; J, Janag drain) during both winter (W) and summer (S) seasons

Water body →	Q		M		K		J	
↓ Taxon	W	S	W	S	W	S	W	S
Bacillariophyta								
Amphora coffeaeformis (Ag.) Kütz.					+			
Aulacoseira granulata (Ehr.) Sim.	+	+	+	+	+	+	+	+
A. granulata var. *angustissima* (Müller) Sim.	+	+	+	+		+	+	+
Bacillaria paxillifera (Müller) Marsson	+		+					
Caloneis amphisbaena (Bory) Cleve	+							
Chaetoceros sp.					+			
Cocconeis placentula (Ehr.) sensu lato	+	+	+	+		+	+	
C. placentula var. *lineata* (Ehr.) Van Heurck	+		+					
C. placentula var. *euglypta* (Ehr.) Grunow	+	+	+					
Craticula molestiformis (Hust.) Mayama	+							
C. accomoda (Hust.) Mann	+	+	+					
C. ambigua (Ehr.) Mann		+	+	+				
C. cuspidata (Kütz.) Mann			+					
Cyclostephanos dubius (Hust.) Round	+				+			
Cyclotella meneghiniana Kütz.	+	+	+	+	+	+	+	+
C. ocellata Pantocsek	+	+	+	+	+	+	+	+
C. rossii Hakansson	+	+						
C. stelligera (Cleve and Grunow) Van Heurck			+					
Cymatopleura solea (Brébisson) Smith	+							
Cymbella affinis Kütz.					+			
Cymbella sp.	+							
Entomoneis paludosa var. *subsalina* (Cleve) Krammer					+	+		
Entomoneis sp.	+					+		
Fallacia pygmaea (Kütz.) Stickle and Mann	+	+			+			
F. subhamulata (Grunow) Mann					+			
Gomphonema parvulum (Kütz.) Rabenh.		+			+			
G. angustatum (Kütz.) Rabenh.		+	+					
G. augur Ehr.	+	+	+					
G. truncatum Ehr.			+					
Grammatophora marina (Lyngbye) Kütz.					+		+	
Gyrosigma attenuatum (Kütz.) Rabenh.	+	+		+				
G. elongatum (Smith) Griffith and Henfrey	+	+	+					
G. scalproides (Rabenh.) Cleve	+							
G. macrum (Smith) Griffith and Henfrey	+							
Hantzschia amphioxys (Ehr.) Grunon					+			
Hippodonta hungarica (Grunow) Lange-Bertalot, Metzeltin, and Witkowski					+			
Lemnicola hungarica (Grunow) Round and Basson					+			
Luticola ventricosa (Kütz.) Mann							+	

(continued)

Table 1 (continued)

Water body →	Q		M		K		J	
↓ Taxon	W	S	W	S	W	S	W	S
Melosira varians Ag.	+		+		+			
Navicula cryptotenella Lange-Bertalot		+		+		+		
N. exigua Gregory		+						
N. gregaria Donkin							+	
N. lanceolata Ehr.			+		+			
N. pygmaea Kütz.					+			
N. recens (Lange-Bertalot) Lange-Bertalot					+			
Navicula sp.	+	+		+	+	+		+
Nitzschia frequens Hust.					+			
N. fruticosa Hust.	+	+		+				
N. gracilis Hantzsch		+	+	+	+			
N. paleacea (Grunow) Grunow			+			+		+
N. reversa Smith		+						
N. acicularis (Kütz.) Smith	+	+		+	+	+		
N. constricta (Gregory) Grunow			+					
N. kurzeana Rabenh.	+	+						
N. linearis Smith	+							
N. palea (Kütz.) Smith	+	+	+	+	+	+	+	+
N. sigmoidea (Nitzsch) Smith	+							
N. umbonata (Ehr.) Lange-Bertalot	+							
Nitzschia sp.			+					
Pinnularia sp.			+		+			
Pseudostaurosira brevistriata (Grunow) Williams and Round	+		+	+				
Sellaphora pupula (Kütz.) Mereschkovsky	+							
Staurosira venter (Ehr.) Cleve and Moeller	+		+					
Staurosirella leptostauron (Ehr.) Williams and Round	+	+	+	+				
S. pinnata (Ehr.) Williams and Round	+	+		+				
Synedra acus Kütz.	+	+	+	+			+	
S. ulna (Nitzsch) Ehr.	+	+	+	+			+	
S. capitata Ehr.	+	+						
S. danica Kützing	+	+	+	+	+	+		+
Synedra sp.			+			+		+
Tabularia fasciculata (Ag.) Williams and Round			+					
Tryblionella hungarica (Grunow) Frenguelli					+			
T. apiculata Gregory	+							
Chlorophyta								
Actinastrum hantzschii Lager.	+		+					
Ankistrodesmus acicularis (Braun) Korshikov	+			+				
A. falcatus (Corda) Ralfs		+	+			+		
A. falcatus var. *tumidus* (West and West) West		+	+			+		
A. fractus (West and West) Collins			+					

(continued)

Table 1 (continued)

Water body →	Q		M		K		J	
↓ Taxon	W	S	W	S	W	S	W	S
A. spiralis (Turn.) Lemm.	+		+					
A. densus Korshikov								
Botryococcus braunii Kütz.		+		+				
Chlamydomonas globosa Snow	+				+	+	+	+
C. reinhardtii Dangeard	+				+	+	+	+
Chlorella vulgaris Beyerinck [Beijerinck]	+	+		+		+		+
Chlorococcum sp.				+	+	+	+	+
Closterium kuetzingii Brébisson					+			
C. aciculare West			+					
C. acutum Brébisson	+							
C. moniliferum Ehr. ex Ralfs	+					+		
Coelastrum astroideum De Notaris				+				
C. reticulatum (Dangeard) Senn				+				
C. sphaericum Nägeli						+		
C. microporum Nägeli	+	+	+	+				+
Crucigenia truncata smith	+							
C. quadrata Morren								
C. rectangularis (Nägeli) Gay		+	+					
C. tetrapedia (Kirchner) Kuntze	+							
Glaucocystis nostochinearum Itzigsohn	+		+					
Kirchenerlla lunaris (Kirch.) Moebius	+							
K. contorta (Schmidle) Bohlin	+		+					
K. obesa (West) West and West	+		+	+				
K. obesa var. *major* (Bernard) Smith		+	+	+				
Lacunastrum gracillimum (West and West) McManus	+	+		+				
Lagerheimia genevensis (Chodat) Chodat	+		+					
L. subsalsa Lemm.				+			+	
Monoraphidium contortum (Thuret) Komárková-Legnerová	+		+					
M. convolutum (Corda) Komárková-Legnerová					+			
M. griffithii (Berk.) Komárková-Legnerová	+							
Mougeotia scalaris Hassall	+		+					
Oedogonium sp.	+							
Oocystis borgei Snow		+				+		
O. lacustris Chodat				+				
Pandorina morum		+						
Pediastrum simplex Meyen		+		+		+		
P. simplex var. duodenarium (Bailey) Rabenh.	+	+	+	+		+		+
P. simplex var. *echinulatum* Wittrock		+		+		+		
P. tetras (Ehr.) Ralfs		+						
Pseudopediastrum boryanum (Turpin) Hegewald		+		+				

(continued)

Table 1 (continued)

Water body →	Q		M		K		J	
↓ Taxon	W	S	W	S	W	S	W	S
Scenedesmus abundans var. *asymmetrica* (Schroeder) Smith	+	+	+					
S. acuminatus (Lager.) Chodat					+			
S. arcuatus var. *capitatus* Smith						+		
S. armatus smith					+	+		+
S. bernardii Smith	+							
S. bijugatus var. *alternans* (Reinsch) Hansgirg		+	+					
S. ecornis (Ehr.) Chodat			+					
S. opoliensis var. *contacta* Prescott		+		+				
S. quadricauda var. *maximus* West and West	+							
S. quadricauda var. *quadrispina* (Chodat) Smith	+	+		+	+			
S. quadricauda var. westii Smith	+	+	+					
S. abundans var. *longicauda* Smith	+	+	+					
S. bijugatus Kütz.	+		+	+		+		
S. denticulatus Lager.		+		+				
S. dimorphus (Turpin) Kütz.	+	+	+	+	+	+		
S. longus var. *naegelii* Brébisson	+		+					
S. obliquus (Turpin) Kütz.	+					+		
S. opoliensis Richter	+	+	+	+		+		+
S. quadricauda (Turpin) Brébisson	+	+	+		+			+
Sorastrum pediastriforme Jena and Bock	+					+		
Sphaerellopsis fluviatilis (Stein) Pascher	+							
Spirogyra sp.	+		+					
Staurastrum paradoxum Meyen	+	+	+	+				
S. dejectum Brébisson			+					
S. gracile Ralfs ex Ralfs	+	+	+	+				
Tetraëdron trigonum (Nägeli) Hansgirg				+				
T. minimum (Braun) Hansgirg	+		+					
T. muticum (Braun) Hansgirg				+				
Tetraspora lubrica (Roth) Ag.					+			
Tetrastrum glabrum (Roll) Ahlstrom and Tiffany	+	+				+		
T. staurogeniiforme (Schröder) Lemm.					+			
Cyanophyta								
Aphanizomenon sp.							+	
Planktothrix sp.							+	+
Anabaena affinis Lemm.	+			+	+		+	
A. constricta (Szafer) Geitler	+				+		+	+
A. laxa Braun				+				
A. affinis Lemm.								
Aphanocapsa sp.	+	+	+			+		
A. grevillei (Berk.) Rabenh.	+	+		+			+	
Aphanothece pallida (Kütz.) Rabenh.	+							

(continued)

Table 1 (continued)

Water body →	Q		M		K		J	
↓ Taxon	W	S	W	S	W	S	W	S
Arthrospira okensis Meyer					+			+
A. platensis Gomont	+							
A. gigantea (Schmidle) Anagnostidis								+
Chroococcus limneticus Lemm.	+	+	+	+		+		
C. minutus (Kütz.) Nägeli	+		+	+		+		
C. dispersus (Keissler) Lemm.	+	+	+			+		
Cyanothece aeruginosa (Nägeli) Komárek			+			+		
Cylindrospermum majus Kütz. ex Bornet and Flahault								
Dictyosphaerium sp.		+						
Gloeocapsa alpina Nägeli			+	+				
G. rupestris Kütz.	+							
G. aeruginosa Kütz.	+		+					
Gloeocystis sp.		+		+				
Gloeothece sp.							+	
Goelosphaerium sp.		+						+
Gomphosphaeria lacustris var. *compacta* Lemm.		+						
Gomphosphaeria sp.		+		+				
Lyngbya major Meneghini ex Gomont	+							
L. limnetica Lemm.				+				
Merismopedia glauca (Ehr.) Kütz.	+	+	+	+				
M. tenuissima Lemm.	+		+	+		+		
M. trolleri Bachmann	+							
M. elegans Braun ex Kütz.	+	+		+		+		+
Microcystis flosaquae (Wittrock) Kirchner	+		+		+			
M. incerta (Lemm.) Lemm.				+				
M. aeruginosa (Kütz.) Kütz.	+	+	+	+				
Oscillatoria annae Goor			+		+		+	
O. chalybea Mertens ex Gomont					+	+		+
O. formosa Bory ex Gomont			+	+				+
O. geminata Schwabe ex Gomont							+	
O. lacustris (Klebahn) Geitler						+		
Oscillatoria princeps		+		+		+		+
O. putrida Schmidle						+		
O. redeckei Goor						+	+	
O. willei Gardner	+						+	+
O. hamelii Frémy	+							
O. limnetica Lemm.	+	+			+	+	+	+
O. limosa Ag. ex Gomont	+		+		+			
O. subtilissima Kütz. ex Forti	+		+				+	+
O. tenuis Ag. ex Gomont			+	+		+		+
Oscillatoria sp.					+			

(continued)

Table 1 (continued)

Water body →	Q		M		K		J	
↓ Taxon	W	S	W	S	W	S	W	S
Palmodictyon viride Kütz.		+						
Phormidium mucicola Nauman and Huber-Pestalozzi		+						
Phormidium sp.					+			+
Planktolyngbya limnetica (Lemm.) Komárková-Legnerová and Cronberg			+					
Pseudoanabanea sp.	+		+	+				
Pseudoanabanea sp. 2		+						
Sphearocystis sp.		+		+				+
Spirulina labyrinthiformis Gomont							+	
S. laxa Smith		+						
S. major Kütz. ex Gomont	+							
S. princeps West and West	+							
S. subsalsa Oersted ex Gomont		+					+	
S. subtilissima Kütz. ex Gomont							+	
Synechococcus aeruginosus Nägeli			+				+	
Woronichinia sp.		+						
Cryptophyta								
Chroomonas sp.					+			
Cryptomonas erosa Ehr.	+			+	+	+		
C. lucens Skuja			+					
C. ovata Ehr.	+		+					
Rhodomonas lacustris Pascher and Ruttner	+							
R. minuta Skuja	+		+	+	+			
Chrysophyta								
Exuviaella compressa (Bailey) Ostenfeld	+			+				
Lagynion sp.	+		+	+				
Synura sp.				+				
Trachelomonas sp.				+				+
Vaucheria sp.	+							
Dinophyta								
Glenodinium pulvisculus (Ehr.) Stein				+		+		
Katodinium vorticella (Stein) Loeblich III		+	+					
Peridinium cinctum (Müller) Ehr.					+			
P. volzii Lemm.		+		+				
Predinium sp.		+						
Preidinium sp. 1				+				
Euglenophyta								
Euglena acus (Müller) Ehr.				+				+
E. anabaena Mainx				+	+	+	+	
E. caudata Hübner						+		
E. clavata Skuja						+		+
E. gracilis Klebs				+	+	+		+

(continued)

Table 1 (continued)

Water body →	Q		M		K		J	
↓ Taxon	W	S	W	S	W	S	W	S
E. obtusa Goor	+		+					
E. oxyuris Schmarda			+					
E. proxima Dangeard				+		+		
E. sanguinea Ehr.							+	
E. variabilis Klebs					+	+		
E. viridis (Müller) Ehr.				+	+	+		
Euglena sp.			+			+	+	
Lepocinclis ovum (Ehr.) Lemm.				+	+		+	
L. playfairiana (Deflandre) Deflandre					+			
Phacus anacoclus Stokes				+				
P. caudatus Hübner			+	+	+			
P. longicauda (Ehr.) Dujardin				+		+		+
P. tortus (Lemm.) Skvortzov						+		
Phacus sp.					+			

The (+) sign means the species is present at least in one station during the season

during winter. Like Qudaba canal results, the total number of phytoplankton increased in the summer compared to winter.

As shown in Fig. 6, Mit-yazed canal showed similar results as Qudaba canal where Bacillariophyta, Chlorophyta, and Cyanophyta were also the most important algal divisions. Bacillariophyta also was abundant in all stations during the two seasons. Chlorophyta was dominant over Cyanophyta during summer in all stations; however, a reverse situation is present during winter except at station II. Cryptophyta appeared in the first three stations during winter; however, it disappeared during summer, and Dinophyta and Euglenophyta appeared in the first two stations. The presence of Euglenophyta at stations I and II during summer may be associated with the observed effluent from Semetay drain.

Most of the taxa were oligohalobus which is tolerant to slightly alkaline water. The winter was characterized by the abundance of *Cyclotella ocellata*, *Synedra ulna*, *Ankistrodesmus* spp., *Scenedesmus* spp., and *Oscillatoria* spp. and the presence of Cryptophyta and the rare presence of Euglenophyta, while in summer, the canal water was characterized by the abundance of *Cyclotella ocellata* and *Synedra ulna* and diversity of *Pediastrum* spp., colonial cyanobacteria, *Oocystis lacustris*, Chrysophyta, Euglenophyta, and Dinophyta.

4.1.3 Pollution Evaluation of the Irrigation Canals

Different organic pollution levels appeared in most stations, especially in summer, through the abundance of tolerant algal species [9, 37]. In general, it is estimated that fluctuations in the temporal productivity (total no. of algal individuals) may be

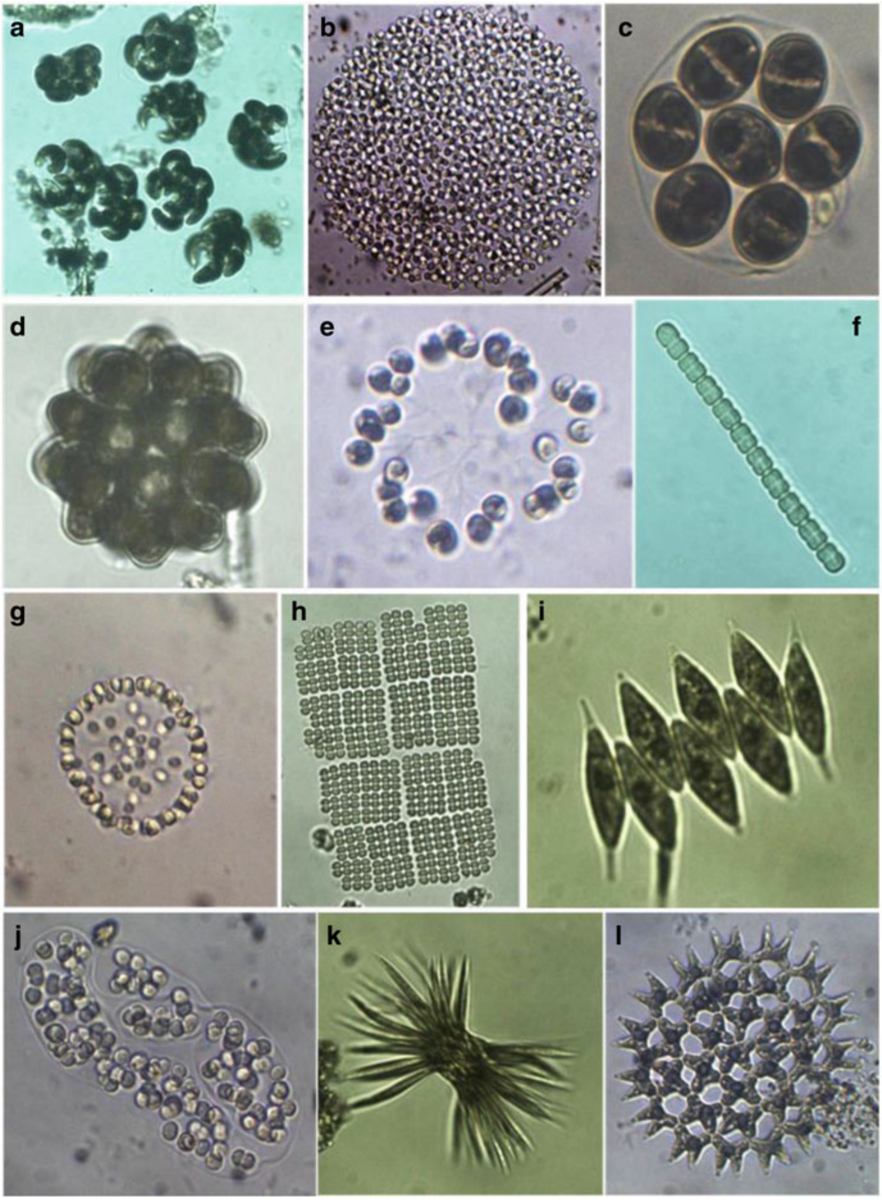


Fig. 2 Optical micrographs of some common species in the studied stations (magnification = 600×). (**a**) *Kircheneriella obesa*, (**b**) *Aphanocapsa* sp., (**c**) *Oocystis lacustris*, (**d**) *Coelastrum microporum*, (**e**) *Dictyosphaerium* sp., (**f**) *Anabaena constricta*, (**g**) *Gomphosphaeria* sp., (**h**) *Merismopedia elegans*, (**i**) *Scenedesmus obliquus*, (**j**) *Palmodictyon viride*, (**k**) *Ankistrodesmus spiralis*, (**l**) *Lacunastrum gracillimum*

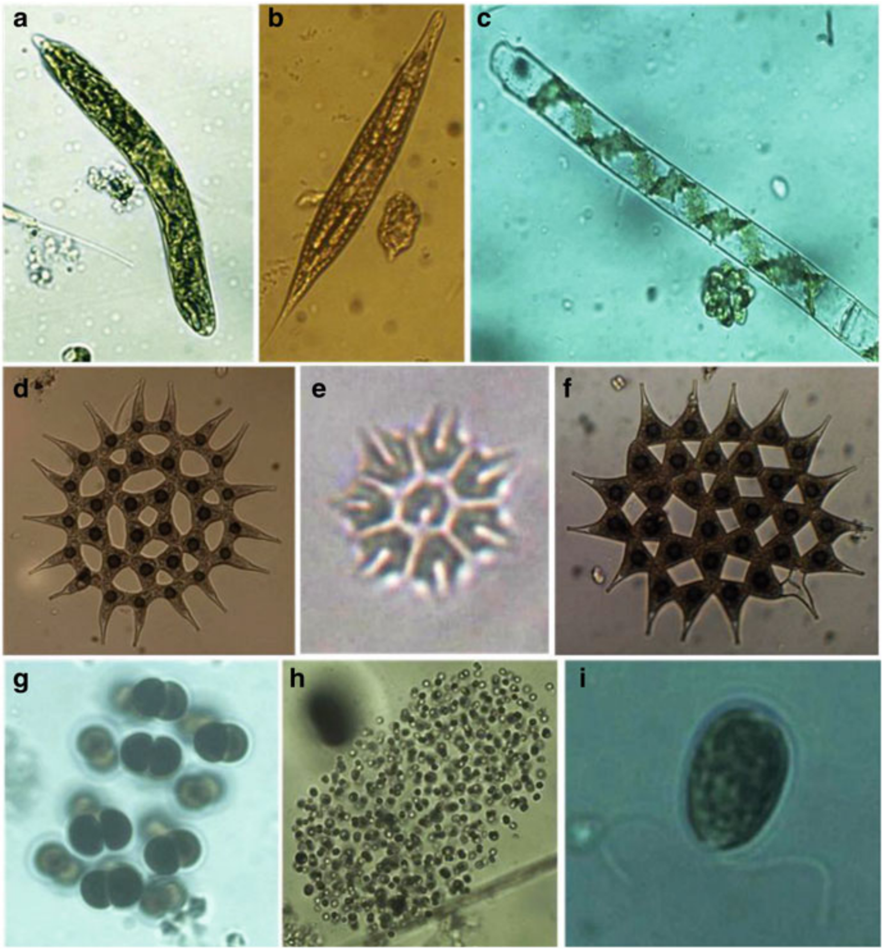


Fig. 3 Optical micrographs of some common species in the studied stations (magnification = 600×). (**a**) *Euglena oxyuris*, (**b**) *Euglena acus*, (**c**) *Spirogyra* sp., (**d**) *Pediastrum simplex*, (**e**) *Pediastrum tetras*, (**f**) *Pediastrum simplex* var. *duodenarium*, (**g**) *Chroococcus limneticus*, (**h**) *Aphanocapsa* sp., (**i**) *Chlamydomonas reinhardatii*

correlated with the mean seasonal variations in water temperature (ranged from 16 to 33.5°C) and variations in light intensity and nutrient availability especially nitrogen and phosphate. That is in agreement with the observed results by Bhasin et al. [46] where the algal biodiversity increases in higher temperatures. Moreover, another species was found to have higher growth in lower temperature [47], where it seemed to be lower during summer.

The algal productivity in the same canal increased starting from the first station reaching the maximum value at the middle of the pathway and then decreased again (Figs. 5 and 6). That may be corresponding to the nutrient availability and organic

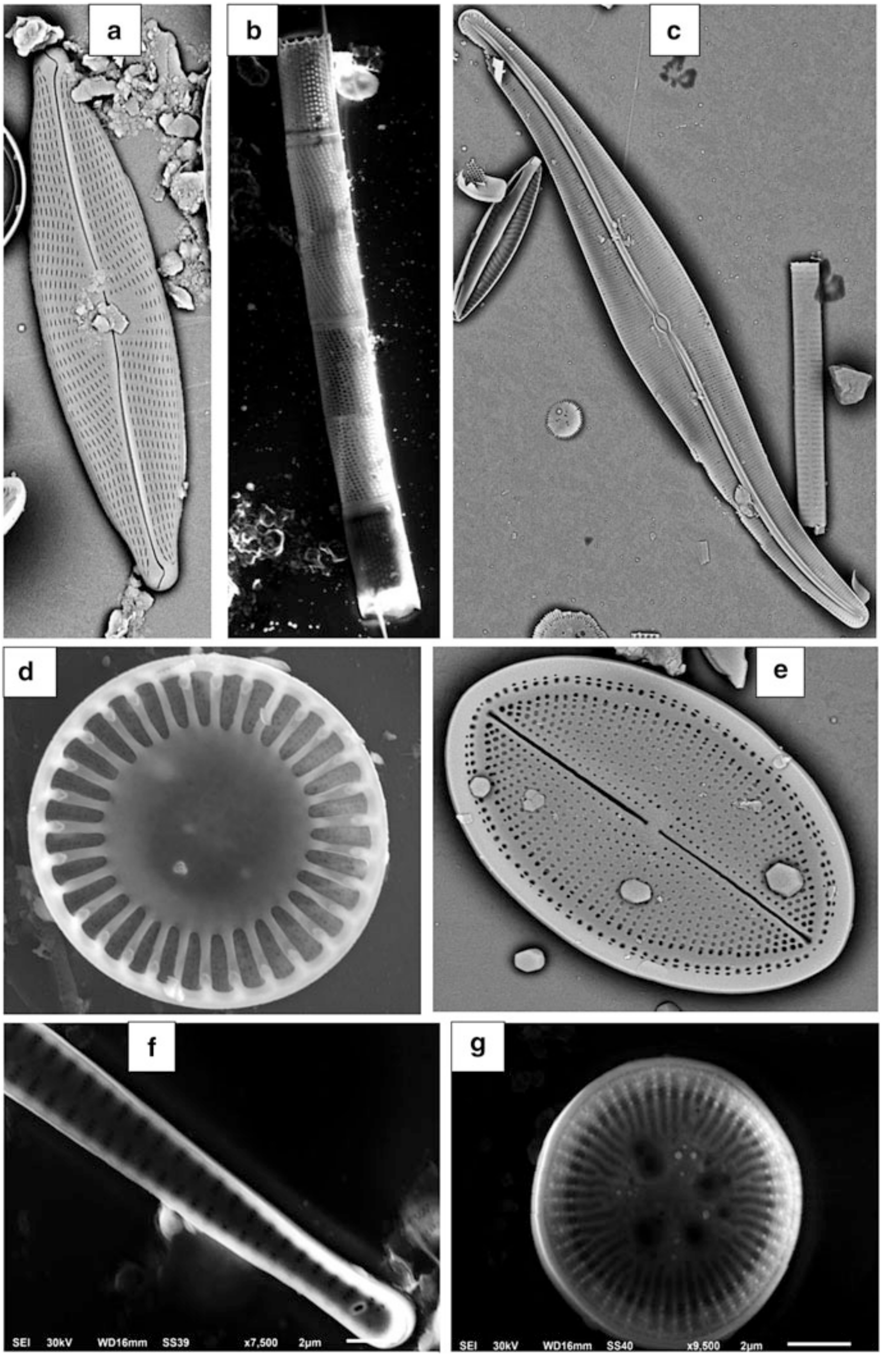


Fig. 4 Scanning electron micrographs of some common diatoms in the studied stations. (**a**) *Navicula cryptocephala*, (**b**) *Aulacoseira granulata*, (**c**) *Gyrosigma attenuatum*, (**d**) *Cyclotella meneghiniana*, (**e**) *Cocconeis placentula*, (**f**) *Synedra ulna* var. *danica*, (**g**) *Cyclotella ocellata*

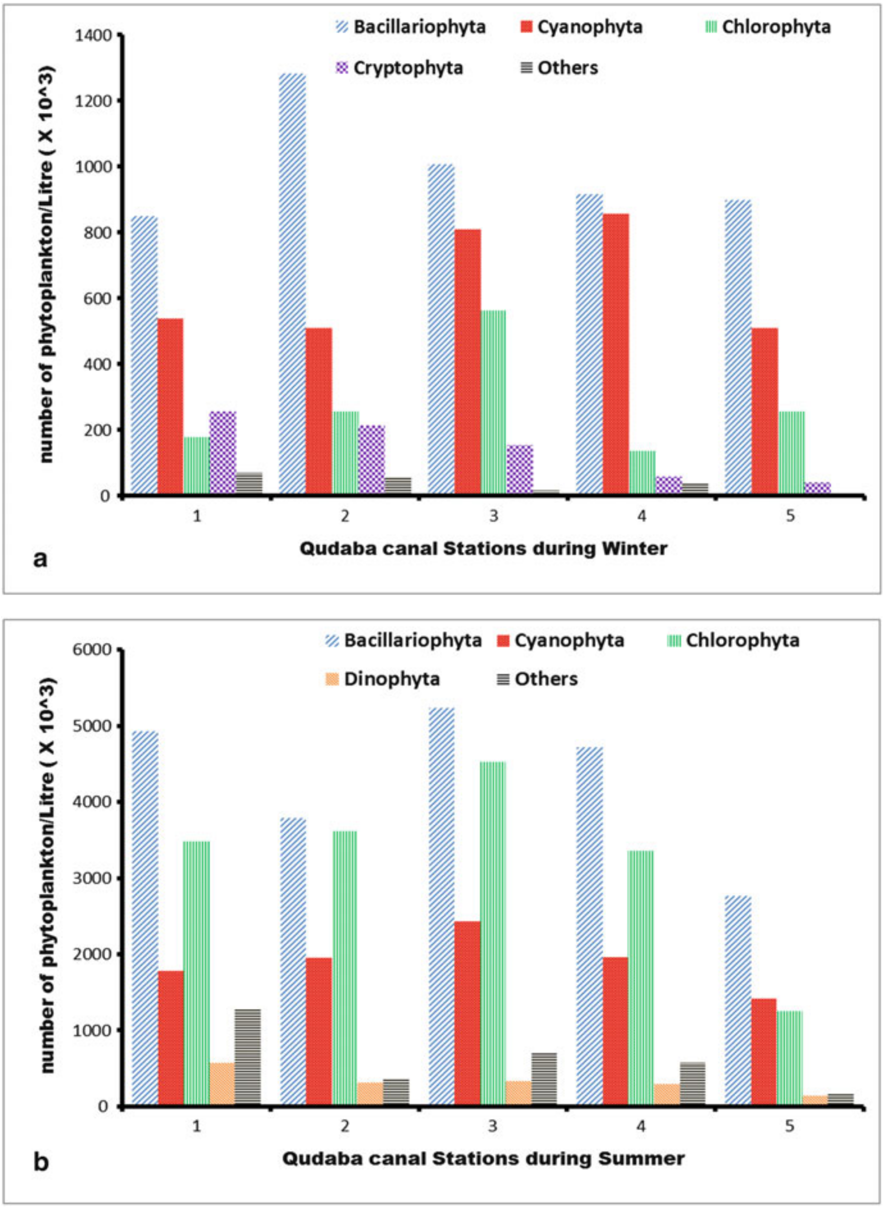
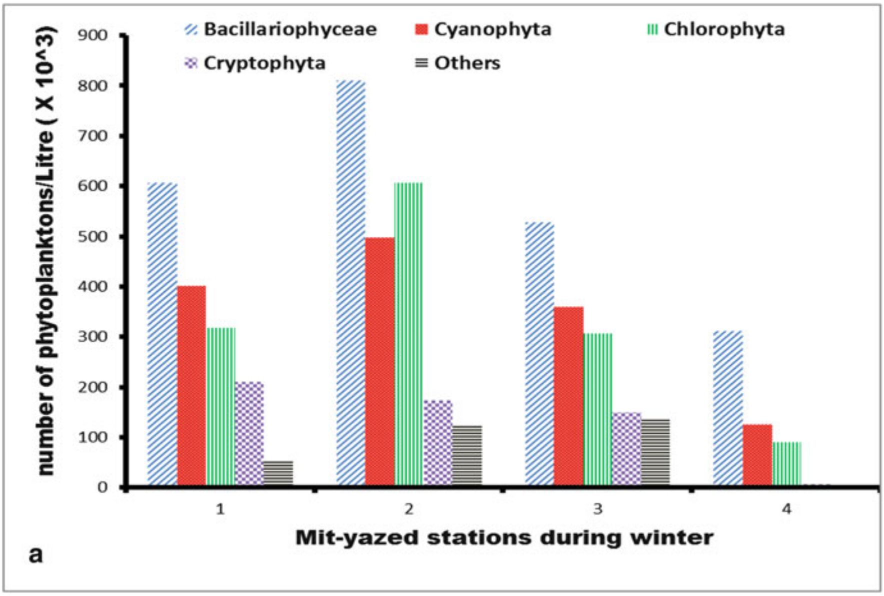


Fig. 5 Diagrams illustrate the spatial variations of the algal divisions along the flow path of Qudaba irrigation canal during winter (**a**) and summer (**b**)

pollution load, which seemed to be higher near big cities and main villages due to human activities [37, 48]. This idea was observed in station III of Qudaba canal, where Qudaba town is located.



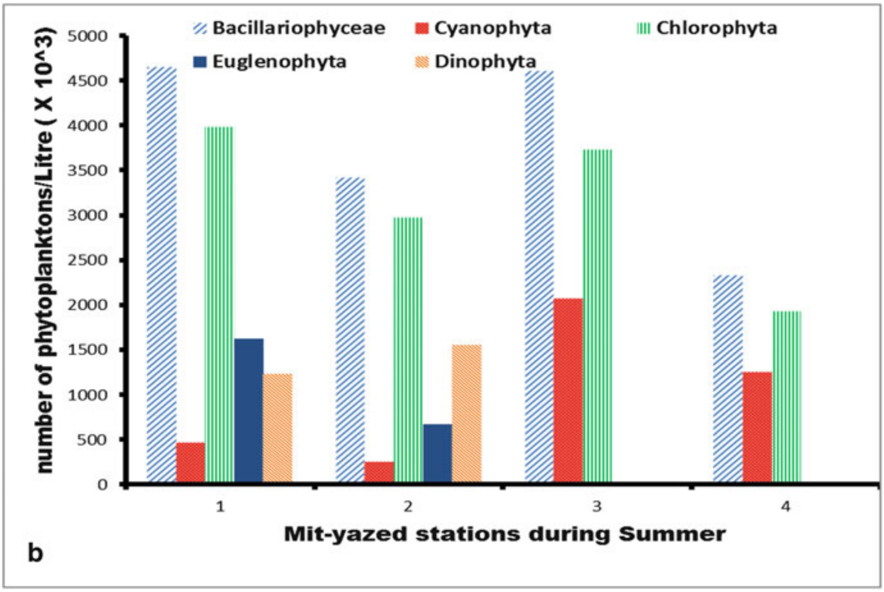


Fig. 6 Diagrams illustrate the spatial variations of the algal divisions along the flow path of Mit-yazed irrigation canal during winter (**a**) and summer (**b**)

Bacillariophyta was the dominant in all stations during both seasons similar to the results that were previously recorded in Rosetta branch [14, 18, 49] and in Damietta branch and El Salam canal [12]. The previous studies suggested that the high silica content may attribute to such results. It was also concluded that the alkaline nature of the River Nile water [18, 36] might be suitable for diatoms. Bacillariophyta was found as the dominant phytoplankton in River Nile followed by Chlorophyta and then Cyanophyta [50, 51]. The current results have the same trend during summer in the two studied canals. This might be attributed to the increase in surface water temperature and nutrient content especially nitrogen content [12, 52, 53]. It also meets with the results of the pioneer experiments of Abou-Waly et al. [50] where higher nitrogen concentrations relative to phosphorus content are needed for the dominance of Bacillariophyta and Chlorophyta. On the other hand, the dominance of Cyanophyta over Chlorophyta during winter may be attributed to the increasing phosphorus content in the surface water [17].

Cryptophyta, Dinophyta, and Chrysophyta were rare in the current sampling stations which met with the results presented in Shehata et al. [51]. The presence of Cryptophyta during winter such as *Cryptomonas ovata* and *Rhodomonas lacustris* indicated relatively clean water [6]. The presence of Dinophyta during summer in both canals and Euglenophyta in Mit-yazed was an indication of high organic pollution levels [37]. The presence of Euglenophyta may be correlated with the presence of domestic sewage effluent from the Semetay drain pipeline that passes below Mit-yazed. Such effluent drainage water gave the suitable organic media for their growth [12, 16]. In Qudaba, during winter, the presence of *Cyclotella meneghiniana* in a considerable amount beside mesohalobus taxa such as *Bacillaria paxillifera* agreed with the shallower water depth.

4.2 Drains

4.2.1 El-Gharbia Main Drain

The total number of phytoplankton increased in the summer where the highest number of individual algal cells was 16.6 m cells per liter at station V during summer, and the lowest number was 0.12 m cells per liter at station II during winter. The recorded number of phytoplankton taxa in the summer was 60 taxa and that of winter was 61 taxa (Table 1).

As shown in Fig. 7, Chlorophyta, Cyanophyta, and Euglenophyta were the most important algal divisions in this drain. During winter, Bacillariophyta was rare except at the last one (the estuary), where it was abundant followed by Euglenophyta, Chlorophyta, and Cyanophyta, respectively. At stations II, III, and IV, Chlorophyta was more quiet than Euglenophyta and Cyanophyta. The first station showed the superiority of Euglenophyta followed by Chlorophyta and Cyanophyta, respectively. During summer, the data was very diverse. Chlorophyta was abundant at the first station followed by Euglenophyta and Cyanophyta,

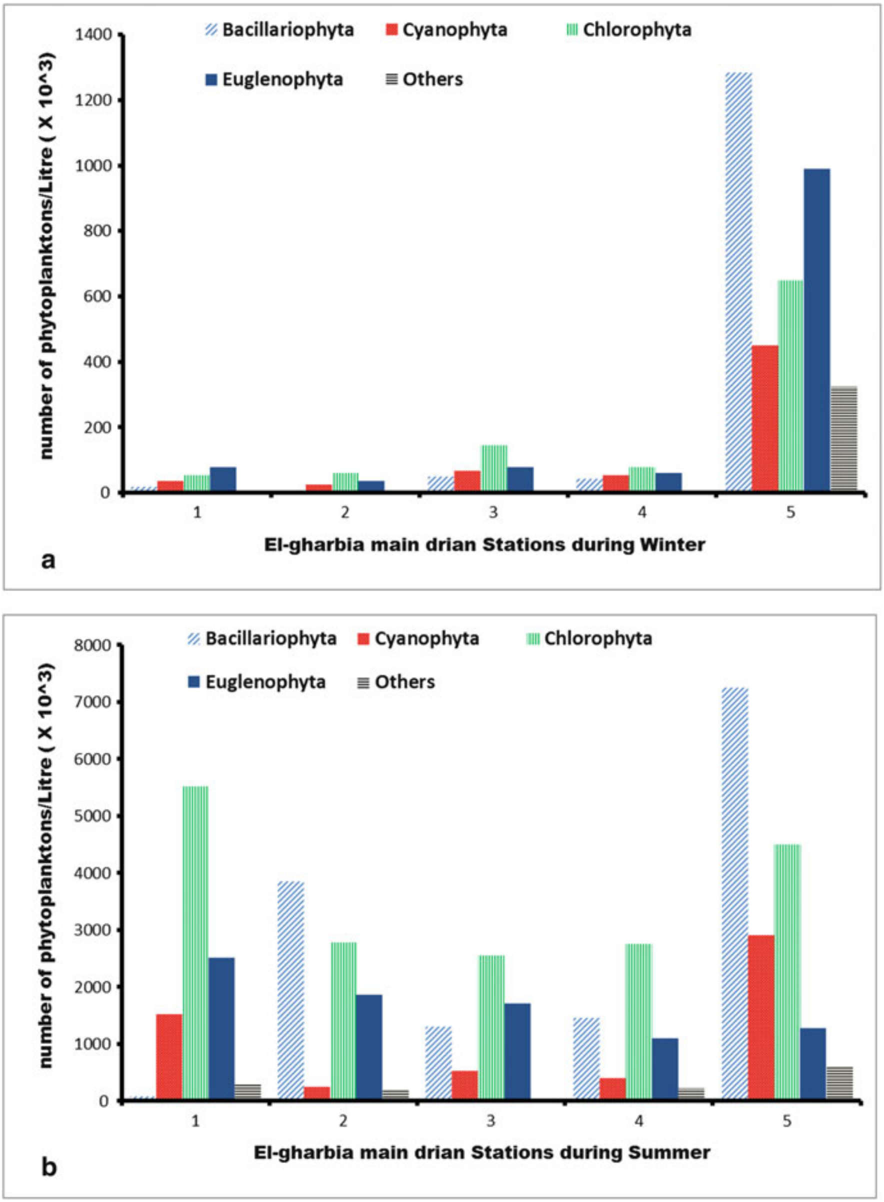


Fig. 7 Diagrams illustrate the spatial variations of the algal divisions along the flow path of El-Gharbia main drain during winter (**a**) and summer (**b**)

respectively. Bacillariophyta showed abundance at the second station followed by Chlorophyta, Euglenophyta, and Cyanophyta, respectively. Station III is characterized by the abundance of Chlorophyta followed by Euglenophyta such as in station

I but was different only due to the presence of Bacillariophyta growth over Cyanophyta. Station IV showed similar results except that Bacillariophyta was more abundant than Euglenophyta. The estuary (station V) was characterized by the abundance of Bacillariophyta followed by Chlorophyta, Cyanophyta, and Euglenophyta, respectively, which is a different situation from winter.

Most of the taxa were oligohalobus except at the last station, where the estuary occurs and mesohalobus and polyhalobus taxa appeared. The winter was characterized by the abundance of *Chlamydomonas* spp. and the presence and diversity of Euglenophyta and *Oscillatoria* spp., while summer was also characterized by the high count of *Chlamydomonas* spp. and *Cyclotella meneghiniana* and diversity with considerable amounts of *Pediastrum* spp. and Euglenophyta and the rare presence of Dinophyta.

The last station (the estuary) was characterized by the presence of mesohalobus taxa such as *Cyclotella meneghiniana* (abundant) and polyhalobus taxa such as *Entomoneis paludosa* var. *subsalina*, *Navicula recens*, *Nitzschia frequens*, *Tryblionella hungarica*, and *Oscillatoria chalybea*.

4.2.2 Janag Drain

The total number of phytoplankton increased in the summer. The numbers of phytoplankton taxa in the summer were 38 taxa and that of winter were 35 taxa (Table 1). The highest number of individual algal cells was 5.46 m cells per liter at station II during summer, while the lowest number was 0.24 m cells per liter at station IV during winter.

As shown in Fig. 8, Chlorophyta, Cyanophyta, and Euglenophyta were the most important algal divisions in Janag drain. During winter, Cyanophyta was abundant in all stations followed by Chlorophyta at the first and last stations. During summer, the Chlorophyta was abundant in the first three stations followed by Cyanophyta, Bacillariophyta, and Euglenophyta, respectively, while the last station showed an abundance of Cyanophyta with a significant increase in their counts followed by Chlorophyta and Euglenophyta. Both winter and summer were characterized by the presence of *Chlamydomonas* spp. and *Oscillatoria* spp. as well as the presence of one Euglenophyta taxa. Almost neither Cryptophyta, Chrysophyta, nor Dinophyta was detected.

4.2.3 Pollution Evaluation of Drain Water

The heavy organic pollution and eutrophication were clearly proved in most stations, especially in summer, through the abundance and presence of tolerant algal species [9, 37]. Both drains showed significant fluctuations in the seasonal productivity (total no. of algal individuals) that may be related to the fluctuations in surface water temperature and effluent pollutant loads. Also, the algal productivity in the same drains fluctuated along the path (Figs. 7 and 8) that may be corresponding to the

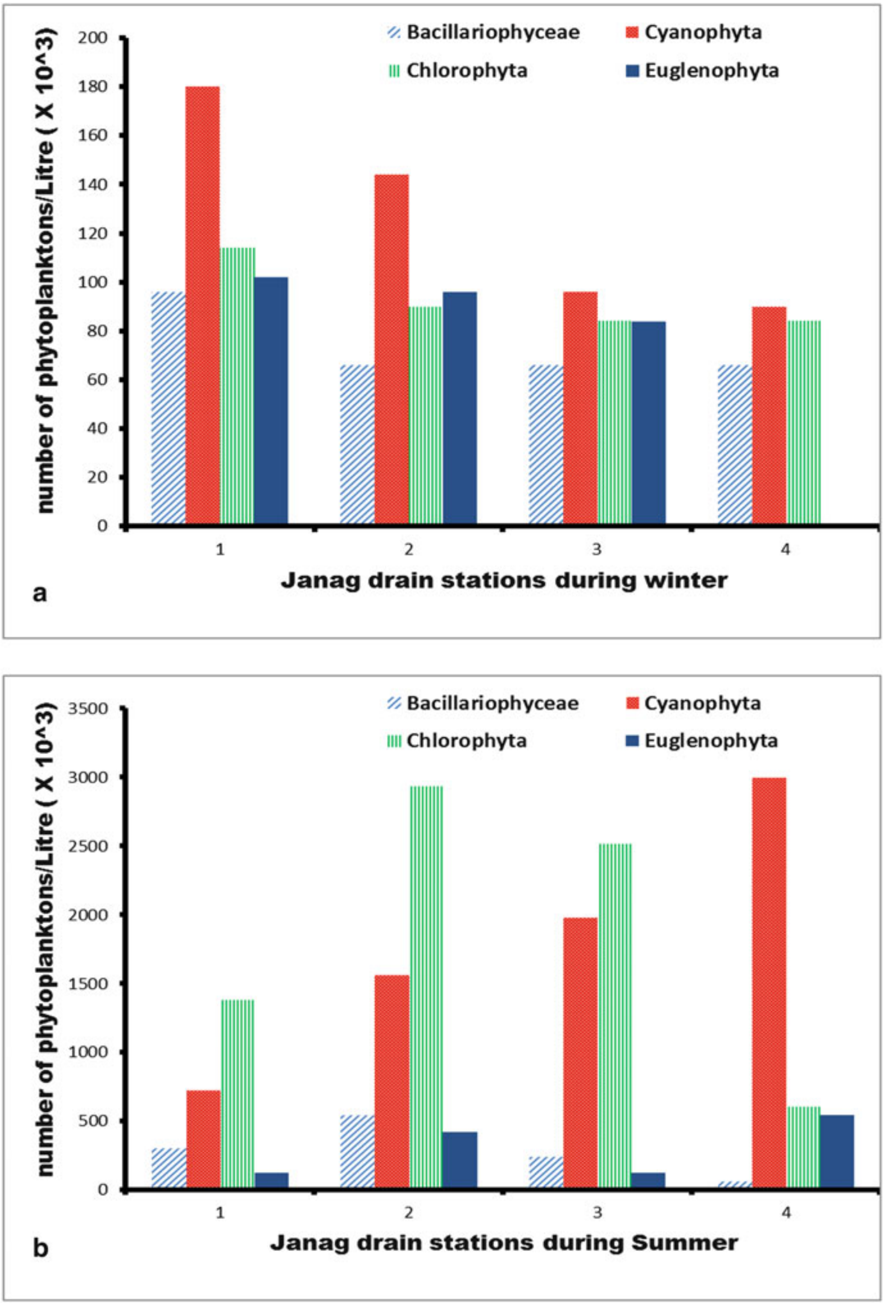


Fig. 8 Diagram illustrates the spatial variations of the algal divisions along the flow path of Janag drain during winter (**a**) and summer (**b**)

changing of physicochemical parameters including salinity, heavy metal content, nutrient concentration, and organic pollutant load [12, 54, 55] as a result of the flowing water from the smaller drains into the main drain along its path.

During winter, the first four stations of El-Gharbia main drain beside the four stations of Janag drain showed a very low count of algal cells that might be correlated with pollution level, high turbidity, and relatively low dissolved oxygen that also make the Bacillariophyta rare [12]. The relative high pollution state of drainage water is related to the agriculture, domestic, and sewage discharges [3, 4]. The drain water mostly shows higher turbidity values compared with the River Nile and its branches [12]. The relatively low dissolved oxygen may combine with some factors especially the high consumption of oxygen via bacteria to reduce organic debris [9].

In general, the abundance of organic-tolerant species especially *Chlamydomonas* spp., *Cyclotella meneghiniana*, and Euglenophyta corresponds to the high availability of organic source for N and P (organic pollution) [37]. Abdel-Baky [16] concluded that organic matter within domestic sewage discharge gave a suitable medium for the growth of Euglenophyta. In Janag drain, during winter, the Cyanophyta showed abundance that may be related to high organic pollutants accompanied with significant increase of phosphorus [17]. Based on field observations and Fig. 1, El-Gharbia main drain is wider and too long compared to Janag drain and receives water from several braches along its bath. Therefore, the results of the main drain showed a big difference when Chlorophyta and Cyanophyta showed an increase in productivity due to the availability of nutrients and higher temperature. The last station of El-Gharbia main drain was a different ecosystem (estuary): the salinity increased, and the environment became brackish. Mixing of drainage water with seawater caused the availability of silicate and relative increasing of dissolved oxygen and decreasing of HCO_3 that makes diatoms abundant in both winter and summer.

4.3 Palmer Index (PI)

The authors used the current algal data in Salem et al. [37] to evaluate the water pollution in the studied canals and drains using the algal Palmer index (PI). The PI calculation methodology was discussed in details in that research paper. Palmer index numerical values were calculated for both species and genera and then compared with the reference values that were proposed by Palmer as following: 0–10 indicate no evidence of organic pollution, 10–15 indicate moderate pollution, 15–20 indicate probable high organic pollution, and 20 or more indicate high organic pollution. The calculated Palmer index in the studied water bodies is shown in Figs. 9, 10, 11, and 12.

To sum up, they stated the following: Palmer index was a significant tool to show the pollution probability in the surface water of the Nile Delta either irrigation canals or drains. Pollution load in the form of Palmer index changes spatially along the water pathways or temporally from winter to summer for the same sampling

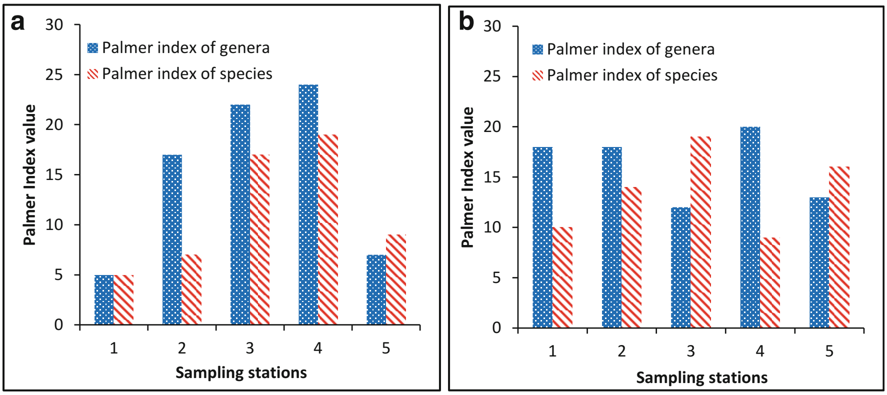


Fig. 9 Pollution index scores of algal genera (blue) and species (red) at the selected sampling stations of Qudaba irrigation canal. (**a**) is the Palmer index during winter and (**b**) is the Palmer index during summer (after [37])

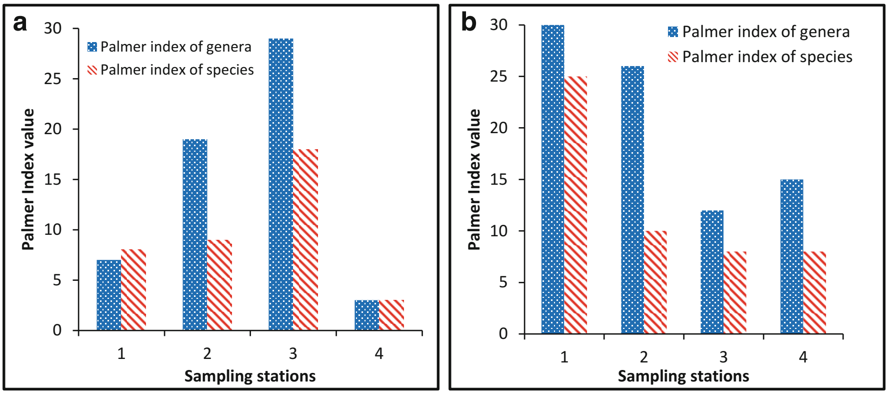


Fig. 10 Pollution index score of algal genera (blue) and species (red) at the selected sampling stations of Mit-yazed irrigation canal. (**a**) is the Palmer index during winter and (**b**) is the Palmer index during summer (after [37])

station. In general, the surface water of the Nile Delta suffers from organic pollution in most of the sampled stations. In winter where the water depth is shallow and either canals or drains received a little water, the organic pollution was lower than that of the summer and, generally, increased along the water pathways from south to north. In summer where the water depth was higher than winter, organic pollution load was noticed at all the stations. Mit-yazed maximum organic pollution (Fig. 10) was higher than that of Qudaba canal (Fig. 9), due to the higher urbanization along Mit-yazed canal pathway compared to Qudaba canal. El-Gharbia main drain (Fig. 11) as a big drain had higher Palmer index scores than Janag drain (Fig. 12). As the canal water is used for drinking and the drain water is sometimes used for fish farms and irrigation, therefore, caution and treatment should be done to avoid the hazardous effects of the detected pollution.

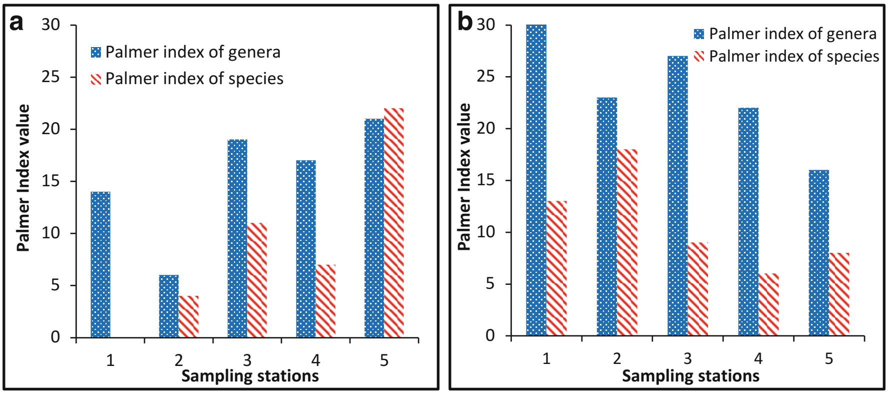


Fig. 11 Pollution index score of algal genera (blue) and species (red) at the selected sampling stations of El-Gharbia main drain. (**a**) is the Palmer index during winter and (**b**) is the Palmer index during summer (after [37])

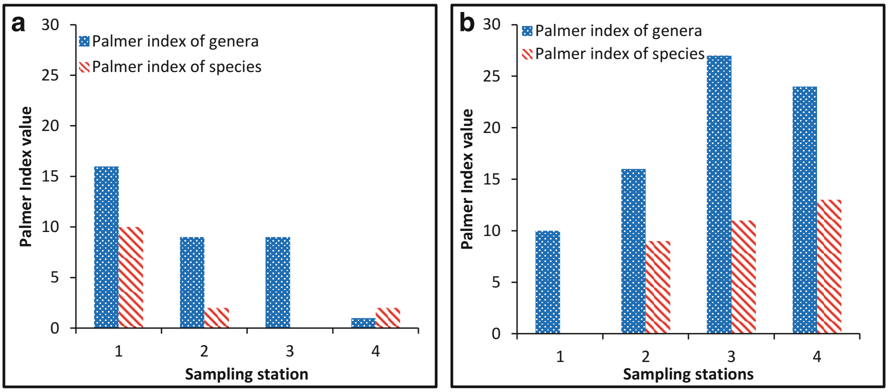


Fig. 12 Pollution index scores of algal genera (blue) and species (red) at the selected sampling stations of Janag drain. (**a**) is the Palmer index during winter and (**b**) is the Palmer index during summer (after [37])

5 Conclusions

The target of this work is to prepare a checklist of the phytoplankton species and varieties for further usage as environmental bioindicators and other applications. It also aimed to investigate the spatial and temporal fluctuations of the phytoplankton composition of the studied irrigation canals and drains. Water was sampled from 18 sites (twice from each location during 2015) and distributed along the flow path of two main irrigation canals (Qudaba and Mit-yazed canals) and two main drains (Janag drain and El-Gharbia main drain). A total number of 250 species and varieties belonging to 100 genera and 7 algal divisions were recorded.

However, the evidence of heavy organic pollution in most stations, the harmful phytoplankton blooming, was not detected in any of the investigated stations during both winter and summer due to the relatively low dissolved oxygen and high turbidity, especially in drainage water. Despite that, there were considerable amounts of phytoplankton, especially during summer. The phytoplankton communities of the irrigation canals had a quiet similar composition, while the communities of drains showed similar behavior except at the last station of El-Gharbia main drain. In the summer, there was a higher productivity in both irrigation and drainage water. The evidence for heavy organic pollution were provided through the presence of pollution and eutrophication-tolerant algal taxa. Bacillariophyta, Chlorophyta, Cyanophyta, and Euglenophyta were the most important and effective algal divisions in inland water of the Delta. According to the Palmer index, the surface water of the Nile Delta suffers from organic pollution in most of the sampled stations. In winter where the water depth is shallow and either canals or drains received a little water, the organic pollution was lower than that of summer. The Palmer index increased along the water pathways from south to north.

6 Recommendations

It became necessary to use the phytoplankton analysis as an environmental monitoring procedure for the organic pollution more than the regular methods. Developing checklists and special indices is required to facilitate the task for the fast analysis and revealing the aquatic environmental crimes and the presence of dangerous blooming with harmful toxins.

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Groundwater Assessment for Agricultural Irrigation in Toshka Area, Western Desert, Egypt

Abbas M. Sharaky, El Sayed A. El Abd, and Emad F. Shanab

Abstract Toshka area is located southeastern of the Western Desert. In 1997, Egypt established a development project to irrigate 216,000 ha (540 feddan) by 2017 through pumping surface water from High Dam Lake as a part of the mega project "Developing Southern Egypt." Currently, the Egyptian government plans to extend the project by about 100,000 feddan depending on surface water irrigation and 25,000 feddan depending on groundwater (through 102 wells) as a part of the recent mega project called "1.5 Million Feddan Project." Egypt is now fully utilizing its annual share of the Nile waters 55.5 km^3 from the Nile, and it has a shortage of water estimated at 20 km^3.

The present chapter aims to evaluate the groundwater conditions to determine the sustainability of the groundwater resource, the expected changes in groundwater levels, the amount of recharge and the suitable discharge from the groundwater for irrigation of 25,500 feddan through 100 years, and the changes in water quality. The hydrochemical analysis was carried out using 38 productive wells and 1 surface sample from Aswan High Dam Lake (AHDL) for major ions.

The present study was carried out in Toshka using 102 groundwater wells located west of AHDL using static, dynamic water levels, well depth, discharge, and pumping tests to determine the hydraulic parameters of the aquifer system in the study area and building the groundwater model. Visual MODFLOW 2011.1

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software was used to estimate the expected drawdown in the groundwater levels using four different scenarios. A conceptual model was constructed to simulate water flow system of the Nubian Sandstone Aquifer through 100 years.

The safe water use of groundwater for 100 years is 1,007 m^3/day from each well working 8.4 h/day at 120 m^3/h, to provide 1,500 m^3/feddan/year for a total of 25,000 feddan. The expected lowering in the groundwater level after 100 years is 15 m. The salinity ranges from 480 to 1,200 ppm with an average of 648.5 ppm. It increases with increasing distance from AHDL.

Keywords Groundwater, High Dam Lake, MODFLOW, Pumping test, Toshka project

Contents

1 Introduction

Egypt is characterized by an important geographic location that has enabled it to perform its role throughout the historical ages. It is divided into two main parts: the northern part extending from north of Cairo to the Mediterranean Sea, which is known as Lower Egypt for its descent toward the sea, and the southern part that runs south of Cairo on the banks of the Nile to the border of Sudan, which is called Upper Egypt. Egypt has an area of about 1 million square kilometers. It is geologically divided into four natural subregions (see Fig. 1):

1. Nile Valley and Delta (4% of the total area of Egypt)
2. Western Desert (68%)
3. Eastern Desert (22%)
4. Sinai Peninsula (6%)

Egypt is one of the oldest agricultural civilizations in the world. Agriculture is currently a major source in the Egyptian economy, accounting for 11.2% of the GDP in 2015, up to 14.5% in 2014 [1]. The Egyptian agricultural lands are

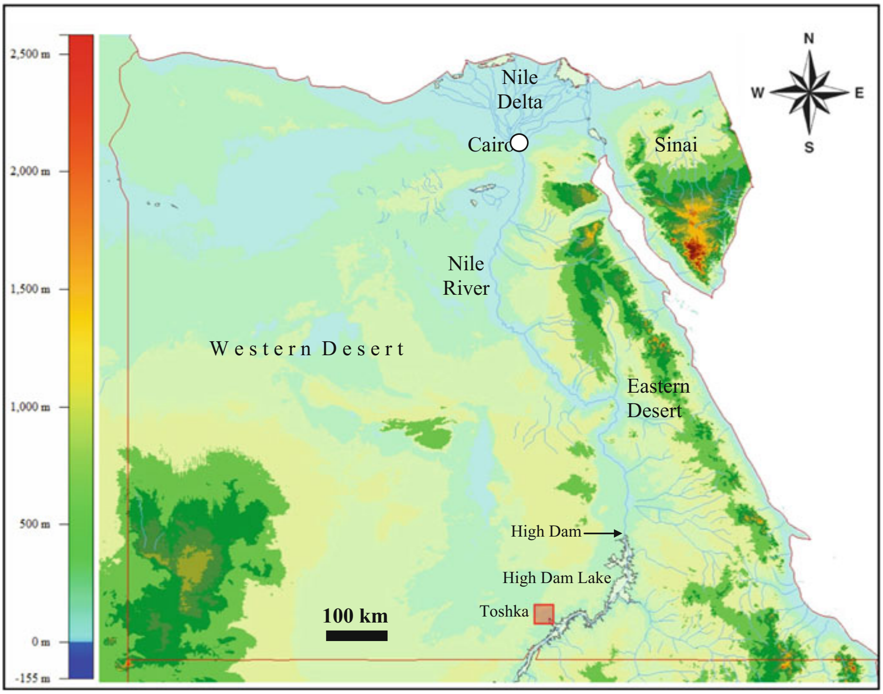


Fig. 1 The four geological regions of Egypt on 3D map using ASTER DEM (USGS)

concentrated in the Nile Valley and the Delta, which consist of sand and gravel overlain by a layer of the Nile silt and clay deposited during floods.

According to the Food and Agriculture Organization (FAO) of the United Nations, the old cultivated area was 6 million feddan (1 feddan = 1.038 acres) that increased from 1964 (the actual start of the High Dam) to 1973 by about 1.1 million feddan. The agricultural sector has also increased by 2 million feddan in 1993 and continued to increase gradually until the total agricultural land reached 9.2 million feddan in 2009. It was decreased after the Egyptian revolution in January 2011 by about 215,000 feddan due to illegal urbanization.

The Egyptian government has planned to reclaim 4 million feddan in few years, starting with 1.5 million feddan in 2016. The first phase of the agricultural reclamation project has been started with 1 million feddan since 2015, which increased 500,000 feddan in 2016. They mostly (90%) depend on nonrenewable groundwater of the Nubian Sandstone Aquifer, Western Desert. About 130,000 feddan from the 1.5 Million Feddan Project is located in Toshka area.

1.1 Aswan High Dam Lake

Construction of the Aswan High Dam in 1964 created the second largest man-made lake (6,000 km^2) in the world after Lake Volta, Ghana (8,500 km^2). The Aswan High Dam reservoir extends for about 500 km along the Nile River from Aswan, Egypt, to Wadi Halfa, Sudan. At 182 m above sea level (m amsl), its total storage capacity reaches 162 km^3. The reservoir in Egypt is known as High Dam Lake, which has a length of 350 km (see Fig. 1). The Sudanese refer to the extended lake in Sudan (150 km) as Nubia [2, 3]. The Aswan High Dam Lake has about 8,000 km shoreline at 180m asl [4]. It is characterized by about 100 dendritic inlets, or side extensions of the reservoir, known as khors or wadies that extend for long distances, 70 km in Wadi Allaqi to the east and 50 km in Toshka Khor to the west.

The depressions west of Toshka Khor are used as a natural flood diversion basin to protect the High Dam from any exceptional flooding that happened only from 1998 to 2001 since the construction of the High Dam. The Aswan High Dam (AHD) was designed to flow water at 178 m level through a free spillway "Toshka Canal" at an elevation of 178 m with a width of 750 m and 40 km length, located at 250 km south of the AHD and west of AHDL.

To reserve the water of the Nile in case of flooding, Egypt built a small earth-fill dam on Toshka spillway at 40 km from the main lake with an elevation of 178 m above mean sea level (amsl).

The water levels in Aswan High Dam Lake (AHDL) vary around 175 m up and down by about 5 m. During the past decade, the minimum water levels have remained above 170 m, fluctuating by 2–4 m/year (see Fig. 2). The lowest level after construction of the High Dam was recorded in 1988, when it reached to 150 m asl, just above the operating level by 3 m.

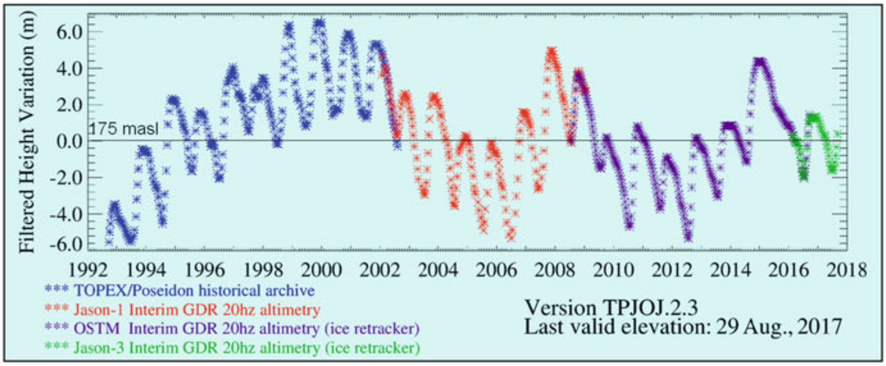


Fig. 2 Aswan High Dam Lake elevation variations computed from TOPEX/POSEIDON (T/P), Jason-1 and Jason-2/OSTM altimetry with respect to a datum that is based on a single flyover date of the Jason-2/OSTM mission (source: [5])

1.2 Toshka Project

Egypt has undertaken agricultural strategies since 1952 with great success at the beginning and limited success later. Land reclamation for agriculture has started in the 1950s during the construction of the Aswan High Dam, followed by two other phases in the late 1990s and in 2014. The Egyptian government reclaimed about 800,000 ha (2.0 million feddan) of desert land from 1952 to 1987 and an additional 250,000 ha (627,000 feddan) from 1987 to 1991 [6].

The second phase of reclamation projects is to cultivate 200,000 ha (500,000 feddan) of desert land through the Toshka project, 88,000 ha (220,000 feddan) in the southeastern part of the Western Desert, Egypt, and 248,000 ha (620,000 feddan) in the eastern part of the Nile Delta and northwestern Sinai (El-Salam Canal Project). In the late 1990s, the Egyptian government has begun a mega project called "Developing Southern Egypt" from Aswan to Assiut. It aimed to have new communities of people from the dense Nile Valley and Delta (about 90 million people in 2017) to a new green landscape. Southern Egypt region comprises an area of 520,000 ha (1.3 million feddan) of arable lands, mainly concentrated in Assiut, Sohag, Qena, and Aswan governorates [6].

Toshka project is a part of the mega project "Developing Southern Egypt." It is located in the area of Toshka depressions, but independent from them (see Fig. 3). It is a large-scale project of surface irrigation, using pumped water from the High Dam Lake to irrigate 216,000 ha (540 feddan) by 2017. According to the Landsat image of 24 September 2017, the total cultivated area was 24,000 ha (60,000 feddan), representing only 11.1% of the target (see Fig. 4).

As the Egyptian government prepares in its current 4-year master plan to reclaim 1.6 million ha (4 million feddan) from the desert in 4 years through four stages starting from June 2014. The first stage was to reclaim 1 million feddan, raised to be

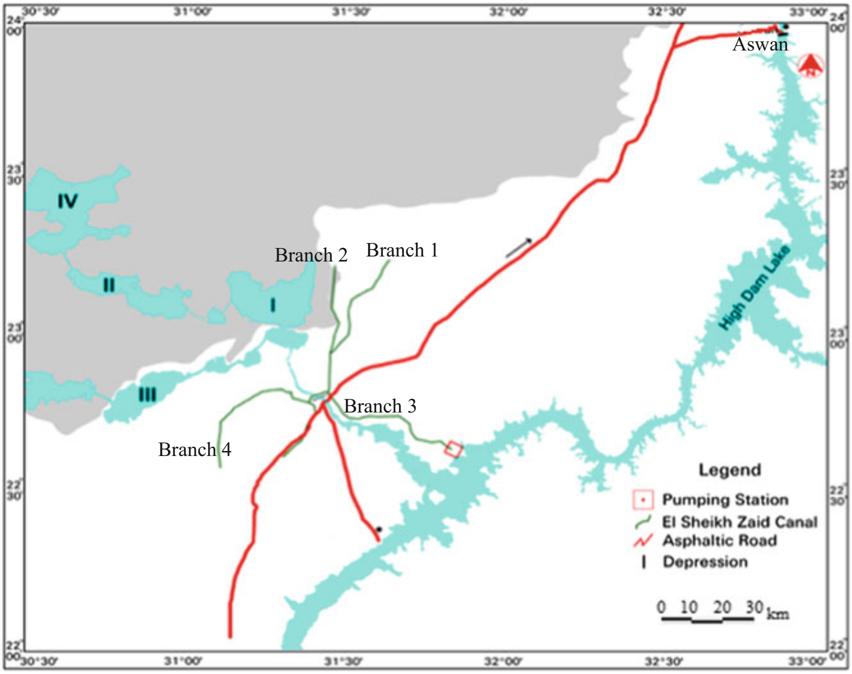


Fig. 3 The Toshka project, Toshka spillway (Khor), and Toshka Lakes (after [7])

1.5 million feddan in August 2015. About 90% of the 1.5 million feddan depend on nonrenewable and deep groundwater through 5,000 water wells. The new reclamation project will be carried out in three subphases in nine areas of the Western Desert, including Toshka, Farafra Oasis, Dakhla Oasis, Bahariya Oasis, Qattara Depression (Moghra), West Minya, and East Owainat.

In addition to the 540,000 feddan in Toshka, about 100,000 feddan depending on surface water and 32,000 feddan depending groundwater (through 102 wells) are included in the "1.5 Million Feddan Project."

1.3 Toshka Area

Toshka area lies in the southeastern of the Western Desert, Egypt, covering an area of 15,000 km^2. It is located in the west of the High Dam Lake (HDL), between latitudes 22°30′ and 23°30′ N and 31°00′ and 32°00′ E (see Fig. 3). Toshka area is limited from the east by the shoreline of the HDL.

The largest pumping station in the world was constructed in Toshka to pump and transfer water from High Dam Lake at a water head of 52.5 m to cover the difference between the lowest level of the lake (147.5 m) and the water level in

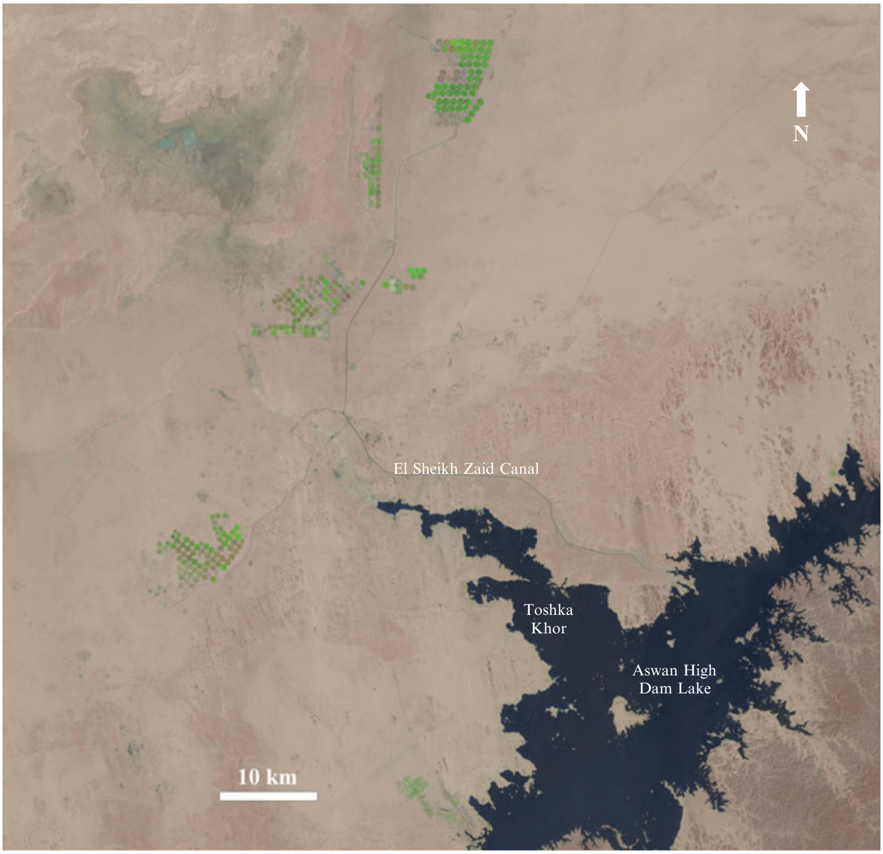


Fig. 4 The Landsat L8 OLI/TIRS image showing the center-pivot irrigation fields (60,000 feddan) as of 24 September 2017

the station canal at 200 m. The main canal called El Sheikh Zayed feeds four distributed canals called branches (1–4) (see Fig. 3).

In 2014, the Egyptian government released the mega project "Reclamation of 1.5 Million Feddan Project," depending mainly on groundwater. In Toshka region, reclamation of 25,000 feddan on groundwater requires 102 productive wells, 52 wells were implemented in 2002 (from phase 1, 2, and 3), and the 50 wells were implemented in 2015–2016 (see Fig. 5).

The present chapter aims to assess the groundwater conditions from quantity and quality views to determine the sustainability of the groundwater resource and the development life in the study area.

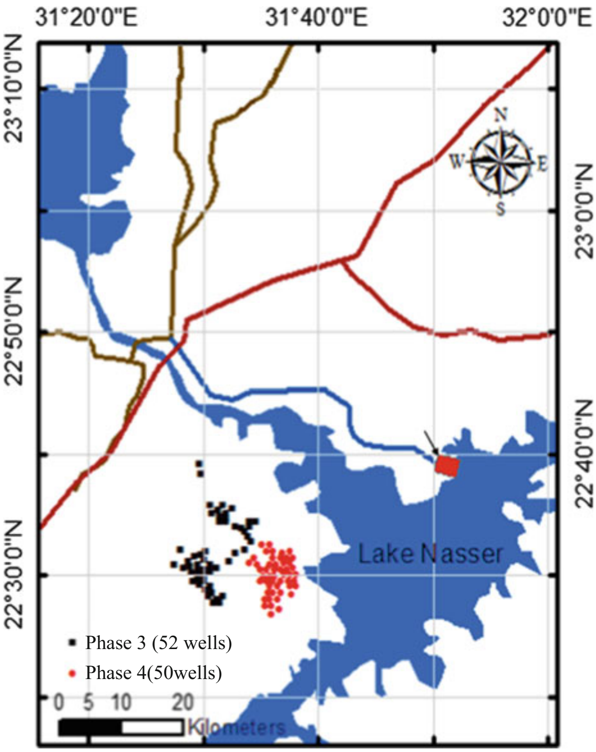


Fig. 5 The water wells (102) in Toshka project area

2 Geologic Setting

The geological and the hydrogeological conditions of the Nubian Sandstone Aquifer System in the Western Desert of Egypt, including Toshka, received the attention of many authors; among them are [3, 7–32]. Toshka area is dominated by a sedimentary succession ranging in age from Cretaceous to Quaternary, with exposures of Late Precambrian basement including granites, granodiorite, and gneiss. The sedimentary rocks are dominated by sandstone overlain by limestone and shale Paleozoic to Cenozoic rocks [7, 33].

2.1 Geomorphologic and Geologic Aspects

The Toshka area is a part of the Western Desert of Egypt that has subjected to alternative arid and wet periods that left their effect on the present land features. It shows some geomorphologic units that are distinguished in the study area: High Dam Lake, alluvial plain, Toshka depressions, hilly areas, sandy plains, erosional plains, and pediplain [25].

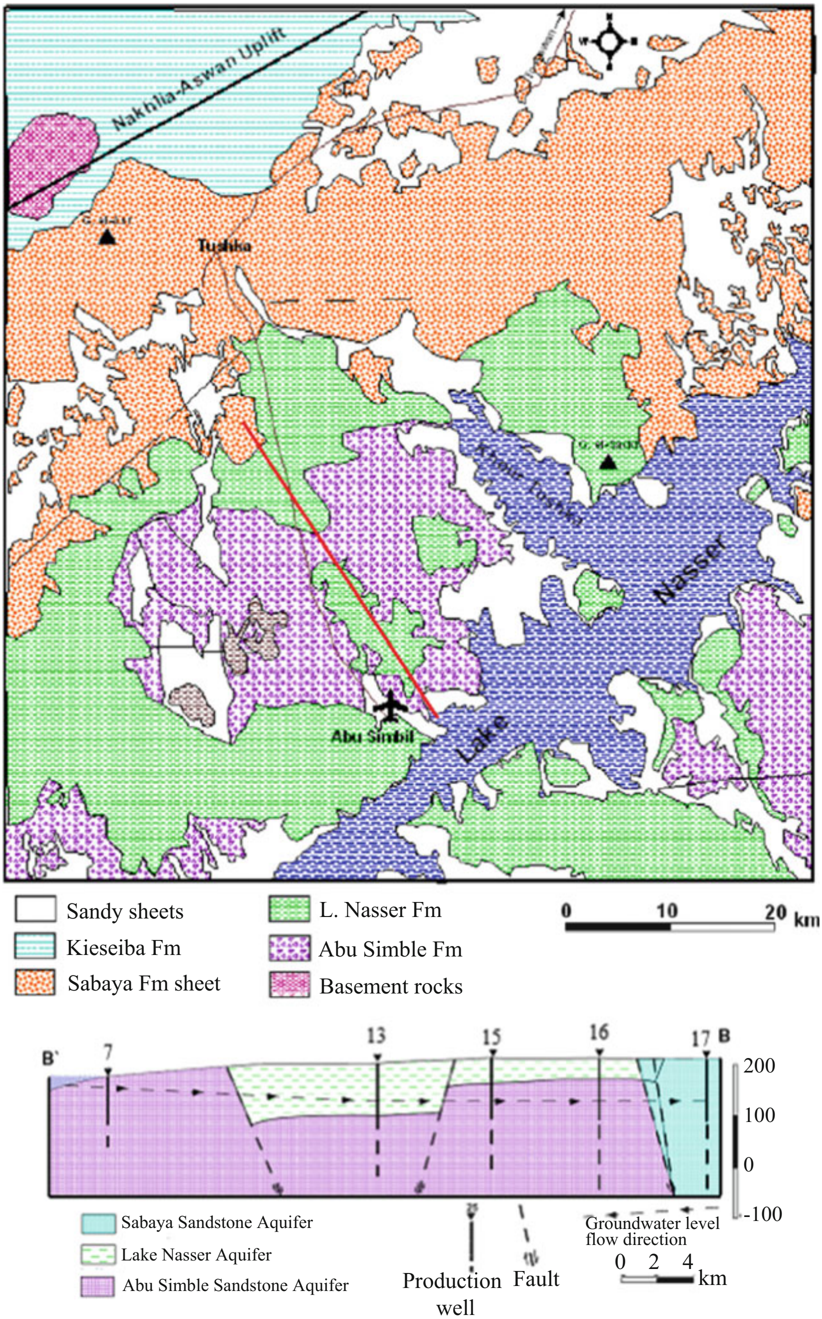
The Toshka area is mainly covered by sedimentary rocks represented by Upper and Lower Cretaceous and Quaternary as well as by Precambrian basement rocks [34, 35] (see Fig. 6). The basement rocks crop out to the west of the study area within the Nakhlai-Aswan uplift, where they consist of low relief exposures of coarse-grained pink granites, gneisses, and metasediments with an age of about 550–900 Ma [33]. The basement, which represents the basal boundary of the Nubian aquifer system in the area, slopes regionally to the southeast close to the shoreline of the Aswan High Dam Lake [25]. The basement rocks form an impervious lower boundary for the Nubian Sandstone Aquifer acting as a barrier to lateral groundwater flow west of the study area [3]. The sedimentary cover is relatively thin in the northwest of the study area, where the depth to basement varies between 50 and 100 m. Kiseiba Claystone Formation overlies directly the Precambrian basement rocks in this area [36].

In the subsurface, the Paleozoic rocks are mostly represented by the Gilf Formation. It overlies the Precambrian basement rocks and consists mainly of brown shale, sandstone, and shaley sandstone with abundant iron oxides [37]. Cretaceous rocks unconformably overlie the Paleozoic rocks and are differentiated into Lower Cretaceous Formations from base to top as follows: Abu Simbel, High Dam Lake, and Sabaya Formations, Upper Cretaceous Formation, and Kiseiba Formation (see Fig. 7).

Abu Simbel Formation overlies the Gilf Formation and consists mainly of medium- to coarse-grained sandstone of fluviatile origin, sometimes intercalated with fine-grained sediment (siltstone or clay lenses). Overlying the Abu Simbel Formation is the fluvio-marine lake (AHD Lake) formation, consisting of siltstone, argillaceous sandstone, and mudstone intercalations. The Sabaya Formation crops out at Gebel El Sad north to Toshka Khor and west of the area of study. It mainly consists of ferruginous sandstone in the lower part overlain by siltstone and fine sandstone [26].

The Kiseiba Formation is composed of fine-grained sandstone with shale and siltstone intercalations cropping out in Toshka depressions. Some Oligocene rocks (basalt extrusions) exposed on the surface of the area of study are widespread, especially near the head of Toshka Khor. The Quaternary deposits are represented by continental sand accumulations (mainly sheets) and alluvial sediments [31].

The study area comprises different structural elements; among them are a basement uplift represented to the west by Nakhlai-Aswan uplift; four major sets of faults generally trending NNW–SSE, E–W, N–S, and NE–SW directions; and three types of folds trending N–S, NE–SW, and E–W directions [29]. The interpreted fault trends are associated with either vertical or horizontal displacements having a significant control effect on the course of River Nile and the western and eastern extensions of High Dam Lake. The depicted folds are influencing either the basement rocks or superimposed on the sedimentary cover [16]. Nubia sandstone sequences in the study area are dissected by E–W and N–S fault systems. The E–W system plays very important role for recharging Nubia Sandstone Aquifer from High Dam Lake [26].



Hydrogeological cross section (B-B′)

Fig. 6 Geological map of the Toshka area [34, 35] and hydrogeological cross section (B–B′) from Ghoubachi [24]

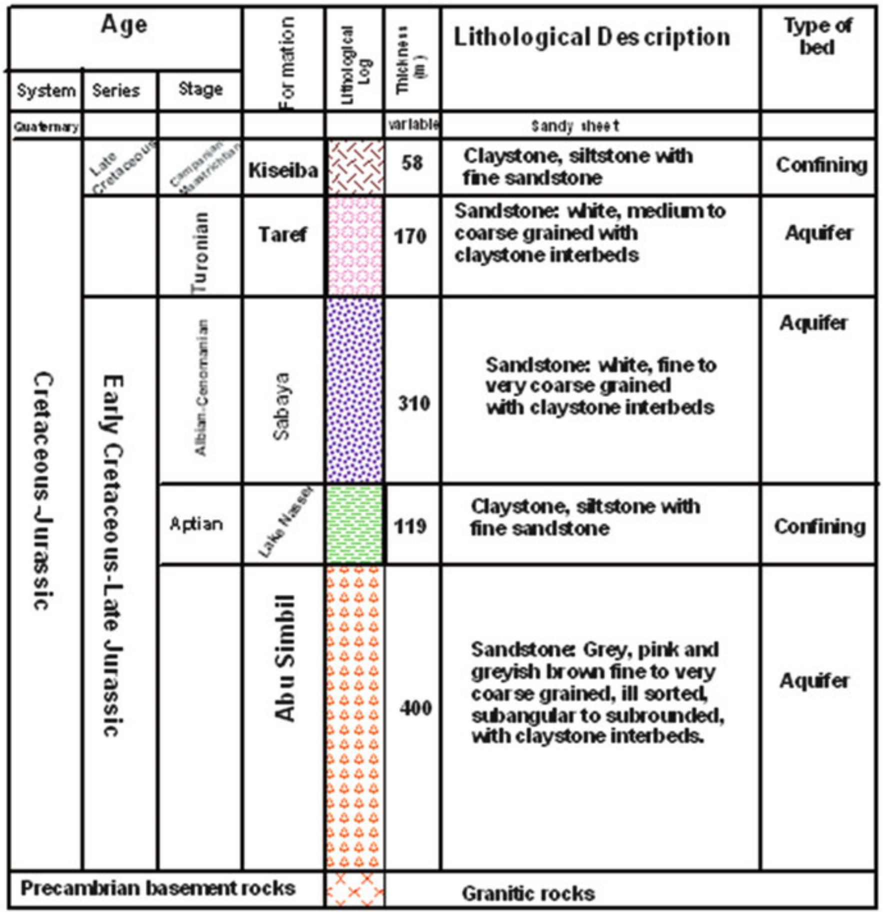


Fig. 7 Stratigraphic succession (after [26])

2.2 Hydrogeological Conditions

Based upon the lithology of drilled groundwater wells in Toshka area and two hydrogeological cross sections, the groundwater in the Nubian aquifer resides in continental sandstone that unconformably overlies basement rocks and underlies Quaternary deposits. It is the main groundwater aquifer system in the area and composed mainly of sand and sandstone intercalated with clay. The aquifer is of multilayered nature and represents the eastern fringes of the multilayered artesian aquifer of the Western Desert of Egypt. In Toshka, the aquifer system included three formations from top to bottom: Lake Nasser, Abu Simbel, and Gilf (see Fig. 8).

The Lake Nasser Formation varies in thickness from 40 to 80 m as shown in section A–A′ (see Fig. 8). The Abu Simbel Formation is mainly composed of

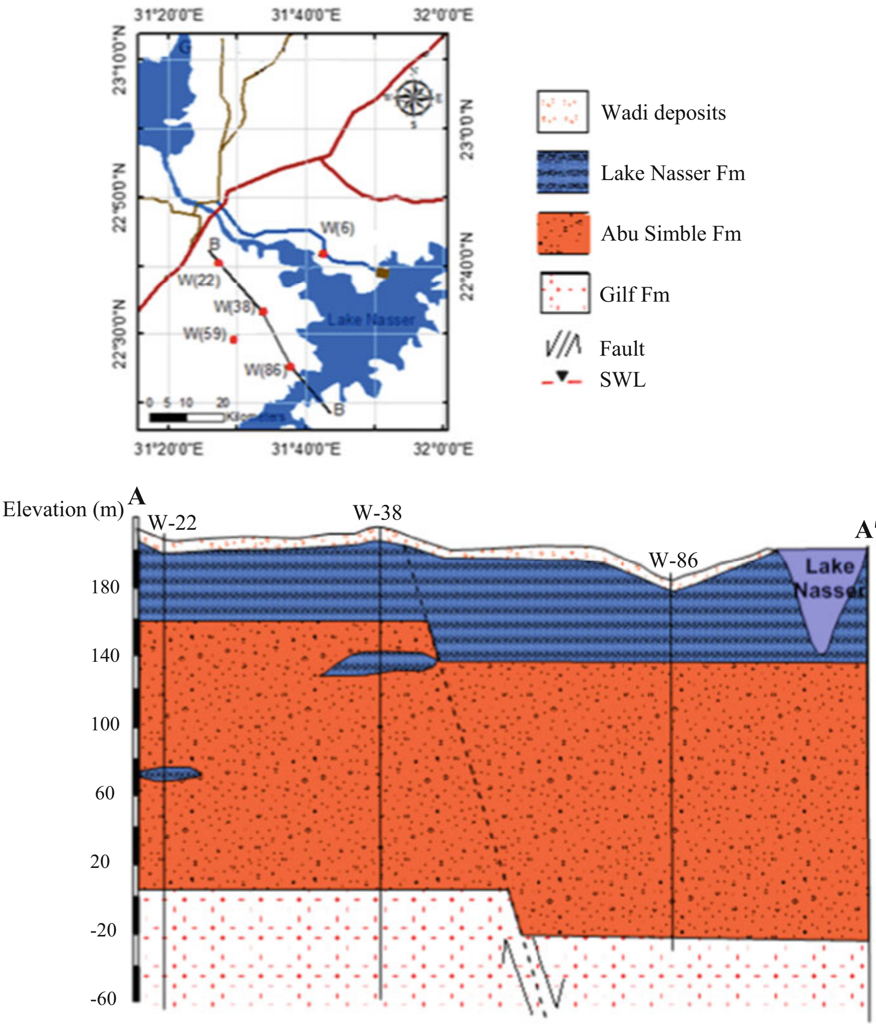


Fig. 8 Hydrogeological cross sections in Toshka area

sandstone with minor varicolored clay intercalations. The thickness of Abu Simbel Sandstone varies from 110 m in the northeast (Well 6) to 140 m to the southwest (Well 59) as shown in cross-section A–A′. It ranges between 80 m in the southeast (Well 86) and 130 m in the northwest (Well 22) as shown in section B–B′. The third formation belongs to Paleozoic undifferentiated sandstones. It directly overlies the basement complex. The thickness of the Gilf Formation ranges from few meters to less than 70 m.

3 Hydraulic Properties of the Nubian Sandstone Aquifer

Pumping tests on 102 productive wells were carried out (step test, long duration test, and recovery test) to determine the hydraulic parameters of the aquifer system in the study area and build the groundwater model.

3.1 Pumping Test

The pumping tests were carried out for 102 productive wells, and the hydraulic parameters were calculated. The influence of each well on the other wells when all of them operated together for 1 day is shown in Fig. 9. Also, the transmissivity distribution in the study area has been mapped as shown in Fig. 10 to describe the groundwater potential briefly in the area. The maximum transmissivity value was 1,558 m^2/day (Well 108), and the minimum value was 321 m^2/day (Well 123), and the estimated average transmissivity value for the selected 102 wells is 650 m^2/day. The hydraulic conductivity was calculated, and its maximum value was found as

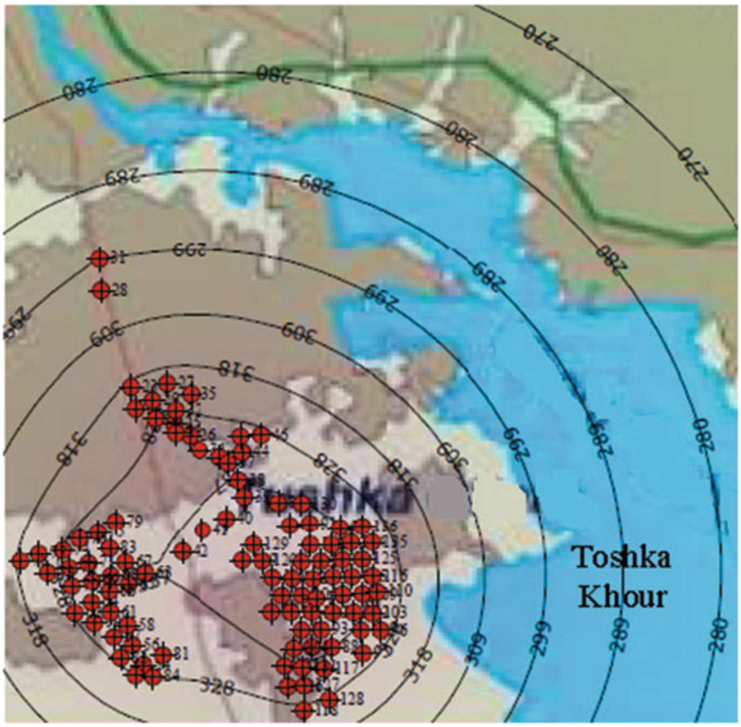


Fig. 9 Drawdown distribution for the 102 wells in Toshka

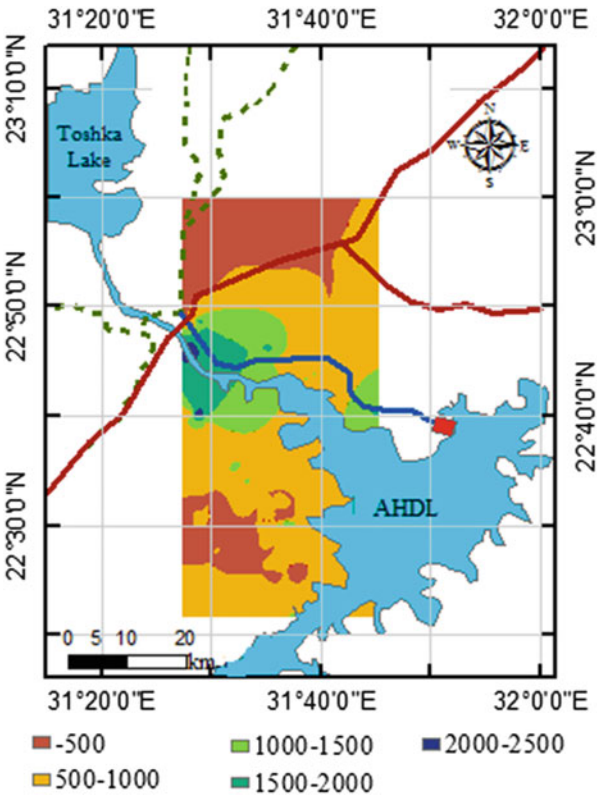


Fig. 10 Transmissivity (m^2/day) map in Toshka area

21 m/day (Well 3), while the minimum value was found as 3 m/day (Well 15) with an average value of about 6 m/day. The transmissivity distribution map indicates that the aquifer potentiality is increasing toward the northwest of the study area and it is decreasing in other directions. This is probably due to high hydraulic conductivity and aquifer thickness northwest of the area.

The aquifer parameters in Abu Simbel-Toshka area are 2,740 m^2/day for transmissivity and 22.4 m/day for hydraulic conductivity in average [19]. The obtained results recorded high-potential and good-quality aquifer in the eastern and southern parts and low-potential to moderate-quality aquifer in the western and northern parts [15].

The amount of sand of Nubian Sandstone Aquifer in Toshka-Abu Simbel area varies from 6.8% in northwest to about 91% near Toshka Khor, reflecting high potentiality as aquifer at the southeast. The increase of transmissivity toward the shoreline of the lake (close to Toshka Khor) is mainly attributed to the increase of the saturated thickness of the water-bearing units. The expected increase of hydraulic conductivity is associated with the increase of sand percent and the grain size as well as the increase of the fracturing intensities.

The Nubian Sandstone Aquifer System in Toshka receives continuous recharge confirmed by the difference of heads between the aquifer and the HDL. The direct and faster response between the lake and the aquifer is recorded along the shoreline of the HDL. This is mainly attributed to the excited non-equilibrium of the hydraulic conditions between the two water bodies [29]. A regional groundwater movement from south to southwest proved the presence of remote sources of recharge at southwest [8]. The estimated age, using ^{14}C, for the groundwater in the Nubian Sandstone Aquifer East Oweinat and Toshka areas varies between 14,780 and 17,070 years [21]. The aquifer potentiality decreases at the northern and middle areas, where the clay content increases and saturated thickness decreases at such localities [14]. Transmissivity ranges between 336.9 and 2,802 m^2/day with an average value of 1,569 m^2/day [15]. For future impact of the new reclamation activities on groundwater used for irrigation together with surface water, the general pattern of the groundwater level is expected to show considerable changes. The northern and middle areas are subjected to show a decrease in groundwater levels with the exception of an area with shallow impervious basement and in the southern wells. The expected water level decline ranges between 5 and 55 m [19].

3.2 Changes in Groundwater Level

To investigate the changes in groundwater level in the area, data concerning the water elevation in the existing wells were collected and analyzed during the period from 1998 to 2006 (see Fig. 11). Groundwater extracted from these wells is used for land reclamation in the areas. The extracted water is used to supplement the surface water for land reclamation in the area. It is noticed that there is a drop in water level during that period ranging between 0.5 in Well 21 and 13.8 m in Well 4 in 8 years (see Fig. 12). Such drop indicates that the extraction rate of water is much higher than the recharging rate. The drop is expected to continue with the continuous extraction of groundwater leading to aquifer depletion in the area. The average water level drop per year for the observed wells was 0.77 m/year, indicating that the expected drawdown for 100 years' development is 77 m for the old phases of drilled wells. The effect of the new wells drilled in 2015/2016 (50 wells) as a part of the "1.5 Million Feddan Project," will increase the drop in groundwater level in the area. Groundwater model must be used to predict the influence of different development scenarios on the groundwater levels based on the historical data to build, calibrate, and validate the model. The present chapter focuses on estimating the expected change in groundwater levels and water quality for different operation scenarios.

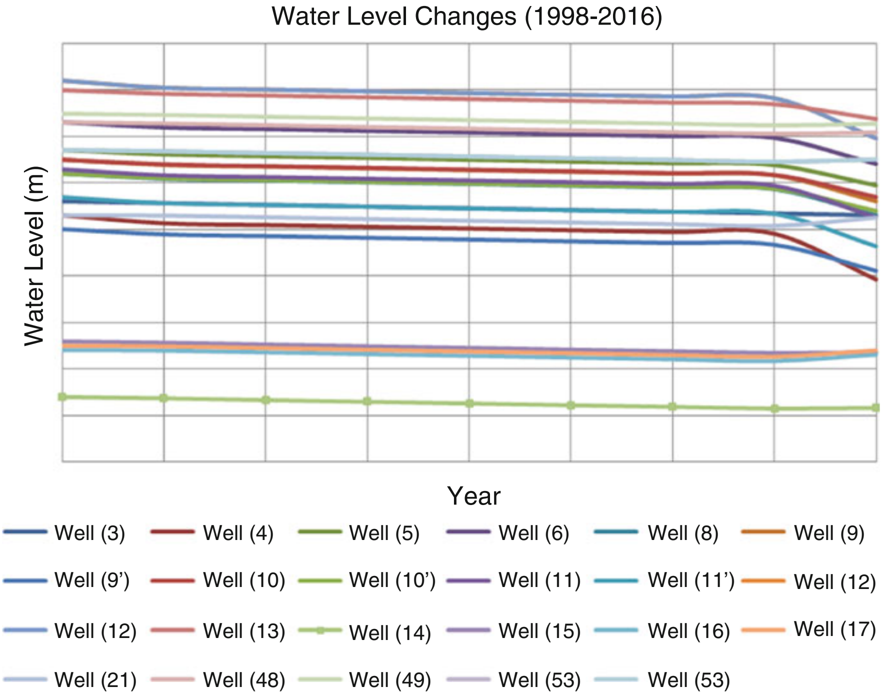


Fig. 11 Change in groundwater levels for some wells in the study area

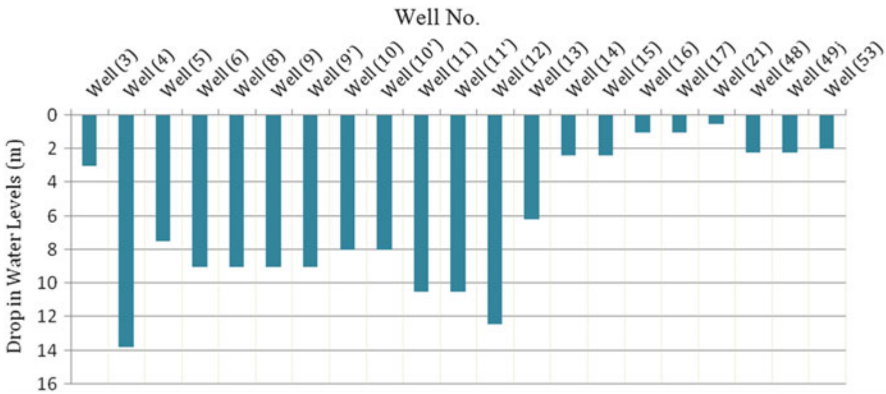


Fig. 12 Drop in groundwater levels for some wells in Toshka area

4 Impact of AHD Lake on the Groundwater

4.1 Changes in Water Level

The study area is surrounded by the High Dam Lake, Toshka Khor, and irrigation system. The relation between the groundwater in the aquifer and AHDL is essential to estimate the annual recharge from the surface water to the vicinity aquifers. After the construction of the AHD and the formation of AHDL with 500 km length (350 km inside Egypt border and 150 km inside Sudan border) and average width of 12 km with a depth of 130 m and a maximum water level of 183 m, the yearly cycle of groundwater fluctuation was changed due to rapid variation in lake water levels. The water level using a piezometer lying west of High Dam Lake (31°51′8″ E, 22°37′10″ N) was measured four times in 31 December 1965 (during the period of construction of High Dam), 25 December 1969, 2 December 1979, and 22 July 1996. It was compared with the recorded water levels of High Dam Lake (see Fig. 13). There is a direct connection between High Dam Lake and groundwater level with time lag according to the distance of wells from the lake and the nature of the water-bearing formation. Hantush [39] equation was used to calculate the effect of High Dam Lake on groundwater level.

Figure 14 shows the rising in groundwater levels for different transmissivity values, indicating the effects related to the aquifer properties and the distance from the HDL. Therefore, the hydraulic connection is effective for only small distance, not more than 10 km.

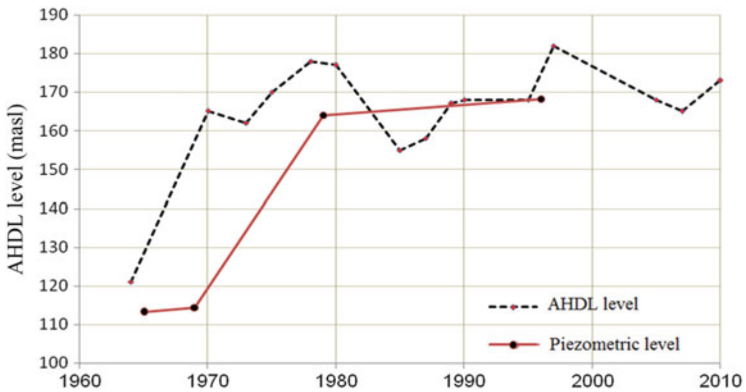


Fig. 13 Changes in AHDL and piezometric levels in Toshka area (AHDL level data from [5, 38])

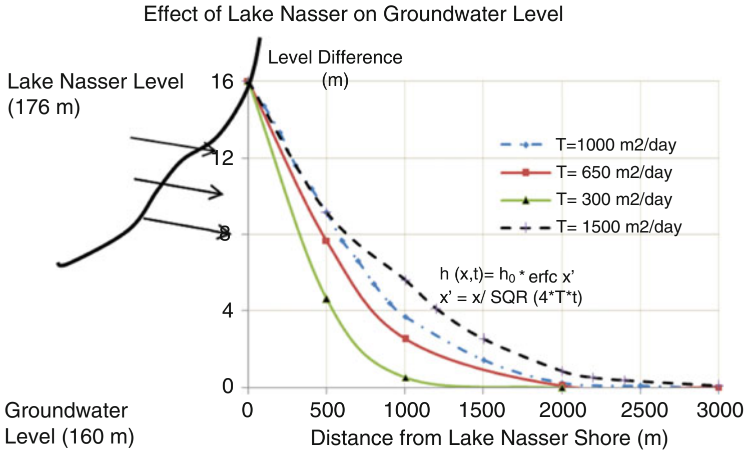


Fig. 14 Effect of Lake Nasser on groundwater levels in Toshka

4.2 Annual Recharge from High Dam Lake

Estimation of the recharge from High Dam Lake into the adjacent aquifers is one of the main factors influencing the water balance of the lake. The discharge or the seepage from High Dam Lake to the adjacent aquifers for 1 km of the shoreline is estimated by Darcy's law as:

$$Q = K \cdot I \cdot A$$

where Q is the discharge in m^3/day, K is the hydraulic conductivity (m/day), A is the area of discharge ($L \times B$) in m^2, L is the shoreline length (1,000 m), B is the saturated length of the aquifer (m), and I is the hydraulic gradient = ($\Delta h/\Delta l$) = (13 m/ 1,000 m) = 0.0013.

Applying the Darcy's law on 1 km sections using the available data on groundwater level distribution and taking into consideration that the transmissivity (T) = $K \times B$, the transmissivity map shows that the average transmissivity value is about 650 m^2/day along the shoreline. The recharge can be calculated as:

$$\begin{aligned} Q &= K \cdot I \cdot A \\ &= K \cdot I \times (L \times B) \\ &= (K \times B) \times L \times I = T \times L \times I \\ &= 650 \times 1{,}000 \times 0.0013 \\ &= 845 \ \text{m}^3/\text{day}/\text{km} \\ Q &= 308{,}425 \ \text{m}^3/\text{year}/\text{km} \end{aligned}$$

It is important to mention that the recharge value depends on the changes in the levels of groundwater in the aquifer and surface water of the lake. Therefore, the amount of water recharge changes from one season to another.

5 Assessment of Groundwater Potential

5.1 *Radius of Influence*

Radius of influence is taken as the designed distance between wells, and it plays an important role to avoid the drawdown interference effect among wells. It must be calculated before designing the well field from the available data. In the current project, the wells were designed at a distance of 1 km from each other. The analysis presented here is a pumping test analysis in which drawdown at a piezometer distance (r) from the abstraction well is monitored over time. This is also based on the Theis method.

For the Theis equation, using $S = 0.0003$ and $t = 0.41$ day (10 h operation per day), the radius of influence (r) for maximum, minimum, and average transmissivity can be calculated. The relation between the drawdown and the radius of influence indicates that the suitable value of r that minimizes or avoids the drawdown interference lies in the range from 1,000 to 2,000 m depending on the value of T and S (see Fig. 15). The radius of influence corresponding to the average value of transmissivity in the study area (650 m^2/day) is 1,400 m.

5.2 *Groundwater Sustainability*

Sustainability of groundwater potential quantity and quality is mainly dependent on the following:

1. The total amount of daily extraction water from the wells

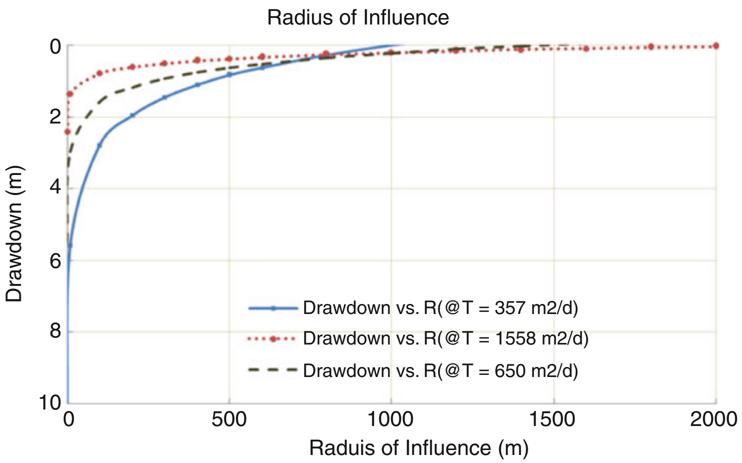


Fig. 15 Radius of influence vs. drawdown in Toshka area

2. The daily operation hours
3. The source of energy used to extract water
4. The agriculture drainage system
5. The crop pattern
6. The climate changes
7. The aquifer geology and properties

To evaluate and predict the future changes in the groundwater potential, Visual MODFLOW 2011.1 software was used to estimate the expected drawdown in the groundwater levels for different scenarios. The model was constructed and built to simulate the study area as follows.

5.2.1 Conceptual Model

A conceptual model to simulate water flow system of Nubian sandstone aquifer is constructed based on the following assumptions:

– Unconfined aquifer.
– One layer based on a basement rock.
– The flow direction moves from south and southeast to north and northwest.
– The hydraulic conductivity has spatial variations according to the variation in the saturated thickness.

5.2.2 Model Design

A grid of 1,600 cells (40 × 40) is constructed to cover the area including active and inactive cells as shown in Fig. 16. A grid surfer package was used to simulate the aquifer geometry and hydraulic parameters. The basement map (see Fig. 17) and the ground surface levels (see Fig. 18) represent the bottom and the top of the aquifer, and a 3D view of aquifer geometry simulation is shown in Fig. 19.

5.2.3 Boundary Conditions

The southeast boundary is represented by High Dam Lake which is considered as a constant boundary of 176 m above sea level. The north and west boundaries are represented as general boundary heads.

5.2.4 Building the Groundwater Model

The model was built based on the hydraulic parameters which are calculated from the pumping test analysis such as the hydraulic conductivity, transmissivity, initial heads, specific storage, specific yield, etc.

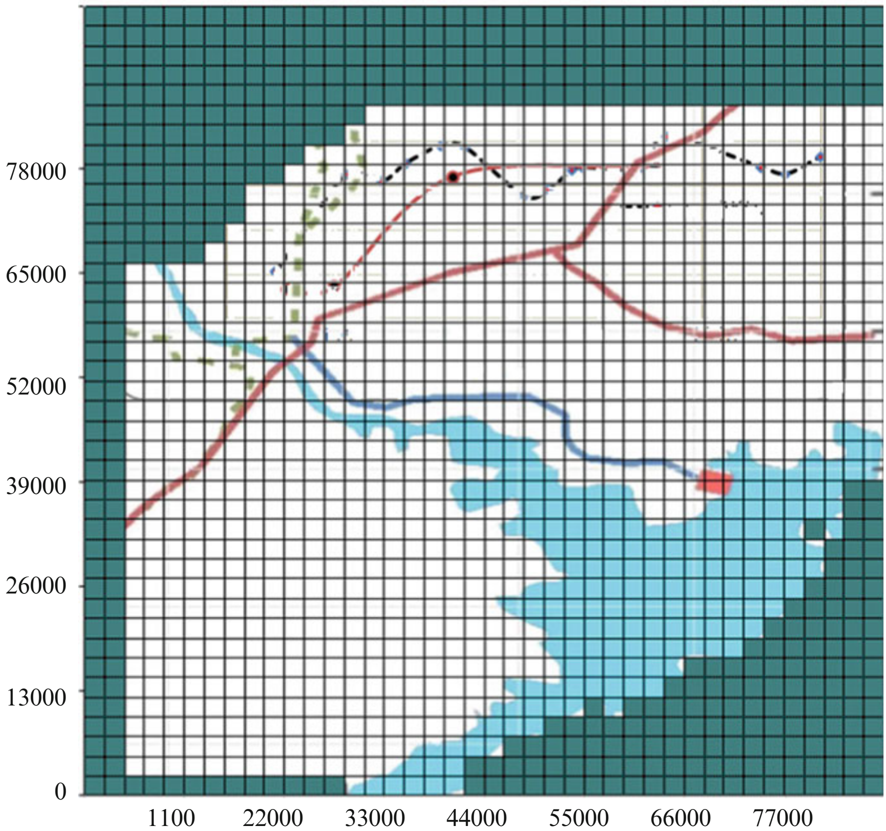


Fig. 16 A grid of 40 row × 40 column

5.2.5 Model Calibration (Steady State)

Six observation wells were used to check the relation between the calculated and observed heads. After many times of changing the hydraulic conductivity and transmissivity, the produced water head map became close to the measured map. The hydraulic conductivity distribution map and the calibration diagram are shown in Figs. 20 and 21.

5.2.6 Model Calibration (Unsteady State)

Model calibration (unsteady state) is done by changing the time variant into transient by simulation time of 100 years together with the storage coefficient 10 running the model. By changing the storage coefficient several times, the

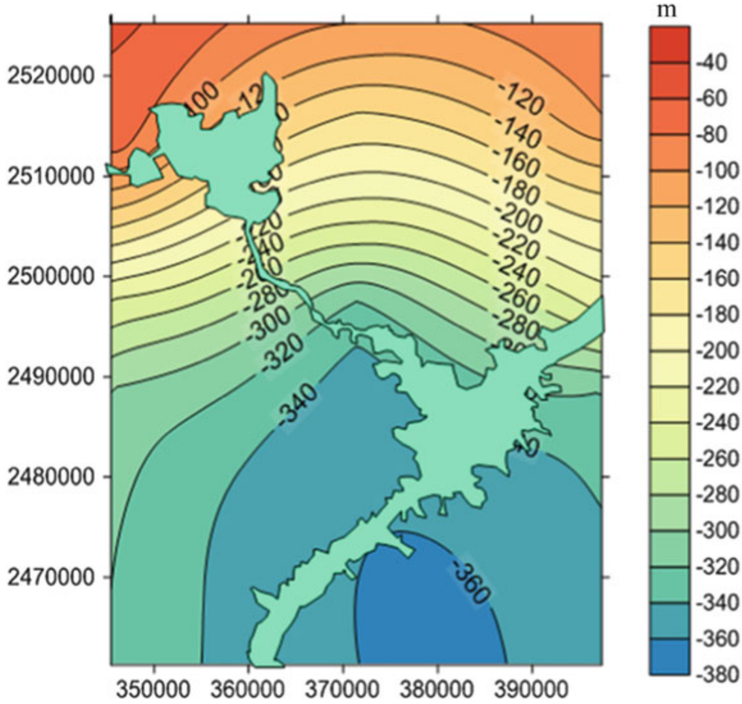


Fig. 17 Depth to basement rock map in Toshka area

calculated heads became close to the observed heads, and the model became suitable for future management of groundwater in the study area.

6 Water Requirement Scenarios for Reclamation of 25,000 Feddan

The government strategy intends to reclaim a total area of 25,000 feddan on groundwater in Toshka. To do this, some development scenarios have been made taking into consideration the groundwater aquifer delimiters, safe yield, and the recovery cost. Four scenarios were made based on the assumed water duty (requirement) per feddan per year and the corresponding drawdown in the groundwater levels (see Table 1).

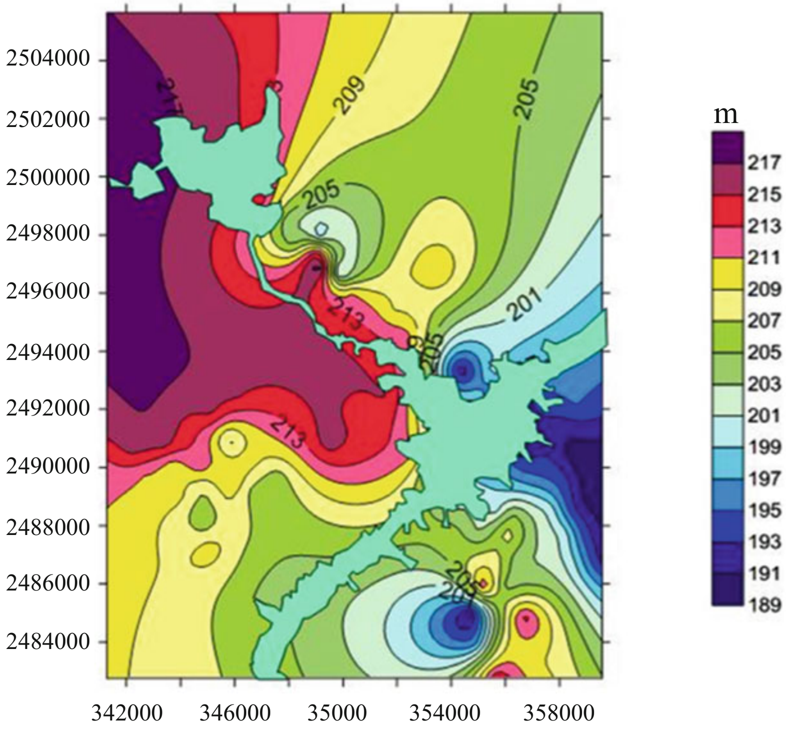


Fig. 18 Ground surface level map in Toshka area

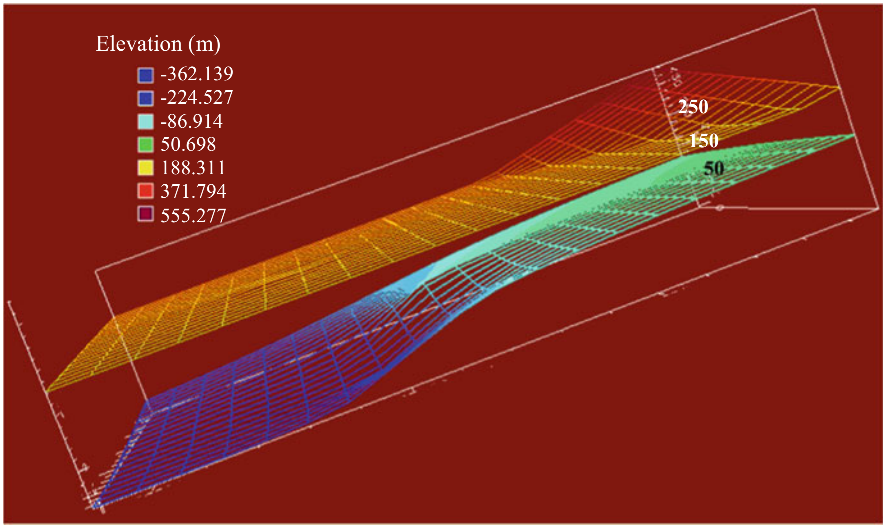


Fig. 19 Geometry simulation of Toshka area

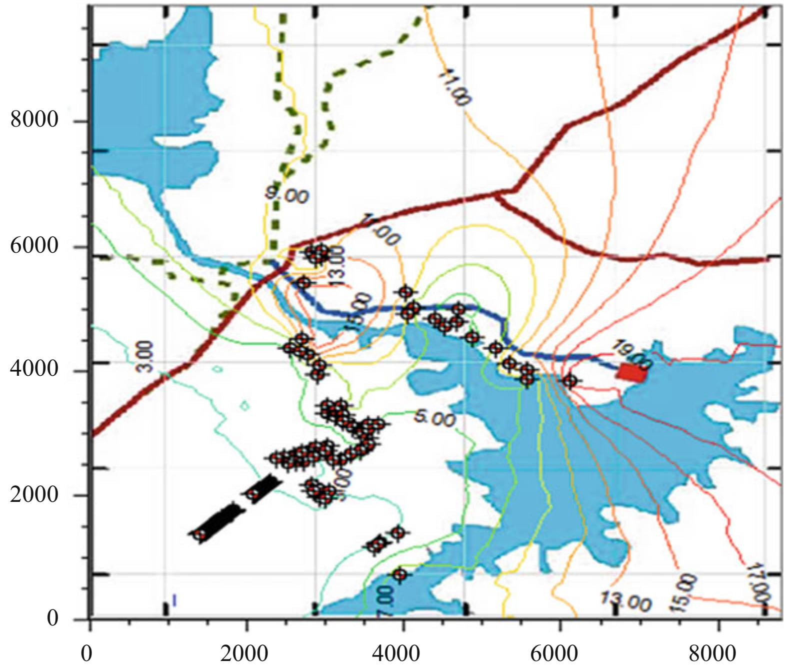


Fig. 20 Hydraulic conductivity distribution map in Toshka area

6.1 Scenario Assessments

1. It is clear that the maximum allowable daily operation time is 16.8 h with the daily discharge of $120 \times 16.8 = 2{,}014$ m^3/day.
2. The maximum daily sunrise is 12 h with the daily discharge of $120 \times 12 = 1{,}440$ m^3/day.
3. The preferable total amount of water extracted from 102 wells is ($120 \times 12 \times 365 \times 102$ wells) $= 53{,}611{,}200$ m^3/year.
4. For water duty of 5,000, 4,000, 3,000, and 1,500 m^3/feddan/year, the maximum cultivated area is 10,700, 13,400, 17,850, and 35,700 feddan, respectively (see Fig. 22).
5. The percentage of the maximum cultivated area with respect to the total required area of 25,000 feddan is 43%, 54%, 71%, and 143% for 5,000, 4,000, 3,000, and 1,500 m^3/feddan/year, respectively (see Fig. 23).
6. The expected drawdowns after 100 years for 1,200, 1,400, 1,600, and 1,800 m^3/day/well are 15, 20, 25, and 28 m, respectively.
7. For 1,400 m^3/day/well that assigned as a safe and recommended yield:

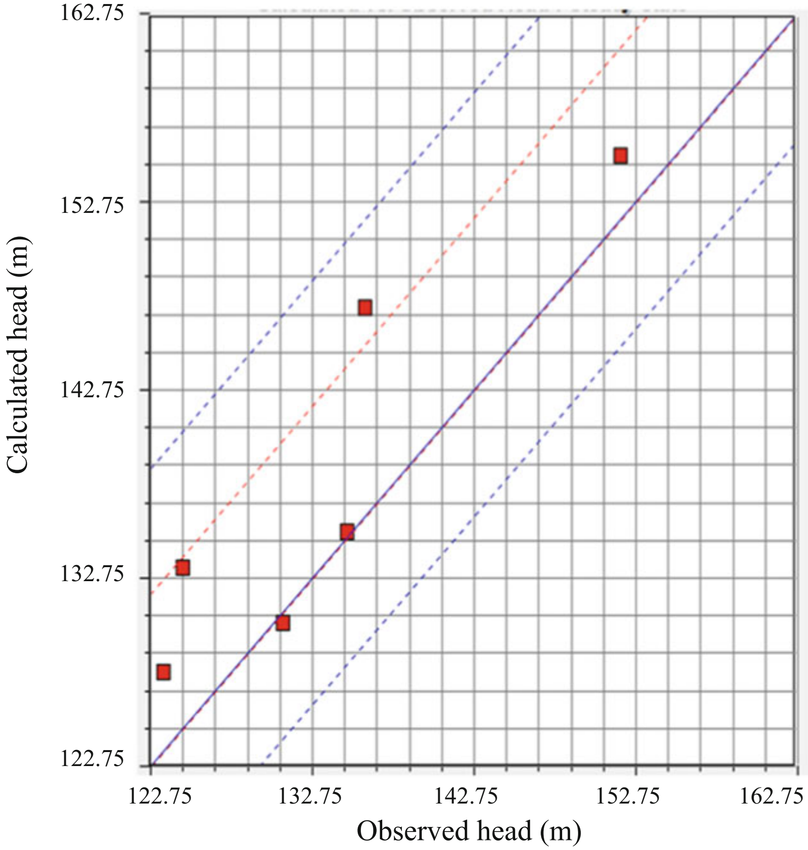


Fig. 21 Model calibration results

(a) The cultivated area according to the assigned discharge (1,400 m^3/day) mainly depends on the crop pattern. It is inversely proportional to the water requirement (see Fig. 23).
(b) The expected lowering in groundwater levels after 100 years is 15 m (see Fig. 24).
(c) The mass flow balance indicates that the calculated total recharge from the High Dam Lake in 100 years is 9.41 billion m^3 (94.1 million m^3/year) (see Fig. 25).
(d) The total extracted water from the wells is 52 million m^3/year, and the calculated recharge from High Dam Lake is 94 million m^3/year. This recharge was only estimated for Abu Simbel area. It means that the inflow is more than the outflow which guarantees the sustainability of development projects.
(e) Many studies have been done to estimate the recharge from High Dam Lake as the following.

Table 1 Different scenarios of water usage for 100 years

Scenario no.	Water requirements (m^3/feddan/year)	Total water requirements for 25,000 feddan (million m^3/year)	Total water requirements from one well (m^3/day)	Max drawdown (m) after 100 years	Required operation daily hours (safe discharge of 120 m^3/h)	Remarks
1	5,000	125	3,357	55	28	Refused 24 h
2	4,000	100	2,686	40	22.4	Very dangerous
3	3,000	75	2,014	25	16.8	Critical
4	1,500	37.5	1,007	15	8.4	Acceptable

1. The specific yield (S_y) method (see Table 2):

$$Q = A \times \left(\frac{dh}{dt}\right) \times S_y$$

where Q is recharge (million m^3/year), A is area estimated from Fig. 26 in km^2, dh is change in groundwater level (measured), dt is time of groundwater level change, and S_y is specific yield [40].

2. Darcy's law method:
   Figure 27 indicates the cross-section method calculation and shows 26 sections and estimated hydraulic conductivity, hydraulic gradient, and saturated thickness for each length. Table 3 indicates the estimated value for each section.

7 Hydrochemistry

Groundwater samples for chemical analysis were obtained from 38 productive wells and 1 surface sample from Lake High Dam in Abu Simbel City. Sampling was carried out in 2000, 2001, and 2002. The major cations of Na^+, K^+, Ca^{2+}, and Mg^{2+} and anions of Cl^-, SO_4^{2}, and HCO_3^- were measured in the laboratory of the Desert Research Center (see Table 4).

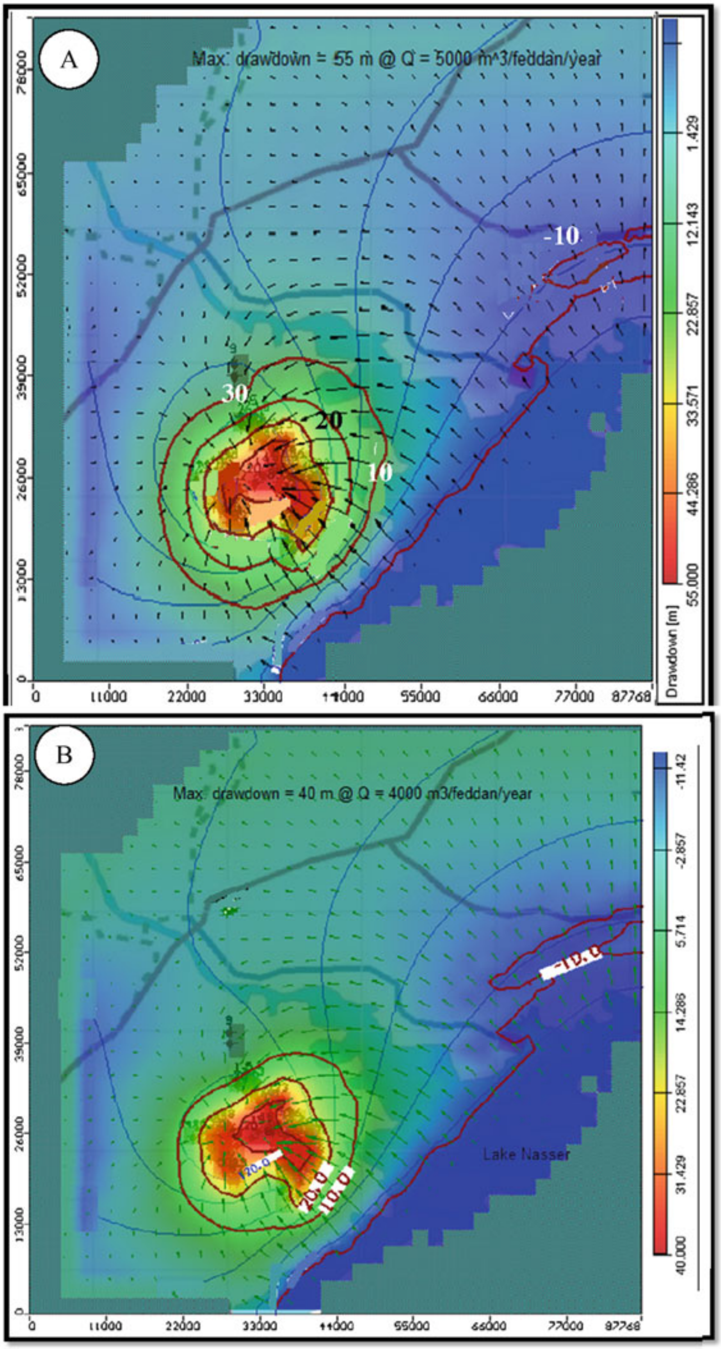


Fig. 22 The predicted drawdown after 100 years for different scenarios: (**a**) in case of 5,000 m^3/feddan/year, (**b**) in case of 4,000 m^3/feddan/year, (**c**) in case of 3,000 m^3/feddan/year, (**d**) in case of 1,500 m^3/feddan/year

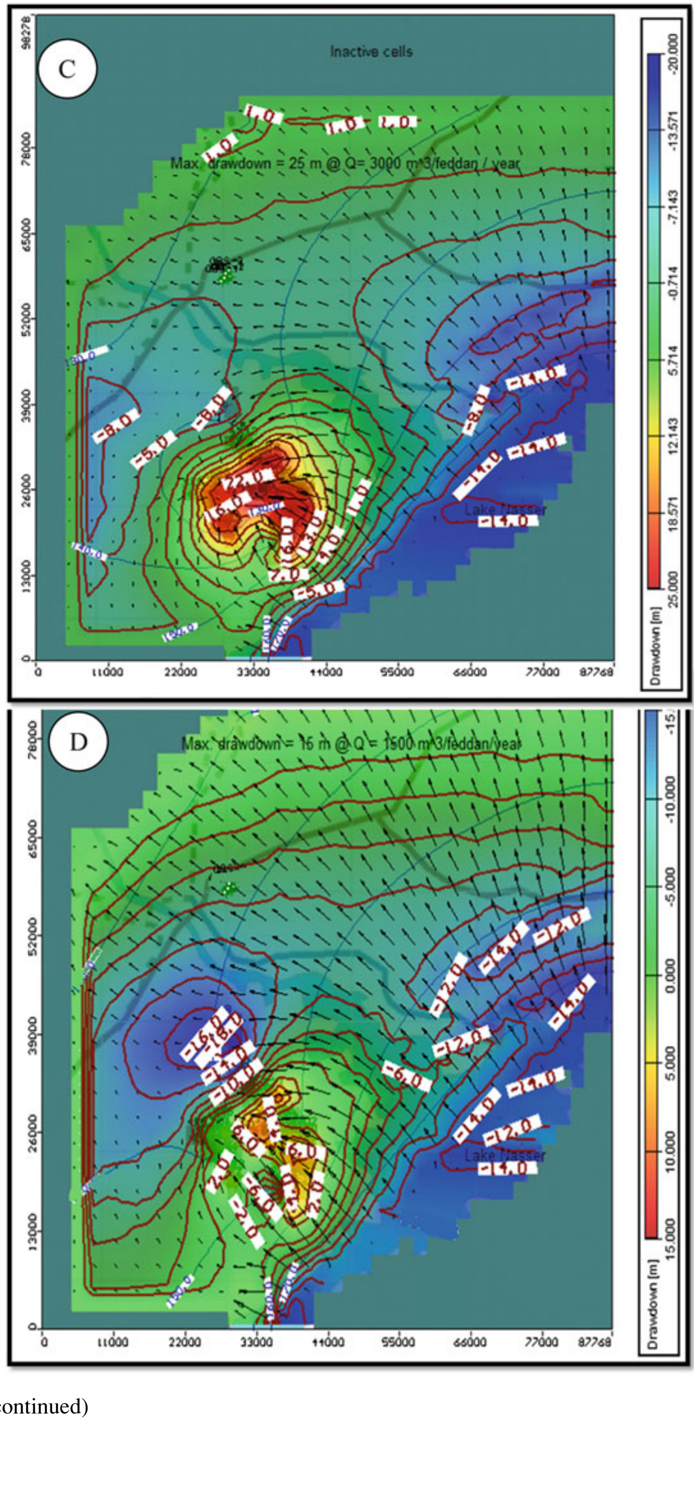


Fig. 22 (continued)

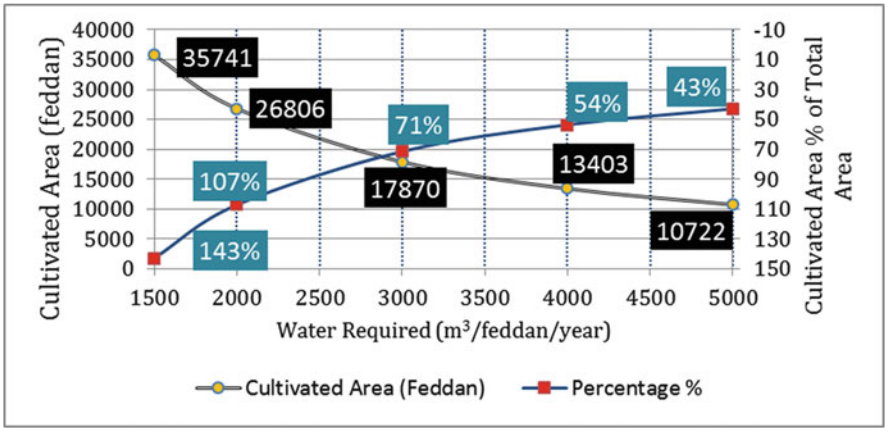


Fig. 23 Drawdown after 100 years for 1,400 m^3/day/well (total 102 wells)

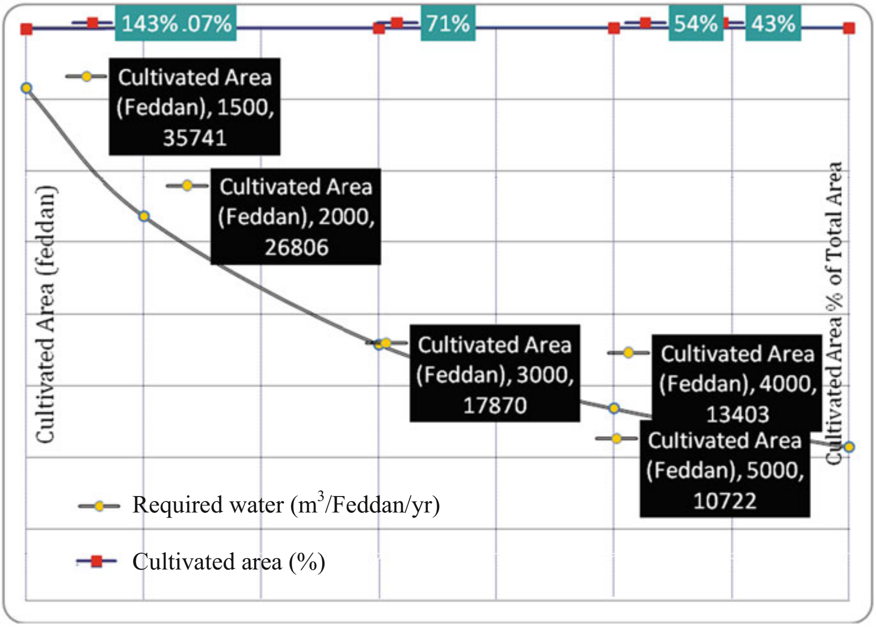


Fig. 24 Cultivated area vs. water requirements in Toshka

7.1 Groundwater Salinity in the Study Area

The majority of groundwater samples (38 samples) of the Nubian sandstone aquifer in the study area belong to freshwater type (<1,000 ppm). The salinity of groundwater increases toward the northwest directions coinciding with groundwater flow.

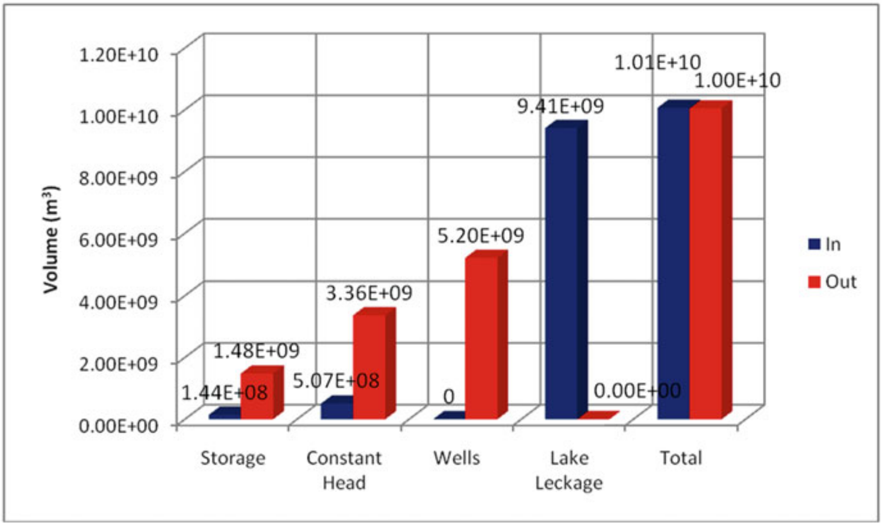


Fig. 25 Mass flow balance after 100 years for 1,400 m^3/day/well

Table 2 Total recharge in Toshka (specific yield method)

Region	*A* (km^2)	*dh*/*dt*	Specific yield	*Q* (million m^3/year)
W. Halfa road	845	0.18	0.135	20.5
Abu Simbel road	929	0.70	0.165	107.3
Zayed canal	507	0.83	0.145	60.6
Amada road	676	0.67	0.129	58.4
Toshka depression	338	0.11	0.030	1.1
Total				259.9

Lower groundwater salinity is decreased due to the recharge from the High Dam Lake. The salinity ranges from 480 to 1,200 ppm with an average of 648.5 ppm (see Fig. 28).

7.2 *Piper Diagram*

Most of water samples belong to (NaCl) water type, and a few samples belong to ($NaSO_4$) water type for wells 26, 41, 44, 45, 73, 76, and 78 (see Fig. 29).

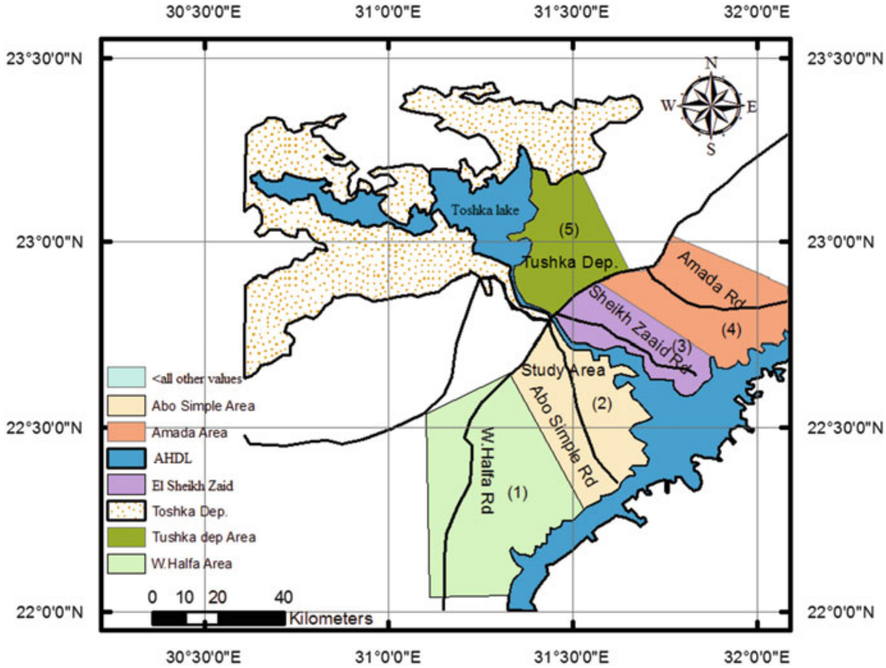


Fig. 26 Specific yield method to estimate the annual recharge

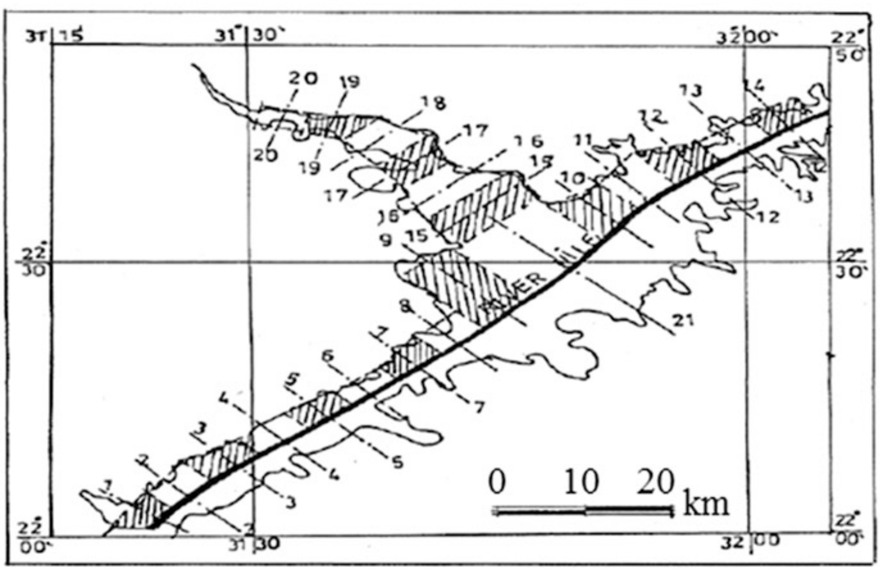


Fig. 27 Darcy's law method to estimate the annual recharge

Table 3 Total recharge in Toshka (Darcy's law method)

Section no.	Length (m)	Hydraulic gradient (I)	Saturated thick (m)	*K* (m/day)	*Q* (1,000 m^3/day)
1	3,900	0.002564	250	10	25
2	5,200	0.001923	250	10	25
3	5,200	0.001923	250	10	25
4	66,500	0.001538	250	6	15
5	6,500	0.001538	250	6	15
6	6,500	0.001538	250	6	21
7	6,500	0.001538	250	5	17.5
8	5,200	0.001923	250	5	17.5
9	5,200	0.001923	250	4	10
10	3,900	0.002564	250	6	15
11	2,600	0.003846	250	6	15
12	2,600	0.003846	250	6	15
13	2,600	0.003846	250	6	15
14	2,600	0.007692	250	8	40
15	3,900	0.005128	250	6	30
16	5,200	0.003846	250	3	15
17	6,500	0.003077	250	3	15
18	6,500	0.003077	250	4	20
19	7,800	0.002564	250	4	20
20	9,100	0.002198	200	4	16
21	9,100	0.002198	120	8	19.2
22	6,500	0.003077	120	8	19.2
23	6,500	0.003077	150	0.1	0.300
24	6,500	0.003077	150	0.1	0.300
25	6,500	0.003077	150	0.1	0.300
26	6,500	0.003077	150	0.1	0.300
Total					426.6
Total annual recharge = 155 million m^3					

7.3 Wilcox Diagram

Wilcox diagram shows that the majority of samples are located in C3–S1. S1 means low value of sodium hazard, and C3 means high salinity hazard (see Fig. 30).

7.4 Durov Diagram

Durov diagram describes the sample's water type and salinity. Most of the samples belong to NaCl type and salinity from 336 to 1,000 ppm (see Fig. 31).

Table 4 Chemical analysis of Toshka groundwater (mg/l)

Well no.	Date	N^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	HCO_3^-	$^-CO_2$	SO_4^{2-}	TDS (ppm)
22	9/7/2000	188	5.8	112	29.2	280	108	0	290	1,175
23	24/09/2000	114	5.2	76	9.73	168	104	0	160	662
24	11/10/2000	108	4.8	80	17	160	112	0	195	640
25	12/9/2000	132	4.5	58	25.5	184	114	0	165	722
26	25/12/2000	108	5.2	86	18.2	136	128	0	210	652
27	16/09/2000	132	4.5	58	25.5	184	114	0	165	722
28	25/07/2000	136	4.8	62	35.3	192	140	0	195	744
29	6/12/2000	116	4.8	77	14.6	160	112	0	180	602
30	15/10/2000	98	4.4	76	20.7	144	116	0	180	676
31	1/7/2000	144	4.3	86	24.3	216	108	0	190	766
32	26/10/2000	100	4.8	80	15.8	142	108	0	160	625
33	27/08/2000	104	4.7	78	21.9	144	132	0	180	630
34	28/10/2000	88	4.6	75	10.9	116	124	0	145	545
35	3/6/2000	136	4.3	78	13.4	168	116	0	205	708
36	10/9/2000	90	4.6	64	15.8	124	140	0	140	530
37	18/10/2000	86	4.4	73	11.6	135	138	0	135	532
38	22/11/2000	88	4.2	68	13.4	112	140	0	130	576
39	24/02/2000	76	4.6	66	15.2	104	116	0	140	488
40	20/08/2000	100	4	66	21.9	136	116	0	140	600
41	26/10/2000	96	4.6	72	13.4	108	136	0	165	600
42	3/8/2000	108	4.4	72	17	128	196	0	150	684
43	27/06/2000	94	4.8	50	32.8	216	104	0	135	598
44	2/10/2000	98	4.4	76	10.9	110	132	0	160	575
45	2/10/2000	110	4.1	76	14	128	116	0	190	585
46	25/11/2000	104	4	70	12.8	136	110	0	165	600
47	20/02/2001	190	5.6	104	19.5	280	76	0	280	940
51	21/03/2001	210	7.1	134	19.5	370	84	0	310	1,200
52	20/03/2001	280	6.8	142	26.8	410	84	0	380	530
60	11/5/2002	92	5	68	19.5	140	108	0	160	1,360
71	1/9/2002	72	5.1	56	24.3	124	128	0	130	574
72	12/9/2002	76	4.4	56	24.3	128	124	0	130	480
73	31/01/2002	88	3.4	52	21.9	112	100	0	165	484
74	10/9/2002	100	5.4	64	21.9	144	152	0	160	518
75	11/8/2002	88	5.3	56	29.2	120	136	0	160	604
76	31/01/2002	104	5.2	54	28	132	118	0	180	546
77	20/04/2002	100	5	46	25.5	130	128	0	134	568
78	10/3/2002	82	5.9	32	41.3	108	128	0	154	540
79	12/9/2002	112	4.8	79	19.5	154	120	0	202	540
AHDL		12	8	36	4.86	24.8	100	0	35	170

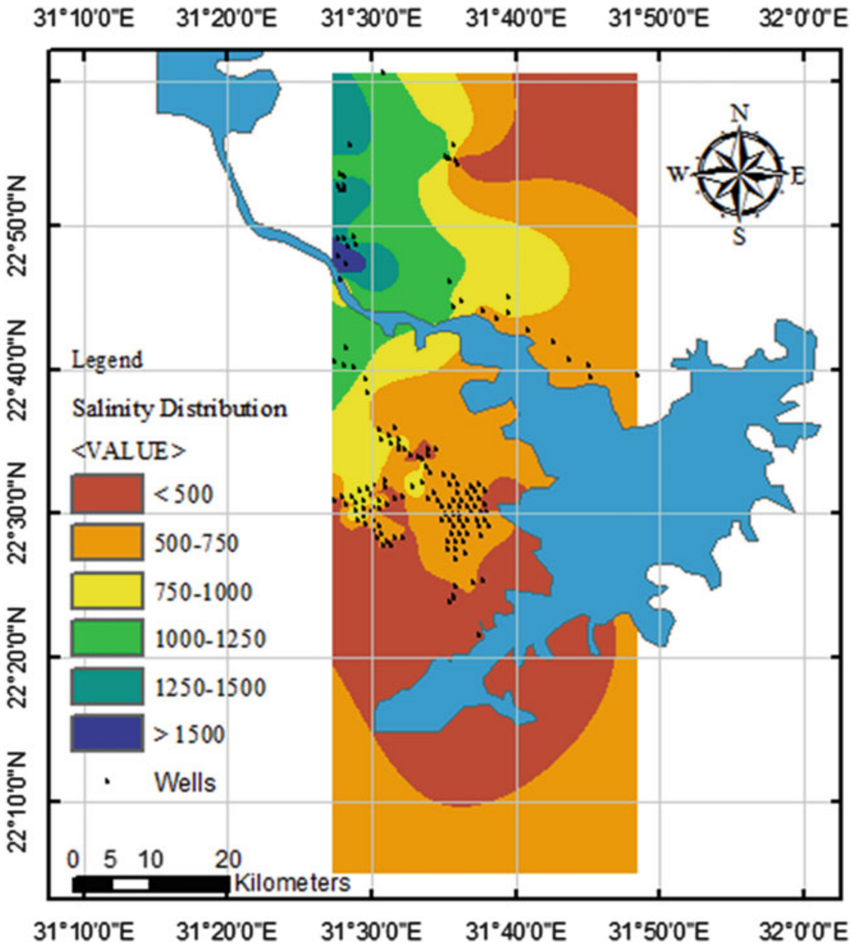


Fig. 28 Distribution of salinity content (ppm) in the study area

7.5 Suitability of Groundwater for Irrigation Purposes

The groundwater quality in the study area was classified according to its chemical properties such as TDS, SAR, RSC, chloride, and trace elements as discussed below.

7.6 Total Dissolved Salts (TDS)

Total dissolved salts (TDS) parameter is one of the most important ones to assess the suitability of water for irrigation. According to the distribution map of salinity

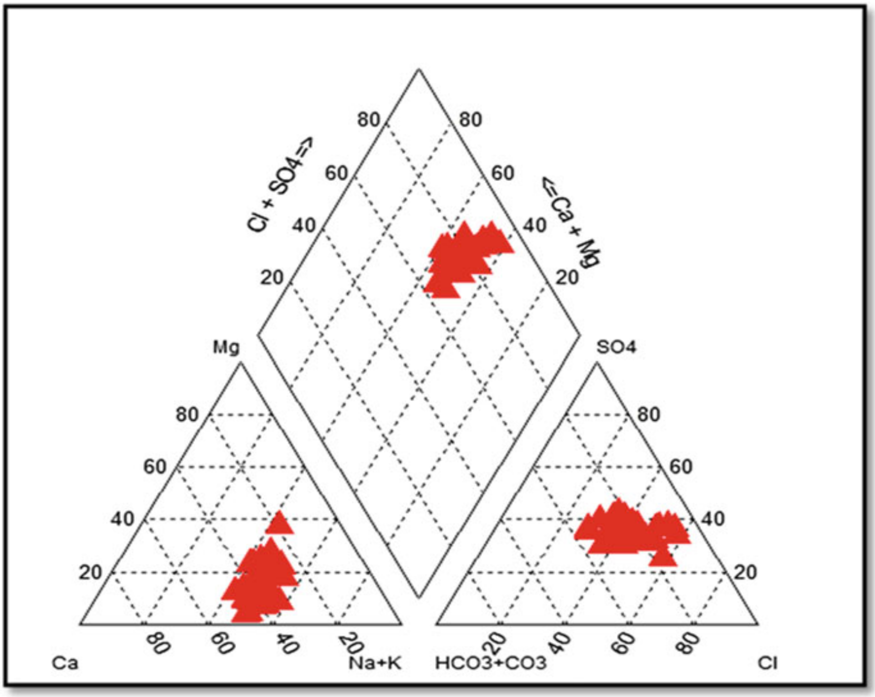


Fig. 29 Piper diagram of hydrochemical classification of groundwater samples in Toshka area

(see Fig. 28), most of the water samples range between 500 and 1,500 mg/l. US Salinity Laboratory (USSL) classification and Wilcox plot show that all of the samples are located in region C3. The salinity of this class ranges between 500 and 1,500 g/l, and electric conductance ranges between 750 and 2,250 µmoh/cm. It can be used for moderate-good permeable soils, while it cannot be used on soils with restricted drainage. Even in the soils with adequate drainage, special management of salinity control may be required, and plants with good salt tolerance should be selected.

7.7 *Sodium Adsorption Ratio (SAR)*

Sodium adsorption ratio (SAR) measures the relative concentration of sodium to calcium and magnesium. High sodium ions in water affect the permeability of the soil and cause infiltration problems. Sodium replaces calcium and magnesium adsorbed on the soil clays and causes dispersion of soil particles. Therefore, the soil when dry becomes hard and compact with low permeability [41].

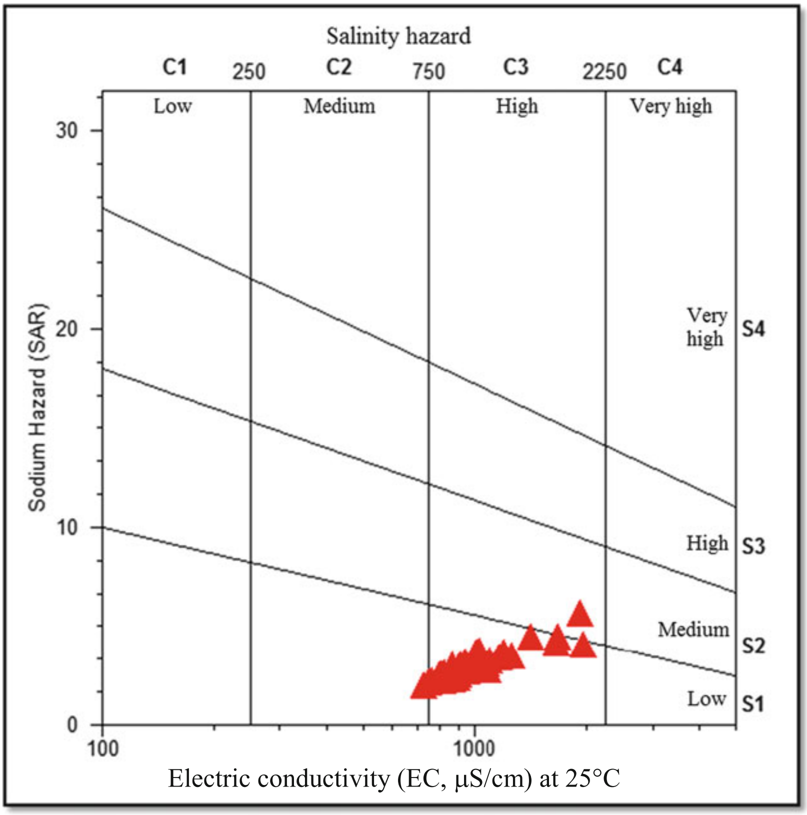


Fig. 30 Wilcox diagram for the groundwater samples in Toshka area

Most of the samples are located in S1 class (see Fig. 32), indicating a low value of sodium. All SAR values are less than 10 emp, which is classified according to US Salinity Laboratory (USSL) as an excellent class for irrigation and good for fruits, nuts, citrus, and avocado.

7.8 *Residual Sodium Carbonate (RSC)*

In water concentrated with bicarbonate, it has a tendency for calcium and magnesium to precipitate. As a result, the relative proportion of sodium in the water is increased in the form of sodium carbonate. RSC is calculated using the following equation:

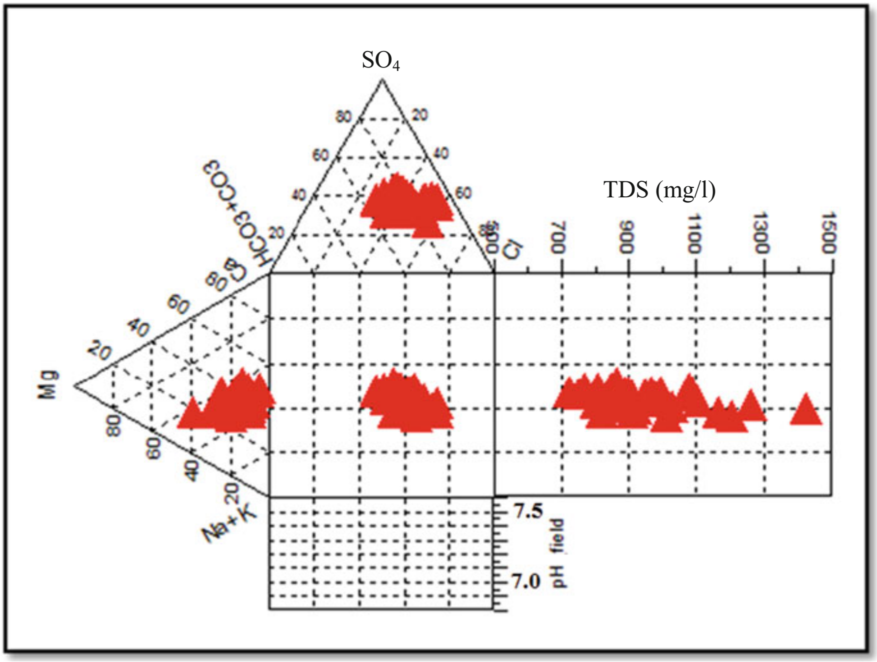


Fig. 31 Durov diagram for groundwater samples in Toshka area

$$RSC = \left(HCO^{3-} + CO_3^{2-}\right) - \left(Ca^{2+} + Mg^{2+}\right)$$

According to the US Department of Agriculture, water having more than 2.5 epm of RSC is not suitable for irrigation purposes. RSC is classified into three classes (<1.25, 1.25–2.5, and >2.5) which are good, doubtful, and unsuitable, respectively. By applying RSC equation, the results for all samples showed negative values, indicating good class.

8 Conclusions

The present chapter focuses on estimating the expected change in groundwater levels and water quality for different operation scenarios.

The minimum water level of the AHDL had remained above 170 m, fluctuating by 2–4 m/year. There is a direct relation between the AHDL and the characteristics of the groundwater in Toshka area that is mainly covered by sedimentary sequence up to 300 m. It is represented by brown shale, sandstone, and shaley sandstone, which overlie the Precambrian basement rocks.

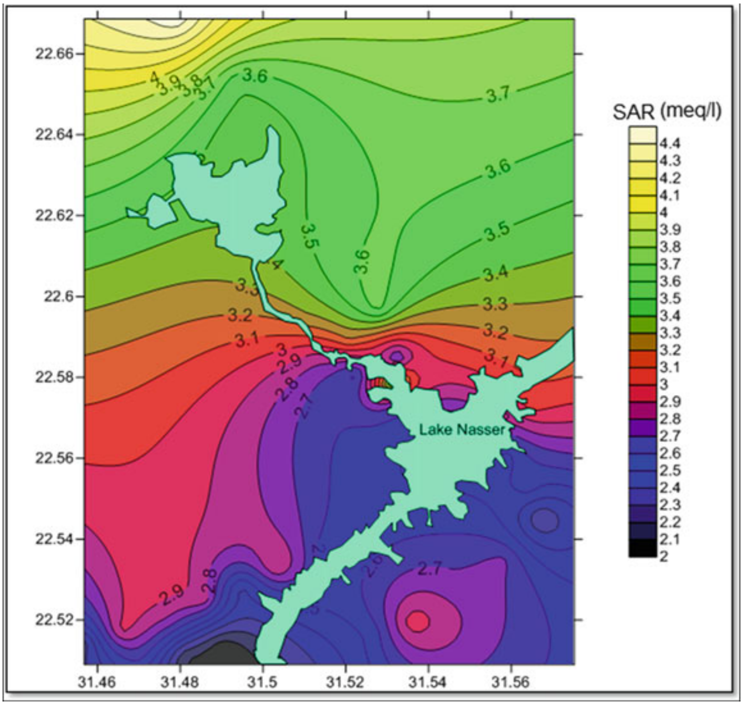


Fig. 32 Spatial distribution map of SAR in Toshka area

The Nubian Sandstone Aquifer System in Toshka receives continuous recharge confirmed by the difference of heads between the aquifer and the AHDL.

The transmissivity varies between 321 and 1,558 m^2/day with an average of 650 m^2/day. The hydraulic conductivity ranges from 3 to 21 m/day with an average of 6 m/day. The aquifer potentiality is increasing toward the northwest of the study area due to high hydraulic conductivity and aquifer thickness in the northwest.

The water drop in water level from 1998 to 2006 ranged between 0.5 and 13.8 m in Toshka. Such drop indicates that the extraction rate of water is much higher than the recharging rate. The drop is expected to continue with the continuous extraction of groundwater.

The effect of the new 50 wells drilled in 2015/2016 to irrigate the 25,500 feddan as a part of the "1.5 Million Feddan Project" will increase the drop in groundwater level in the area.

The preferable total amount of water extracted from the 102 wells is 53,611,200 m^3/year at 120 m^3/h for 12 h/day. For water duty of 5,000, 4,000, 3,000, and 1,500 m^3/feddan/year, the maximum cultivated area will be 10,700, 13,400, 17,850, and 35,700 feddan, respectively. The expected drawdowns after 100 years for 1,200, 1,400, 1,600, and 1,800 m^3/day/well are 15, 20, 25, and 28 m, respectively. The cultivated area, according to the assigned discharge for each well

(1,400 m^3/day), mainly depends on the crop pattern. It is inversely proportional to the water requirement.

The total extracted water from the 102 wells is 52 million m^3/year, and the calculated recharge from AHD Lake is 94 million m^3/year. This recharge was only estimated for Abu Simbel area. It means that the inflow is more than the outflow (under the assumptions of the study) which guarantees the sustainability of development projects. The recharge studies showed to be done for the whole area.

The recommended safe water use of groundwater for 100 years is 1,007 m^3/day from each well working 8.4 h/day at 120 m^3/h, to provide 1,500 m^3/feddan/year for a total of 25,000 feddan. The expected lowering in the groundwater level after 100 years is 15 m.

The groundwater in Toshka is classified as a freshwater type (<1,000 ppm). The salinity ranges from 480 to 1,200 ppm with an average of 648.5 ppm. It increases toward the northwest directions coinciding with groundwater flow. Lower groundwater salinity is decreased due to the recharge from the AHD Lake. The groundwater is an excellent class for irrigation.

9 Recommendations

Groundwater model must be used to predict the influence of different development scenarios on the groundwater levels. Building, calibration, and validation of such model could be based on the available historical data. There is a direct recharge from the AHDL to the groundwater in Abu Simbel area. Groundwater recharge is expected to increase from the new surface irrigation. Detailed recharge studies showed to be done for the whole area. The safe abstraction from the water wells in Toshka is 120 m^3/day for 8–12 h/day. The 102 wells are good for 25,000 feddan at 1,500 m^3/feddan or 12,500 at 3,000 m^3/feddan. Water quality monitoring is required for all wells in general and the new ones in particular. Water is very precious in the desert regions; therefore, good feasibility studies are required to be done on Toshka projects. The climatic conditions and consequences of the new irrigation projects in Toshka need detailed studies. New Toshka lakes were formed during the AHDL flood in 1998 to 2001. They disappeared after about 10 years due to mostly high evaporation and water infiltration. Geo-environmental problems especially soil salinization are likely to arise from the concentration of salts after the lakes dry up. Studying the salinity of soil and its effect on the groundwater is strongly recommended to be carried out. The new irrigation projects in Toshka should use the most drought tolerant crops and get benefit from the virgin soils in organic agriculture.

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Part VI
Impacts of GERD and Tekeze Dams on Egypt's Water Resources

Impacts of Filling Scenarios of GERD's Reservoir on Egypt's Water Resources and Their Impacts on Agriculture Sector

Noha Donia and Abdelazim Negm

Abstract The Ethiopian government builds the Grand Ethiopian Renaissance Dam (GERD) that is a 6,000 MW hydropower project on the Blue Nile to fulfill the country's energy needs. This dam will have many impacts on the water supply of downstream countries like Egypt and Sudan. The objective of this chapter is to model the impacts of GERD on AHD. Illustration of the model constructed to simulate impacts of filling options for the GERD reservoir is provided. Many scenarios were conducted using the developed model to predict the optimum filling scenario to minimize these impacts on downstream countries. Simulating results show that the live water storage in AHD will reach its minimum with the minimum water level of 147 m by the end of 5 years filling period of the full storage capacity of GERD (74 BCM). Scenarios of changing GERD's filling period and GERD filling storage capacity have been conducted, and their effect on agriculture has been sesed. Scenario results show that decreasing the water supply required for agriculture will cause a high loss in income especially in case of 5 years filling period of GERD. Therefore, increasing filling period is a solution, or the other solution is the changing of the GERD storage capacity to minimize downstream impacts on AHD. However, this will not eliminate the impacts but will just relief them. The net loss in the return of each crop was computed for all scenarios to enable the decision takers to plan for the future for the different scenarios.

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Contents

1 Introduction

The Nile River flows through 11 countries. It is the longest transboundary river, but also its basin suffers from water scarcity and conflicting issues in its water management [1]. Egypt has been listed among the ten countries that are threatened by the need of water by the year 2025 due to the rapidly increasing population [2]. The conventional water resources in Egypt are limited to the Nile River; groundwater in the Delta, Western Desert, and Sinai; rainfall; and flashfloods. More than 96% of Egypt's all freshwater resources are supplied by the Nile River, which originates from outside of the country boundaries. Sixty-eight percent Blue Nile (Abay), 14% Atbara (a tributary of the Blue Nile), and 18% White Nile meet at Khartoum, and its water flows to Aswan in the Nile is composed. That means that 82% of the Nile at Aswan originates in the Ethiopian Highlands since the Blue Nile (Abay) and the Atbara originate in the Ethiopian Highlands [3].

Freshwater sources from the Nile are limited to Egypt by the agreement between Sudan and Egypt since 1959. This agreement entitled Egypt to 55.5 billion cubic meters (BCM) of Nile water per year and assigned 18.5 BCM for Sudan [3].

In 2011, the Ethiopian government announced a plan to construct a hydroelectric dam on the Blue Nile River, about 45 kilometers (km) east of its border with Sudan in Ethiopia, which has been named the Grand Ethiopian Renaissance Dam (GERD). It will create a lake with a total volume of more than 74 BCM [4]. The GERD is a 6,000 MW hydropower dam, which is intended for power generation and not for agricultural purposes [5].

Ramadan et al. [6] investigated the effect of new upper Nile projects on the integrated management of the Nile basin. Their results may enable the water manager to evaluate and choose the most suitable operation guidelines for local conditions and objectives.

Sadek [7] studied the effect of implementing upper Nile projects such as Ethiopia hydroelectric power dams and agriculture projects on water share of Egypt. She indicated that the discharge that reaches Nasser Lake might reduce by 5 BCM/year. Also, the water level upstream of AHD will decrease. Sadek [8] studied water scarcity and its impacts on the social and economic national projects in Egypt. In her study, GSTAR3.0 numerical model was implemented to simulate the water flow and sediment transport in the fourth reach of the Nile River in Egypt. Locations of navigation bottlenecks were identified. Also, affected drinking pump stations were evaluated. Ismail [9] investigated the impact of the reduction of AHD outflow on irrigation pump stations along the Nile River from Aswan to Delta Barrages numerically. Different scenarios of flow reduction downstream of AHD ranged between 0 and 25% were tested, and water levels along the Nile River were computed to examine the impacts of flow reduction on the irrigation pump stations.

Donia [10] developed a management system for Aswan High Dam and investigated the effect of climate change and GERD on the operation of AHD. It was concluded that overall, applying the new operating rules would decrease the percentage of occurrence of minimum water levels. Also, the GERD will increase the percentage of occurrence of minimum water levels. Finally, the period III (2070–2099) for the two global emission scenarios is very critical for the dam operation [9].

Nada and Fathy [11] studied the effect of different scenarios of filling the GERD on the reduction of water levels and discharges downstream of the AHD. They found that the water levels decreased from 0.40 to 0.75 m when discharge decreased from 90 to 80% of the maximum outflow. Ramadan et al. [12] studied the environmental impacts of GERD on the Egyptian water resources. They used a hydrological model (the river basin modeling and simulation package (MODSIM)). They concluded that impounding of GERD at normal flow from the Blue Nile through 6, 3, and 2 years will decrease the active storage of Nasser Lake by 13.287, 25.413, and 37.263 BCM through each year. While impounding of GERD at min of average flow from the Blue Nile through 6, 3, and 2 years will decrease the active storage of Nasser Lake by 25.963, 37.814, and 45.105 BCM/year. On the other hand, impounding of GERD at minimum flow case through 6, 3, and 2 years will decrease the active storage of Nasser Lake by 44.398, 54.415, and 55.138 BCM through each year. Bastawesy et al. [13] assessed the impacts of the GERD on the performance of AHD. They used the Mike Basin river basin simulation model. They concluded that if 6 years were used to fill the GERD, yearly outflows of the GERD during the impounding stage would never be lower than 28.9 BCM/year (about 58% of the mean flow).

Ramadan et al. [14] presented hydrological scenarios of GERD to estimate the water storage for its lake to assess the impact of the dam on the net annual discharge downstream. They mentioned that the anticipated negative impacts of the GERD on downstream would be more pronounced for Egypt as it mostly relies on the Nile water. They concluded that the completion of this project could occur over a short duration and during low-flood seasons. Consequently, the net annual discharge of the Blue Nile downstream could be minimal, and the Nasser Lake would struggle to sustain the required water for all the Nile Valley and its Delta in Egypt.

Mulat and Moges [15] quantified using a hydrological model, the shortage of water in the active storage of Nasser Lake due to impounding of GERD reservoir. Different scenarios of impounding were considered as 6, 3, and 2 years under different inflow conditions. Their results indicated that the negative impacts on Egyptian water resources were severe especially if the filling period is shorter than 6 years and their results agreed well with the results obtained by FAO [16].

This chapter investigates the effect of water reduction especially during the dam reservoir filling period [10, 15] on agricultural production and income loss for most essential crops in Egypt.

2 Background

According to Awad [17], the surface water resources in Ethiopia is 122 BCM yearly from which 85% flows to Nile River equivalent to 72 BCM. Therefore it remains to Ethiopia from surface water 51 BCM in addition to 936 BCM rainwater yearly. A comparison between the water resources in Egypt and Ethiopia is shown in Table 1.

It is evident from Table 1 that there is an excess of water availability but not efficiently used for any development required in Ethiopia compared with Egypt which suffers from water scarcity due to the large population it supports and decreased water supplies from the Nile River. This does not mean that Ethiopia cannot benefit from the river resources but should do so in a manner that will not affect the downstream countries. Historically before 2011, the GERD was designed to the capacity of 18 milliards, but a peripheral dam was constructed to store water up to 70 BCM that has a significant influence on water coming to Egypt. If Ethiopia retains the initial design of GERD, this will not affect Egypt significantly. Therefore, a prediction model is needed to manage the water supply to Egypt especially from the Blue Nile from Ethiopia after the construction of GERD and that is described in details in the following section.

Table 1 Comparison of water resources in Egypt and Ethiopia according to Awad [17]

Water resources	Egypt	Ethiopia
Rain (BCM)	51.07	936.4
Renewable water resources (BCM/year)	85.8	122
Water share per person (m^3/person/year)	702.8	1.512
The abstraction percentage from renewable water resources	117.3	5.1
The abstraction percentage from renewable water resources in agriculture (2002)	103	4.3
Dependence on river percentage	96.86	0
Irrigation capability (thousands ha)	4,420.00	2,700.00
Surface required for irrigation (thousands of ha)	3.422	290

3 Model Implementation

3.1 General Overview

The previously calibrated model developed by Donia [10] will be briefly presented then will be used in the simulation of filling scenarios of the GERD. The developed management system is a computer-based tool comprising three subsystems: the modeling subsystem, the database subsystem, and the user interface subsystem, interconnected with each other. A computer software was developed, using Visual Basic, by the author, and it is named "Aswan High Dam Reservoir Management System (AHDRMS)." The AHDRMS can help in understanding a given problem, explore the consequences of different alternatives, and facilitate sensitivity analyses.

The simulation model operates on the basic principle of water balance accounting, where both the engineered and biophysical components of a water system are represented to facilitate multi-stakeholder water management dialogue for reservoir operations and hydropower generation, Typically AHDRMS is applied by configuring the system to simulate a recent "baseline" year, for which the water availability and demands can be confidently determined. The model is then used to simulate alternative scenarios (i.e., plausible futures based on "what if" propositions) to assess the impact of different development and management options. This model is considered as unique because it is developed based on mass balance hydrologic routing equations, hydropower, discharges, and head relationships with special conditions related to the nature of the location and the special complicated nature of the problem since the storage volume reaches up to 162 BCM/year with a length of about 500 km and the existence of many types of outflows (point and nonpoint outflows) at different locations, Donia [10].

One of the main objectives of this study was to determine the possible filling scenarios of GERD by changing the filling period and storage capacity and then incorporate this information into the AHDRMS to determine the impact is likely to water availability to the AHD.

3.2 Model Background

The conceptual presentation of the modeling subsystem is shown in Fig. 1, Donia [10].

Input Module

Inflow – Historical data were considered for water inflow discharge input. These historical data are measured at Dongla gauging station (750 km US HAD) from 1971 to 2001.

Sudan Abstraction – According to an agreement with Egypt signed in 1959, Sudan's share of the water available from the Nile is 18.5 BCM/year. This allocation is based on an average natural inflow into the reservoir of 84 BCM/year (period

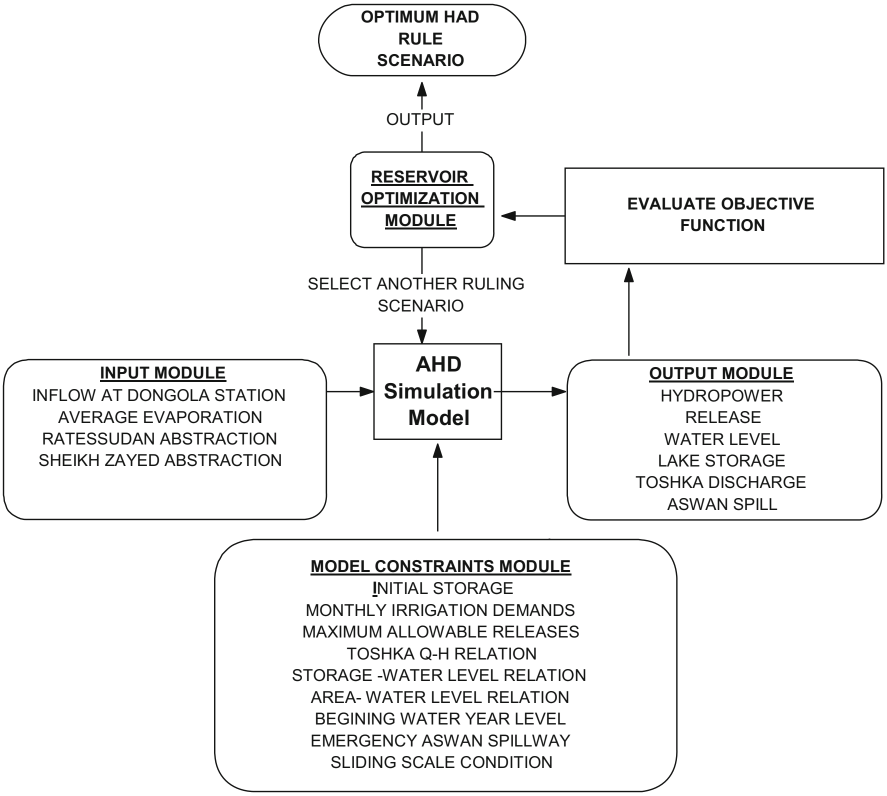

Fig. 1 Conceptual presentation of the modeling subsystem of the AHDRMS

1900–1959) and an estimated 10 BCM/year of reservoir losses. However, the actual use of Nile water by Sudan during the past period was about 14.5 BCM/year.

El-sheikh Zayed Canal – El-sheikh Zayed Canal conveys water discharge from Lake Nasser to the newly cultivated lands in the national project of El-Sheikh Zayed, constructed 1998–1999. The huge pump station (on Lake Nasser left bank) is used to elevate water from Lake Nasser to the El-Sheikh Zayed Canal. The station has been designed to have a maximum static lifting of about 52.5 m to ensure its operation when the water level in Lake Nasser reaches its lowest level of storage, which is 147 m above (MASL). The designed maximum discharge of the pumping station was estimated to be about 300 m^3/s (25 million m^3/day). The expected annual water discharges from the lake into the canal are estimated to be 5 BCM. The canal has a length of 60 km, bed width of 30 m, and side slopes with 2:1 gradient and is lined to prevent seepage from the canal.

Operation Rules Restriction Module

This module monitors both the upstream water level and the outflow downstream of the dam. The task of this module is to ensure that the maximum water level upstream of the dam is not exceeding the maximum limit during any time step and, also, to avoid increasing of the outflow discharge downstream of the dam higher than the safe limits if possible. Lake Nasser operation policies were determined by the Ministry of Water Resources and Irrigation (MWRI) according to different restrictions to ensure dam safety and suitable water management. These restrictions can be summarized as follows:

1. Maximum water level upstream of the Aswan High Dam should not exceed 182.00 m at any time.
2. The released discharge downstream of the dam should not exceed the safe discharges to avoid damage to the riverbed, riverbanks, and hydraulic structures.
3. The water level at the beginning of the water year (August 1st) should be kept, if possible, at 175 m to account for coming floods. Any water more than this discharge program is evenly distributed in the months with the lower water requirements in such a way that the peak monthly discharges during the peak summer months remain unchanged. The months with the lowest requirements receive a higher volume of the excess water so that all months in which any additional water is spilled have the same total discharge.
4. Daily and monthly water released should be compatible with water requirements. The monthly discharges from the AHD follow a fixed pattern of releases.
5. The simulation model uses the sliding scale for reduction which the Ministry of Water Resources and Irrigation (MWRI) suggested for coping with a series of low floods. The reductions in withdrawals should come into being if the reservoir content in the live storage zone was less than 60 BCM on July 31. It is worth noting that if there are successive high floods and the water level in the lake exceeds 178 m, the excess water is diverted to a free spillway and then to Toshka depressions. In more emergency cases, when the flood capacity exceeds the Toshka spillway capacity, the West Bank spillway operates to ensure that the upstream reservoir elevation does not exceed 183 m. When the level is not higher than 182 m, the water will be stored in the Toshka depression with a maximum discharge of 250 million m^3/day.

Simulation Submodule

The Aswan High Dam Reservoir simulation model has been conceptualized and should perform the following operations:

1. Prepare the input data, which should include the inflow, initial storage, evaporation, and water demands, besides the operation rules of the reservoir. The initial storage of the reservoir for the first month of the operation period was assumed. The inflow at Dongola is discounted by the losses and abstractions from Sudan and El-Sheikh Zayed Canal on a monthly basis.
2. The demand will be calculated with on a monthly basis based upon the monthly irrigation water requirements and should be neither more than the maximum nor less than the minimum permissible flow of the river.
3. The difference between the inflow and the demand will be calculated in order to obtain the new stored volume (with reference to the volume of the previous month), on a monthly basis.

4. Based on this new stored volume, the new surface area of the lake and the new water elevation upstream of the dam will be calculated (monthly average), based on the available historical series of data and/or formulas presently used by the Nile Sector. The resulting storage should be within the operation rules range and be neither more than the design operation storage nor less than the minimum operation storage of the reservoir. If it exceeds the rule, then the computed storage and water level are readjusted through readjusting the release.
5. The calculation of evaporation losses and seepage losses will be operated based on the surface area and the water level (monthly average), based again on available historical data and/or formulas used by the Nile Sector. The calculation of flow to Toshka spillway and Aswan spill was calculated based on operation rules restrictions.
6. Calculate the outflow from the power generating outlets, (Qp), which should not exceed the capacity of the power outlets. The minimum operation level represents the minimum level for operating the power generators.
7. Repeat the respective steps for the following months.

The operation of a reservoir is described by the water balance equation under various constraints concerning storage volume, outflow from the reservoir, and water losses. The water balance equation applied on a monthly basis has the following form:

$$\frac{\mathrm{d}S(t)}{\mathrm{d}t} = \sum_{i=1}^{n_{\text{in}}} Q_{\text{in},i} - \sum_{j=1}^{n_{\text{out}}} Q_{\text{out},j} \tag{1}$$

$$S(t+\mathrm{d}t) = S_t + I_t - R_t - L_{\text{evp}} - L_{\text{seep}} - L_{\text{abs}} - Q_{\text{tosh}} - Q_{\text{emg}} - Q_{\text{southvalley}} \tag{2}$$

where $S_{(t+\mathrm{d}t)}$: storage at time $(t + \mathrm{d}t)$ (m^3), S_t: storage at time t (month) (m^3), I_t: mean inflow to the storage in month t (m^3), R_t: water discharged from the storage in month t downstream the dam (m^3), L_{evp}: mean evaporation from the storage reservoir in month t (m^3), L_{seep}: seepage losses from the storage reservoir in month t (m^3), L_{abs}: bank storage absorption losses (m^3), Q_{tosh}: water released from Toshka spillway in month t (m^3), Q_{emg}: water released from the emergency spillway in the dam in month t (m^3), $Q_{\text{southvalley}}$: the water demand for (South Valley) in month t (m^3)

Volume elevation (million m^3, m) empirical relation is given by:

$$H = 79.9734 + 0.0369801\ V + 8.87056\ \ln(V) \tag{3}$$

$$A = -3164.28 + 25.4914\ V + 1092.92\ \ln(V) \tag{4}$$

The constraint concerning storage volume V_t is:

$$V_{\text{min}} < V_t < V_{\text{max}}$$

where V_{min} = dead storage volume = 31.60 BCM corresponding to the minimum power pool level (147 m) and V_{max} = maximum storage volume = 162.30 BCM corresponding to the maximum power pool level (182 m).

The mean monthly outflow discharge Q_t during month t must satisfy the constraint:

$$Q_{\min} < Q_t < Q_{\max}$$

where $Q_{\min}$ = minimum releases = 3.2 BCM/year and $Q_{\max}$ = maximum releases = 7.5 BCM/year.

Output Module

Hydropower Module – The general equation which presents hydropower generation is a function of several factors such as discharge through the turbines, water head on turbines, the specific weight of water, and the turbine's efficiency. The general equation is:

$$P = \frac{\eta\gamma QH}{1000} \tag{5}$$

where P = generated electric power output in (Kw), Q = water flow through the turbine (discharge) in m^3/s, H = net head of water in m (the difference in water level between upstream and turbine downstream), η = station (turbine and generator) efficiency factor, and γ = specific weight of water (9,810 N/m^3).

Toshka and Aswan Outflow Computation Module – The Toshka spillway (260 km upstream HAD) is in the Western Desert, at the end of Toshka Khor with a width of 700 m and a crest level of 178 m constructed 1998–1999. The spillway is an ungated canal without a regulator. Excavation works started in 1978 and completed in 1982. It was constructed to release the excess water when water level reaches 178.00 m (MASL). The excess water is discharged to a natural depression located at the western side. This flow will help in limiting the outflow behind the dam to values ranging from 350 to 400 million m^3/day which are the discharge values that cause no harm to the Nile bed. The connecting canal from the spillway to the downstream depression area has an inlet width of 500 m and an outlet width of 275 m with a total length of 20.5 km. The outlet weir of the canal has a crest level of 176.00 m, and the canal slope is 14.6 cm/km.The lowest level of the depression is 150 m (MASL), while the highest level is 190 m (MASL).

This module is based on the computations of the proposed project outflow hydrograph. The following equation for Toshka demands is used:

$$Q = 19(H - 178)^{5/3} \times 30.4/1000 \text{ where } H > 178, \text{otherwise } 0 \tag{6}$$

where Q = Toshka spill (BCM/month) and H = lake water level (m). Toshka spill cannot exceed 6 BCM/month. Aswan spill = max release if $H > 182.6$ m or $S > 162$ BCM.

Losses Computation Module – The major Lake Nasser losses are evaporation and seepage losses. They are both incorporated in the model by this module. The Ministry of Water Resources and Irrigation in Egypt (MWRI) for many years adopted the figure of 7.5 mm/day as the annual mean evaporation which corresponds to an evaporation rate of 2.70 m/year [18]. A later review of previous literature data established a large range for evaporation from AHDR between 1.7 and 2.9 m/year. Based on water balance, energy budget, and modeling techniques, a narrower range of 2.1–2.6 m/year, with an average of 2.35 m/year, was calculated by [19]. In a 2002 technical report, based on the available data at the Nile Forecasting Center in Cairo, it was estimated that the annual evaporation from the AHDR varied between 12 and 12.6 BCM/year which corresponds to an evaporation rate of 2.0–2.1 m/year. In this simulation analysis, evaporation is calculated monthly as a function of the surface area of the AHDR by the following equation:

$$\text{Evaporation loss } L_{\text{evp}}\left(\text{m}^3\right) = ((A_t + A_t + 1)/2) \times C_t \times 1000 \tag{7}$$

where A_t = reservoir area at the beginning of month t (km^2), $A_t + 1$ = reservoir area as at the end of month t (km^2), and C_t = evaporation coefficient pertaining to month t (mm).

For the seepage losses, the empirical regression functions for seepage losses and water levels used for this part are as follows:

$$\text{Monthly seepage } S = 0.038\ (H - 110) \tag{8}$$

where S = the flow in BCM/month to the groundwater in Lake Nasser and H = the storage level in meters.

Outflow Hydrograph Generation Module – The proposed outflow hydrograph downstream the Aswan High Dam is computed using this module. The module computations are based on the water requirements for different months, the restrictions of the maximum allowable outflow downstream of the dam, and the maximum allowed water levels upstream of the dam. So the basic outflow hydrograph is composed of the historical data and water demand and water discharges and levels restrictions. Over the 30 years of simulation, releases, reservoir elevations, power generation, and spills are tabulated on both a monthly and annual basis.

3.3 Data Preparation

The evaporation rate in AHD Lake is about 2,970 mm/year, which amounts to nearly 10 BCM or 12% of the total annual discharge of the Nile at Aswan. Conversely, evaporation rates in Ethiopia are much lower at 1,520 mm/year [20]. Data used in filling (2014–2019) is the sequence of selected average flow (1973–1978). For operation phase, the flow data is the monthly time series average from 1961 to 2002. The AHD “has an official minimum operation level needed in Lake Nasser of 147 m and a maximum operation level of 182m. However, some studies say that the minimum water level in the reservoir needed for power generation is 165 m” [16, 21].

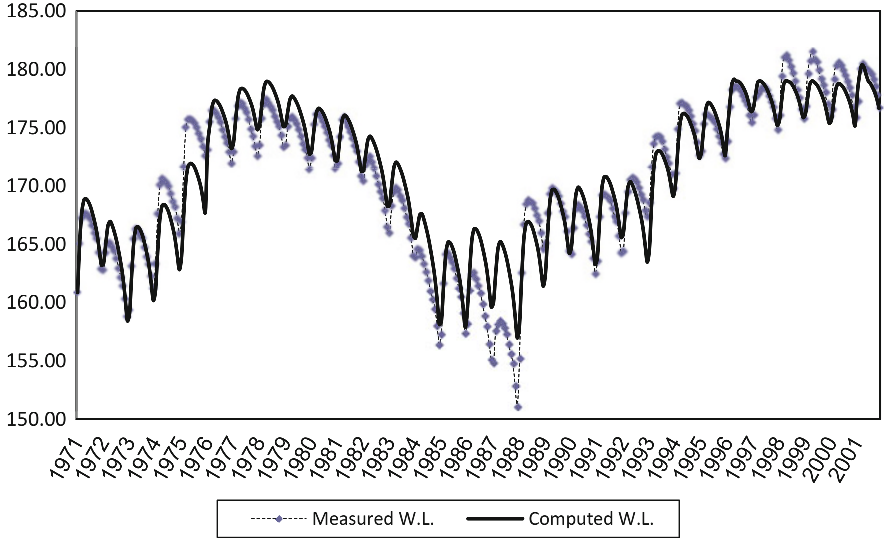

Fig. 2 The calibration results for years from 1971–2001

3.4 Model Calibration

The developed model was calibrated using actual measurements. The calibration was performed in the study done by Donia [10]. Research results concluded that calibration process for water levels upstream HAD given close relationships between the model computed results and the actual readings. For different years the maximum difference between computed and measured water levels did not exceed 0.40 m as shown in Fig. 2.

3.5 Scenario Analysis

Many scenarios have been conducted using the pre-calibrated model by first changing the filling scenarios by changing the storage capacity of the GERD beginning with the designed 74 milliards capacity and with decreasing 50% of the designed capacity and to 75% of the designed capacity referring to the first design of GERD in 2011. Other scenarios have been conducted by changing the filling period from 6 years to 10 years and finally to 20 years filling period. Another scenario simulated the operation of the AHD without the GERD and compared to the operation of the dam after operation of the GERD. The scenarios considered starting elevation of Lake Nasser at the AHD of 178 m which reflect the optimistic assumptions of the lake level at the start of the GERD filling.

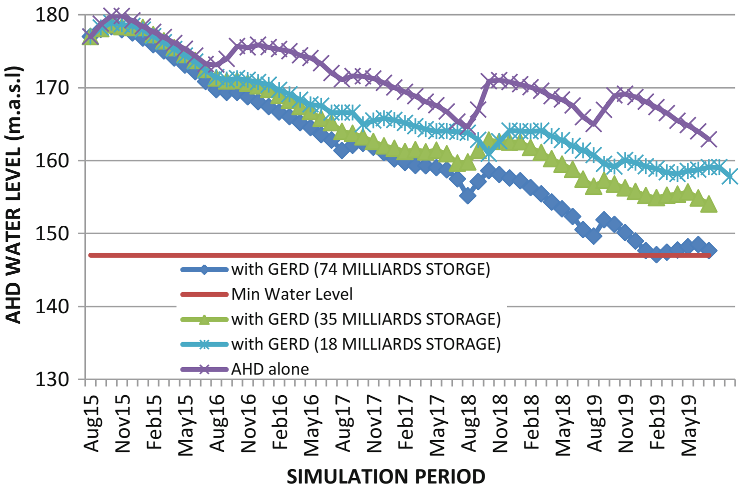

Fig. 3 AHD water level variation with different GERD storage

4 Results and Discussion

4.1 Change in GERD Filling Storage Capacity

Figures 3, 4, 5, and 6 show the scenarios of changing the filling storage of GERD and its influence on AHD compared to the operation of AHD alone.

4.1.1 AHD Water Level

It is evident from Fig. 3 that the water level in AHD reservoir decreases to the minimum level 147 in case of the full storage capacity of GERD (74 BCM). If 50% of storage capacity decreases, the minimum water level will be 154 m, while with a storage capacity of 75%, the water level will be 157 m compared with AHD alone 162 m.

4.1.2 AHD Water Storage

It is obvious from Fig. 4 that the reservoir will be empty, and the life storage will decrease to 33 BCM by 2019 in case of the full storage capacity of GERD (74 BCM). If 50% of storage capacity decreases to 35 BCM, the minimum water storage will be 46 BCM and with 75% of storage capacity decreases to 50 BCM compared to 67 BCM in case of AHD alone.

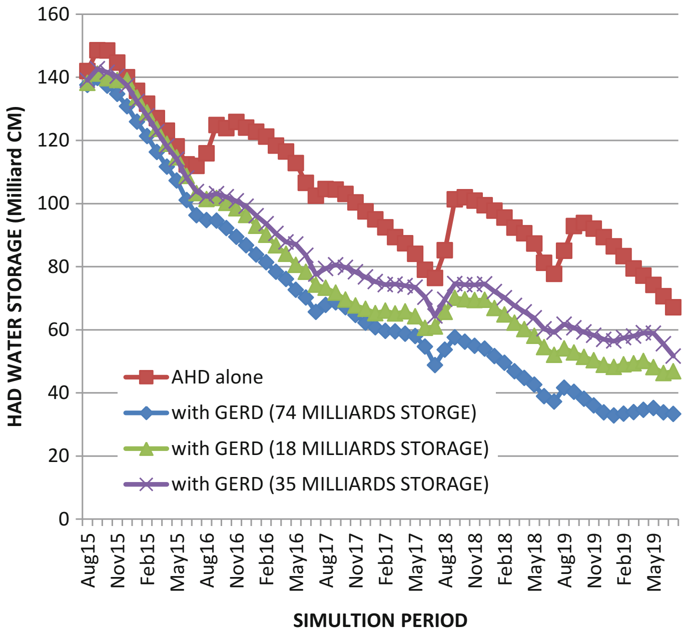

Fig. 4 AHD water storage with different GERD storage

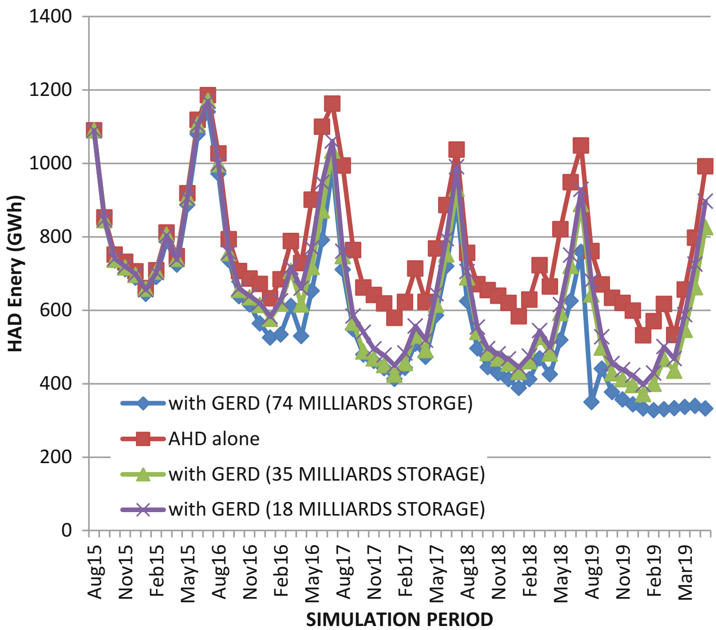

Fig. 5 AHD energy generation with different GERD storage

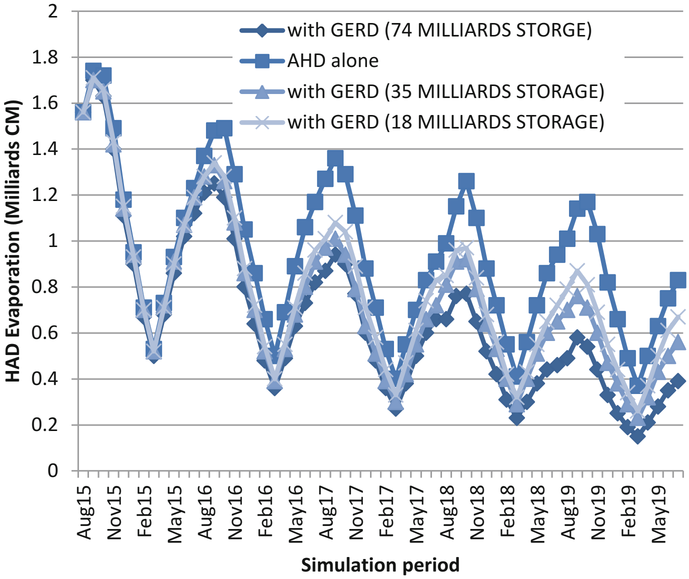

Fig. 6 AHD evaporation with different GERD storage

4.1.3 The Hydropower Generation

It is evident from Fig. 5 that the reservoir energy generation will decrease by 2019 in case of the full storage capacity of GERD (74 BCM). If 50% of storage capacity decreases to 35 milliards cubic meters, the minimum water storage will be 46 BCM and with 75% decreases to 50 BCM. The maximum decrease of energy generation will be 24% in case of the full storage capacity of GERD (74 BCM) compared to the energy generated in case of High Aswan Dam alone as shown in Table 2. If we take the findings of Abdel-Salam et al. [22] that turbines will stop operation below water level 160 m, therefore, by the third year of filling, the hydropower generation will cease.

4.1.4 The Evaporation Loss

The AHD evaporation loss will be minimum in case of the full storage capacity of GERD (74 BCM) with a decrease of 31.9% in average compared to the other two scenarios as shown in Table 3 and Fig. 6. This is due to the decrease in Lake Nasser surface area.

Table 2 Difference (%) of AHD generated energy case AHD alone and in case of different GERD storage capacity filling scenarios

Year	AHD alone	GERD 74 BCM storage		GERD 35 BCM storage		GERD 18 BCM storage	
	AHD energy (GWh)	AHD energy (GWh)	Diff (%)	AHD energy (GWh)	Diff (%)	AHD energy (GWh)	Diff (%)
2015	10,281.09	10,022.54	−2.51	10,178.43	−1.00	10,172.62	−1.06
2016	9,880.61	8,158.06	−17.43	8,797.11	−10.97	9,037.19	−8.54
2017	8,909.91	6,675.21	−25.08	6,920.12	−22.33	7,295.79	−18.12
2018	8,758.05	6,002.74	−31.46	6,740.30	−23.04	6,958.90	−20.54
2019	7,979.84	4,198.05	−47.39	6,084.83	−23.75	6,527.10	−18.21
Mean	9,161.9	7,011.32	24.7763	7,744.158	16.2166	7,998.32	−13.291

Table 3 Difference (%) of AHD evaporation in case AHD alone and in case of different GERD storage capacity filling scenarios

Year	AHD alone	GERD 74 BCM storage		GERD 35 BCM storage		GERD 18 BCM storage	
		Evaporation (BCM)	Diff (%)	Evaporation (BCM)	Diff (%)	Evaporation (BCM)	Diff (%)
2015	13.87	13.15	−5.19	13.52	−2.52	13.53	−2.45
2016	12.51	9.61	−23.18	10.34	−17.35	9.66	−22.78
2017	10.54	7.33	−30.46	7.89	−25.14	8.73	−17.17
2018	10.14	5.90	−41.81	7.45	−26.53	7.95	−21.60
2019	9.40	4.20	−55.32	5.95	−36.70	6.90	−26.60
Mean	11.29	8.04	−31.19	9.03	−21.65	9.35	−18.12

4.1.5 The Water Withdrawal

The water withdrawal for agriculture will be affected; it will decrease in case of the full storage capacity of GERD (74 BCM) compared to the other two scenarios and with AHD alone. The maximum decrease in water release will be 10.5% in case of the full storage capacity of GERD as shown in Table 4.

4.2 Change in GERD Filling Period

Figures 7, 8, 9, and 10 show the scenarios of changing filling period of GERD and its influence on AHD compared to the operation of AHD alone.

Table 4 Difference (%) of AHD release in case AHD alone and in case of different GERD storage capacity filling scenarios

Year	AHD alone	GERD 74 BCM Storage Release	Diff (%)	GERD 35 BCM Storage Release	Diff (%)	GERD 18 BCM Storage Release	Diff (%)
2015	55.80	55.80	0.00	55.80	0.00	55.80	0.00
2016	55.80	52.30	−6.27	54.45	−2.42	55.22	−1.04
2017	54.70	48.46	−11.41	48.46	−11.41	48.65	−11.06
2018	54.37	48.46	−10.87	48.46	−10.87	48.46	−10.87
2019	51.56	39.17	−24.03	48.46	−6.01	48.46	−6.01
Mean	54.446	48.838	−10.52	51.126	−6.14	51.318	−5.80

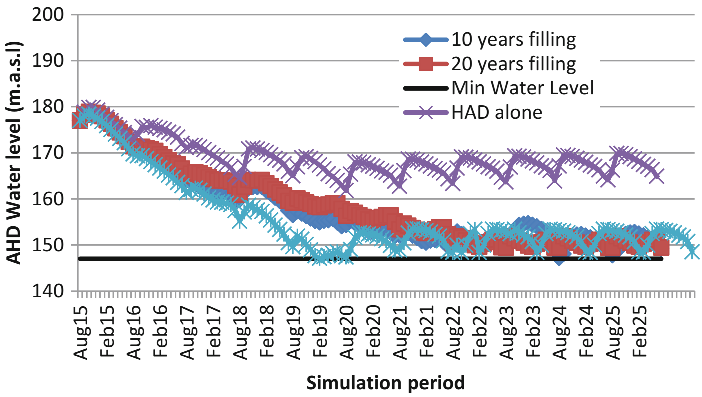

Fig. 7 AHD water level variation due to change in GERD filling periods

4.2.1 AHD Water Level

It is evident from Fig. 7 that the water level in AHD reservoir decreases to the minimum level 147 by the year 2019 in case of 5 years filling period. The minimum water level will be reached by the end of 10 years filling period and by the end of 20 years filling period with the same storage capacity of GERD (74 BCM).

4.2.2 AHD Water Storage

It is evident from Fig. 8 that the reservoir will be empty, and the life storage will decrease to 33 BCM by 2019 in case of 5 years filling period. In case of 10 years filling period, the storage capacity decreases to 35 BCM; the minimum water storage will be 37 BCM by the end of 20 years filling period compared to 67 BCM in case of AHD alone.

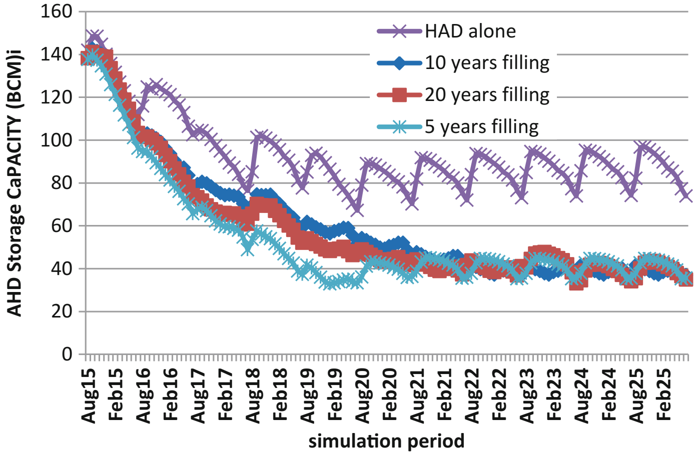

Fig. 8 AHD water storage variation due to change in GERD filling periods

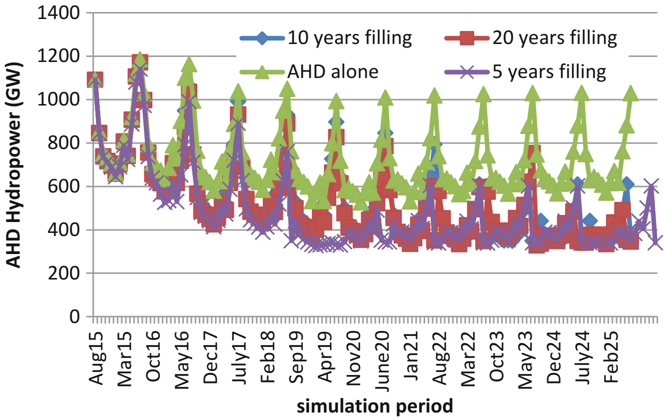

Fig. 9 AHD hydropower variation due to change in GERD filling periods

4.2.3 The Hydropower Generation

From Fig. 9, the AHD energy generation will decrease to a minimum of 330 GWh by 2019 in case of 5 years filling period. In case of 10 years filling period, AHD energy generation decreases to 345 GWh; the minimum water storage will be 348 GWh by the end of 20 years filling period compared to 1,028 BCM in case of AHD alone.

4.2.4 Evaporation

It is evident from Fig. 10 that the AHD evaporation will decrease in case of 5 years filling period compared to 10 years filling period and 20 years filling period. The

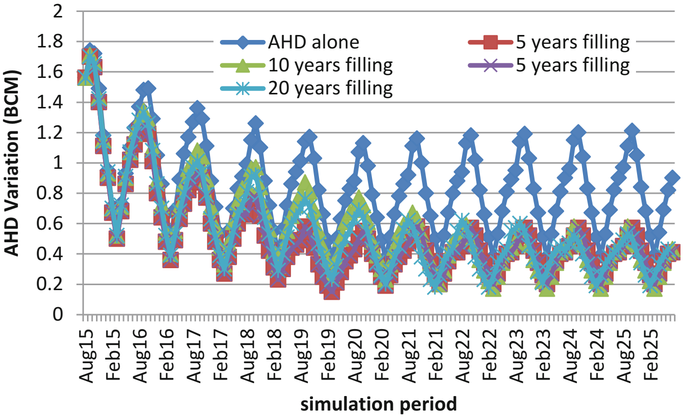

Fig. 10 AHD evaporation variation due to change in GERD filling periods

evaporation is maximum in case of AHD alone due to the increase of reservoir surface area.

5 Impacts on Agriculture

Egypt is an agriculture-based country. The agricultural sector has over centuries been responsible for providing food as well as employing the majority of the population. However, the agricultural sector is currently facing many challenges, on top of which is water scarcity. Agriculture alone uses about 80% of the freshwater from the Nile; the agricultural sector plays a significant role in the Egyptian economy. It is contributing 11.3% of total GDP [23]. The agricultural land covers about 4% – about 9 million feddan out of total area of Egypt which equals 245 million feddan. The cropping area per year is about 15 million feddan; about 7 million feddan are cultivated in the winter, and 6 million feddan in the summer and nili seasons, and about 2 million feddan are permanent trees [24, 25].

6 Discussions

Table 5 shows the impact of water shortage on income loss for each crop based upon the water return value calculated from Capmas [26] taking into consideration the percentage of water shortage resulting from the simulation (see Table 4) in case of different water storage capacity and different filling periods.

Table 5 Loss in return value of most important crops in Egypt as a result of water shortage due to different filling scenarios of GERD

Crops type	Cultivated area in feddan	Water requirement	Net return per unit of water	The loss in return value (5 years filling)	Loss in return value (10 years filling)	Loss in return value (20 years filling)
		m^3/feddan	L.E/ 1,000 m^3	Million L.E	Million L.E	Million L.E
Wheat	3,475,669	1,760	1,766	1,620.44	648.18	183.65
Broad bean	87,581	1,318	1,548	26.80	10.72	3.037
One-cut clover	228,061	1,104	2,638	99.62	39.85	11.29
Perennial clover	1,297,898	2,917	2,122	1,205.07	482.03	136.5
Sugar beet	554,941	2,204	1,491	273.54	109.42	31.1
Onion	202,558	1,908	3,417	198.09	79.24	22.45
Garlic	29,961	3,243	3,675	53.56	21.42	6.07
Winter tomatoes	187,135	2,099	4,438	261.48	104.59	29.63
Cotton	240,866	2,985	662	71.39	28.56	8.09
Summer rice	1,215,830	6,294	432	495.87	198.35	56.19
Summer maize	1,743,783	3,179	607	504.73	201.89	57.20
Summer sorghum	354,720	3,209	442	75.46	30.19	8.55
Soybean	33,896	3,172	320	5.16	2.06	0.58
Sesame	84,310	2,813	594	21.13	8.45	2.39
Peanut	143,022	4,143	1,091	96.96	38.79	10.98
Summer potatoes	128,939	3,091	2,010	120.16	48.07	13.61
Summer tomatoes	242,103	3,091	3,106	348.65	139.46	39.51
Nili mai	193,333	2,599	573	43.187	17.28	4.89
Nili potatoes	36,873	2,334	766	9.88	3.96	1.12
Nili tomatoes	39,272	2,334	453	6.22	2.49	0.71
Sugarcane	328,116	9,573	600	282.69	113.08	32.04
Total average			32,751	5,820.17	648.18	659.62

The loss in return value of each crop is calculated based upon the following equation:

$$\begin{aligned}\text{The loss return value} = {} & \text{the cultivated area in feddan} \times \text{water requirements} \\ & \times \text{net return value per water} \\ & \times \text{percent reduction of water quantity for each scenario}\end{aligned}$$

From Table 5 and Fig. 11, it is shown that there is a loss in crop return value about (18%) in 5 years filling especially in wheat crop. The loss in return value decreases if the filling period increases to 10 years to (7%) and decreases to (2%) if the filling period increases to 20 years. It is shown that there is a loss in crop return value about (15%) in 5 years filling especially in all crops. The loss in return value decreases if the filling period increases to 10 years to (6%) and decreases to (1.7%) if the filling period increases to 20 years.

From Table 6 and Fig. 12, it is clear that there is a loss in crop return value about (7%) if the total GERD capacity is 35 BCM. While the loss in return value decreases to 4% if GERD capacity is 18 BCM. It is also shown that there is a loss in crop return value about (6%) if GERD capacity is 35 BCM, especially in wheat crop, while the loss in return value decreases to 3.8% if GERD capacity 18 BCM.

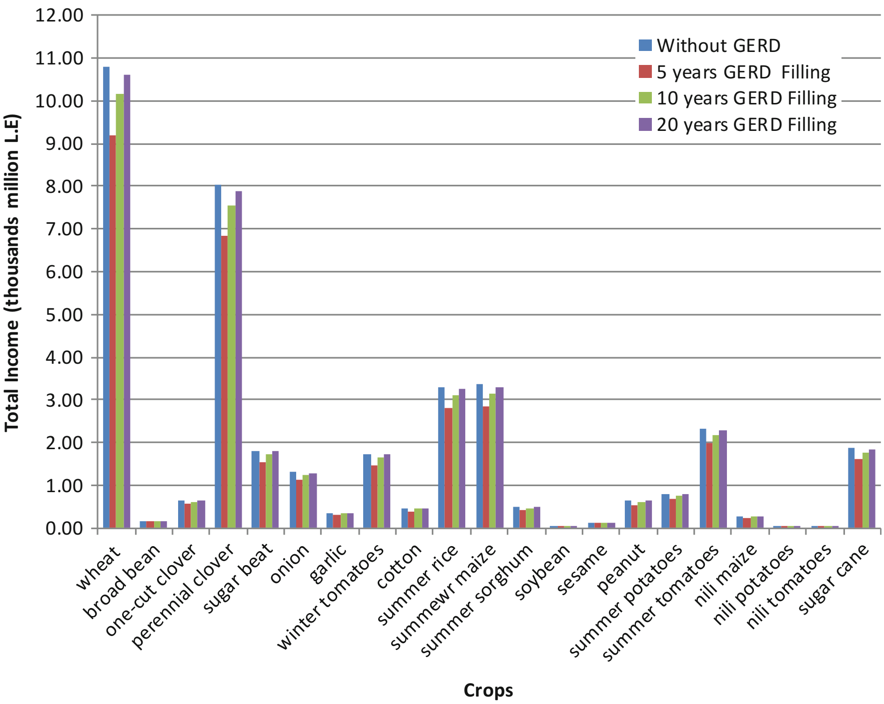

Fig. 11 Total income in billion EGP for different important crops in Egypt without GERD and with three filling scenarios of 5, 10 and 20 years

Table 6 Loss in return value of most important crops in Egypt as a result of water shortage due to different storage capacity of GERD

Crops type	Cultivated area in feddan	Water requirement	Net return per unit of water	The loss in return value (GERD 74 BCM)	Loss in return value (GERD 35 BCM)	Loss in return value (GERD 18 BCM)
		m^3/feddan	L.E/ 1,000 m^3	Million L.E	Million L.E	Million L.E
Wheat	3,475,669	1,760	1,766	1,620.44	540.15	410.51
Broad bean	87,581	1,318	1,548	26.80	8.93	6.79
One-cut clover	228,061	1,104	2,638	99.62	33.21	25.23
Perennial clover	1,297,898	2,917	2,122	1,205.07	401.69	305.28
Sugar beet	554,941	2,204	1,491	273.54	91.18	69.29
Onion	202,558	1,908	3,417	198.09	66.03	50.18
Garlic	29,961	3,243	3,675	53.56	17.85	13.56
Winter tomatoes	187,135	2,099	4,438	261.48	87.16	66.24
Cotton	240,866	2,985	662	71.39	23.80	18.08
Summer rice	1,215,830	6,294	432	495.87	165.29	125.62
Summer maize	1,743,783	3,179	607	504.73	168.24	127.86
Summer sorghum	354,720	3,209	442	75.46	25.16	19.11
Soybean	33,896	3,172	320	5.16	1.72	1.30
Sesame	84,310	2,813	594	21.13	7.04	5.35
Peanut	143,022	4,143	1,091	96.96	32.32	24.56
Summer potatoes	128,939	3,091	2,010	120.16	40.05	30.44
Summer tomatoes	242,103	3,091	3,106	348.65	116.22	88.32
Nili mai	193,333	2,599	573	43.187	14.40	10.94
Nili potatoes	36,873	2,334	766	9.88	3.30	2.5
Nili tomatoes	39,272	2,334	453	6.22	2.08	1.57
Sugarcane	328,116	9,573	600	282.69	94.23	71.61
Total average			32,751	5,820.17	540.15	1,474.45

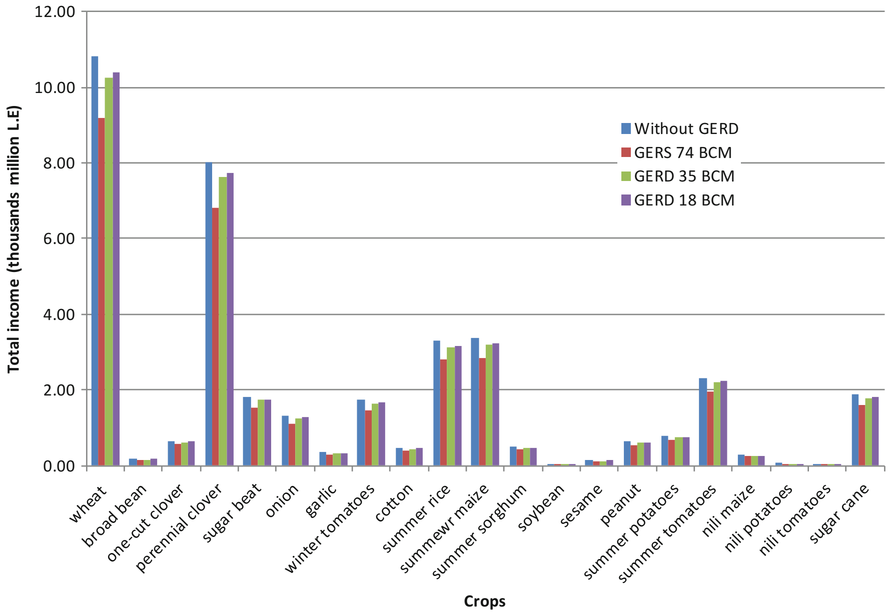

Fig. 12 Total income in billion EGP for different important crops in Egypt without GERD and with three storage capacity scenarios of GERD of 18 BCM, 35 BCM and 74 BCM

Figures 11 and 12 and Tables 5 and 6 can help the decision takers to plan and decide the proper strategy to stop planting certain crops to reduce the amount of loss in the strategic crops based on the availability of water.

7 Conclusions

Many storage capacity scenarios of GERD have been conducted to assess its effect on AHD. The first type of scenario is assumed to change the storage capacity of GERD to 18 BCM (the initial design storage capacity), to double this capacity (i.e., 35 BCM), and finally with the existing storage capacity (i.e., 74 BCM). Scenario results indicated that, if the filling period of GERD with 74 BCM is 5 years, the AHD reservoir will empty and will reach its minimum water level. Consequently, the turbines will stop generating hydropower.

The impact of resulting water shortage on agriculture due to GERD is also computed and tabulated for both filling scenarios and GERD storage capacity scenarios. The greatest loss of crop return value exists in case of 5 years filling period and full storage capacity of GERD as presented in Table 5 (Fig. 11) and Table 6 (Fig. 12).

8 Recommendation

The developed AHD management model was used successfully in assessing the impact of GERD on AHD operation. The results proved that there is a significant impact on water availability in Egypt especially if the filling period is 5 years with the actual storage of the GERD reservoir. It is recommended from the model results to increase the filling period to a minimum of 10 years of actual storage or reduce the storage capacity to its primary designed one of 14–18 BCM.

Meanwhile, the authors encourage the concerning authorities in Egypt to look forward for other sources of water to help in compensating the expected decrease in water availability. Some opportunities include looking for implementing another water harvesting project with Nile basin countries, reuse of wastewater, and water desalination from its long shores on Red Sea and Mediterranean Sea. Water conservation strategies must also be incorporated especially in agriculture sectors as changing crop pattern or introducing new irrigation methods like drip irrigation. The developed AHD model can help in scenario analysis of different water management and conservation to help decision-makers to weight scenario outcomes and choose the optimum scenario and best strategy to ensure safe water availability in Egypt.

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Ecohydrogeological Challenges on Ethiopian Water Projects and Their Impacts on Annual Water Share of Egypt: Case Study of Tekeze Dam

Abbas M. Sharaky

Abstract Ecohydrogeology provides detailed instructions among water (surface or groundwater), geology, environment, and biological processes to improve water security. Ecohydrogeological challenges are dominant in the territory of Ethiopia. According to the 1959 treaty with Sudan, the annual water share of Egypt is 55.5 km^3.

The main controlling factor on water resources in East Africa is the East African Rift that is the largest continental rift on Earth, resulting in crustal mobility between the Arabian and African plates. Ethiopia is characterized by rugged topography, a unique regime of the short intense rainy season, high evaporation, flooding, drought, dominant basaltic rocks, an abundance of geologic faults and fractures, active volcanic eruptions and earthquakes, severe erosion and land degradation, siltation, and lack of major groundwater aquifers.

The Nile basin countries suffer from lack of electrical energy. By the end of the last twentieth century and the beginning of the new twenty-first century, the demand for hydropower energy has been increased for development in the Nile basin countries especially Ethiopia, resulting in political tension between the upstream and downstream countries.

Egypt has almost completely relied on the Nile River water for irrigation since the pharaohs. The Egyptian government signed about 15 agreements with some Nile basin countries for utilization of the Nile water. The construction of water projects in the Nile basin region in Ethiopia has produced political tensions between Egypt and Ethiopia over the construction of Tekeze in 2009, the Tana-Beles diversion in 2010, and the under-construction Grand Ethiopian Renaissance Dam (GERD) that has started in April 2011.

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The present chapter deals with the geological characteristics of the Nile region in Ethiopia. It also discusses the environmental challenges in the region of Tekeze River (Atbara) in Ethiopia and its impacts on downstream countries Egypt and Sudan. Analysis of ASTER DEM of Tekeze River basin showed that it has a dendritic pattern. Tekeze reservoir area is 155 km^2 at 1,140 m asl with a volume of 9.3 km^3. Egypt and Sudan lost 4 km^3 in 2008 and 2009 due to dead storage in addition to an annual loss estimated at 200–700 Mm^3 from evaporation and irrigation.

Keywords Aswan High Dam, Blue Nile, Ecohydrogeology, Geological challenges, GERD, Tekeze River

Contents

1 Introduction

The Nile River is the longest river in the world, extending from south to north with a length of 6,670 km from Lake Victoria in the south to the Mediterranean Sea in the north, making it the longest river in the world [1]. It drains some 3.2 million km^2 and stretches from south to north over 35° of latitude through the most hyper-arid deserts on Earth.

The average annual discharge of the Nile between 1899 and 1959 was 84 km^3 at Aswan, Egypt, which constitutes 1% of the total amount of rainfall in the Nile basin countries and 5% of the rainfall in the basin itself. The average flow between 1869 and 1984 was 87.1 km^3/year [2]. The Nile basin includes the northwestern highlands of Ethiopia, which form one third of the country.

The present chapter deals with the geological characteristics of the Nile region in Ethiopia as the main source of the Nile, which mostly forms natural challenges in the construction of water projects in Ethiopia. It discusses the environmental and geological challenges in the region of Tekeze River (Atbara) in Ethiopia and its impacts on the catchment area and annual water share of the downstream countries Egypt and Sudan. It is built in a canyon surrounded by steep topography. Landslides and high rate of sedimentation are already problems for development projects. Analysis of ASTER DEM of Tekeze River basin was carried out to investigate the potential irrigable lands and the physical characteristics of the Tekeze reservoir.

1.1 Sources of the Nile

The Nile originates from two main sources, the Ethiopian Plateau (85%) and the equatorial region (15%). The Nile basin is shared by 11 countries with a population close to 500 million in mid-2017; more than 50% of them live in the Nile basin. They are from south to north: Rwanda, Burundi, the Democratic Republic of Congo, Tanzania, Kenya, Uganda, Eritrea, Ethiopia, South Sudan, Sudan, and Egypt (see Fig. 1). The Nile River basin countries are known regionally as (a) the Eastern Nile basin that includes Eritrea, Ethiopia, Sudan, and Egypt and (b) the Equatorial Nile Basin or Great Lakes Basin that includes South Sudan, Uganda, Rwanda, Burundi, the Democratic Republic of the Congo, Kenya, and Tanzania.

About 86% of the Nile flow measured at Aswan, Egypt (or 72 km^3/year), originates in Ethiopia. Although the Blue Nile basin comprises only about 8% of the total Nile catchment area [4], it contributes about 59% of the Nile water at Aswan, Egypt. The Baro-Akobo-Sobat basin contributes 14%, while the Tekeze/ Atbara basin provides 13%. The remaining 14% comes from the equatorial lakes after losses of evaporation in the Sudd region and Machar Marshes [5].

The Nile basin of Ethiopia covers a total of about 358,889 km^2 (34% of the country). About 40% of the population of Ethiopia lives in this basin [6].

1.2 People in Ethiopia

Ethiopia is an ancient country with many ethnic groups that differ in cultures, religions, and traditions for more than 3,000 years. Ethiopia emerged from civil wars and the independence of Eritrea in 1993 as one of the ten poorest least developed and most impoverished countries in the world. The potentially irrigable

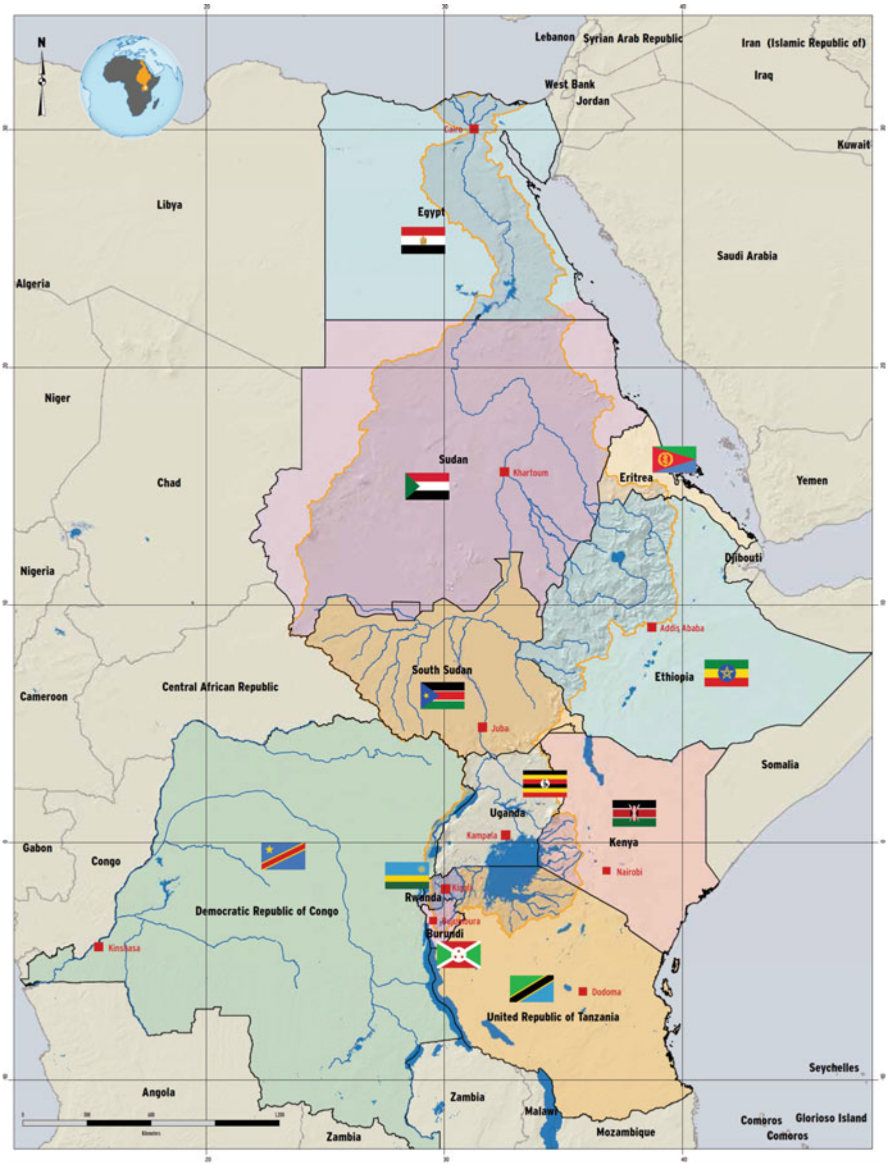

Fig. 1 The Nile River basin and its 11 countries [3]

land in Ethiopia is about 3.6 million hectares (9 million feddans), out of which only 5% has been developed [7]. The total population in Ethiopia has been increased from 77.1 in 2007 to 105 million in 2017 with a growth rate of 2.79% [8]. Ethiopia is the 2nd most populous country in Africa after Nigeria (190.9 million) and the 14th most populous country in the world [9].

The Ethiopian government tries to fight poverty through a series of clean water projects as the main electrical energy sources for development, which amounted to 478 MW in 2009, despite the considerable hydropower potential of about 30,000 MW [10]. The electrical energy has been increased to about 4,000 MW in 2016. The recent completed projects include Tekeze Dam in 2009 (300 MW) and Tana-Beles project in 2010 (460 GW) in the Nile basin. In Omo River basin, Gibe II was inaugurated in 2010 and Gibe III in 2016, producing 420 and 1,870 MW, respectively. The Grand Ethiopian Renaissance Dam (GERD) is under-construction to produce 6,450 MW.

The Ethiopian government turned to the Ethiopian people, so it established the constitution that recognized the right of self-determination to the independence of the peoples and nationalities of Ethiopia and divided the country into autonomous ethnic states. It has a master plan for development through establishing several water projects to generate electricity including the Tekeze Dam on Atbara River and the ongoing project of Renaissance Dam on the Blue Nile.

1.3 Water Resources in Ethiopia

Ethiopia is the main water tower in East Africa, where water flows in all directions to the five neighboring countries: Sudan, South Sudan, Kenya, Somalia, Djibouti, and Eretria. It is endowed with a substantial amount of water resources, with an average annual precipitation of 848 mm/year and an annual total of 936 km^3 [11], while Egypt is ranked last in Africa regarding average annual rainfall 51 mm/year [12].

The internal renewable water resources in Ethiopia comprise 122 km^3/year in 12 basins (see Fig. 2), 9 of which are transboundary and 3 are located in the Eastern Nile basin (the Blue Nile or Abay, Atbara or Tekeze, and Sobat or Baro-Akobo). About 75% of the total water resources drain to neighboring countries [7], and no perennial flows cross into the Ethiopian lands [14]. More than 80% of the Ethiopian surface water resources are generated by four river basins in the western part of the country. They are Blue Nile (Abay), Sobat (Baro-Akobo-Pibor), Atbara (Tekeze), and Omo rivers, covering about 40% of the Ethiopian landmass.

1.4 Groundwater Resources in Ethiopia

Civilization in Ethiopia has been developed in areas where groundwater has been available mainly as springs. The occurrence of groundwater in Ethiopia is not uniform because it depends on various environmental and geological factors. The groundwater reserve is estimated at 185 km^3 distributed unevenly in areas of 924,140 km^2 made of sedimentary, volcanic, and Quaternary rocks and sediments [15]. There are four major categories of groundwater aquifers related to geological

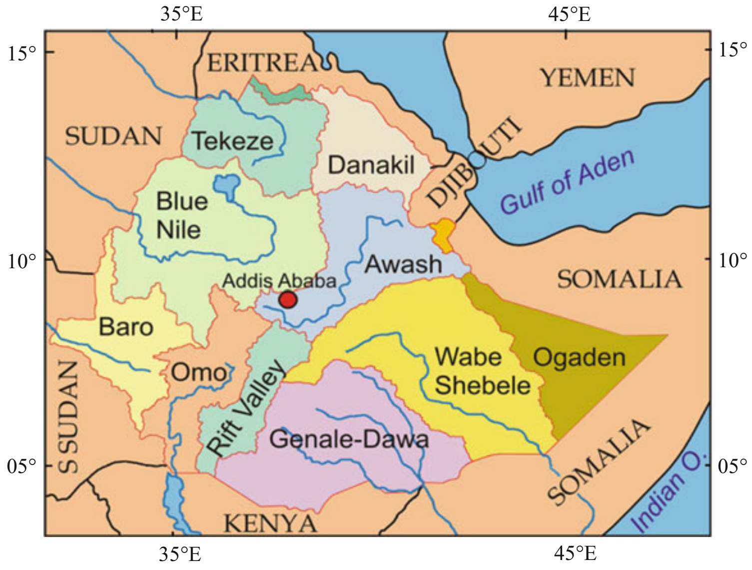

Fig. 2 The main 12 river basins in Ethiopia [13]

processes [16]. They are loose sediments and volcanic, sedimentary, and metamorphic rocks. The Ethiopian aquifers are complex and relatively low storage aquifers [17]. Ethiopia is mainly covered by volcanic rocks in addition to sedimentary and metamorphic rocks. They are highly fractured due to the active East African Rift. Annual renewable groundwater was estimated at 2.6 km^3, which needs to be revised. It may reach to 30 km^3 if all aquifers are well assessed [18].

2 Geological and Environmental Challenges

Geological, geomorphological, and environmental hazards are the most dominant natural obstacles in the territory of Ethiopia. The main controlling factor is the largest continental rift on Earth that causes crustal mobility between the Arabian and African plates. Ethiopia is characterized by rugged topography, the unique regime of the short intense rainy season, high evaporation, flooding, drought, dominant basaltic rocks, an abundance of geologic faults and fractures, active volcanic eruptions and earthquakes, severe erosion and land degradation, siltation, and lack of major groundwater aquifers. Therefore, all of these processes and more induce different levels of risk to the recent development projects of the country. They include roads, dams, reservoirs, and agricultural schemes, which may sustain partial failure during construction or after inauguration. The Gibe II water tunnel project was collapsed on Omo River after 10 days of inauguration in January 2010.

The Nile River has been formed since 30 million years ago in the mid-Tertiary. The connection of the different Niles (Ethiopian and equatorial) occurred during the cyclic wet periods. It is believed that the Nile flow from Ethiopia through Sudan to Egypt and the Mediterranean was in Lower Quaternary age [19].

The Nile River flows through five major geologic regions from south to north:

1. The great Lake Plateau or the equatorial region
2. The Sudd area in the South Sudan Republic
3. The Ethiopian Highlands
4. The Cataract tract from Khartoum to Aswan
5. The Egyptian deserts from Aswan to the Mediterranean through the Nile Valley and Delta

In the recent decade, the Ethiopian government implemented some development projects including small-scale irrigation projects.

2.1 Climate of Ethiopia

The Ethiopian climate is mainly controlled by the seasonal migration of the Intertropical Convergence Zone (ITCZ) and the complex terrain. It ranges from arid and semiarid in the northeastern and southeastern lowlands, tropical in the south and southwest, to cool highlands in the north and northwest. The highlands are generally above 2,400 m in elevation, where the average daily highs range from near freezing to 16°C, with March, April, and May the warmest months. Lower areas of the plateau, between 1,500 and 2,400 m in elevation, constitute the temperate zone. Daily highs in the lower areas range from 16 to 30°C. The mean minimum temperatures are low all across the highlands and high in the Danakil Depression that is one of the hottest areas on Earth [20].

The complex physiographic terrain in Ethiopia has created five climatic zones [21]:

1. The hot, arid zone covers the desert lowlands below 500 m, where the average annual rainfall is less than 400 mm and 28–34°C or higher.
2. The warm to hot, semiarid zone includes those areas with elevation ranging from 500 to 1,500 m, 600 mm average annual rainfall, and temperature range of 20–28°C.
3. The warm to cool, semi-humid zone includes the highlands between 1,500 and 2,500 m in elevation. Average annual temperatures vary between 16 and 20°C, and annual rainfall is about 1,200 mm in the southwest.
4. The cool to cold humid zone includes the highlands between 2,500 and 3,200 m, where average temperatures range between 10 and 16°C, with an annual rainfall of 1,000 mm and up to 2,000 mm in higher areas.
5. The cold, moist temperate zone covers the highest plateaus between 3,200 and 3,500 m; temperatures are below 10°C and annual rainfall averages less than 800 mm.

2.1.1 Rainfall in Ethiopia

The rainfall in Ethiopia is characterized by highly uneven distribution in both temporal and spatial distribution (see Figs. 3 and 4). Kiremt is the main monsoon-type rainy season, and belg is the small, spring time rainfall totals and rainy days over the largest part of Ethiopia [23]. Based on the data of 16 meteo-stations, spanning the 1950–2000, the rainfall varies with latitude. It increases toward the center west of Addis Ababa, where it is deeply affected by elevation of the high mountains.

The average annual rainfall is 848 mm although there is a great regional variance from 100 mm in the southeast to 2,400 mm in the southwestern highlands of the Oromia Region. The total volume of the annual rainfall is 936 km^3 [24]. The amount of rainfall gradually decreases to about 600 mm in the north in areas bordering Eritrea, and it drops to less than 100 mm in the northeast in the Afar Depression and to about 200 mm in the southeast in the Ogaden desert.

El Niño-Southern Oscillation (ENSO) can be one of the main causes of climate variability in Ethiopia as well as in East Africa.

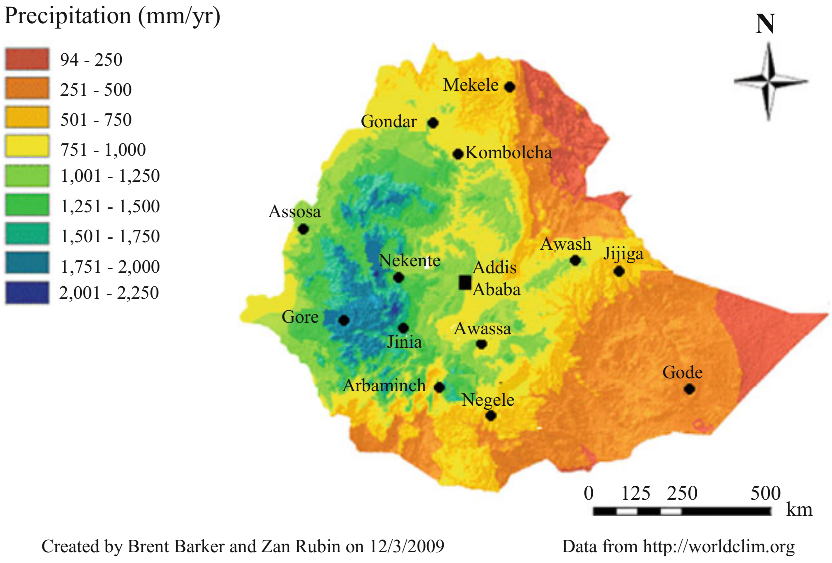

Fig. 3 Spatial variability of the mean annual rainfall in Ethiopia (from [22])

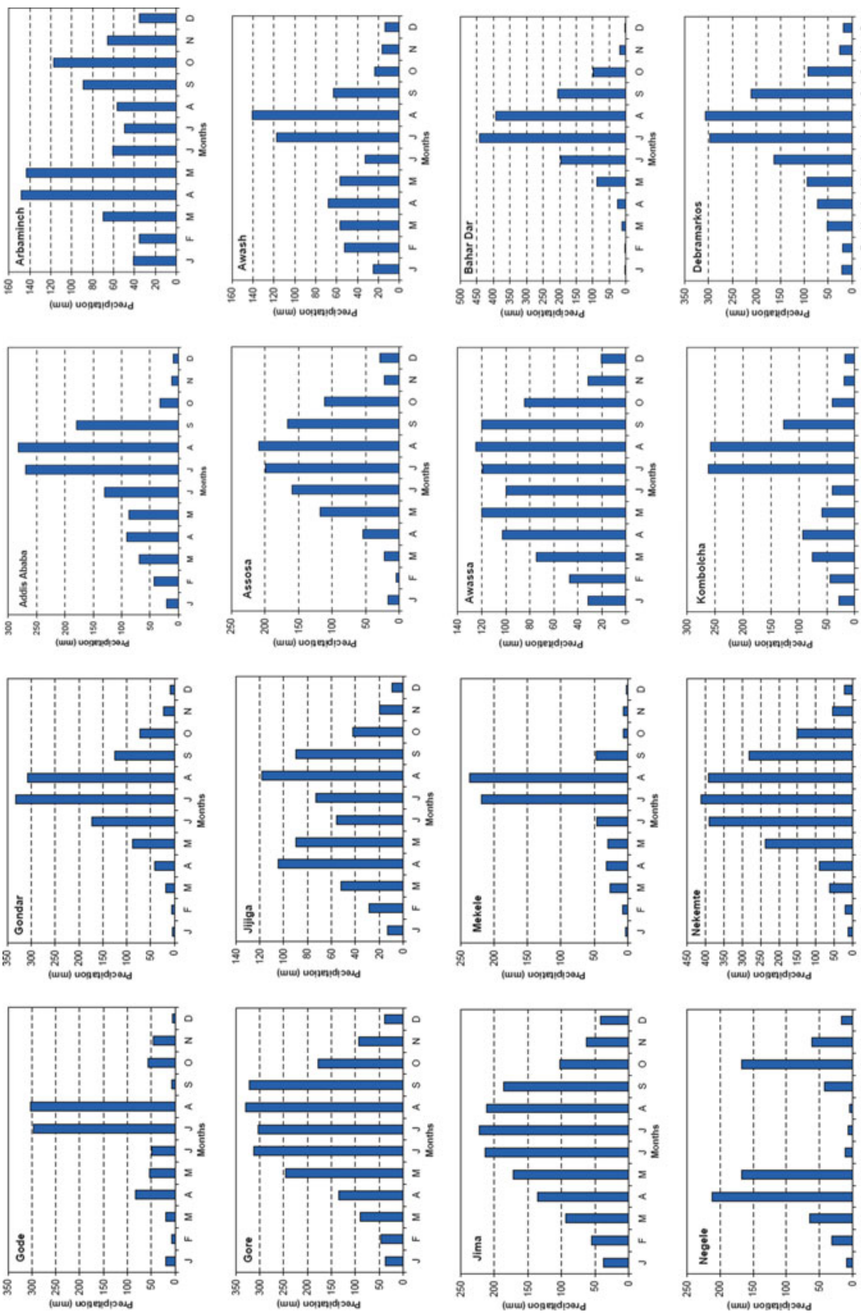

Fig. 4 Average monthly rainfall in 16 meteorological stations in Ethiopia (1950–2000) from the Global Historical Climate Network (GHCN) dataset and National Climatic Data Center and Ethiopia Meteorological Authority

Table 1 Annual rainfall and evaporation at various altitudes in the three main river basins in Ethiopia [26]

	Abay basin (Blue Nile)		Tekeze basin (Atbara)		Baro-Akobo basin (Sobat)	
Altitude (m amsl)	Rainfall	Evaporation	Rainfall	Evaporation	Rainfall	Evaporation
2,200	1,608	1,140	552	1,356	2,316	1,068
1,700	1,116	1,404	636	1,560	2,292	1,140
600–160	900	2,700	612	1,767	1,212	1,680

Ethiopia has four major rainfall regimes based on rainfall distribution pattern [21]:

1. Central, eastern, and northern areas of the country experience a bimodal rainfall pattern. The high rainfall starts from June to September.
2. Western and southwestern parts of the country experience a unimodal rainfall pattern from April to October.
3. Southern and southeastern parts of the country experience a bimodal rainfall pattern from September to November and from March to May. The most reliable rainy months are April and May.
4. Northeastern parts of the country comprise part of the western escarpment of the Pitt Valley and the adjacent Afar Depression. The lowlands have only one rainy season during which only a little rain falls. However, the escarpment, particularly in the north, can have a third rainy season brought by moist winds from Asia which have crossed the Arabian Peninsula and cool as they rise over the Ethiopian escarpment. These can bring mist and rain anytime between November and February.

The precipitation over the Blue Nile basin varies from 1,000 mm in the northeastern part to 1,450–2,100 mm over the southwestern part of the basin [3] with an average of 1,608 mm/year. Rainfall exceeds 2,000 mm in parts of the Didessa and Beles catchments [25].

In Tekeze-Atbara basin, the rainfall shows narrow unimodal that is dominated in August and September with mean annual rainfall of 600 mm. The average annual precipitation in Tekeze is the lowest among the other Nile subbasins (see Table 1).

The total precipitation in Baro-Akobo (Sobat) basin in Ethiopia is about 291 billion m^3 in 2006, with an average of 1,212 mm/year [26]. Rainfall in the meteorological stations Gore and Jima (see Fig. 4) show wide unimodal distributed in which the maximum precipitation occurs from May to September.

The rainfall in the three basins shows unimodal pattern of one rainy season with significant rainfall from June to September and maximum concentration in August and September (see Fig. 4).

2.1.2 Evaporation in Ethiopia

Like most of the African continent, the evaporation in Ethiopia is about 80% of the total precipitation due to high temperature. In Ethiopia, evaporation is relatively less than Sudan or Egypt due to its high elevation above sea level. Throughout the Blue Nile watershed and at all altitudes, surface evaporation is high. It depends mainly on the geological characteristics of the bedrock for runoff or water reservoirs, elevation and temperature, wind speed, plant cover, and amount of rainfall.

The Blue Nile (Abay) basin has a range of surface evaporation from 1,300 m in the highlands to 2,000 mm/year at lower altitudes. There may be a net loss of water, compensated only by surface runoff. Rainfall over Lake Tana, the source of the Blue Nile, ranges from 1,000 to 1,500 mm/year, while surface evaporation ranges from 1,200 to 1,300 mm/year, forming little net gain to the lake from rainfall itself [26]. The average annual potential evapotranspiration over the basin is 1,765 mm [3].

Evaporation at Bahir Dar station for 4 years shows an annual average of 1,634 mm/year. Potential evapotranspiration (PET) in the Blue Nile basin ranges between 1,056 and 2,232 mm/year. High PET (1,800–2,232 mm/year) is shown in northwestern parts of the basin.

The Atbara watershed shows chronic water deficit. Average surface evaporation is 1,300 mm/year, while rainfall averages 1,000–1,500 mm/year.

There is only a significant net water surplus in the southwestern Sobat (Baro-Akobo) basin, where rainfall averages 2,200 mm/year and surface evaporation averages 1,000 mm/year in the highlands and 1,700 mm/year in the lowlands and swamps [26].

2.2 Topography

Ethiopia is the 4th largest landlocked country in Africa after Chad, Niger, and Mali. It is a part of the East African Rift plateau, covering an area of 1.27 million km^2. Ethiopia is characterized by a ragged land surface with the spectacular topography of high volcanic mountains, plateaus, deep narrow valleys, rifts, and lowlands. The average surface elevation in Ethiopia ranges from 1,000 to 3,000 m above sea level (m amsl).

The slope of the Blue basin ranges from steep as of 45% in the Eastern part to gentle slope at the border with Sudan with an average of about 4% [27]. The highest mountain is Ras Dashen Terara northeast of Gonder (4,620 m amsl), and the lowest point is located in Afar Triangle at 125 m below sea level (see Fig. 5).

Ethiopia contains about 50% of the African highlands greater than 2,000 m in elevation [28]. They comprise much of the country and often refer as the Ethiopian Plateau that is divided by the East African Rift into northern and southern halves. It is known in Ethiopia as the Ethiopian Rift extending for 900 km from Lake Turkana in the southwest to Djibouti in the northeast. The Rift floor varies in elevation from below sea level to 1,000 m. The width of the main Rift ranges between 50 and 100 km for 600 km from the southwestern border at Lake Turkana to the head of Afar Triangle. It contains several shallow lakes that have mostly no outlet and alkaline water. Lake Abaya is the largest one (1,160 km^2, elevation 1,285 m); other major lakes include Lake Chamo (551 km^2, 1,235 m), Lake Awasa (129 km^2, elevation 1,708 m), and Lake Zway (485 km^2, elevation 1,636 m) [14].

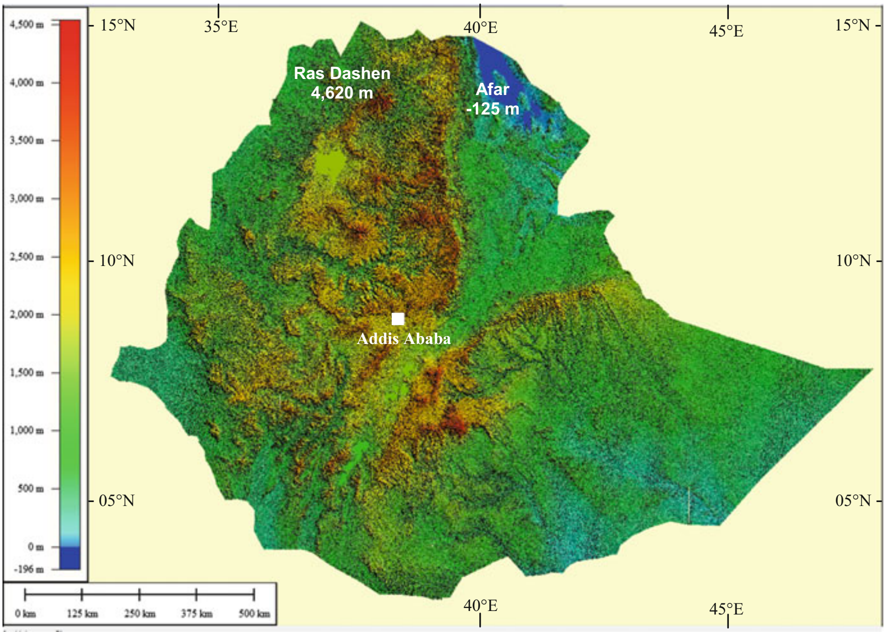

Fig. 5 Digital elevation model of Ethiopia from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) resolution of 90 m

The northwestern highlands are located in the Nile basin region. They are massive with an average height ranges from 2,000 to 2,500 m and decrease in elevation to less than 500 m at the border with Sudan. The complexity of the Ethiopian topography may cause troubles and challenges for development projects such as:

1. Movement of surface water from place to another on the mountain lands in Ethiopia is relatively difficult, causing challenges in irrigation.
2. Steep slopes do not allow to have a great extension of flat irrigable lands for agriculture. The potential irrigation lands in the Blue Nile basin are limited and estimated at 815,581 ha (two million feddans) [29] forming about 2.4% of the basin area.
3. High gradient leads to rapid surface water flow to Sudan and Egypt. The water flow of the Blue Nile in August averages from 500,000 to 800,000 m^3/day, providing Ethiopia the opportunity for generating hydroelectric power. Ethiopia is the second African country after the Democratic Republic of the Congo in hydroelectric power potential that is estimated at 40,000 MW. Currently, Ethiopia acquires the majority of its energy from 15 different hydropower plants ranging in capacity from 11.4 to 1,870 MW, totaling about 4,000 MW.
4. Erosion is caused by large quantities of surface water flowing at high speeds. Land degradation is one of the most important problems in Ethiopia, with more

than 85% of the land degraded to different degrees [30]. Water erosion is the most common form of land degradation, lowering crop yields and leading to higher poverty rates among agricultural households.

5. The Nile tributaries originating in the Ethiopian highlands show high energy gradients that are capable of transporting high sediment loads resulting in blocked drains and culverts decreasing storage capacity of dams in Sudan and Egypt.
6. Roads with steep gradients are often troubled with severe water erosion in Ethiopia.
7. High gradients do not give the necessary time for surface water to infiltrate to the local groundwater.
8. Narrow and steep slopes do not also allow great storage capacity in dam reservoirs.
9. Deep valleys impede access to water from the river especially in the dry season. The average depth of the Blue Nile Valley is greater than 500 m.
10. No floodplain can form.

The complex terrain, severity of landslides, soil erosion, silt flow, and rockfall in Ethiopia may cause failure of water projects. The collapsed projects include the Gibe II that transfers water from the first reservoir of the Gibe I on the Omo River.

2.3 Lithology

Several geological studies were conducted in Ethiopia. They include Assefa [31], Tadesse et al. [32–34], Miller et al. [35], Asrat et al. [36], Alene et al. [37], Stern et al. [38], Gani et al. [39], and Abbate et al. [13].

The bedrock geology of Ethiopia is characterized by a great variety of rock types from Precambrian to Quaternary, including Precambrian metamorphic and igneous rocks that cover 23% of the country, which are unconformably overlain by thick successions of Paleozoic and Mesozoic sediments (25%) of limestone and sandstone [40].

2.3.1 The Precambrian Rocks

The Precambrian rocks are mostly exposed in the peripheral lowlands at the boundary with Sudan, where younger rocks have been removed by erosion (see Fig. 6). They contain a wide variety of sedimentary, volcanic, granitic, and metamorphic rocks. The granitic and gneisses predominant basement rocks in the south and west have been highly metamorphosed [43]. The Precambrian contains most of the known metallic deposits (precious, platinum, lead, copper, zinc, nickel, iron, chromium, manganese, and tantalum) and some industrial minerals (kaolin, feldspar, clay, asbestos, talc, marble, limestone, and granite) [33].

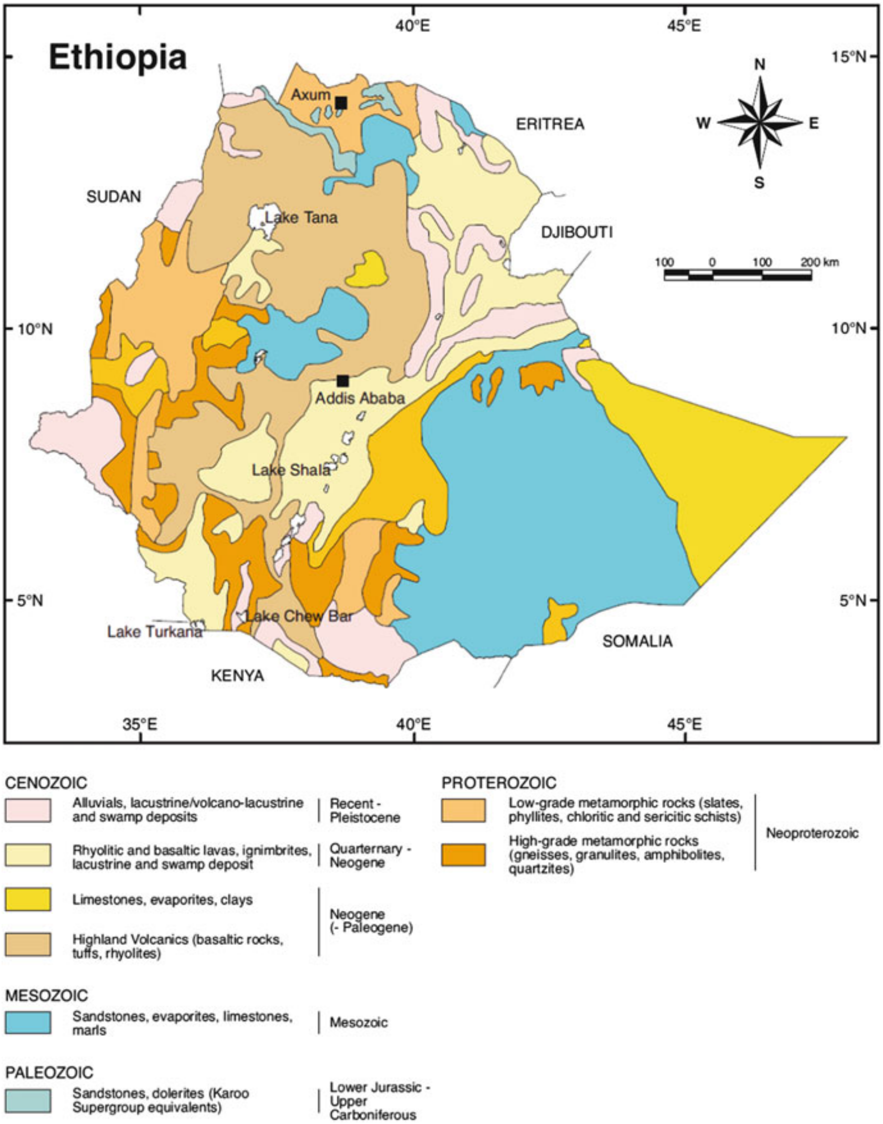

Fig. 6 Geological overview of Ethiopia [41, 42]

2.3.2 The Mesozoic Rocks

Mesozoic sandstone and limestone are not common in the Nile basin rivers in Ethiopia. It is found in the east-central and central part of the country. They are highly fractured causing challenges to hold groundwater. The carbonate deposits in northern Ethiopian area are truncated by an erosional surface due to an Early Cretaceous tectonic event marked by faulting and tilting [44].

2.3.3 The Cenozoic Rocks

Cenozoic sedimentary rocks occur in eastern Ogaden, the Danakil Depression, and the lower Omo Valley. Tertiary volcanic erupted from fissures during early Tertiary (54–13 Ma). They consist of piles of flood basalts and minor ignimbrites. The basalts are transitional from alkaline to tholeiitic in composition and erupted from fissures [45]. The flows range in thickness from 500 to 1,500 m [46] to up to 3,000 m. Basaltic rocks cover more than 40% of the Ethiopian surface area and more than 75% of the Blue Nile basin. The mineralogy of basalt is calcic plagioclase, pyroxene, and olivine [47].

2.3.4 Challenges of Basaltic Rocks

The challenges of basaltic rocks on the water projects in Ethiopia are:

1. Basalt is easily weathered and eroded by rainfall to form silt and clay. It is responsible for more than 90% of the Egyptian soil in Nile Valley and Delta. The Nile is the life of Egypt. A Greek historian Herodotus called Egypt the "gift of the Nile" because the Egyptian civilization depended on the resources of the great river water and soil.
2. The Ethiopian rivers in the Nile basin carry large quantities of sediments. The Blue Nile carries sediments that turn the water color into dark brown or almost black.
3. Rivers originating from the Ethiopian Highlands are characterized by huge sediment load, turning the water dark brown or almost black.
4. Unlike the Blue Nile, the White Nile originates from a granitic area in the equatorial region with little sediments that deposit in Sudd region, South Sudan. It flows to Khartoum without sediments, forming clear water.
5. Because of low porosity and permeability, basalts cannot absorb and store water to form groundwater. Some small groundwater forms in fractures.
6. Sedimentations from the Ethiopian rivers in reservoirs of Sudan cause a loss in capacity and reduce the hydroelectric power generation.
7. Basaltic sheets of successive volcanic eruptions hold gaps and cavities between them and form weakness plains. They have less strength compared to granites to be the bedrock for large and heavy dams. Therefore, construction of large dams on the Blue Nile River should have intense investigation studies.
8. Seepage of water through fractures beneath the dam or from the reservoir.

2.3.5 Carbonate Rocks

Carbonate rocks outcrop mainly in northern Ethiopia (Tekeze basin), central Ethiopia (southeastern part of the Blue Nile basin), and Ogaden area (Fig. 6 geology). They are fractured and intercalated with variegated, calcareous shale and marl

[48]. The carbonate rocks were affected by major and minor faults and joints due to an Early Cretaceous tectonic event marked by faulting and tilting [44]. They are moderate to highly weathered and considered as weak engineering geological unit with low mass strength [48].

Water development projects in northern Ethiopia have a number of constraints in their planning and execution due to the geological engineering problems posed by the various foundation rocks. More than 64% of 70 earth-fill dams that were constructed in Tigray (northern Ethiopia) between 1994 and 2002 for irrigation could not attain their planned objectives through excessive leakage via the reservoir bottom and/or via the dam foundation [49, 50]. The leakage was more pronounced in the large dams than the small dams in Tigray area. The dam failure increases as reservoir capacity or head increases even with the same geology [50, 51].

2.3.6 Quaternary Sediments

The Quaternary sediments consist of alluvial and colluvial deposits and residual soils. The alluvial deposit includes clay and sand with minor boulders. It is widely observed along streams and northern and northwest of the town [52].

2.3.7 Failure of Micro-dams

Although the magnitude of the problems differs from one project to another, the major technical problems observed in many of the micro-dams include [53]:

1. Excessive leakage from reservoirs (related to geological and geotechnical conditions)
2. Insufficient inflow toward reservoirs (related to hydrological aspects)
3. Reservoir early sedimentation (related partly to geological properties of Earth materials and high erodibility of shale)
4. Structural and dam stability (related to geology and geotechnical reasons)
5. Poor irrigation water management application
6. Social- and institutional-related problems (related to agriculture and social aspects)

2.4 Erosion and Sedimentation

Erosion and land degradation are the major geological processes in Ethiopia due to extended dry seasons, torrential rain, and geological nature in terms of rock types and structure. They bring large quantities of sediment in the drainage systems. The deposition of sediment in the reservoirs or irrigation systems downstream leads to a reduction in reservoir storage capacities and decrease of hydropower generation. It raises the bed level and may cause flood risks. The sedimentation in the irrigation channels leads to water shortage and irritation management difficulties. On the other side, erosion often causes severe damage to agricultural land by reducing the natural soil fertility and agronomic productivity. The river sediments are the largest pollutant for the surface waters.

The erosion in the Blue Nile and Atbara is extreme. About 85–95% of the Nile sediments came from the Blue Nile (90%) and Atbara (10%) rivers during the flood seasons [29, 54, 55]. Due to severe soil erosion, some regions such as Wolo, Tigray, and Hararghe have about 50% of their soils with depths less than 10 cm, which makes them unsuitable for farming [56].

The White Nile and its tributaries originating from mostly granitic sources in the equatorial region with little sediment load lose most of it by spilling and deposition over swamps, floodplains, and lakes inside South Sudan.

Nile tributaries, originating from the Ethiopian Highlands, carry large quantities of sediment. The sediment load of the Blue Nile at El Diem (at the border with Ethiopia) was estimated to be 140 million tons per year. At the High Dam, Egypt, the estimation of the sediment load was 160 million tons originating from the Blue Nile and Atbara rivers [57]. The amount of sediments transported from the Blue Nile basin through the last 29 million years is estimated at 93,200 billion m^3 [39]. Other estimations indicated that the annual losses from the Blue Nile and Atbara basins in Ethiopia alone are estimated at 525 million m^3, about 66% of which comes from basaltic rocks directly or nonagricultural lands [58].

As a result, the Sudanese reservoirs, Roseires, Sennar, and Khashm el-Girba, have suffered extensively from sedimentation. The reservoir capacities have declined significantly [25]. The Roseires reservoir has lost 41% of its original storage capacity (3.3 billion m^3 in 41 years), about 1.0% per year from 1966 to 2007 [59, 60]. The dam was recently heightened by 10 m in January 1, 2013, to compensate for storage lost through sedimentation, which resulted in increasing the old storage capacity by additional 3.7 km^3.

Sennar Dam is the first reservoir constructed on the Blue Nile in Sudan 1925 at 300 km South Khartoum, with a storage capacity of 0.93 billion m^3 to irrigate the Gezira Scheme and secure drinking water supply (see Table 2). The annual rate of sedimentation between 1925 and 1981 was 0.5% of the original capacity [61].

Khashm el-Girba reservoir is constructed on the Atbara River at 200 km downstream of the Ethiopian border. The storage capacity was reduced by 0.66 km^3 in 41 years due to the sedimentation, which represents 50% of its capacity [54, 57].

Table 2 Sedimentation in some of the Nile reservoirs in Egypt and Sudan [57]

Reservoir	Year of construction	Original capacity (km^3)	Estimated loss (%)	Sedimentation (Mm^3/year)
Sennar	1925	0.93	71	8
Khashm el-Girba	1964	1.3	50	17
Roseires	1966	3.3	41	33
Merowe	2009	12.5	–	–
High Dam	1970	162	3	140

The annual rate of sedimentation at the High Dam is 140 Mm^3 with a total of 5,180 Mm^3 (3% of the total capacity of 162 km^3). The sediment deposition started in the tail zone of the reservoir in Sudan [54]. The low amount of sediments at the High Dam refers to their deposition in the Sudanese reservoirs that increase the life span of the High Dam.

2.5 Volcanism

The Great African Rift is the largest rift on the Earth's continental crust. It divides Ethiopia into two halves separated by the Ethiopian Rift and the Afar Triangle depression (the triple junction between the Nubian, Somalian, and Arabian plates). They are characterized by numerous volcanoes and widespread seismicity (see Fig. 7).

A

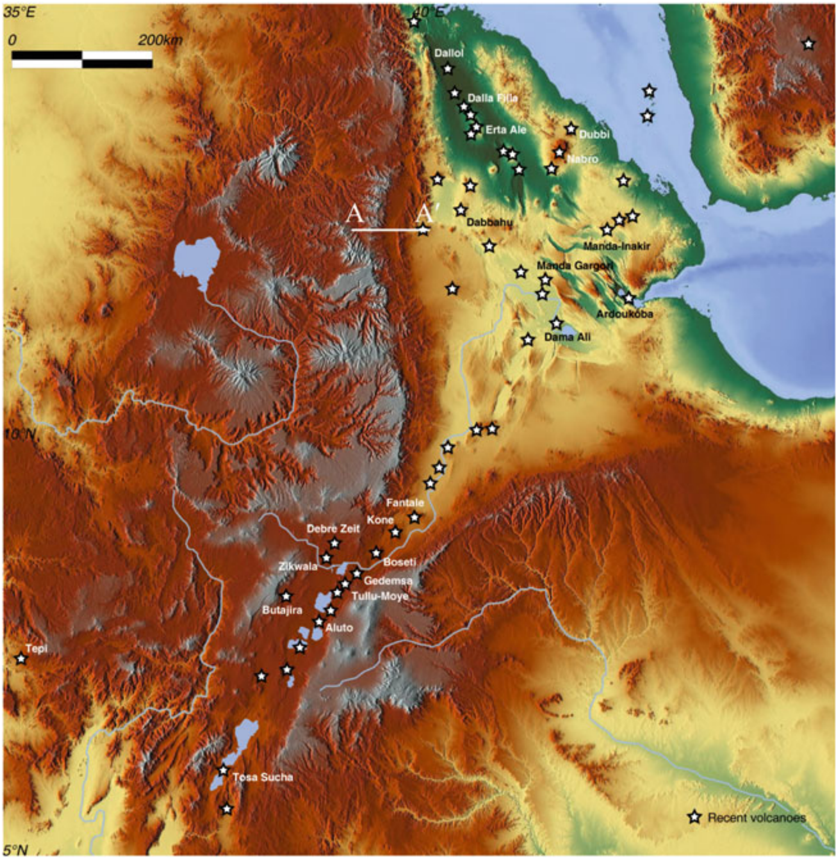

Fig. 7 Recent volcanism and seismicity in Ethiopia: (**a**) volcanism and (**b**) seismicity [62]

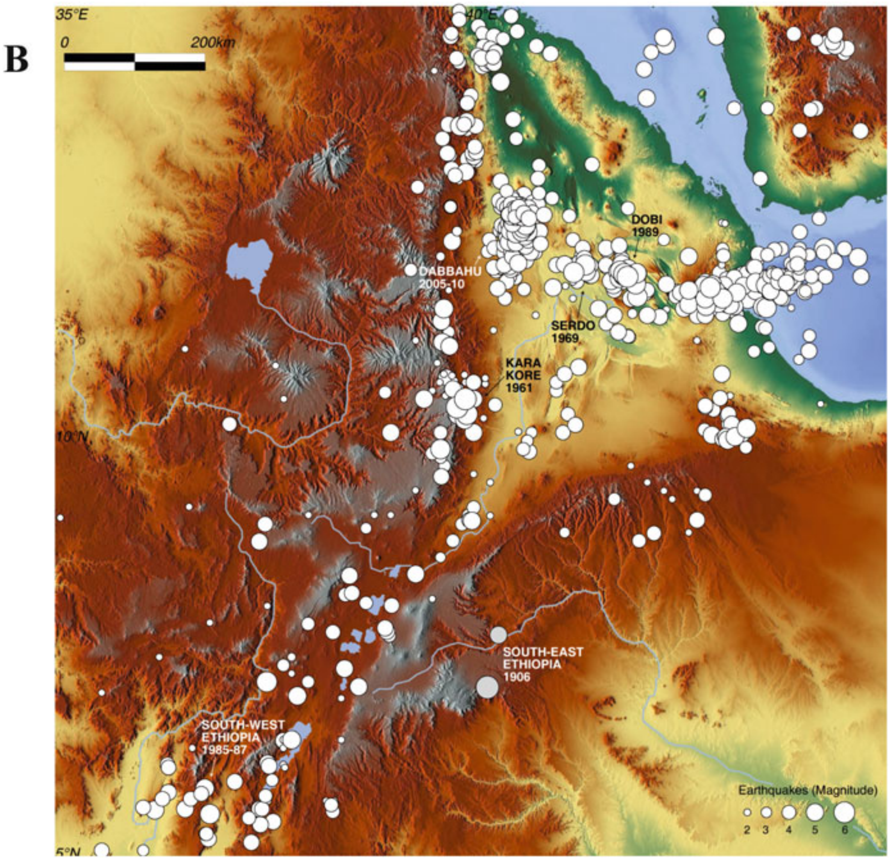

Fig. 7 (continued)

About 50 volcanic edifices in Ethiopia have documented activity during the Holocene. They are mostly located within the Afar Depression; among the active volcanoes, the most famous Erta Ale is a basaltic volcano characterized by lava lake on its summit caldera that has been active more or less continuously in the last 120 years [62].

A major eruption occurred at Nabro Volcano in June 15, 2011, at Eritrean-Ethiopian border. It is the highest volcano in the Danakil Depression. Nabro is a stratovolcano that emitted a thick plume of volcanic gases and the plume rose to an altitude of 11,000 m and consisted mainly of sulfur dioxide [63].

2.6 Seismicity

The Ethiopian Rift Valley shows a diffuse seismic activity. The seismicity with larger magnitude more than 5 is common [64]. The seismic activity is concentrated close to major volcanoes in the Afar Depression. A strong seismic sequence occurred in August 1989 in the Dobi area with 6.2 Richter, followed by 14 events with a magnitude higher than 5 Richter, 2 of them reached magnitudes 6.1 and 6.3 Richter [62]. The most recent earthquake was in the Ethiopian Rift at 29 km south of Ziway and 19 km from Alutu volcano. It triggered the area in January 27, 2017, with a moderate magnitude of 5.3 Richter at 10.0 km depth [65].

2.7 Landslides

Landslide implies a sudden event in which large quantities of rock and soil plunge down steep slopes. Landslides occur in connection with other major natural disasters, including earthquakes, volcanic eruptions, wildfires, and severe storms [66].

There are several triggering factors for landslides in Ethiopia including:

1. High relief (on average between 2,000 and 3,000 m).
2. Very deep valleys and gorges.
3. Steep slopes.
4. Steep escarpments that were produced by faulting [67].
5. Heavy rainfalls in short season (June to September).
6. Common earthquakes.
7. High fractures due to Ethiopian Rift and faults.
8. High rates of water infiltration into the ground through fractured bedrock may be enhanced by the presence of deep desiccation cracks in the covering soil, which develop especially at the end of the dry season [68].
9. Inclined sedimentary layers underlay volcanic rocks.
10. Widespread slope wash due to steep slopes and heavy rains.
11. Common fractured basaltic rocks.
12. Flooding.
13. Riverbank erosion of weak basaltic rocks.
14. Man-made activities, such as the construction of buildings and roads.

Water development projects in Ethiopia usually take more time and money than scheduled to overcome the common complex geological processes. The Tekeze Dam on Tekeze River, and the Gilgel Gibe II tunnel on Omo River cost more money to be completed. They were delayed more than two years.

2.7.1 The Gilgel Gibe II Project

The Gilgel Gibe II is long tunnel hydropower project on Omo River, approximately 240 km southwest of Addis Ababa, Ethiopia. The tunnel has a diameter of 6.98 m and extends for 26 km and is designed to withstand a maximum pressure of 7 bar. It is buried deep in the ridge formed by Fofa Mountain [69]. The tunnel channels the water discharged from the Gilgel Gibe II dam to the power plant in the Omo River valley.

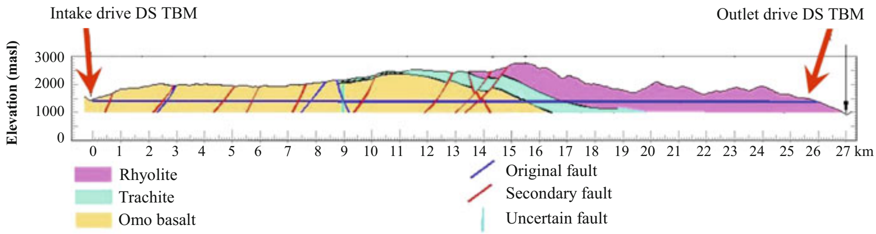

Fig. 8 Longitudinal section of the 26 km headrace conditions Gibe II [71]

The Gilgel Gibe II hydroelectric project generates power by exploiting the drop between the basin created by the Gilgel Gibe I dam (1,500 m asl) on the Gilgel Gibe River and the Omo River below (1,000 m asl) with 500 m drop to generate 420 MW. The project was the biggest power plant in Ethiopia at that time. The Gilgel Gibe II, being built by Italian firm Salini, had already been delayed by more than 2 years [70].

The tunnel was dug in a ridge of a nonuniform rock formation with different types of volcanic rocks [71]. Basalt is the most dominant rock on the west followed by trachyte and rhyolite on the east, which is intersected by numerous faults generally inclined to the east (see Fig. 8).

The project was subjected to three main collapses [71]:

1. The first collapse was during the construction of the tunnel happened in October 2006 when the tunneling crew hit a pocket of wet Earth along a major fault line only 4 km into the boring. It was explained as a result of an exceptional geological event [72].
2. The second failure occurred in June 2007 resulting in the collapse of the front face of an exploratory tunnel which eventually filled 80 m of the main tunnel with mud.
3. The latest collapse occurred at 17 km from boring, 10 days after the ceremony of the inauguration on January 14, 2010, due to structural and geological problems [69, 73], and a large quantity of rock and mud fall into the tunnel [74].

2.8 Geologic Structures

The Great African Rift Valley is the largest tectonic structures on the continental crust. It divides the Ethiopian Plateau into two halves. It is called in Ethiopia the Ethiopian Rift with an apparent NE-SW orientation and average width of about 70 km. During the Triassic-Cretaceous time, NW-trending Mesozoic rift basins were formed as a result of the main Ethiopian Rift, including the Muglad, the Melut, the Blue Nile, and the Anza rift basins [75]. They terminate sharply in the northwest against the NE-trending Central African Shear Zone.

The Ethiopian Rift consists of three main sections [76]:

1. The southern portion, from the Lake Turkana in the south to the hydrological divide between Lakes Abaya and Awasa
2. The Great Lakes Region of Ethiopia, stretching as far as the Awash River
3. The northern portion, from the Awash to the apex of the Afar Triangle

Rifting in Ethiopia was associated with the huge volume of volcanic rocks that were concentrated in a very short time of one million years around 30 Ma. They form volcanic mountains that have been regarded as a possible cause of climatic change [77].

2.9 Flooding and Drought

Floods and droughts occur in Ethiopia significantly every 3–5 years. Ethiopia is very sensitive to rainfall variations due to inadequate water storage capacity to smooth and schedule water delivery and lack of available groundwater. Both flood and drought cause significant damage to agricultural lands, watersheds, hydropower generation (the main source of electricity), pastures, and livestock [10].

2.9.1 Flooding

Floods are rising in intensity and extent in Ethiopia, which hinder the development projects. Flooding occurs along all the riverine areas, affecting productive agricultural land basins in Ethiopia. The river plains of the Abay, Awash, Baro-Akobo, and Wabi-Shebele basins are prone to flooding [10].

From 1900 to 2013, they killed 1,976 Ethiopian people and affected 2.4 million people and cost about US$17 million of damages [78].

The worst floods occurred in 2006, with 862 fatalities, 361,600 people being affected, damage of property, and destruction of livelihoods [79].

Rugged topography, steep slopes, heavy rains, high soil degradation, and common rock fractures cause frequent floods in Ethiopia. Dam reservoirs may face flooding due to high sedimentation rate and narrow and deep valleys forming limited storage capacity. For example, Tekeze Dam was flooded twice during the construction in 2006 and 2007 [69] (see Fig. 9).

Fig. 9 Overtopping the Tekeze Dam due to large flood in September 2007 (Photographer Paul Snook: http://www.panoramio.com/photo/76171558)

2.9.2 Drought

Although Ethiopia is the water tower in Africa, it has repeatedly been threatened by extreme droughts that have a major impact on water resources, especially river flow and the availability of water for human and livestock. About 15 drought events happened in Ethiopia in the period from 1965 to 2012 and caused 402,367 deaths with 66 million people affected [80] and a direct economic cost of US$1.1 billion per year [81]. One of the worst droughts in Ethiopia is that happened from 1983 to 1985. It declined the Ethiopian GDP by 9.7%, agriculture by 21%, and gross domestic savings by 58.6% [10], and up to one million people died. In the period from 2015 to 2016, El Niño induced drought in the lowlands of the southern and southeastern parts of the country.

3 Tekeze Dam Area

Tekeze River is a major tributary of the Atbara River that joins the main Nile 320 km downstream north of Khartoum, Sudan. The Tekeze-Setit becomes Atbara with tributaries from Eritrea. The total watershed area in Ethiopia, Eritrea, and Sudan is 227,128 km^2 [82]. The length of the Tekeze River from its source to the Sudanese border is more than 600 km.

3.1 Topography of Tekeze Basin

Observation of DEM map (see Fig. 10) shows that the Tekeze basin has an average elevation of 2,000 m asl and a catchment area of about 60,000 km^2. About 70% of the basin lies in the highlands at an altitude of over 1,500 m asl. It includes the Semien Mountains (4,620 m asl). The Tekeze riverbed is very deep compared to the nearby agricultural fields. The riverbed in the Tekeze averages 500 m from the banks. The tributaries of Tekeze River have a dendritic network in soft sandstones.

3.2 Geology

The Tekeze River cuts in the Precambrian basement rocks, with a very thin layer of sandstone (Lower Cretaceous) underlying a huge pile of Tertiary volcanic rocks. There was a long time gap, about 300 million between deposition of sandstone and the basements that belong to the Arabian-Nubian Shield. The basements are formed mainly of metamorphosed volcanic rocks and ocean sediments, with numerous granite intrusions. The metamorphic rocks are soft and crumbly slate which is very easily eroded due to penetration of water through the slatey foliations resulting in water erosion and sliding of the slatey layers. The Tekeze River cut its gorge into

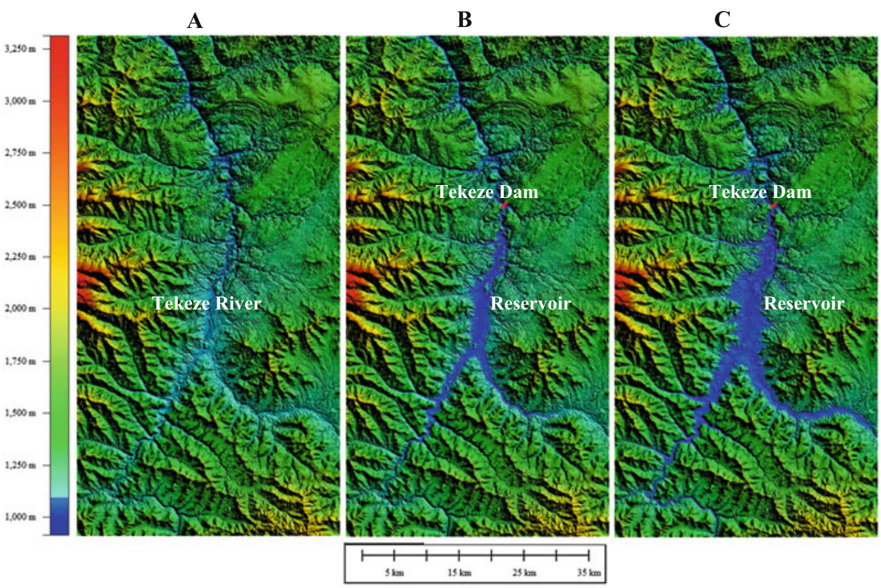

Fig. 10 Digital elevation model (DEM) of the Tekeze Dam area: (**a**) before dam construction, (**b**) Tekeze reservoir at the minimum operation level at 1,096 m amsl, and (**c**) Tekeze reservoir at the maximum operation level at 1,140 m amsl

the Mesozoic sandstone and is carved around the hard volcanic basalts and Precambrian basement rocks to the north [83].

The rate of water erosion and sedimentation is very high in the Tekeze basin due to its topography and rock types. There are different rates for soil loss. The average annual soil loss rate ranges between 42 and 300 tons/ha for croplands [84]. About 120 million tons of soil are eroded annually [5].

3.3 Climate

Looking into the rainfall variability in Tekeze River basin, the area receives a mean annual rainfall ranges from 600 to 1,200 mm with an average of 675 mm. The main feature of the rainfall is the very high temporal variability when July and August show more than two thirds of the total rainfall. August and September are the months of the kiremt season over Tekeze River basin. The minimum temperature is less than 10°C, and the maximum is more than 22°C. The Tekeze basin suffers from severe loss of water due to the high rate of evaporation that reaches to 1,400 mm/year [14]. The groundwater resource is not so promising except in a few areas [85].

3.4 The Tekeze Dam

The Tekeze Dam is located 903 km north of Addis Ababa, at coordinates 13° 21′ N and 38° 45′ E. Tekeze is the tallest arch dam in Africa at 188 m, eclipsing the previous record height of Katse Dam of 185 m in Lesotho. The dam is located in a steep, narrow gorge, which the river has carved through the surrounding plateau. The base of the Tekeze Dam was set at an altitude of 957 m asl, whereas the crest is elevated at 1,145 m asl, with a dam height of 188 m across 350 m deep natural gorge (see Fig. 11).

3.5 The Tekeze Reservoir

The maximum retention level is 1,140 m asl. The catchment area of the Tekeze reservoir is 30,000 km^2, forming 36.4% of the total catchment area of the Tekeze basin in Ethiopia (82,350 km^2). The total mean annual flow from the river basins is estimated to be 8.2 km^3 [85]. The annual inflow in the Tekeze Dam is 3.7 km^3 (see Table 3). The digital elevation model (DEM) of the Tekeze area was extracted from the USGS [65]. The Tekeze Dam created a reservoir of 70 km in length, an average width of 2.2 km, and a surface area of 155 km^2 at the maximum water level 1,140 m asl (see Fig. 10c). The total water storage capacity of the reservoir is 9.23 km^3, forming the largest man-made lake in Ethiopia. The dead storage of the Tekeze

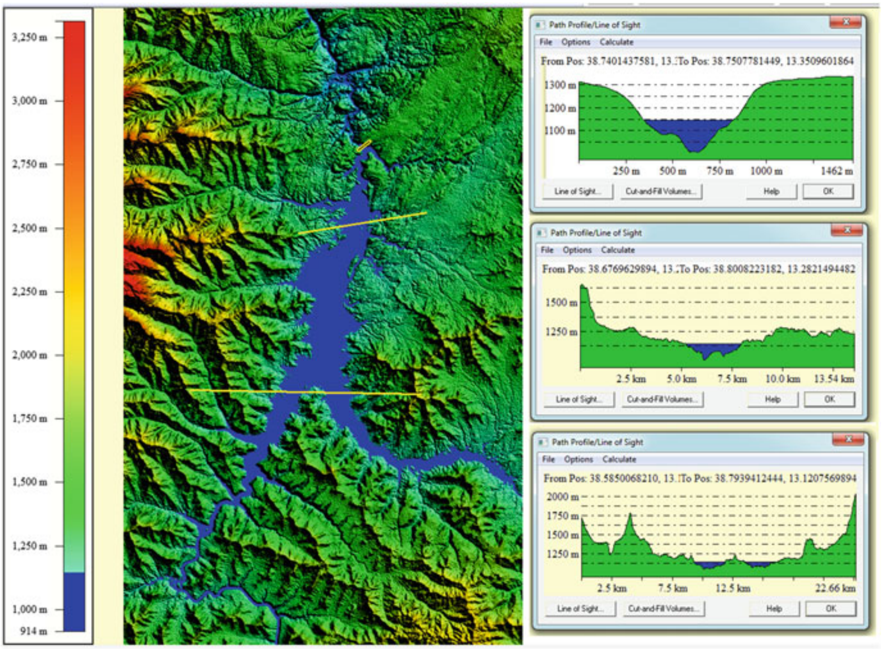

Fig. 11 Cross sections through the Tekeze Dam area showing steep slope of the river banks and extension of the reservoir at the maximum level of 1,140 m amsl

Dam is 4 km^3, forming a reservoir with dimensions of 88.5 km^2 in area and 45 m in depth (see Table 4).

3.5.1 Landslides in Tekeze Dam

The Chinese contractor from the China National Water Resources and Hydropower Engineering Corporation (CWHEC) requested two extensions for 1 year in 2004 and 18 months in 2006 due to geological problems. InApril 2008, landslides of the reservoir walls delayed the project, increasing the original budget of US$224 million by at least $35 million [87].

3.6 The Effect of Tekeze Dam on Egypt and Sudan

The construction of the dam was officially launched in August 2002. It was scheduled to be completed in 2008, but it was inaugurated on November 14, 2009, due to landslide and shortage of funds [88]. The effect of Tekeze Dam on the annual water share of Egypt and Sudan comes from dead storage, evaporation, evapotranspiration loss, seepage through rocks and fractures, and water used for irrigation.

Table 3 Hydrology and reservoir data of the Tekeze Dam [86]

Total storage	9.3 km^3
Maximum retention level	1,140 m asl
Minimum operation level	1,096 m asl
Surface area at MRL	147 km^2
Live storage	5.3 km^3
Dead storage	4.0 Bkm^3
Catchment area	30,000 km^2
Annual inflow	3.75 km^3
Sedimentation	30 Mm^3/year
Arch dam features	
Height	188 m
Crest length	420 m
Crest elevation	1,145 m asl
Powerhouse type	Underground
Turbine number and type	4 Francis
Total installed capacity	300 MW
Maximum net head	162.8 m
Minimum net head	120 m
Maximum discharge	220 m^3/s

Table 4 The water capacity of the Tekeze reservoir at different water levels

Elevation (m asl)	Average depth (m)	Area (km^2)	Volume (km^3)
1,096	45	88.5	4.0 (dead storage)
1,120	33	122	6.5
1,140	60	155	9.3 (max. storage)
1,150	62	178	11.0

Two successive high floods in 2006 and 2007 affected the construction of Tekeze Dam, especially the second one that lasted 81 days, from July 13, 2007, to October 2, 2007, and spilled over the two dam low blocks (see Fig. 9). It caused extra cost close to two billion birr (US$86 million) over-budget, running out 2 years past the original deadline and resulting in loss of lives of 47 workers. The dam stored the entire floodwater for the whole season in 2008 accounted for less than 3 km^3. By the start of the 2009 wet season, the dam was complete but unable to exceed the dead storage capacity (4 km^3) because both the 2008 and 2009 floods were low by normal standards, so the reservoir did not completely fill to the maximum capacity of 9.23 km^3. However, the average annual inflow recorded during the years 2008 and 2009 was low, so the reservoir was still only 4.8 km^3 full at the end of the 2009 wet season. The water level was above the minimum operating level for the turbines (4 km^3 at 1,096 m amsl), so power generation was able to commence in August 2009 [87].

The direct water loss from the reservoir by evaporation is calculated as 217 Mm^3/year from the average evaporation of 1,400 mm/year at a surface area of 155 km. Seepage through rocks and fractures was not determined.

The downstream countries (Egypt and Sudan) lost directly 4 km^3 (the dead storage) in 2 years of 2008 and 2009 in addition to the annual water loss from evaporation of 217 Mm^3.

According to Tekeze master plan, the Tekeze basin has a potential for three large-scale irrigation sites with an estimated potential irrigable area of 83,368 ha (208,420 feddans) in three sites: the lower Tekeze basin Humera, Angereb, and Metama [85]. The potential irrigable lands need water only during the dry seasons, which is estimated at a total of about 500 Mm^3 at 2,500 m^3/feddan.

4 Conclusions

Geological, geomorphological, and environmental hazards are dominant in the territory of Ethiopia. The main controlling factor is the largest continental rift on Earth that causes crustal mobility between the Arabian and African plates. Ethiopia is characterized by rugged topography, the unique regime of the short intense rainy season, high evaporation, flooding, drought, dominant basaltic rocks, an abundance of geologic faults and fractures, active volcanic eruptions and earthquakes, severe erosion and land degradation, siltation, and lack of major groundwater aquifers.

Egypt has almost completely relied on the Nile River water for irrigation since the pharaohs. The construction of water projects in the Nile basin region in Ethiopia has produced political tensions between Egypt and Ethiopia over the construction of Tekeze (2009), the Tana-Beles diversion (2010), and the under-construction GERD which started in April 2011 in Egypt.

Ethiopia has great potential to generate hydropower electricity, but it faces geological and environmental challenges to establish major water projects especially in the area located within the Nile basin to store water due to:

1. Spatial and temporal variations of the heavy rainfall. The concentration of as much as 75% of rainfall in short rainy season (3–4 months) is followed by the dry spell.
2. High evaporation that averages 85%.
3. The dissected nature of the landscape, high relief, and steep slopes.
4. Rock types that are mostly fractured basaltic rocks (50%), Precambrian metamorphic rocks (25%), and soft rocks of jointed cavernous limestones (25%), causing water leakage.
5. Severe water erosion degradation and associated siltation in the surface water reservoirs, decreasing the water storage capacity.
6. Geologic tectonics and common earthquakes due to the activity of the African Rift that bisects Ethiopia.
7. Landslides triggered by heavy rainfall, steep slopes, thick hard rock underlain by clay, fractured rocks, common earthquakes, and deforestation.

The Tekeze Dam was built in a canyon surrounded by steep topography; landslide and high rate of sedimentation are already a problem. Analysis of ASTER DEM of Tekeze River basin showed that it has a dendritic pattern. Tekeze reservoir area is 155 km^2 at 1,140 m amsl with a volume of 9.3 km^3. Egypt and Sudan lost 4 km^3 in 2008 and 2009 in addition to an annual loss estimated at 200–700 Mm^3.

5 Recommendations

Failure of water projects in Ethiopia is mainly due to geological, technical, and lack of studies. Technical and environmental studies should be done before construction. Further studies are required for Tekeze Dam such as leakage of water from its reservoir, the rate of sedimentation, and water quality of the reservoir. The social, environmental, and economic impacts on the downstream countries, Egypt and Sudan, have not been completed yet. The Eastern Nile basin countries (Egypt, Sudan, and Ethiopia) should cooperate in the reservoir operation to maximize the benefits for Ethiopia and minimize the harmful impacts of the Tekeze Dam on Egypt and Sudan.

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Part VII
Sustainable Use of Water Resources and Future of Irrigation Projects

Estimation of Crops Water Consumptions Using Remote Sensing with Case Studies from Egypt

Mohammed A. El-Shirbeny, E. S. Mohamed, and Abdelazim Negm

Abstract Actual evapotranspiration (ETa) represents crop water consumption in consideration, the water conserved in plant tissue structure representing about 1% or less. Many researchers understood the importance of ETa, and they did their best to measure or calculate ETa. Tens of experimental and mathematical models were used to calculate evapotranspiration in last century. Many weather, plant, and soil parameters were inserted in these models. Most of these models were acceptable for local scale and used for certain climate. Only a very few models were used on a global scale but need a lot of parameters and well-distributed weather stations. The crop pattern was the main obstacle to using these models on a large scale. The early satellite age was the beginning of the development of global-scale models through using satellite images to calculate ETa and manage crop water consumption. Triangle and crop water stress index (CWSI) methods were used and developed in the 1970s and the 1980s, respectively. In 1990s and beginning of 2000s, the SEBAL and SEBS models represent a new step in the way of evapotranspiration development models. In the last decade, METRIC, ETLook, Alexi, and ET watch models were developed to fill the gaps of SEBAL and SEBS models. Researchers around the world still try to modify these models to improve the results.

Keywords Crop, Evapotranspiration, Modeling, Remote sensing, Water, Water consumption

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Contents

1 Introduction

In the western USA, since about the 1890s, rationalization of water losses became more important. Water applied significantly exceeded the consumptive-use values [1]. After that date, many researchers started to formulate the water losses in the agriculture field. They tried to represent the physical processes of water losses from soil and plant leaves which is called ETa. The ETa can be measured correctly using weighing lysimeters and could be estimated from empirical methods. Unfortunately, these methods produce point values of ETa. It is used for a specific location and fails to provide the ETa on a regional scale, although it is costly. The ETa is calculated in many ways and steps.

ETa is the real amount of crop water consumption during all phonological stages from cultivation to senescence. It is affected with weather parameters, crop characteristics, and water availability [2]. To calculate ETa, many parameters must be inserted in the next equation:

$$\mathrm{ETa} = \mathrm{ETc} \times \mathrm{Ks} \quad (1)$$

$$\mathrm{ETc} = \mathrm{ETo} \times \mathrm{Kc} \quad (2)$$

where ETc is crop evapotranspiration (mm/day), ETo is reference evapotranspiration (mm/day), Kc is crop coefficient, and Ks is water stress coefficient.

The major limiting factors controlling ETo are water availability, amount of energy, and wind speed. These factors depend on many other quantities such as soil moisture, land surface temperature, air temperature, vegetation cover, vapor pressure, wind speed, which vary according to the latitude of the region, the season of the year, time of day, and cloud cover. It requires daily data to provide an acceptable estimation of crop water requirements [3].

Numerous models which varied in complexity were used to calculate ETo. Penman-Monteith method is one of the most accurate models to estimate ETo.

Recently, the modified FAO Penman-Monteith equation presented in the FAO paper 56 has been widely used to estimate both the hourly and daily ETo from climatic data, either measured in the field or official meteorological records [2].

The advancements in satellite, airborne, and ground-based remotely sensed data are extremely being used in agriculture. The use this data was evaluated in many agriculture activities. Many studies investigated the potentiality of remote sensing data in crop monitoring, yield prediction, weed control and pest management, and crop water requirements [4–10].

Oki and Kanae [11] predicted soil water availability for irrigation water management by the use of remotely sensed data. Remote sensing estimation of ET can help detect, map, and provide guidance for crop water requirements in irrigated lands [12]. It is also very beneficial in monitoring water stress in precision agriculture [13].

Remote sensing technique is a powerful, economic, and efficient tool for estimating ETa. The irrigated farms and crop coefficient (Kc) curves may be monitored and developed through remote sensing techniques [14]. Choudhury [15] proposed a method to assess solar radiation, air temperature, and vapor pressure deficit using remotely sensed data. The general approach to estimate physical parameters is using a combination of remote sensing data, ancillary data, and atmospheric data for ET estimation [16, 17]. Accurate characterization of global ET distribution with satellite remote sensing independent of ground observations is a very difficult task. The estimation of ET rates to both Ts and NDVI values derived from remotely sensed data using multiple regression analyses [18].

Ray and Dadhwal [19] used remote sensing and geographic information system tools for estimating seasonal ETc. They generated a ETc map from meteorological observations. They used meteorological data to compute ETo by using FAO Blaney-Criddle method.

The point data of ETo were interpolated using the inverse square distance approach available in ARC/INFO. However, they combined the Kc and ETo maps to generate seasonal ETc map. This technique can cover hundreds of fields.

Dibella et al. [18] tested the predictive power of models based on NDVI and surface temperature to estimate ET. They found a significant relationship with high correlation between temperature and NDVI data and ET.

$$\mathrm{ET} = a1(\mathrm{LST}) + a2(\mathrm{NDVI}) + b \tag{3}$$

where LST is land surface temperature, NDVI is normalized difference vegetation index, and $a1$, $a2$, and b are empirically coefficients.

Several studies have analyzed the relationship between ET flux and NDVI and surface temperature information generated from sensors onboard meteorological satellites [20]. Kalma et al. [21] reviewed most of evapotranspiration estimation by using remote sensing technique as follows.

2 The Water Stress Method

In the previous decade, many researchers studied and evaluated the crop water stress index (CWSI) for scheduling irrigation purposes [22–25]. The CWSI is detecting water stress (WS) remotely through the measurements of a crop's surface temperature (ST). The relation between ST and WS is based on cooling the plant leaves through transpiration. Under water shortage conditions, the crop's temperature will increase due to the increase in plant transpiration.

The prevalent used CWSI method [26, 27] depends theoretically on the observed canopy and air temperature differences as:

$$\mathrm{CWSI} = \left[(T_c - T_a) - (T_c - T_a)_{\min}\right] / \left[(T_c - T_a)_{\max} - (T_c - T_a)_{\min}\right] \tag{4}$$

where the subscripts min refers to unstressed conditions and conditions of maximum stress. The CWSI value ranged from 0 to 1. Zero is no water stress, and 1 represents fully water stress. The CWSI take into account the evaporation from the soil and crop. It could be interpreted as a measure of the amount of ET actually occurring relative to the ETc (Eq. 5).

$$\mathrm{CWSI} = 1 - \mathrm{ETa}/\mathrm{ETc} \tag{5}$$

Moran et al. [16] promoted the water deficit index (WDI) (see Fig. 1). The WDI is a function of ETa to ETc ratio [28]. Yield water stress response depends on crop type

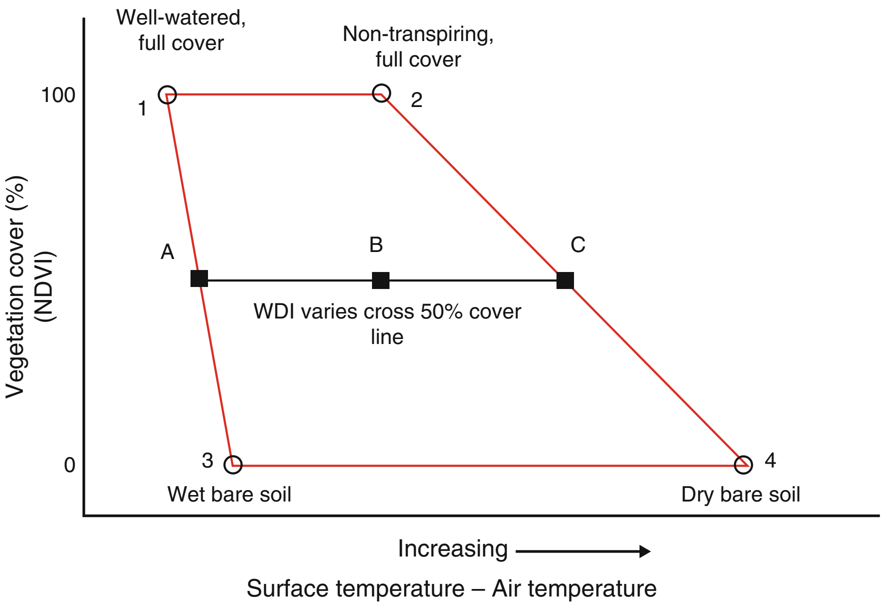

Fig. 1 Represents the WDI trapezoid

and the phonological stage, soil, and climatic conditions. The use of WDI in yield predictions or irrigation management requires estimation of WDI for that particular crop under different soil, growth stage, and climatic conditions [29]. Several satellite data sources were used to calculate WDI such as Landsat, NOAA/AVHRR, and MODIS. El-Shirbeny et al. [4] used NOAA/AVHRR to calculate WDI in the eastern part of Nile Delta, Egypt. A MODIS index based on the spatial relationship between LST and NDVI was evaluated by Garcia et al. [30] to estimate WDI in two sites with different climatic controls on ETa in Andalusia, Spain. It is found that accounting for the spatial variation in Tair is one of the most critical factors to achieve accurate estimation of the temperature vegetation dryness index (TVDI).

The crop started to detect water stress when the WDI is located to the right of the line connecting points 1 and 4 [31].

Although the calculated data is largely common, but it still needs calibration and validation with measuring data.

2.1 Case Study for Water Stress Method

El-Shirbeny et al. [32] applied the WDI on Elsalhyia region in the eastern part of Nile Delta. The results of ETa varied from 0 to 3.7 mm/day. ETa was affected by the changing in CWSI and ETc according to Eq. (5). As shown in Fig. 2, the variation of ETa was observed according to land cover type, crop stage, weather conditions, and water stress conditions.

In arid and semiarid climatic region, ET ranges over a large interval depending on water regimes. Moreover, the variation in one weather parameter immediately affects all the other which are mutually related. This fact makes it difficult to correctly evaluate the ETa [33]. Er-Raki et al. [34] have analyzed the efficiency of three methods based on the FAO-56 Kc approach to estimate ETa for winter wheat under different irrigation treatments in the semiarid conditions of Morocco. ETa (mm/day) is the product of an uptake coefficient (α, mm/day) and available water ($\theta - \theta$WP) when ETa is less than ETc (mm/day): If ETa $<$ ETc, ETa $= \alpha$ ($\theta - \theta$WP), and if ETa $\geq$ ETc, ETa $=$ ETc. ETc occurs when the availability of soil water does not limit transpiration [35], and it could be estimated using the FPM model [2].

3 Surface Energy Balance (SEB) Model

In the period from 1950s to 1960s, there was a belief that evapotranspiration from well-watered land surfaces was mainly controlled through weather data only. However, the variation of vegetation and soil parameters was an obstacle. By the 1980s, the scientists started to care about land surface parameters [21].

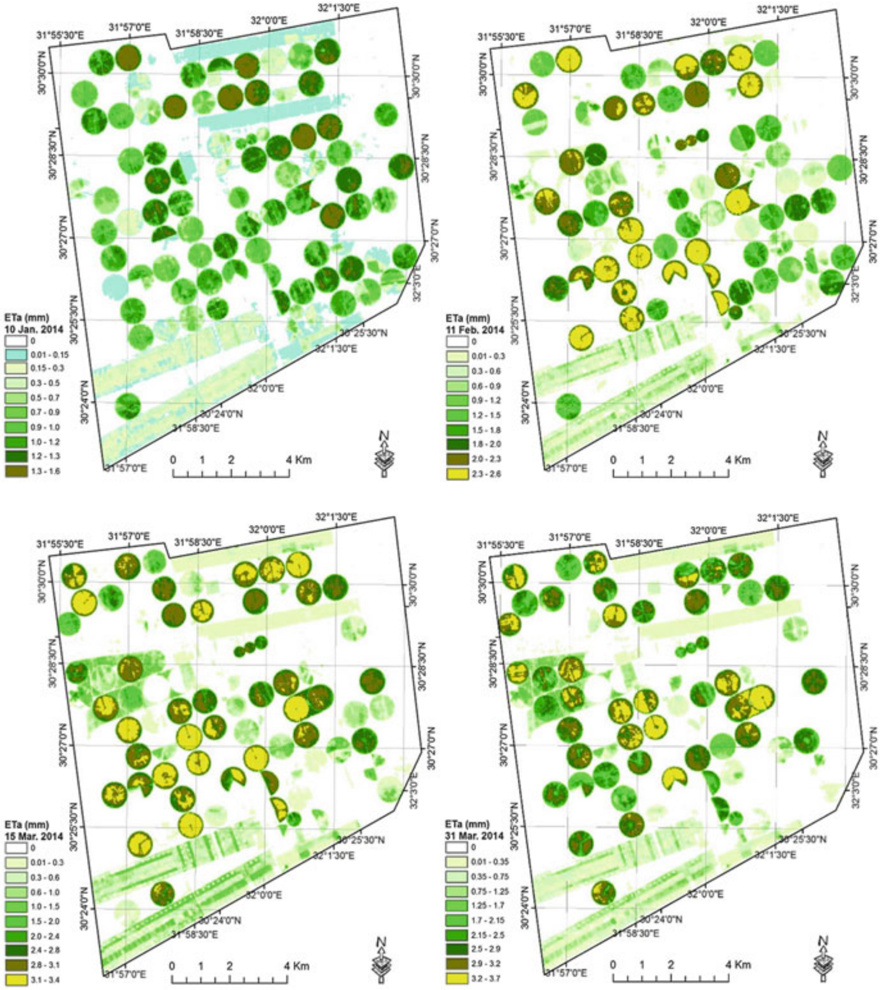

Fig. 2 Shows ETa distribution in the study area

SEB models were divided into two main groups. The first is one-source models, and the second is two-source models. The one-source models do not differentiate between evaporation from the soil and transpiration from the vegetation. Conversely, the two-source models distinguish between fluxes from the soil and the vegetation. The two-source models have been developed for use with incomplete canopies [36] (Fig. 3).

The SEB equation described as:

$$\mathrm{Rn} = \lambda\mathrm{E} + H + G \tag{6}$$

where G is soil heat flux, λE is latent heat flux, Rn is net radiant energy, and H is sensible heat flux. All units are expressed in W m^{-2}.

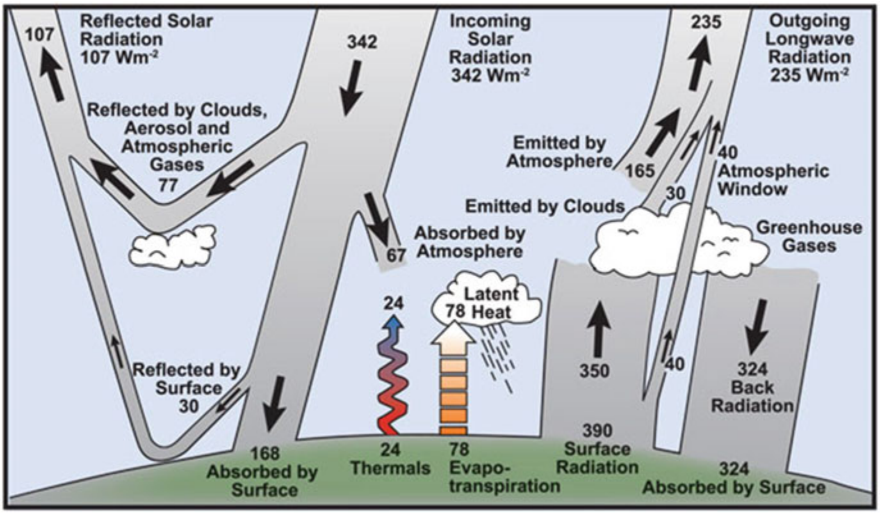

Fig. 3 Explains the physical theoretical concept of energy balance. Source: Kiehl and Trenberth [37]

E is the rate of water evaporation (kg m^{-2} s^{-1}), and λ is the latent heat of water vaporization (J kg^{-1}). All parameters of Eq. (6) are depending on the LST. The Rn term is taken as positive if it is a gain to the surface, whereas the other fluxes are taken as positive if they are away from the surface. Eq. (6) can be prepared as:

$$\mathrm{Rn} - G = \lambda\mathrm{E} + H \tag{7}$$

The part of (Rn $-$ G) is named the available energy. It is required for each SEB scheme. The radiation budget represented by Rn is written as:

$$\mathrm{Rn} = K\downarrow - K\uparrow + L\downarrow - L\uparrow \tag{8}$$

where $K\downarrow$ is downwelling shortwave radiation which depends on atmospheric transmissivity, time of day, day of year, and geographic position, $K\uparrow$ is reflected shortwave radiation which relies on surface albedo (α) and $K\downarrow$, $L\downarrow$ are downwelling longwave radiation (which relies on the atmospheric emissivity which in turn is affected by amounts of atmospheric water vapor, carbon dioxide, and oxygen and by air temperature), and $L\uparrow$ is upwelling longwave radiation (which relies on LST and emissivity). G, which normally ranged from 5 to 20% of Rn during daylight hours, relies on the soil's thermal conductivity and the vertical temperature gradient. LST impacts on all four terms of the energy balance of Eq. (1) and in particular on $L\uparrow$ in the radiation balance of Eq. (8) [21].

SEB models are determined through a solution of the surface energy budget. According to Su [38], three broad SEB approaches were used for determining a real ET. The first one estimates the sensible heat flux (H) and then gets the latent heat flux

(λE) as the remaining of the energy balance equation. This so-called residual method is represented by:

$$\lambda E = Rn - G - H \tag{9}$$

All terms of this equation is described above. The second approach uses a water stress index to estimate the relative evaporation (Er), i.e., the ratio of real to potential evaporation (Ea/Ep).

As some of the SEB models are more complicated, need a large number of surface information, and depend on (Trad = LST) which specific sensors are provided, some attempts have been developed to estimate evapotranspiration. These attempts aimed to extract and estimate number of vegetation indices which are related to and describe the crop status and characteristics such as chlorophyll content, leaf area index, crop height, and vegetation to soil ratio. Using these indices helps to enter into the estimation of Kc that can be used beside ETo to estimate crop ET.

3.1 SEBAL Model

The Surface Energy Balance Algorithms for Land (SEBAL) methodology [39, 40] is applied with surface temperature, surface reflectivity, and NDVI data. The plan describes a one-source cover transfer plan which determines rs, H, λE, and near-surface soil moisture. The plan makes precise use of the detected spatial variability in surface temperature and surface reflectance over a single cloud-free view. SEBAL has been produced at the territorial scale, and it needs some collective ground-level measurements from within the view. $K\downarrow$ and $L\downarrow$ are calculated using a fixed atmospheric transmissivity, a suitable atmospheric emissivity value, and an experimental function of Ta, sequentially. G is determined as a portion of Rn depending on Trad, NDVI, and α [41].

SEBAL estimates the instant value of the sensible heat flux in three principal levels. It firstly recognizes that Taero is not equal to Trad. It concludes that the relationship between Trad and the gradient of surface temperature (ΔT) is represented as Taero. Two extremes are distinguished from the scene: a wet extreme where $\lambda E > H$ and $\Delta T = 0$ and a dry extreme where $\lambda E = 0$ and $H = Rn - G$. Secondly, a scatter plot is achieved for all pixels in the whole scene of broadband α values against Trad. Pixels with high ET rates ($\lambda E > H$) are assumed to have low temperature and low reflectance values, while regions with limited or no ET ($\lambda E \approx 0$ and $H \approx Rn - G$) possess high surface temperatures and commonly high reflectance values. Finally, H can be determined for each pixel with λE as the remaining term in Eq. (4) by using the local surface roughness (zom) based on the NDVI and the assumption of a fixed zom/zoh ratio. The SEBAL plan has been accepted internationally with space-borne and airborne data over approximately horizontal landscapes with and without irrigation [39, 40].

3.2 SEBS Model

The one-dimensional Surface Energy Balance System (SEBS) of Su [38] assesses heat fluxes through space-borne data and available weather data. SEBS needs three groups of input data. The first set consists of α, ε, Trad, LAI, partial vegetation coverage, and the plant height. If vegetation information is not accessible, the NDVI is used as a substitution. The second group involves measurements of Ta, u, real vapor pressure (ea) at a standard height, as well as complete air pressure. The third group of data involves observed (or determined) $K\downarrow$ and $L\downarrow$. SEBS is made up of various separate modules to determine Rn and G and divide the (Rn $-$ G) into H and λE. H is answered using the similarity theory. SEBS has been assessed over farming, grassland, and forested sites and over different spatial scales. It has been used with tower-based data and with Landsat, ASTER, and MODIS space-borne data.

3.3 METRIC Model

The Mapping ET at high Resolution and Internalized Calibration (METRIC) method [42] was obtained from SEBAL. METRIC uses the crop's ETo to describe fully transpiring plants. Extreme (cool/wet and warm/dry) pixels are classified in the given agricultural perspective with the cool/wet extreme relative to a reference crop with its transpiration rate calculated from the Penman-Monteith incorporation equation. Evaporation from the warm/dry pixel is determined with a soil water budget utilizing local weather data. Field studies with irrigated alfalfa in Idaho gave approval to within 5% between METRIC estimations and lysimeter measurements. METRIC also uses the ETo to extrapolate from instantaneous ET fluxes to daily rates.

3.4 ETWatch Model

Wu et al. [43] produced ETWatch model which depended firstly on SEBAL model to calculate ETa. Wu et al. [44] developed the model to be a stand-alone model away from SEBAL. ETWatch is still a local Chinese model, but it started to go through the border outside China. The ETWatch model was applied for the first time outside China last year on Egypt.

3.5 ETLook

Numerous algorithms based on actual evapotranspiration (ET act) mapping using visible, near-infrared, and thermal data exist. The ET mapping of river basins and continents at a moderate resolution (1 km) is vital to detect the spatial heterogeneity of ET and its response to weather events (rainfall or drought). Surface energy balance techniques like RSEB [21], SEBI [45], SEBAL [39, 40], SEBS [38], and METRIC [42] estimate ET act as a latent heat flux (residual term in surface energy balance). The major challenge (or disadvantage) of these techniques is the need for thermal infrared data to assess surface temperature. Thermal infrared data cannot provide reliable estimates of surface temperature under cloudy or hazy conditions, rendering the algorithms less useful in temperate climates. The visible and near-infrared data are used to provide information on vegetation conditions and surface albedo for absorbed solar energy. These parameters are less critical to cloudy conditions, as their variation is not as significant and irregular as the surface temperature.

Verhoef [46] showed that missing data of NDVI and surface albedo could be estimated using observations from other data. ETLook is specially developed to map ET act for large areas on a daily to weekly basis for more extended time periods with a resolution of 1 km. Typical outputs consist of yearly ET act with an interval of 1 week associated with biomass growth and with an interval of 2 weeks for large watersheds. Sufficient detail within the watersheds can be used to monitor local differences in water management.

ETLook is a newly developed algorithm to compute ET act of large areas using soil moisture estimates from the passive microwave sensor AMSRE. A drawback of the passive microwave sensor data is the low resolution of the data. The global soil map was used to downscale the soil moisture from the AMSRE sensor.

ETLook uses moderate resolution VNIR images from the MODIS sensor for defining surface albedo and vegetation cover. Regular weather measurements (wind speed, air temperature, and relative humidity) at a number of stations inside the study area are used to conclude the current meteorological conditions. Because the main driving power of the process is soil moisture derived from passive microwave sensors, the algorithm is appropriate under all weather conditions. Therefore the algorithm can be used operationally, making it useful for real-time hydrological modeling and operational land surface models.

3.6 A Case Study for SEB Method

A case study on Nile Delta, using METEOSAT measurements, was studied by Bastiaanssen et al. [39, 40].

The water balance models usually compute ET from vegetation and bare soil based on the unstressed transpiration and bare soil potential evaporation. Empirical reduction factors related to actual soil moisture content and salinity are then applied to correct for less optimal soil water and salinity conditions. When this category of models is locally calibrated against soil water, groundwater table variation, and return flow, they give reasonable estimates of regional evaporation [39, 40].

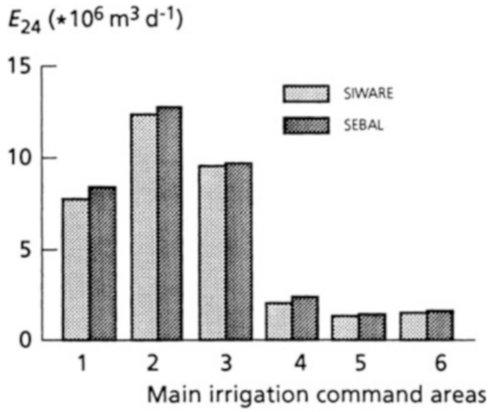

Fig. 4 Relative difference in daily evaporation between SIWARE and SEBAL for the six main irrigation command areas. The numbers represent the (1) Ismaileya, (2) Rayah Tawfiki, (3) Mansureya, (4) Sharqaweya, (5) Bassoseya, and (6) Abu Managa areas [39, 40]

Pelgrum [47] studied the water consumption of the irrigated Nile Delta. An attempt was made to determine the surface energy balance for each daytime hour using METEOSAT. The 24-h SEBAL evaporation rates obtained for the Nile Delta were compared by Bastiaanssen et al. [17] with the 24-h evaporation figures obtained from the calibrated hydrological model SIWARE [48]. At the time of image acquisition in August 1986, maize, cotton, orchards, and vegetables were grown on the irrigated Nile Delta. The SIWARE network in the Eastern Nile Delta governorates is 82 irrigation units. The total gross irrigated area covered by the 82 irrigation units is 695,000 ha. The results for six irrigation commands are demonstrated in Fig. 4. The relative error of the command areas DE24/E24 (SIWARE-SEBAL)/SIWARE appeared to be small (see Fig. 4), with a mean for the six cases of DE24/E24 = −0.08 and SD = 0.06 [39, 40].

A further downscaling allows extension of the comparative study to the level of each of the 82 irrigation units. The average difference between SEBAL and SIWARE for the individual irrigation units was DE24/E24 = −0.08 (SD = 0.26). With the exception of units 15, 19, and 27, the results were encouraging (see Fig. 5). For all 82 irrigation units together, daily values of SEBAL were found to be 5.1% higher than the SIWARE predictions. A 5.1% deviation is within the allowable range of the SIWARE model accuracy (10% on an annual basis). Hence, the error in evaporation from remote sensing increases as one goes from extensive composite regions (5.1% deviation) via command areas (8% deviation ±6%) to isolated irrigation units (8% ± 26%) [39, 40].

4 ET MODIS Products

The MOD16 global ET/LE/ETc/potential LE datasets are consistent 1-km^2 ET databases. It covers the 109.03×10^6 km^2 global vegetated land areas, every 8-day, monthly, and annual periods from 2000 to 2014.

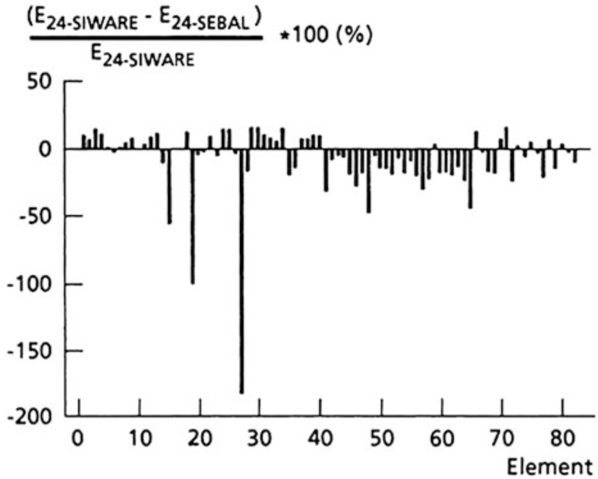

Fig. 5 Determination of the relative deviation DE/E for each of the 82 irrigation units of SIWARE on August 5, 1986. The average value turned out to be DE/E = −0.08 ± 0.26 [39, 40]

The MOD16 ET datasets are estimated using Mu et al.'s developed ET algorithm [49] superior to the previous Mu et al.'s article [50]. The ET algorithm is calculated according to the Penman-Monteith equation [51]. Surface resistance is a sufficient resistance to transpiration from the plant canopy and evaporation from the land surface.

Physical ET involves evaporation from wet and moist soil, from rainwater prevented by the canopy before it touches the soil and the transpiration through stomata on crop leaves and stems. Evaporation of water appropriated by the canopy is a highly significant water flux for ecosystems with a high LAI. Canopy conductance for plant transpiration is estimated by applying LAI to scale stomatal conductance up to canopy level.

For several plant varieties during growing periods, stomatal conductance is regulated by VPD [50] and daily minimum air temperature (T_{min}). T_{min} is used to control latent and dynamic growing seasons for evergreen biomes. High temperatures are often followed by high VPDs, directing to the incomplete or full closing of stomata.

4.1 A Case Study for ET MODIS Calibration Under Egyptian Conditions

A case study on Nile Delta was investigated by El-Shirbeny et al. [52]. The flowchart of the used methodology is shown in Fig. 6. The MODIS16 ET data were validated under Egyptian conditions. The changing in weather condition and/or changing in vegetation cover means changing in ETa. The mean of ETa according to MODIS

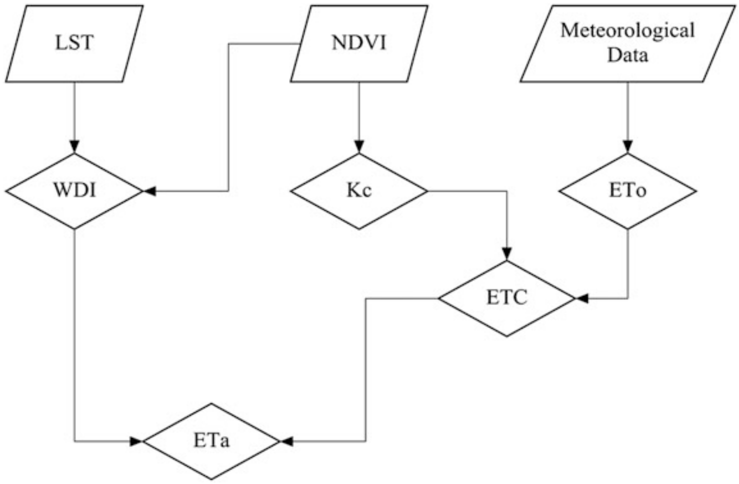

Fig. 6 Explains the method of ET MODIS's calibration

product was changed, and the results were 45.6, 50.2, and 45.4 (mm/month) at years 2002, 2007, and 2013, respectively. On the other hand, the mean of ETa according to estimated method changed, and the results were 56.6, 62.7, and 57.4 (mm/month) at years 2002, 2007, and 2013, respectively (Fig. 7). The northern part of the study area consumes water more than the southern part because of rice cultivation in summer in this part which consumes a lot of water; on the other hand, rice cultivation is not allowed in the southern part. In the last decade, the government started developing field irrigation systems in the northern part of Nile Delta shared with the German government.

From Figs. 8 and 9, there are two seasons; the first one starts from the beginning of June and finishes at the end of September and the second from the beginning of November to the end of April. On the other hand, May and October almost are in-between seasons. The maximum ETa according to MODIS product in 2002 and 2007 were 70.7 and 84.2 (mm/month) in August, respectively, but the minimum were 25.8 and 27 (mm/month) in October and June, respectively. In 2013, the minimum of ETa was 23 (mm/month) in May, and the maximum was 76.1 (mm/month) in July.

On the other hand, the maximum ETa according to WDI in 2002 and 2007 were 90.5 and 98.8 (mm/month) in August, respectively, but the minimum were 34.1 and 41.3 (mm/month) in May and November, respectively. In 2013, the minimum of ETa was 35.4 (mm/month) in May, and the maximum was 94.8 (mm/month) in July. Linear relation between ETa based on MODIS product and ETa based on estimated method was established with R2 as high as 0.86 (Fig. 10).

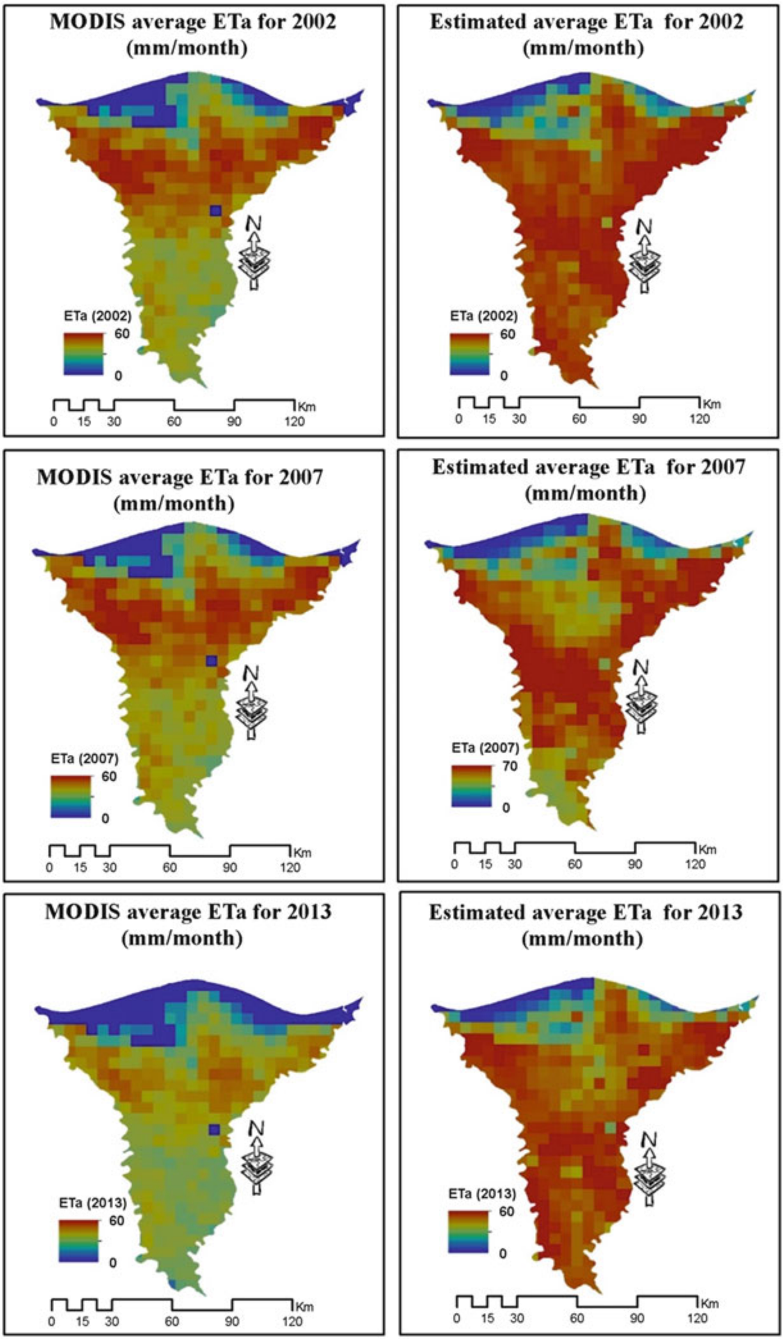

Fig. 7 Annual average ETa maps according to MODIS product and estimated method at years 2002, 2007, and 2013 [52]

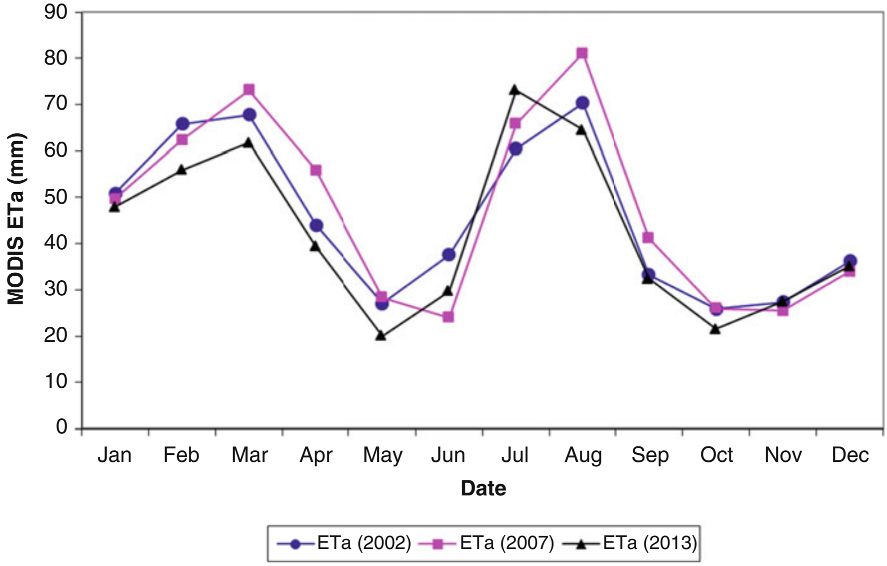

Fig. 8 Monthly MODIS ETa product (mm/month) at years of 2002, 2007, and 2013 [52]

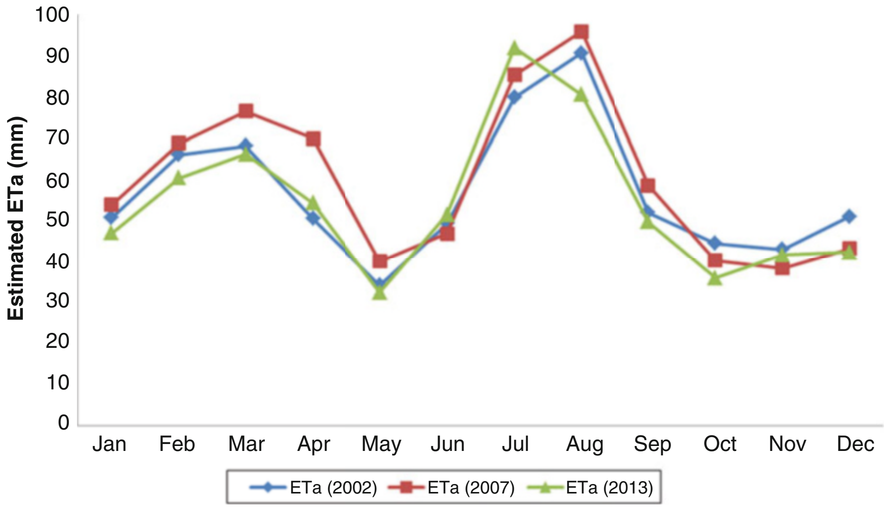

Fig. 9 Monthly estimated ETa (mm/month) at years of 2002, 2007, and 2013 [52]

5 Conclusion

Crop water consumption has to be estimated with a high level of accuracy to save water and to maximize water unit uses. The limitation of water resources and scarcity of water in arid and semiarid regions put many countries in critical situation. Dealing

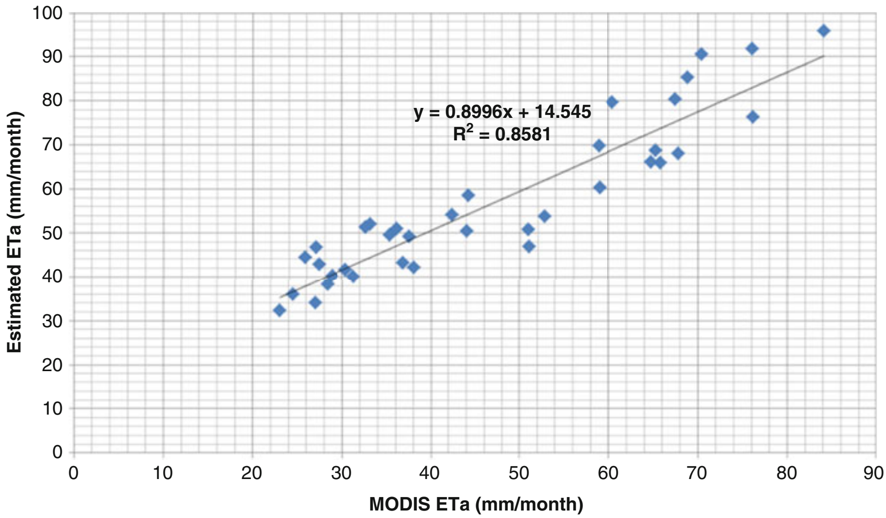

Fig. 10 The relation between MODIS ETa product and estimated ETa [52]

with water shortage must be planned, and good models were needed to estimate water consumption. Space-borne technologies are a good and powerful tool but need calibration and validation. Maybe in the future, it may be a stand-alone technology, but first, we must deal with it using new methods. It must have its own methodologies.

6 Recommendations

Remote sensing techniques are powerful on the large scale if it is used after calibration and validation. Developing the old irrigation water consumption calculation methods is necessary to be more accurate. Numerous ET calculation models are so complicated and it needs to be simplest.

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Crop Water Requirements and Irrigation Efficiencies in Egypt

M.A. Mahmoud and A.Z. El-Bably

Abstract Water scarcity is the major factor that limits the ambitious hopes to expand and increase the agricultural area to meet the present gap between food production and consumption. In areas like Egypt, located in an arid/semiarid region, where vegetation water requirement represents an important fraction of the total water consumption, the pressure of population growth and increasing domestic demand and other sectors for water represent other challenges for the agricultural sector. Agricultural activity in Egypt consumes from 80 to 85% of water resources. To meet these challenges, good water governance, which aims to reduce losses and increase benefits per unit of water, should be adopted. One of the most important ways to improve water use efficiency and optimize plant production is to provide crops only with the water they *need* based on the climate-plant-soil relationship.

There are many ways to increase water use efficiency, such as improving irrigation canals in old land to increase the conveyance efficiency; using a pressurized irrigation system in new reclaimed lands, in addition to water management practices on farm like laser land leveling; using the raised bed irrigation method, irrigation scheduling, intercropping, crop intensification, and mulching; using soil amendments and organic fertilizers; and using short and drought tolerance varieties. The integrated management for soil, water, and crops is very important to maximize crop yield and water productivity, so in this chapter, the author will provide an overview on how to maximize crop yield with minimal water use.

Keywords Egypt, Irrigation efficiency, Water management, Water requirements

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Contents

1 Introduction

Due to the growing and more affluent population, over the coming decades, the agricultural product demand will increase rapidly, with serious implications for the demand for agricultural water. Symptoms of the scarcity of water are increasingly apparent, threatening food production sustainability and ecosystem services. Improving water productivity will shrink the extra water requirements in agriculture [1]. Improving water productivity in rain-fed and irrigated agriculture decreases the need for extra water and is thus a critical reaction to growing water scarcity [2].

Egypt is located in North Africa in an arid and semiarid region. Water resources are limited, and the Nile River is the main source of freshwater. Egypt's population is growing rapidly, so the per capita water availability is continually decreasing. However, food production and industrial activities and productions should increase; therefore, water demand is expected to continuously increase for agriculture, industrial, and domestic sectors. Egypt is one of the most vulnerable countries to the impact of projected climate change [3]. This will cause more pressure on water resources to meet expected increases in crop water requirements, in addition to the new areas of agricultural production that is expected to continue to grow. Implications could include a reduction in crop yields. All of these challenges lead scientists and policymakers to search about how to maximize irrigation efficiency.

Agriculture plays a vital role in Egypt's economy contributing to about 15% of the gross domestic product and employing about 30% of the national workforce [4]. Over 95% of Egyptian agricultural land lies within the Nile Valley and Delta. There are three cropping seasons in Egypt, the summer season (April to October) and late summer season (July until October) and the winter season commencing from November to May. The main summer crops are cotton, maize, and rice, and the dominant winter crops are wheat, sugar beet, berseem (Egyptian clover), and broad beans. In addition, vegetable crops such as potato, tomato, and others are cultivated in all seasons. Sugarcane is growing mainly in Upper Egypt, while rice cultivates in the North Nile Delta. There are several areas in the West and East Delta which grow fruits and medical and aromatic plants.

2 Water Resources and Usage in Egypt

2.1 Water Resources

Water resources in Egypt are limited as follows [5]:

Nile River is the main source of water in Egypt. The Nile water comes from outside Egypt's borders; Egypt's per share according to the Nile water agreement with Sudan allocates 55.5 billion cubic meters (BCM)/year to Egypt.

Rainfall in Egypt happens only in the winter season as scattered showers. The effectively annual average amount of rainfall water is estimated to be 1.3 BCM/year. Due to the high temporal and spatial variability of the rainfall, this amount cannot be considered a reliable source of water.

Groundwater exists in the Sinai and the Western Desert aquifers that are generally deep and nonrenewable. The total amount of groundwater has been estimated to be about 40,000 BCM. However, the current extraction is estimated to be only 2.0 BCM/year. This may be due to the great depth of these aquifers up to 1,500 m and degradation of water quality at increasing depths.

Shallow groundwater in the Nile aquifer cannot be considered as a distinct source of water. Seepage losses from irrigation and drainage canals and the Nile and percolation losses from irrigated lands are the source of recharging this aquifer. This water must not be added to Egypt's water resources. Therefore, it is considered as a reservoir in the Nile River system with a huge capacity but rechargeable live storage of only 7.5 BCM/year. The current suction from this aquifer was estimated at 6.5 BCM in 2013.

Desalination of seawater in Egypt has been given little priority as a water resource due to the high cost of the treatment compared to other sources. There are several desalination practices on the coast of the Red Sea area to supply resorts and tourist villages with adequate clean water. Other desalination units of groundwater have been constructed at numerous locations in Sinai as a water source for Bedouins.

Treated domestic sewage is being reused as a source of irrigation with or without mixed freshwater. The total quantity of reused treated wastewater in Egypt was estimated to be 0.3 BCM in 2013.

Reuse of nonconventional water sources such as treated sewage water and agricultural drainage water cannot be added to Egypt's freshwater resources. Using these sources is a recycling process of the fresh Nile water which has been previously used. The total amount of reused water was about 13 BCM in 2013. The reuse practices increased the overall system efficiency as comparable to the efficiency of new irrigation systems.

2.2 Sectoral Water Demand

Due to a rapid increase in population and improving living standards as well as the industrialization policy encouraged by the government, water requirements in Egypt are increasing continuously. Water demand can be characterized in classes representing the major items on the demand side of the water balance according to [5] as the following:

- *The agriculture sector* represents the largest consumer of water resources; it consumes more than 85% of Egypt's per share of Nile water yearly.
- *Municipal water requirements* include water needs for major urban and rural villages. Municipal water demand was estimated to be 10 BCM in 2013. Municipal water production is diverted from two sources, surface water and groundwater, which represent about 83% and 17%, respectively, of total municipal water demand.
- *The industrial sector* is vital to social and economic progress. The water requirement for the industrial sector was 2.50 BCM/year during the year 2013.

In summary, there exists a 20 BCM/year gap between the availability and the demand for water. This gap is overcome by water recycling. The overall efficiency of the Nile system in Egypt is about 75%. By the year 2020, water requirements are expected to increase by 20% (15 BCM/year) [5]. The main consumer of freshwater is irrigated agriculture. Globally, irrigated land contributes to more than 40% from food production [6]. Water availability is a major challenge facing agricultural sustainable development in Egypt. Water resources in Egypt are highly limited [7]. Renewable water resources are estimated at 57.3 BCM/year, almost 97% of which originates from the Nile River [8].

3 Water Scarcity in Egypt

Freshwater is an increasingly limited resource [9]. As world population increases and standard of living is improved, the water need is expected to increase. Huge areas worldwide will suffer from water scarcity during the growing seasons, and natural environments may be affected [10]. The available per capita of freshwater in Egypt has fallen from 1,893 m^3 in 1959 to 900–950 m^3 in 2000 [11]. Further, the average per capita of the available water in Egypt reached about 710 cm^3 in 2014, and it is expected to reach to about 350 cm^3 by 2050 [12]. In Egypt, the water shortage amounts to 13.5 BCM/year and is expected to increase continuously. This water shortage is remunerated by using drainage reuse which subsequently declines water quality. By 2025 the water shortage is expected to be 26 BCM/year in the case of using the same current policies [13].

The economic and political factors are the major driving forces to water scarcity in Egypt, in addition to the population growth, physical variables (land expansion and water resources), and social factors (quality of life, poverty, crop pattern, consumer's behavior, and imbalanced distribution of water) [14]. Rapid population increase, increased urbanization, food security concerns, and the expected potential climate change impacts are increasing the attention given to more efficient and sustainable water management in Egypt [15]. The major challenge facing water resources in Egypt is the limited availability of supply resources. There are many challenges found on the demand side, such as water surface evaporation loss, seepage losses, evaporation losses, and infiltration losses from aquatic weeds in canals and agricultural lands, as well as imperfection in control gates, the efficiency of water distribution operation, expansion of agricultural lands such as sugarcane and rice areas, and extra pumping rates from wells and lack of extraction control in deep groundwater, use of sprinkler irrigation, damages in drip irrigation systems, low distribution efficiency in drinking water network, and weak public awareness in domestic water division [13].

4 Crop Water Requirements and Irrigation Efficiencies in Egypt

Water requirements for various crops depend mainly on evapotranspiration which is affected by weather parameters, management, and environmental factors. Also water requirements for the same crop differ from one place to another depending on the agro-metrological zone, irrigation system, variety, and management. Data in Tables 1, 2, and 3 represent the optimum water requirements as m^3/feddan for winter, summer, and nili (late summer) crops, respectively, which are grown in the main three regions in Egypt (Delta, Middle Egypt, and Upper Egypt) under surface irrigation. Application efficiency reached 80% at farm level according to [16].

Irrigation efficiency mentions to the amount of water removed from the source of the water that is used by the crop. This value is determined by water distribution characteristics, management of irrigation system, crop water use rates, and soil and weather conditions. Ideal water efficiency for crop irrigation means reducing losses in evaporation, runoff, or subsurface drainage and however increasing production [17].

Utilization efficiency for water resources in Egypt is very low. Large amounts of irrigation water are being lost during water transmission from Aswan High Dam to fields. The recorded data indicated that the irrigation water at the Aswan Dam has increased by about 20% from 2000 to 2009. However, the losses during the transferring irrigation water from Aswan High Dam to fields due to evaporation and transpiration have increased by 30.90% and 35.46% in 1985 and 2005,

Table 1 The optimum water requirements for winter crops (m^3/feddan) at farm level of the main three regions in Egypt on 2016 [16]

Winter crops	Delta	Middle Egypt	Upper Egypt
Wheat	1,984	2,070	2,727
Broad bean	1,779	1,864	2,550
Barley	1,511	1,492	2,040
Fenugreek	1,689	1,740	2,379
Lupines	1,216	1,100	1,511
Chickpeas	1,689	1,740	2,379
Lentil	1,156	1,015	1,395
Temp. clover	1,160	889	1,237
Clover	2,741	3,028	3,974
Flax	1,511	1,492	2,040
Onion	1,910	1,947	2,520
Sugar beet	2,384	2,581	–
Garlic	1,910	1,947	2,520
Medical and aromatic crops	1,600	1,616	2,209
Vegetables	1,601	1,458	1,956
Miscellaneous crops	1,723	1,731	2,321

N.B: 1 feddan = 0.42 ha

Table 2 The optimum water requirements for summer crops (m^3/feddan) at farm level of the main three regions in Egypt on 2016 [16]

Summer crops	Delta	Middle Egypt	Upper Egypt
Cotton	3,945	4,351	5,591
Rice	5,200	–	–
Corn	2,754	3,001	3,814
Sorghum	2,832	3,102	3,952
Soybean	3,034	3,324	4,235
Sugarcane	7,643	8,642	11,443
Sesame	2,913	3,191	4,065
Ground nut	2,913	3,191	4,065
Onion	3,864	4,230	5,386
Henna	4,450	4,900	6,365
Chatters	5,229	5,951	7,829
Sunflower	2,277	2,539	3,288
Green fodder	2,429	2,709	3,507
Medical and aromatic crops	4,035	4,474	5,782
Vegetables	2,970	3,306	4,290
Miscellaneous crops	3,702	4,104	5,258

N.B: 1 feddan = 0.42 ha

respectively, and reached 33% in 2010. The efficiency of the field irrigation system is about 50% [18].

Table 3 The optimum water requirements for nili crops and fruits (m^3/feddan) at farm level of the main three regions in Egypt on 2016 [16]

Summer crops	Delta	Middle Egypt	Upper Egypt
Corn	2,450	2,603	3,215
Sorghum	2,450	2,603	3,215
Onion	3,088	3,295	4,183
Sunflower	2,142	2,270	2,825
Vegetables	2,730	2,899	3,582
Miscellaneous crops	2,785	2,960	3,679
Fruits			
Evergreen	5,047	5,583	7,250
Deciduous	5,632	6,408	8,432

N.B: 1 feddan = 0.42 ha

5 Sustainable Water Use and Management to Cope with Water Scarcity

In order to secure the stability of food production globally under climate change condition [19], increasing water use efficiency in agricultural systems is very important for agricultural production, industrial and municipal purposes, and ecosystem health. Egypt can utilize the available quantity of water resources through expansion of less-water-consuming crops and reducing areas of high-water-consuming crops like rice and sugarcane, as well as enhancing the water supply system efficiency by detecting leakages, improving irrigation conveyance and distribution efficiency, and, in addition, introducing water conservation tariffs which might contain several kinds of crop or land taxes, water pricing, production charges, or subsidies for conservation of water and introducing public awareness for the society of a new water culture based on conservation principles [14]. The Egyptian national food security strategy is influenced particularly by growing cash crops on new lands, decreasing the areas of sugarcane and rice, increasing the cereal production on old lands, and giving attention to positive effects of the market-oriented economy [20].

Strategies for water saving in agriculture do not only include irrigation practices, but they extend into the other areas affecting on-farm water application including cultivation methods, varieties, and benefits of land leveling [21, 22]. Other water-saving strategies include covering canals with effective reaches, the timing of land irrigation, removing aquatic weeds in water passes, and turning sugarcane areas to beet in old lands. In addition, suitable pumping rates from deep groundwater aquifers using high-efficiency irrigation systems like sprinkler and drip irrigation systems in newly reclaimed lands were suggested as proposed planning alternatives which would completely eliminate Egypt's water shortage in 2025 [13].

There are many strategies to sustain water use and management in the agriculture sector to reduce water scarcity. These strategies are related to irrigation system management, farm practices, and breeding programs.

5.1 Increasing Irrigation Efficiency on Mesqa and Marwa level in Old Lands

The irrigation system in Egypt starts from the Aswan High Dam to the confluence of the two river branches Rosetta and Damietta with the Mediterranean Sea. It is a very complicated system; water passes many and through principle canals, main canals, branch canals, tertiary canals called Mesqa, and a field ditch that is called Marwa. The overall irrigation efficiency in Egypt is very low about 40–60%, due to evaporation, seepage, deep percolation, and transpiration from aquatic crops in irrigation canals. The cultivated area in Egypt is only 7.9 million feddan, about 3.3% from the total land area. This area is distributed as 9% oases and deserts, 12% new lands, and 79% old lands. The irrigation efficiency in the old land which has the main cultivated area in Egypt is about 40–60%. Thus, it is essential to improve the irrigation system and hence efficiency in the old land [23]. Several changes have the potential to reduce surface evaporation from free water, seepage, and aquatic weeds so irrigation efficiency increases such as changing earth field ditches called Mesqas to canals or pipelines, changing water abstraction from multi-point in the Mesqa to one point in the top end of the raised Mesqa, and changing the control from upstream to downstream [14].

Rice yield increased by 11.4% under Mesqa improvement. This increase is due to good water availability by the equity distributing between the tail and head of the Mesqa. The irrigation water applied was decreased as mean of 15.55% and water use efficiency was increased [24]. The Irrigation Improvement Project (IIP) was one of the main irrigation projects for using modern methods in land networks and on-farm development. Land leveling/tillage and rehabilitation of main and branch canals especially Mesqas (replace earth Mesqa with pipeline) were included. This promotes cooperation between the irrigation directorate and farmers by forming water user associations in irrigation distribution management [25]. Integrated Irrigation Improvement and Management Project (IIIMP) is expected to achieve additional positive effects on water distribution, quality, quantity, equity, timeliness, and water savings by replacing earth Marwa with pipeline and other technical assistance required for establishing water boards and water user associations [26]. Under the World Bank-funded IIP from 1996 to 2006 and IIIMP, the main objective of the two projects is improving the management of irrigation and drainage in the Nile Delta of Egypt. The specific objectives of the irrigation modernization are to enhance equitable water distribution, water quality, and water use efficiency and ultimately to increase agricultural production and decrease poverty. Irrigation improvements under the IIP have taken place at the Mesqa level, Mesqa for the tertiary level of irrigation canals, while IIIMP has taken place at the Marwa level, the term Marwa is used for the infrastructure at farm levels. Modernization of the Marwas under IIIMP is ongoing currently at selected areas. Seepage losses from the Mesqas are reduced by the piping of the tertiary canals, in addition allowing for pressurized water delivery. Similar improvements have newly been made to selected Marwas under IIIMP [27].

5.2 Using Pressurized Irrigation System in Newly Reclaimed Lands

Using modern irrigation system such as sprinkler and drip irrigation system in newly reclaimed lands is one of the most common strategies to cope with water scarcity in Egypt, because these systems save irrigation water and maximize efficiency. Moreover, these techniques can help overcome unsuitable soil, topography, climate, and water quality conditions. Drip irrigation is the best irrigation system when using saline water because it causes the highest irrigation application efficiency. Moreover, it causes less salt accumulation in the soil, prevention of leaf burn, and short irrigation frequency which prevents the soil from drying. Also, it helps to avoid higher peaks in salt concentration through continuous leaching of salts away from the wetted area accumulating at the wetting edges away from the active root zone [28]. Drip irrigation saves about 30–50% of irrigation water compared to surface irrigation, moreover reduces waterlogging and salinization, and achieves irrigation efficiency up to 95% [29].

Irrigation application efficiency can be designed as 60%, 75%, and 90% for surface (border, basin, and furrow), sprinkler, and drip irrigation, respectively [30]. Using drip and sprinkler irrigation systems in the newly reclaimed land in the desert is required, and it is prohibited to use flood irrigation in these places because of the high permeability of these soils and low water holding capacity [14]. Sprinkler irrigation saves water, time, and financial costs and can provide additional income generation [31]. Drip irrigation could be used as a possible solution for the problems of water scarcity [32].

5.3 On-Farm Water Management Practices to Maximize Water Productivity

Many agricultural practices on farm level could be applied in Egypt and could enhance productivity by implementing the following:

Laser land leveling is a very important practice to enhance water use efficiency and rationalize irrigation water through decreasing losses such as runoff and deep percolation, especially for high-water-consuming crop such as rice and sugarcane. Land leveling prevents water logging and water stress, and also it reduces water runoff, so the application uniformity is enhanced which thus contributes to increased crop production [33]. Laser land leveling reduces deep percolation and runoff by 8% and 24%, respectively, compared to non-leveled fields in Tajikistan [34]. Land leveling has a positive influence on the reduction of water applied because it minimizes surface runoff especially of the highest-water-consuming crops like sugarcane and rice [14]. Mechanization management in soil preparation and laser leveling with transplanting could decrease irrigation water applied for rice by 29% and increase water use efficiency [35].

Raised beds is one of planting methods as another on-farm practice that is effective to save irrigation water. Raised beds were originally used in row crops, but nowadays there are many researchers that have indicated the importance of this planting method to apply on non-row crops like rice, clover (berseem), and wheat. Growing berseem on raised seed beds is a successful practice to save irrigation water by 18% and, moreover, increase fresh and dry yield from 20 to 26% and 23 to 28%, respectively, compared to the traditional growing on flat soil [36]. Raised bed planting method with deficit irrigation saved about 1,600 and 1,500 m^3 water/ha and increased water productivity by 30 and 45% for maize and wheat, respectively, compared to farmers' practice with full irrigation practice [37]. Transplanting rice in bottom of beds can save a large amount of irrigation water ranging from 27 to 38% and increased irrigation water productivity by 56–66% without yield reduction or even slight yield increase [38–40].

Alternate furrow irrigation is one of the most applicable on-farm practices to reduce irrigation water applied and irrigation costs and increase crop yield, so it improves water productivity. Corn yield increased and irrigation efficiency improved with applied alternate furrow irrigation practice [41–43]. Alternative furrow irrigation technique saved about 22% and 42% from applied irrigation water compared to irrigating each furrow and basin irrigation, respectively, for cotton plants. This technique can increase water productivity without any yield reduction [44]. Alternative furrow irrigation can save about 30% compared to traditional furrow irrigation, in addition to slight increased on cotton yield [45].

Alternative root drying or partial root-zone drying can save a considerable amount of irrigation water especially for vegetables and fruit plants under drip irrigation system. This practice increased water use efficiency by 40% and increased yield by 43% per vine of wine grapes compared to traditional drip system [46]. Partial root-zone drying enhances irrigation water with respect to controls [47]. Applying alternative root drying strategies for potatoes and tomatoes could save 20–30% of irrigation water compared to fully irrigated plants. This technique increases significantly the potatoes marketable yield by 15% due to better size distribution [48].

Deficit irrigation, that is irrigated plants with amounts of water less than that required for full irrigation without any reduction in crop yield. Deficit irrigation allows for better water use efficiency compared to full irrigation, as presented experimentally for many crops [49, 50]. Also water-saving strategies can be used such as regulated deficit irrigation, that is, to irrigate in drought-sensitive stages of growth with minimum amounts of irrigation water [19].

Surge irrigation is applied as cycles of on and off from the stream which is delivered to the head of furrows. This technique saves a large amount of irrigation water and improves irrigation water productivity [51, 52]. In Egypt this technique is very important to maximize water productivity especially in heavy clay soils. On and off cycles give an appropriate chance to close soil cracks and decrease deep percolation. Surge irrigation practice reduces the irrigation water necessary during application by 14.5% and 18.6% for wheat and maize, respectively, while yield increased by 7% and 7.87% for wheat and maize, respectively [53]. Irrigation efficiency increased by 11.66% and 28.37% for the cutback and surge irrigation methods, respectively [32].

Schedule irrigation is applying a metric that identifies when to irrigate and by how much. It is very important to know the accurate crop water requirement depending on crop stages. Schedule irrigation leads to enhancing water use through decrease on on-farm water losses due to evaporation and can enhance crop yield.

Nighttime irrigation is important to improve water productivity through reducing evaporation during daytime hours and produce healthy plants. Farmers should irrigate crops at night, because it reduces losses of evaporation which are carried out during sunlight and tail end losses to drainage system if there is no abstraction of freshwater during night time [14].

Supplemental irrigation is one of the important strategies that is used in arid areas through applying small amounts of irrigation water to winter crops that are normally grown under rain-fed conditions [54]. Many of the agronomic practices for improving the efficiency of water use rain-fed systems and depend on reducing water losses by runoff, soil evaporation, deep percolation, and competing weeds. Supplemental irrigation technique is used to overcome periods of low rainfall or high temperatures, and it is suggested to improve crop production [19].

5.4 Sustainable Use of Groundwater

According to MWRI [5], extraction from deep groundwater aquifers in Sinai and the Western Desert is estimated to be only 2.0 BCM/year and 6.5 BCM in 2013 from shallow groundwater in the Nile aquifers.

The quality of the groundwater in the Nile areas especially in North Nile Delta is expected to be affected strongly by the impact of sea level rise combined with changes of Nile River flows, which will lead to an increase in the salinity levels of the groundwater [55]. In addition, current and future human activities, especially extensive and unplanned groundwater abstraction, are resulting in degradation of the availability of groundwater resources. Serious negative socioeconomic impacts can follow as a consequence. In the Nile Delta, extensive groundwater abstraction is also a very significant factor that increases seawater intrusion, and groundwater wells which were beyond salinization zones in the past are consequently showing upcoming of saline or brackish water [56].

There is a gap in information and implementation of groundwater resources development sustainability and protection of the environment in Nile Delta as a regional strategy. In addition, there is deficit knowledge about groundwater quality deterioration [57]. So, detailed studies should be applied to include all groundwater resources and data on quality deterioration in the Nile Delta aquifers, as well as hydrological studies of all groundwater resource aquifers in whole Egypt including Sinai and the Western Desert to define the available quantities and the secure yield of abstraction for sustainable use.

5.5 Reuse of Drainage Water

The importance of using nonconventional water resources like the reuse of drainage water, treated wastewater, and desalination of brackish and seawater are becoming increasingly important around the world particularly in water-scarce areas. Optimization of the use of water resources in Egypt is implemented via recycling industrial and domestic wastewater, reuse of drainage water, and desalination [14]. The reuse of agricultural drainage water in Egypt is considered as an integral addition to the water sources. Pumping stations of the government and farmers' small diesel pumps extract water from drainage ditches and put it directly in the irrigation canals to reuse in agriculture irrigation; these actions have increased the country's water resources by 20% [58]. Water shortage in Egypt is 13.5 BCM/year and it expected to increase continuously. This water shortage is compensated by the reuse of drainage which deteriorates the water quality [13].

5.6 Modification of Cropping Pattern

Using the optimum cropping pattern which achieves the maximum water return from the unit of water, it is a main factor to cope water scarcity in Egypt. Moreover it should have priority in the next years especially cropping patterns which save irrigation water. Expansion of less-water-consuming crops and reducing areas of high-water-consuming crops like rice and sugarcane is one of the encouraged strategies to cope with water scarcity in Egypt [14]. The main problem for water distribution engineers in Egypt lie in the free cropping pattern. These difficulties resulted from the randomized distribution of crop along the network canals, with their different areas [7].

Planting drought- and salt-tolerant crop species as amaranth, Andean lupin, and quinoa may result in more resilient high-value cash crop products and crop rotations [19]. As water scarcity is considered a main limitation for agricultural expansion, high efficient crop patterns are recommended to minimize the consumed water amount [7].

6 Breeding for High Water Use Efficiency Crops

Breeding programs for the different crops always have two strategies to cope with water shortage. The first strategy is to introduce short-duration varieties especially for a high-water consumer such as rice. The Egypt's rice program developed many rice varieties such as Giza 177 and Sakha 102 which require less water consumption. These varieties reduce the duration from seed to seed by 40 days [59]. Replacing long-duration varieties by new short-duration varieties is an encouraging way to save irrigation water in Egyptian agriculture. Rice is a great example for short-duration varieties. Maize, wheat legumes, and cotton are other examples. The reduction in the number of days means a reduction in a number of irrigations and consequently in the water quantity used [14]. Cultivating short-duration rice varieties saved about 18% of the water deliveries needed compared to long-duration rice varieties [35].

The second strategy is breeding drought-tolerant plants and varieties through genetic transfer or agronomic practices. Breeding programs introduced new rice varieties that are more drought-tolerant and achieved higher yield with less water applied. Aerobic rice saves about 40% from irrigation water applied through irrigating every 12–15 days compared to the same varieties under conventional irrigation [60]. Developed types of rice withstanding drought, "Oraby 1 and 2," consume 50% of the water when grown in furrows compared to traditional rice without any reduction of productivity [61]. The hybrid rice varieties as the Egyptian hybrid "1" and "2" produce higher yield from 14 to 16 ton/ha, while it saves more than 20% from irrigation water [62]. Stresses can be overcome from mild to medium levels by agronomic practices. This can include using different crops through increased salinity and drought tolerance according to their stress adaptation mechanisms to enhance crop productivity [19].

7 Integrated Water Management for Sustainable Agriculture

The integrated water management for sustainable agriculture in Egypt includes many approaches. Some of these approaches are related to water deliveries from Aswan High Dam to farmer's fields in all old agricultural lands. In addition, these approaches also include water harvesting techniques in rain-fed places and integrated management for groundwater resources. The other approaches are related to on-farm practices to rationalize water use and maximize water productivity under different irrigation water resources (Nile River, rain-fed, and groundwater). It is summarized in the following:

- Determining the optimum water requirement and irrigation scheduling for various crops (field crops, fruits, and vegetables)
- Applying the new irrigation systems in new reclaimed lands as sprinkler and trickle irrigation systems and, moreover spreading surface irrigation methods which save irrigation water and improve irrigation water efficiency in old lands
- Studying deficit irrigation and withholding in noncritical physiological growth stages, in addition to cultivated drought-tolerant varieties
- Reducing the areas of high-water-consuming crops like sugarcane and rice and replacing with sugar beet and maize
- Using different cropping patterns which cope with water scarcity

- Expanding use of nontraditional water resources such as treated wastewater, drainage water, and desalinization considering water validity approaches as water quality, kind of crops, soil type, kind of irrigation system, and management
- Using new technology like geographic information systems and remote sensing to determine crop areas and irrigation requirements
- Introducing various water harvest techniques to use these collected water as a supplemental irrigation on sensitive physiological stages for crops in rain-fed areas
- Applying hydrological studies of all groundwater resource aquifers in Egypt including Sinai and the Western Desert to define the available quantities and the secure yield of abstraction for sustainable us
- Studying the projected impacts of climate change on crop water requirements and agricultural productivity
- Expansion of improvement of Mesqas and Marwas on surface irrigation systems in the old land to improve irrigation efficiency and increase crop productivity
- Introducing integrated management for drainage systems, fertilizers programs, soil amendments, and pest and weed control to enhance crop productivity
- Introducing and expanding programs for extension specialists and farmers showing them new technologies and the outputs of new studies in the field of irrigation and agriculture production
- Suggesting an integrated management program for salt-affected soil to enhance its productivity

8 Conclusions and Recommendations

Due to the current and the expected increase in water scarcity in Egypt, we could conclude the following points to maximize crop yield with minimal water use:

- The expansion of improvement on surface irrigation system in old agricultural lands through improvement of Mesqas and Marwas. Moreover, applying on-farm practices which cause increase in water use efficiency as laser land leveling, raised beds, alternative furrow irrigation, deficit irrigation, surge irrigation, irrigation scheduling, and night irrigation
- The spreading use of pressurized irrigation systems such as sprinkler and trickle in new reclaimed lands and desert and in addition applying on-farm practices such as irrigation scheduling, night irrigation, and partial root-zone drying for drip irrigation
- Improving water harvesting techniques in rain-fed areas in the North West coast area and using these water harvesting techniques in supplemental irrigation on critical crop physiological stages
- The expanding use of nonconventional water resources such as desalination of seawater and reuse of drainage water and groundwater under integrated water management for sustainable agriculture

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Greenhouse Operation and Management in Egypt

Safya El-Gayar, Abdelazim Negm, and Mohamed Abdrabbo

Abstract One of the major advantages of producing vegetable crops and ornamental crops under protected cultivation around the world is the ability to produce high yields throughout the year regardless of ambient weather conditions. To accomplish this objective, climatic variables inside greenhouses (such as air and soil temperatures as well as carbon dioxide concentration) should be controlled. The greenhouse sector in Egypt has achieved many success stories related to improvement of food security for Egyptian people via providing the local market during winter season with an adequate quantities of vegetable crops and ornamental plants. However, exports of greenhouses products to the foreign markets are not sufficient until now; there are some constraints such as the adoption of modern technology for greenhouse climate control and the need to further develop these, as well as implementation of food safety legislation during the different production steps.

As production costs increase by using such practices, growing areas in protected cultivation are trending in mild climatic regions of the world, where plants can grow without using artificial control of the greenhouse environment. There are several constraints related to greenhouse irrigation management such as misuse of water resources causing serious yield reductions; low irrigation efficiency can be primarily attributed to poor management of irrigation water in addition to technical problems

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of on-farm irrigation applications, as well as inadequate maintenance of irrigation systems often resulting from inadequate management in operation and maintenance. The use of greenhouse and plastic house techniques has contributed to better water-use efficiency.

The plastic or glass cover creates a modified microclimate in which radiation and wind movement are lower but relative air relative humidity is higher under greenhouses than in the open field, favoring a reduction in evapotranspiration. Furthermore, the higher temperature results in increased crop growth rate and higher obtained yield per unit area of protected cultivated land. Protected cultivation is a proper technology for improving vegetable crops productivity.

This chapter illustrates several beneficial agricultural practices in terms of the greenhouse sector. Work in the greenhouse sector considers greenhouse management and the proper tools that can be used depending on many factors such as the crop type, targeted market, technician availability, head and operation costs, etc.

The scientific background about greenhouse management will be explained in this chapter with the details necessary to provide the background needed about the scientific base of the modern technology. This chapter also took into consideration information needed for the local small farmers who use simple greenhouse technology to give information to inform critical management points such as proper cover materials and greenhouse ventilation systems. Furthermore management of food safety for greenhouses products and how to reduce the use of chemical pesticides through fertilization management are vital.

Recently, Egypt has established a national mega project for the establishment of 100,000 acres of greenhouses during the next few years. This project needs a lot of infrastructure, materials, manufacturing, and labor and technicians. Management of 100,000 acres of greenhouses will need proper qualified advisors and properly trained staff. There are a limited number of advisors and proper technician in Egypt because many good advisors and technicians left to work for in Gulf countries due to better salaries provided. There is an urgent need to prepare a new generation of advisors and technician in a short amount of time. The current chapter is a technical guideline for the greenhouse sector and can be used as a reference for those who work in the protected agricultural field.

Keywords Agriculture, Egypt, Food safety, Greenhouse, Irrigation, Management, Mega project, Pesticide, Technology

Contents

1 Introduction

As a result of agricultural land urbanization, rapid population growth, and insufficient product quantity and quality, a contingency plan must be developed as soon as possible to increase the productivity. These contingency plans should include adopting state of the art, modern technology in agricultural production and extending greenhouse areas. Then, protected cultivation emerged as a way to protect crops from adverse weather conditions allowing production year-round and the application of an integrated crop production and protection management approach for better control over pests and diseases.

Today's greenhouse technologies mean it is possible to commercially cultivate all horticultural crops and species in any region of the world, provided that the greenhouse is properly designed and equipped to control the climatic parameters. Greenhouse design and location must optimize the climatic factors to be suitable for the cultivating crops.

In the eighteenth century, Egypt started commercial production of protected agriculture for vegetables and ornamental plants. During this period, there was significant progress in the following aspects: (1) greenhouse design, (2) use of low tunnels, (3) type and quality of the plastic covering material, (4) fertigation, (5) polyethylene mulch, (6) use of high-yielding hybrids and cultivars, (7) plant training and pruning techniques, (8) integrated pest management, (9) use of pollinator insects, (10) climate control, and (11) soil solarization.

Greenhouse production helps to meet the local market needs from the vegetables and ornamental plants. Besides supplying the local markets, the production of greenhouse should be greatly valued for its export potential to play an important role in the foreign trade balance of several national economies in Egypt. However, the intensification of greenhouse crop production has created favorable conditions for many devastating pests and diseases. This has significantly increased the need for pesticide applications. At the same time, legislative measures and standard requirements regarding the food safety of vegetables have become increasingly demanding. Food safety issues are the main barriers of export of produce to European Union countries according to the GLOBALGAP legislations.

Over the last two decades, use of solar agricultural greenhouses has globally increased especially in developed countries. The primary objective of a greenhouse is to produce high yield and good-quality yields during the non-cultivation season, which is possible by providing and maintaining an optimal level of light intensity, air temperature, and relative humidity at every stage of the crop growth. An appropriate air conditioning including heating and cooling systems can be equipped with the greenhouse for this purpose. These, as a result, will have significant impacts on the cultivation time, quantity, and quality of the products.

The greenhouse climate with the optimum range in terms of light, temperature, ventilation, and moisture directly affects the success of the production. Among these factors, the temperature is one of the most important climatic factors that should be managed inside the greenhouse. The vital (physiological and biological) activities of the plants usually slow down at 10°C and cease at 7°C. Providing appropriate air temperature and relative humidity in the greenhouse help to decrease diseases, infections, and use of chemical pesticides. Thus, the problem of pesticide residue on crops is alleviated and high-quality products are obtained.

Heating of greenhouse is essential and required for an efficient and reliable production especially during the winter season in Egypt. Regarding the greenhouses heating, renewable energy sources should be adopted instead of fossil fuel heat energy sources. Solar energy is an important alternative heat energy source and is a significant opportunity in Egypt.

The most commonly grown species in greenhouses are vegetables with medium thermal requirements (tomato, pepper, cucumber, melon, watermelon, green bean, eggplant, etc.). The aim is to extend the growing calendars beyond the conventional open-air cultivation season, and thus increase profitability. Nowadays, the production of greenhouse crops in geographical areas without suitable climate conditions is highly questionable since it entails significant and expensive artificial climate control.

The technology for vegetable enterprise development in Egypt produced a set of tools and standard operation practices for farmers, technicians, and extension specialists, highlighting the advantages of water management, salinity, and product quality of the greenhouse systems compared with traditional cultivation practices for export and domestic markets.

The overall objective is to restore small-scale farmers' capability to produce high-quality and safe vegetables under protected cultivation. The objectives of the agriculture strategy in Egypt are to increase productivity per unit of land and water through more efficient use of limited resources, as well as reduce the cost of production unit and thereby increase in the national output and farmers' incomes.

2 Planning and Design of Greenhouse

Greenhouse cultivation has a special place in agricultural production. In addition to the traditional greenhouse production, there has been an increase in the number of the modern greenhouse structures that allows environmental control in Egypt in recent years.

A greenhouse has one purpose: to provide and maintain an optimal level of microclimatic conditions that will result in optimum crop production or maximum profit. This also includes an environment for work efficiency as well as for crop growth, development, and productivity.

The factors affecting greenhouse management before investing are as follows:

1. Available marketing systems and the transportation
2. The climatic conditions (ambient air temperature, intensity of solar radiation, rainfall, air relative humidity, wind speed, and prevailing wind direction)
3. The fuel and power availability (gas, oil, coal, or renewable energy sources)
4. The water availability and its quality (a good source of high quality is cheap, while a poor water supply will limit growth and may require additional investment for purification)
5. The kind of available soil and its drainage characteristics

The natural radiation conditions are the main limiting factor to consider when establishing greenhouses. Therefore, the natural radiation conditions make it necessary to design and locate greenhouses to optimize the interception of solar radiation during the autumn and winter months.

Protected cultivation in greenhouses causes the increase of daytime temperature (compared to the outside temperature) to very high values depending on: characteristics of the cladding material, outside wind velocity, and incident solar radiation and transpiration of the crop grown inside the greenhouse.

2.1 Greenhouse Site Selection

Site selection is a key factor for profitable and sustainable greenhouse production. The main factors determining location and site selection of a greenhouse production area are: cost of production unit, quality of produced yield, and transportation cost to markets [1, 2]. Obviously, cost and quality of production depend on the local climate and the greenhouse growing conditions.

The specific selection of a greenhouse location must take into account a variety of factors [2]:

1. Topography: ground slope for drainage, flat in width direction, main axes slope of 0–0.5% (never >1–2%, which would need terracing), and building orientation (a south-facing slope is good for winter light and protection from northerly winds).

2. Microclimate: not frequently fogged areas, windbreaks, air pollution especially near cities, avoid flooded areas, soil characteristics, and expansion for future greenhouse or auxiliary buildings.
3. Irrigation water: a dependable supply of high-quality water is needed for greenhouse operation.
4. Greenhouses need a dependable supply of energy in the form of electricity and fuel for heating, labor availability, and communications network.

2.2 Plan Layout

The individual greenhouse (single-range greenhouse) may be easily constructed. One disadvantage may be that individual greenhouse in total requires more heat per unit area of surface area than a multi-span greenhouse, because of the larger ratio of cover surface area to floor surface area. While the gutter-connected range (multi-span greenhouse) keeps all activities inside one building, a central heating system can easily serve all areas. It may not be as easy to expand or contract space use as with the individual greenhouse.

2.3 Local-Type Greenhouses (Wooden Greenhouses)

These greenhouse types are normally very low-cost structures with little climate control besides natural ventilation; they are built with local materials (i.e., wood) and covered with polyethylene plastic film. The parral-type greenhouse is probably the most widely used in terms of surface area.

The parral greenhouse is made of a vertical structure of rigid pillars (wood or steel) on which a double grid of wire is placed to attach the plastic film.

Local-type greenhouses require a relatively low level of investment, making them suitable for farms operated by small growers. However, there are significant design-associated problems, such as lack of good natural ventilation, as a result of:

- Low ventilation surface area, due to a poor combination of side and roof ventilation and to the construction of excessively small roof vents, resulting from the grower's fear of sudden strong winds that may damage the greenhouse.
- Inefficient ventilator designs – for roof ventilation, flap ventilation is always preferable to rolling ventilators as it provides higher ventilator rates (almost three times greater airflow according to [3].
- Use of low porosity insect screens – insect-proof screens strongly reduces the air exchange rate.

Good agricultural practices require good ventilation and higher light transmission especially during the winter season (main season of greenhouse production). The lack of good ventilation in most local-type greenhouses can be fixed by improved design of the ventilation systems. Light transmission depends on the properties of the covering material and the number of opaque supporting members, as well as the greenhouse geometry and orientation. In terms of roof slope, computer simulations show that during the winter, increasing the roof slope from 11 to 45° can increase daily light transmission by nearly 10%, since losses due to reflection are reduced. In practice, it is more useful to find a compromise between good light transmission and construction costs, and most new greenhouses have a roof slope of 25–30°C.

With regard to greenhouse orientation, there are two main factors that have to be balanced before choosing the best solution: light transmission and ventilation. Moreover, there is research related to produce tropical fruit from the wooden greenhouse covered with screen-proof insect net.

2.4 Utilities

2.4.1 Electric Power

An adequate electric power supply and distribution system should be provided to serve the environmental control and mechanization needs of the greenhouse.

2.4.2 Water

Plants require an adequate supply of moisture for optimum growth and sufficient productivity. Water is the medium by which plants absorb nutrient elements. A correctly designed watering system with adequate supply means adequate amount of water needed each day during the year. This amount will depend upon the area to be watered, kind of crop grown, and climatic conditions. Water absorbed by the root system moves through the roots into branches and leaves. Water vapor then transpires through stomata in the leaves into the atmosphere surrounding the plant.

It is very important to know the existing water quality before using it in the greenhouse. A common problem is that of a high salt content in the irrigation water. This frequently occurs along coastal areas, where the seawater may infiltrate the groundwater. Quantities of sodium bicarbonate or sodium chloride can become high enough to be injurious. Groundwater in the western and southwestern Egypt can contain excessive quantities of sodium and boron. A total soluble-salt reading (via electrical conductivity) gives a good assessment of this problem.

A common problem is high salt content in the irrigation water. When this is experienced, the water should be analyzed, and those specific elements making up the salts should be avoided or at least reduced in the fertilizer program, because the removal of salts is expensive. When high salt levels exist, the root zone should not be allowed to dry excessively, since that would concentrate the salts. Reverse osmosis systems have been used successfully by a few greenhouse firms. This is an added cost which renders the firm all the less competitive.

High boron is a problem in many arid, coastal regions. Boron availability to plants can be reduced by precipitating it in the root media with calcium. Adding calcium or raising the pH to the upper end of the safe range for a crop will lessen boron toxicity. Bicarbonate is particularly damaging to plants. It causes variable chlorosis over the plant, burning of leaf margins, and generally poor growth. Besides by reverse osmosis, bicarbonate can be removed by acidifying the water with such acids as sulfuric acid, nitric acid, or phosphoric acid. These may be injected into the irrigation water source. At the lower pH level desired for plant growth, much of the bicarbonate converts to carbon dioxide gas and water.

2.5 Growing Systems

There are four functions that the root medium must hold water and nutrient in a way that it is available to the plant and provide for the exchange of gases between roots and the atmosphere above the root medium. Field soil is composed of three mineral components as shown in Fig. 1.

Sand provides excellent support and gas exchange but has insufficient water and nutrient holding capacity. The coarse particles of sand have little surface area per unit of volume compared to the finer particles of clayey soil or peat moss. Since water is held on the surfaces of particles, sand has a small reserve. Plants grown in sand would need to be watered three or more times per day in the summer, since most nutrients in a sand medium are held in the water films.

Clay has a high nutrient and water-holding capacity and provides excellent plant support. The water films of adjacent particles come into close contact, leaving little open space for gas exchange. Carbon dioxide produced by the roots and by microorganisms cannot adequately leave the clay. In high concentration it suppresses respiration, which in turn slows growth. Oxygen, also needed to keep the processes

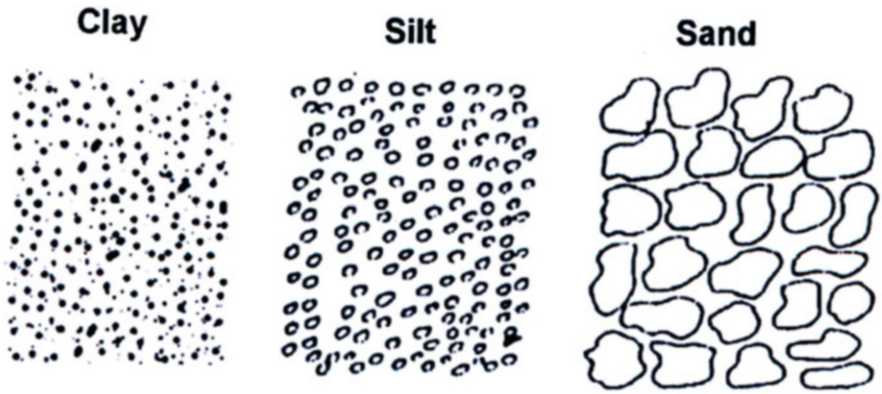

Fig. 1 Texture description of particle sizes for three different types of soil

of respiration going, cannot adequately diffuse into the clay. Consequently, clay is a poor medium for plant growth. The finest particles, clay, extend up to a maximum diameter of 2.0 μm. Clay feels sticky to touch.

Silt is floury and composed of particles up to 50 μm. Texture terms include sandy load, silt loam, and clay loam for soils predominating in sand, silt, and clay, respectively. Loam refers to a reasonable balance of all three materials.

2.5.1 Hydroponics System

Hydroponics is a production method by which plants are grown in a nutrient solution rather than in soil. It used as a root medium but lacks gas exchange and plant support.

Advantages of hydroponics system can be concluded as follows: greater plant density, higher yields and better quality, less water consumption, and less disease and fewer insects. The disadvantages of hydroponics system are as follows: increased initial investment (specific pumps, tanks, control systems, and support systems increase the costs per square meter), higher energy costs (specific pumps, specific heat-distributing system, lights, and additional control system), and more technical skills needed. Several soilless growing systems are illustrated in Fig. 2.

2.5.2 Sand/Stone Culture

Seedlings are set directly into this medium for growing almost any type of plant consists of a deep bed (45–60 cm) of sand, stone, or trap rock placed in a plastic-lined trough or bed which slopes to one point in order to drain off excess nutrient solution (a minimum slope of 2%).

2.5.3 Troughs and Pipes

Open and closed troughs and pipes may contain just the nutrient solution or may be filled with peat moss. PVC pipes has a diameter of 5–7.6 cm with holes each has a diameter of 15 cm on centre. They are used for leaf lettuce production. This system is a suitable for small canopy plants such as strawberry, tomatoes, cucumbers and lettuce.

2.5.4 Bags

A modified hydroponics system uses polyethylene film bags, filled with a peat moss-vermiculite mix or foam, placed end-to-end. Drip tubes supply the nutrient solution into the bags system.

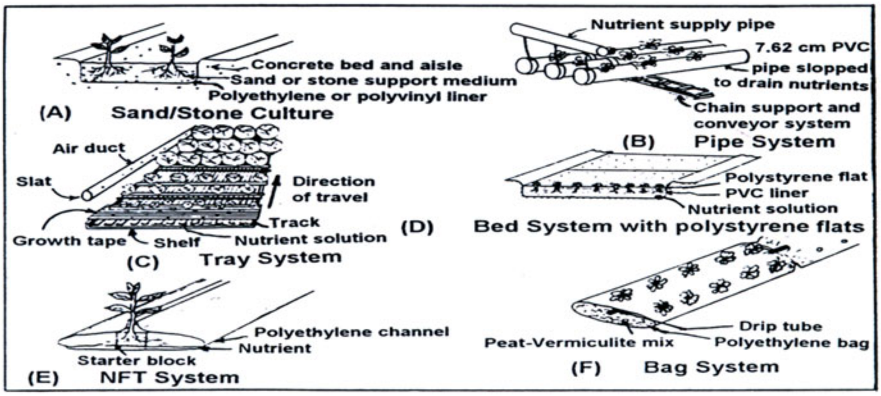

Fig. 2 Major soilless growing systems used in Egypt (**a**) Sand/Stone culture, (**b**) Pipe system, (**c**) Tray system, (**d**) Bed system with polystyrene flats, (**e**) NFT system, (**f**) Bag system

2.5.5 Nutrient Film Technique Solution (NFT)

This NFT system used in Egypt is formed by thin plastic channels film or PVC gullies, plastic channels film has two faces color (one face is white color and another is black) which are placed on the floor and slope the length width of the greenhouse. Nutrient solutions are supplied to one end of the channel through plastic tubing and collected into a below-ground reservoir at the other end by the gravity. Seedlings are usually grown in small pots, poly bags, or growth blocks in the channel. Also, aeroponic-modified system plants are supported through a plastic cover to a closed tank. Nutrient elements are supplied to the root system as a fine mist or fog.

Besides the plant support system, tanks, pumps, and control systems are needed. Tanks of concrete, plastic, or iron coated with epoxy are commonly used. Submersible pumps made for chemical solution should be used because fertilizer salts corrode pumps made for use with freshwater. Control systems can be as simple as a timer, manual switches, or complex computers which automatically adjust the chemical content of the nutrient solution.

3 Greenhouse Climate Control and Energy Use

All greenhouse cultivation systems comprise fundamental climate control components; depending on their design and complexity, they provide more or less climate control and condition to a varying degree plant growth and productivity from the land unit.

The provided tools could control air temperature, light intensity, and air relative humidity inside the greenhouses. It conditions not only crop growth and yield but also energy needs, which can account for up to 40% of the total production costs.

A greenhouse is constructed and operated to provide an acceptable plant environment that will contribute to a profitable enterprise. Photosynthesis is the process by which light energy in the range of 0.39–0.70 μm wavelength interval is converted into usable chemical energy by green plants. It is a process by which carbon dioxide (CO_2) and water (H_2O), in the presence of light and chlorophyll, are converted into carbohydrates and oxygen.

The carbohydrates can be moved from the green stem and leaf cells where photosynthesis occurs to all other parts of the plant. Amino acids may be formed and then combined into chains called protein. Fats maybe formed carbohydrates from all these compounds, yet other compounds arise such as cellulose for cell walls, pectin to cement the walls together, hormones to regulate growth, and DNA to constitute chromosomes. These processes result in the growth of the plant which can be detected as an increase in dry matter.

Respiration is the reverse process of photosynthesis, by which carbohydrates and fats are broken down, and carbon dioxide, water, and energy are released as follows:

$$\text{Carbohydrates} + \text{Oxygen} \rightarrow \text{CarbonDioxide} + \text{Water} + \text{Energy} \tag{1}$$

The respiration process occurs in all living organisms at all times. True photosynthesis depends on air temperature surrounding the pants, light intensity, water, and nutrient elements availability. Energy must be liberated at times to power other processes in the plant. When photosynthesis exceeds respiration, net growth occurs. When they equal each other, net growth stops, and if respiration exceeds photosynthesis, the plant declines vigor and will eventually die. To ensure that photosynthesis exceeds respiration, plants are grown cool at night to keep the respiration rate down and warmer by day to enhance photosynthesis.

3.1 Environmental Parameters Affecting Growth of Protected Cropping

There are eight main parameters that affect growth under greenhouse conditions: light, air temperature, air relative humidity, vapor pressure deficit, carbon dioxide concentration, air speed, root environment, and pollutants.

3.1.1 Light

Visible light (0.39–0.70 μm) provides essential energy for plant development and growth. Intensity, duration, spectral distribution, and quality of light affect plant response. The effect of radiation can be conveniently divided into three parts: (1) effect on flowering, (2) effect on photosynthesis, and (3) effect on plant temperature and water loss. Photosynthesis and water loss are usually considered as being influenced by high intensity. Flowering, however, can be determined by illumination levels less than 0.044 W/m^2. Ultraviolet light (0.29–0.39 μm) is generally detrimental to plants. Photosynthesis proceeds only with visible light, of which the red and blue wavelengths are used most efficiently.

The change from vegetative to product development in many plants is controlled by red light (0.66 μm) and far-red light (0.73 μm). Light intensity is the most critical variable influencing photosynthesis process. Flower crops can be classified as sun or shade plants. Sun plants can be grown in full sunlight with no adverse effects, while shade plants are injured if exposed to light intensity above a specific level. The single leaf reaches its maximum rate of photosynthesis at 131.2 W/m^2. An intensity of 438.6 W/m^2 might be required for the whole plant in order to raise the light intensity within the leaf canopy to 131.2 W/m^2.

When the daily total solar radiation drops below 100 W/m^2, supplemental illumination may be useful. At 500 ppm carbon dioxide, individual leaf photosynthesis reached a maximum near 139 W/m^2. Plants which respond to relative length of day and night are termed photoperiodic. Photoperiodic affects flowering and is generally independent of light intensity. Plants can be grouped as long day, or day neutral, with the length of darkness being more important than the length of the light period.

Not all light is used in the photosynthesis process as light is classified according to the wavelength (μm). This classification is referred to as quality of light; as an example, ultraviolet light (UV) has short wavelengths below 0.4 μm, while blue, green, yellow, orange, and red light occur around wavelengths of 0.46, 0.51, 0.57, 0.61, and 0.65 μm, respectively. Far-red light (0.70–0.75 μm) occurs at the limit of our visual perception and has an influence on plants other than through photosynthesis. Infrared energy occurs at longer wavelengths and is not involved in plant processes.

It is primarily the visible spectrum of light that is used in photosynthesis. There are peaks in the blue and red bands where photosynthetic activity is higher. When blue light alone is supplied to plants, growth is shortened, hard, and dark in color. When grown in red light, growth is soft, and internodes are long resulting in tall plants. All visible light qualities (wavelengths) are readily utilized in photosynthesis.

3.1.2 Air Temperature

The majority of plants grown in greenhouses are warm-season species, adapted to average temperatures in the range 17–28°C, with approximate lower and upper limits of 12 and 32°C [4]. If the average minimum temperature outside greenhouse is less than 10°C, the greenhouse is likely to require operate heating, particularly at night. When the average maximum outside temperature is less than 27°C, then ventilation will prevent excessive greenhouse temperatures during the day; however, if the average maximum temperature is greater than 27–28°C, artificial cooling may be necessary. The maximum greenhouse temperature should not exceed 30–35°C for prolonged periods for most growing crops.

All plants have an air temperature range in which they can be grown. All biochemical reactions in the plant are controlled by enzymes that are heat sensitive. These all have the net effect of building carbohydrates and storing energy. Plant temperature is affected by radiation energy transfer, convective heat transfer, and evaporation from plant surface. The relationship between plant growth and the temperature is complex because it is a factor in the reaction rates of various metabolic processes. Greenhouse crops are grown at specified night air temperatures with a daylight minimum increase of from 4 to 6°C.

As the indoor air temperature is increased above 30°C during the summer season, the green leaves and stem length are thus reduced making the rate of vegetative growth at a minimum level. Also, excessive air temperature of greenhouse causes damping-off, loss of stem strength, delay flowering, decreased vitality and insemination of seeds, loss of fruit set, loss of fruit size, and increased possibilities of infection by pathogenic organisms. Reversely, as the indoor air temperature of the greenhouse is decreased lower than 15°C, the percentage of flowerage and vitality of insemination seeds are decreased making the fruit set at a minimum level.

Heat energy can be reflected, transmitted, absorbed, conducted, reradiated, or used to evaporate water. The latter generally requires over 2,093.4 J/g of water evaporated. Obviously, if radiant energy is absorbed, plant temperature must rise until equilibrium is reached at some higher value. The new temperature equilibrium is determined by the following facts:

1. The fact that plants will radiate thermal energy to their surroundings, the amount depending upon the temperature differential between plant, and the surrounding area (greenhouse roof, heat pipes, etc.).
2. The removal of energy by conduction and convection processes or the flow of cooler air stream over warm leaves of the plant. As air movement increases, more heat is conducted away, and plant temperature comes closer to the indoor air temperature. If the indoor air temperature is higher than the plant temperature, heat can flow in the opposite direction, tending to raise plant temperature.
3. The amount of energy used in photosynthesis is so small. It could be commonly ignored in assessing heat energy balance of growing crops.
4. The evaporative rate of the plant. As a rule, between 70 and 90% of absorbed solar radiation is utilized to evaporate water from the plant. Recent research work revealed that between 48 and 52% of solar radiation available inside the greenhouse is utilized to evaporate water from the plant.
5. The final equilibrium temperature is influenced by the capacity of the plant to store heat energy or thermal heat capacity of the tissue and its mass. Therefore, temperatures of thin leaves will vary faster and farther than thick leaves, or large masses such as flower buds or storage organs, when there is a change in the environment.

In order to investigate the variables determining air temperature inside the greenhouse and calculate the necessary measurements for control air temperature, a simplified model of the greenhouse energy balance is formulated [5]. Equation simplifies the greenhouse energy balance to

$$V_{\mathrm{a}} = \frac{0.0003\tau R_{\mathrm{s,o\text{-}max}}}{\Delta T} \tag{2}$$

where, V_a is the ratio Q/A_g, Q is the ventilation flow rate (m^3 [air]/s), A_g is the greenhouse ground surface area (m^2), τ is the greenhouse transmission coefficient to solar radiation, $R_{s,\ o\text{-}max}$ is the maximum outside solar radiation (W/m^2), ΔT is the temperature difference between a greenhouse and outside air (°C).

4 Temperature Control

4.1 Wind-Dependent Heating

In Spite Of a1°C reduction gives an energy saving of around 10%, low temperature reduces plant growth rate and development of most crops and may significantly reduce crop quality. Thus a lower heating air temperature will save energy but is generally not feasible economically as it results in affected crop production which is not always compensated for by the lower energy costs. A more economic measurement of reduced heating greenhouse air temperatures is wind-dependent air temperature control. Heat losses are increasing linearly with increasing wind speed. Therefore, energy can be conserved by reducing the heating set points when it is windy and compensating for these using increased temperatures at low wind speeds. This method results in energy savings of 5–10%.

Temperature Integration Another option for energy efficient for control air temperature is the so-called temperature integration (TI) method. This method is based on the fact that the effect of greenhouse air temperature on plants growth and production depends on the 24-h average greenhouse air temperature rather than distinct day/night greenhouse air temperatures [6]. However, there are limits to this approach, and plants have to be grown within the sub- and supraoptimal temperatures to prevent reduced quality and/or production levels due to poor fruit or flower development.

In general, application of temperature integration leads to higher greenhouse air temperature during daytime and lower air temperatures at night. However, the approach of using sufficient ventilation set points can also be combined with the use of lower day heating set points and then higher temperatures under thermal screens at night. The advantage is to fully exploit solar heat gain at day and when additional heat is required, to add it preferably at night when heat losses from greenhouse are limited due to the closed thermal screen. There are potential energy savings of up to 20% [7]. However, when setting bandwidths for temperature integration, a balance must be found between maximizing energy savings and minimizing detrimental effects on yield or quality. The balance varies enormously depending on the crop, so specific crop knowledge is required.

4.1.1 Air Relative Humidity

The second important variable is relative humidity. Air relative humidity is the ratio of the actual vapor pressure of water vapor in the air to the vapor pressure that would be present if the air was saturated with moisture at the same temperature. Water vapor moves from one location to another because of vapor pressure differences, so air relative humidity affects transpiration from plants by affecting the vapor pressure difference between a plant leaf and surrounding air. Relative humidity within the range of 60–90% has little effect on plants. Values below 60% may occur during ventilation in arid climates, or when plants are young with small leaves, and this can cause water stress. Serious problems can occur if relative humidity exceeds 95% for long periods, particularly at night as this favors the rapid development of fungus diseases such as *Botrytis cinerea*.

Normal plant growth inside the greenhouse generally occurs at air relative humidity between 35 and 80%. A secondary effect is the response of pathogenic organisms. The third effect is the influence on indoor vapor pressure deficit.

4.2 Humidity Control

An airtight greenhouse will have reduced air exchange and higher air relative humidity. Thermal blankets or double glazing layers will also result in an increase of the air relative humidity. Reduced air exchange will reduce the water vapor removed from the greenhouse. Additional insulation will result in higher inside surface temperatures, reducing the condensation potential. The condensation rate depends on the rate of air movement across the surface, the rate at which heat of condensation is removed from the surface, and the rate of evaporation from other surfaces in the greenhouse. Water vapor of indoor air condenses in a film on fenestration surfaces that are at a temperature below the dew-point temperature of the indoor air.

A major fraction of the heat transfer from the greenhouse to the outside environment is by natural ventilation. Under low radiation condition and moderate ambient temperature, natural ventilation is generally used to prevent high relative humidity inside the greenhouses. Consequently, a substantial fraction (5–20%) of the total energy consumption is related to control relative humidity. Although high relative humidity is generally associated with increased hazard of fungal diseases and reduced product quality (e.g., *Botrytis*, blossom end rot), it may also be a positive effect for crop yield and quality [8]. Reducing the level of air relative humidity is costly as a result of the energy consumed and should be assessed against the added value of the crop price. An increase in the air relative humidity set point of 5% decreases the energy consumption by approximately 6%. To reduce "humidity control related" energy consumption, there are several options: higher humidity set points, reduction of the transpiration level of the crop, and active dehumidification with heat recovery.

In general, the indoor air relative humidity of the greenhouses will be controlled by the temperature of coldest inside surface. The simplest method for air relative humidity control in cool or cold weather is to bring in outdoor air, heat it, and allow it to absorb moisture before exhausting it to outside the greenhouse. A greenhouse filled with mature pot plants may lose up to about 0.75 kg of water vapor per square meter of greenhouse floor surface area per hour during the daylight time; loss at nighttime will be less. If evaporated moisture is not removed, indoor air relative humidity of the greenhouse will increase until the air is saturated or till condensation begins on a cold surface.

Horizontal airflow in the greenhouse will help alleviate the problem by moving air across plant surfaces to keep them dry. Moving air also increases mixing and prevents temperature stratification in the greenhouse.

Thermal Screens Energy-efficient thermal screen control involves achieving a balance between the yield and quality effects related to greenhouse air relative humidity, light intensity, and energy saving. Energy-efficient (humidity) screen control can be achieved by opening the screen prior to the ventilators to maintain a given air relative humidity set point. When closing the screen at night, an additional operational energy saving (4%) can be obtained without any yield losses. If the opening of the thermal screen is delayed until radiation level outside greenhouses becomes 50–150 W m^2, the heat exchange of the greenhouse is thereby reduced for a longer period during the early morning hours [9].

A thermal screen adds an additional barrier between the greenhouse climate conditions and its surroundings and reduces both convection and ventilation loss. Thermal screens can be either fixed or movable. Install fixed thermal screens are normally used during both the early plant growth stage and production stage of the crop. But, both the constant reduction of the light level and the increased air relative humidity limit the period of application. Consequently the potential operational energy saving is achieved. Movable screens have less impact on light transmission than fixed screens or double covering materials. Using thermal screen could reduce energy consumption by more than 35–40%, depending on the material. In practice, movable screens are closed for only part of the entire 24-h period depending on the grower's criteria for opening and closing, which are generally related to humidity and light levels.

Covering Materials and Screens Most energy loss in naturally ventilated greenhouses occurs through convection and radiation from the greenhouse cover and sensible and latent heat transfer through ventilation. Improved insulation and reduced ventilation are therefore the first steps toward creating energy-conserving greenhouses. The basis of energy reduction is a good maintenance of greenhouse hardware (doors, cover, sidewalls, and foundation). Procedures must be taken to prevent unnecessary air leakage from the greenhouse to outside environment: keeping greenhouse's doors closed, sealing air leakages, repair of broken greenhouse cover material and sidewalls, and uniform closure of greenhouse natural ventilators.

Increasing the insulation value of the greenhouse has a major impact on energy use as most energy loss takes place through the greenhouse cover. Therefore different technologies are applied, including an increase of the insulation value using a double or triple layer of cover materials and application of coatings to reduce heat loss [10]. However, a major disadvantage of most insulating materials is the reduction in solar radiation transmission and increased air relative humidity inside the greenhouses. In practice, the potential energy saving of double and triple greenhouse covering materials is rarely achieved, since the grower will try to compensate for the higher air relative humidity levels by increasing the dehumidification of the greenhouse climate [11].

Reduction of Transpiration Reduction of transpiration may have positive effects on energy efficiency since lower transpiring crops bring less water into the air and therefore require less energy for humidity control under low irradiation conditions. Higher CO_2 levels, by decreasing stomatal conductance and thus transpiration, may also improve energy efficiency by 5–10% without affecting photosynthesis or growth. Controlled reduction of the leaf area for crops with a high leaf area index, such as pepper, may reduce energy use without any impact on production. Halving the leaf area by removing old leaves in tomatoes resulted in a 30% reduction in transpiration with no detrimental effect on crop yields [12].

4.2.1 Vapor Pressure Deficit (VPD)

Vapor pressure deficit (VPD) is a valuable way to measure the greenhouse microclimate conditions and consequence the effectiveness of environmental control system. VPD can be used to evaluate the disease threat, condensation potential, and irrigation needs of a greenhouse crop. An important step toward disease management is to prevent conditions that promote disease. Condensation prevention is important since greenhouse pathogens often require a water film on the plant to develop and infect. The air is saturated when it reaches maximum water-holding capacity at a given temperature (dew point). Adding moisture to air beyond its holding capacity leads to deposition of liquid water somewhere in the system.

Air vapor pressure (VP_{air}) is a measurement of how much water vapor in the air, that is, how much water in the gas form is present in the air. More water vapor in the air means greater water vapor pressure. When the air reaches maximum water vapor content, the vapor pressure is called the saturation vapor pressure (VP_{sat}), which is directly related to air temperature. Thus, the differences between the saturation vapor pressure and the actual air vapor pressure ($VP_{sat} - VP_{air}$) is the mathematical definition of vapor pressure deficit (VPD). Higher vapor pressure deficit means that the air has a higher capacity to hold water, stimulating water vapor transfer (transpiration) into the air in this low humidity condition. Lower vapor pressure deficit, on the other hand, means the air is at or near saturation, so the air cannot accept moisture from a leaf in this high humidity conditions. The vapor pressure deficit (VPD_{air}) can be computed according to the following equations [13]:

$$\mathrm{VPD_{air}} = (1 - \mathrm{RH})P_{\mathrm{WS}}\ \mathrm{kPa} \tag{3}$$

where RH = indoor air relative humidity, decimal, P_{WS} = saturation vapor pressure at dry-bulb temperature, (kPa)

For dry-bulb temperature ranges from 0ºC to 200ºC, the saturation vapor pressure (P_{ws}) can be estimated from Eq. (4) [14]:

$$P_{\mathrm{WS}} = \exp(Z) \tag{4}$$

$$Z = \frac{C_1}{T} + C_2 + C_3T + C_4T^2 + C_5T^3 + C_6\ln(T) \tag{5}$$

where T is the dry-bulb temperature in Kelvin, and constants are as follows:

$$C_1 = -5.8002206E + 03$$
$$C_2 = 1.3914993E + 00$$
$$C_3 = -4.8640239E - 02$$
$$C_4 = 4.1764768E - 05$$
$$C_5 = -1.4452093E - 08$$
$$C_6 = 6.5459673E + 00$$

Maintaining the VPD above a minimum value helps to ensure adequate transpiration and also reduces disease problems. During the day, humidity can usually be reduced using ventilation. However, at night, unless the greenhouse is heated, the internal and external temperatures may be similar; if the external humidity is high, reducing the greenhouse humidity is not easy. When the air vapor pressure deficit is too low, air relative humidity too high, and air temperature very low, the water may condense out of the air onto leaves, fruits, and other plant parts. Because the plants are unable to evaporate enough water to enable the transport of minerals (such as calcium) to grow plant cells, even though the stomata may be fully open, this can provide a medium for fungal growth and diseases. Therefore, a VPD target threshold can be used to influence ventilation and/or heating equipment used to increase the vapor pressure deficit by reducing the indoor air moisture level.

When the plants are unable to evaporate water, excessive turgor pressure within the cells can cause splitting and cracking of fruits such as green beans, cucumbers, sweet peppers, and tomatoes. When the vapor pressure deficit is too high (relative humidity is too low), the rate of transpiration from the plant leaves can exceed roots' water uptake. This in turn will cause the stomata to close and then photosynthesis to slow down. Once the stomata closed, the leaves are at risk of high-temperature injury since evaporative cooling is reduced due to the lack of water to transpiration. To avoid high-temperature injury and plant death from wilting, many plant species will curl their leaves or orient them downward in an attempt to expose less surface area to the sun. This can significantly downgrade the quality of potted and foliage plants and can also reduce the growth rate and quality of vegetable crops.

In high vapor pressure deficit (VPD) situations, it can use the current VPD reading to directly operate sprinklers, fog, or missing equipment to add water vapor to the indoor air while simultaneously cooling the indoor air through evaporation. Both of these effects will reduce VPD values and evaporation stress in the crop. Any consequential air temperature or relative humidity changes will be looked after by the standard temperature and humidity climate control strategies. A misting program based on VPD is capable of regulating the on time of the fog or mist nozzles to provide the maximum amount of water for evaporative cooling and VPD set-point control while minimizing plant and soil wetting.

In situations where the vapor pressure deficit (VPD) is too low, moisture must be removed from the indoor air, or the indoor air moisture holding capacity must be increased through a rise in temperature. Moisture removal can be accomplished by substituting the moist air with drier one (typically through ventilation). The need for this is normally established using air relative humidity measurements alone, and it is the standard practice for avoiding direct condensation onto greenhouse surfaces.

4.2.2 Concentration of Carbon Dioxide (CO_2)

Carbon is an essential plant nutrient and is present in the plant in greater quantity than any other nutrient. About 40% of the dry matter of plants is composed of carbon. Plants obtain carbon from carbon dioxide gas (CO_2) in the air. For the most part, CO_2 diffuses through the stomata opening in leaves when they are open. Once inside the leaf, CO_2 moves into cells, where, in the presence of light energy from the sun, it is used to make carbohydrates (sugars). The carbohydrates are translocated to various parts of the plant and transformed into other compounds needed for growth or maintenance of the plant. Air, on the average, contains about 0.03% CO_2.

The absorption rate of CO_2 depends upon several factors, including concentration, stage of growth, air temperature, and light intensity. All plants will respond to increases in CO_2 levels, but not all responses will be economically profitable. The combination of high CO_2 levels, elevated day air temperatures, and optimum light levels will reduce the time between germination and harvest by as much as 50% for some crops. CO_2 enrichment is essential to increase the quality of produce; indeed, a continuous or periodical increase of CO_2 inside the greenhouse may lead to an increase of over 20% in fruit production for both dry and fresh matter [15].

Inside an unenriched greenhouse, the carbon dioxide concentration reduces below the atmospheric level whenever the carbon dioxide consumption level by photosynthesis is greater than the supply rate through the greenhouse vents.

The poor efficiency of greenhouse ventilation systems in low-cost greenhouses coupled with the use of insect-proof nets produces relatively high carbon dioxide depletion (about 20% or more). Possible solutions are: increase the greenhouse ventilation rate through forced air; improve design and management of the existed ventilation system; or inject carbon dioxide inside greenhouses [16].

In the absence of injecting artificial supplies of carbon dioxide in the greenhouse environment, the carbon dioxide consumed during photosynthesis must ultimately come from the external environment through the ventilation openings. The concentration of carbon dioxide within the greenhouse must be lower than that outside in order to obtain inward flow. Since potential assimilation is heavily dependent on carbon dioxide concentration, plant assimilation is reduced, whatever the light level or plant status. The ventilation of the greenhouse implies a trade-off between ensuring inflow of carbon dioxide and maintaining an adequate temperature within the greenhouse, particularly during sunny days [17]. Stanghellini et al. [18] analyzed the cost, potential benefits, and consequences of bringing more carbon dioxide into the greenhouse: either through increased ventilation, at the cost of lowering temperature, or through artificial supply. They found that while the reduction in production caused by depletion is comparable to the reduction resulting from lower temperatures caused by ventilation to avoid depletion, compensating the effect of depletion is much cheaper than making up the loss by heating.

Optimal carbon dioxide enrichment depends on the margin between the increase in crop value and the cost of providing the carbon dioxide. Attempting to establish the optimal concentration by experiment is not feasible because the economic value of enrichment is not constant but varies with solar radiation through photosynthesis rate and with greenhouse ventilation rate through loss of carbon dioxide [19]. The optimal carbon dioxide set point depends on several factors: the effect of CO_2 on the photosynthetic assimilation rate, the partitioning to fruit and to vegetative structure, the distribution of photosynthate in subsequent harvests, and the price of fruit at those harvests, in addition to the amount of carbon dioxide used, greenhouse ventilation rate, and the price of carbon dioxide.

The emission of carbon dioxide depends on the total use and type of fossil fuel. For example, when coal is used, carbon dioxide emission is 80–100 kg/MJ; for diesel, 75 kg/MJ; and for propane, 65 kg/MJ, while for natural gas it is about 58 kg/MJ. The principal source of carbon dioxide enrichment in the greenhouse used to be pure gas; nowadays more frequent use is made of the combustion gases from a hydrocarbon fuel, for example, low sulfur paraffin, propane, and butane or natural gas, and more recently also from biogas. In these cases, attention should be given to monitoring the SO_2, SO_3, and NO_x levels, which can damage the crops even at very low concentrations.

4.2.3 Dehumidification

Water condensation refers to the formation of drops of water onto greenhouse walls from water vapor. Condensation of water drop occurs when warm and moist air in a greenhouse comes into contact with a cold surface such as glass, fiberglass, plastic, or structural members. The air in contact with the cold surface is cooled to the surface temperature. If the greenhouse's wall surface temperature is below the dew-point temperature of the air, the vapor in the air will condense onto the walls. Condensation always occurs in greenhouses from sunset to several hours after sunrise. During daylight hours, there is sufficient heating from solar radiation to prevent water drops condensation, except on cloudy days. Condensation is a symptom of high relative humidity and may cause significant problems (e.g., germination of fungal pathogen spores, including powdery mildew).

4.2.4 Combined Use of Heating and Ventilation

A common dehumidification practice is simply to open the ventilation openings, allowing moist greenhouse air to be substituted by relatively dry outside air. This method does not consume any excess heat available in the greenhouse, and then ventilation is needed to reduce the greenhouse temperature. However, when the ventilation required reducing the temperature is less than that needed to remove moisture from the air, dehumidification consumes energy. Warm greenhouse air is replaced by cold, dry outside air, lowering the temperature in the greenhouse.

4.2.5 Absorption Using Hygroscopic Material

During the process, moist greenhouse air comes into contact with the hygroscopic material, releasing the latent heat of vaporization as water vapor is absorbed. The hygroscopic material has to be regenerated at a higher temperature level. A maximum of 90% of the energy supplied to the material for regeneration can be returned to the greenhouse air with a sophisticated system involving several heat exchange processes including condensation of the vapor produced in the regeneration process.

4.2.6 Condensation on Cold Surfaces

Wet humid air is forced to a cold surface located inside the greenhouse and different from the covering material. Condensation occurs on the cold surface, the water is collected and can be reused, and the absolute humidity of the wet greenhouse air is reduced. One meter of finned pipe used at a temperature of 5°C can remove 54 g of vapor per hour from the air at a temperature of 20°C and with 80% relative humidity.

4.2.7 Forced Ventilation Usually with Combined Use of a Heat Exchanger

Mechanical ventilation is applied to exchange dry outside air with moist greenhouse air, exchanging heat between the two airflows. Based on the results, a ventilator capacity of 0.01 m^3/s is sufficient for all crops [20]. The energy consumption by the ventilators is estimated to be less than 1% of the energy saved [21].

4.2.8 Anti-drop Covering Materials

The use of anti-water drop covering materials is an alternative technology for greenhouse dehumidification. Anti-water drop films contain special additives which eliminate forming of droplets instead of a continuous thin layer of water running down the sides.

4.2.9 Indoor Air Speed

Indoor air speed influences many factors that affect growth, such as transpiration, evaporation, leaf temperature, and carbon dioxide availability. In general, indoor air speed of 6–15 m/min across leaf surfaces facilitates carbon dioxide uptake. At an air speed of 30 m/min, carbon dioxide uptake is reduced to the minimum level, and of 60 m/min, the growth of the plant inside the greenhouse is inhibited.

4.2.10 Root Environment

Rooting media provide plant support, serve as a source of water and plant nutrients, hold water, and permit diffusion of oxygen to the plant root system. During respiration, oxygen moves into roots system, and carbon dioxide moves out. The media should have sufficient pore size and distribution to provide adequate aeration and moisture retention necessary for acceptable crop production. Media range from mineral soil and amended soil mixes to soilless media such as gravel, sand, peat moss, or liquid films (hydroponics system).

Sandy soil provides excellent support and gas exchange but has insufficient water and nutrient supplying capacity (it lacks on holding water). Therefore, plants grown in sand soil would need to be watered three or more times per day, particularly in the summer season. Clay soil has a high nutrient and water-holding capacity and provides excellent plant growth. However, it is poor in gas exchange due to its small particles when the water films of adjacent particles come into close contact, leaving little open space for gas exchange. Consequently, clay soil is a poor root media for plant growth. Water is sometimes used as a root media; it provides water and nutrients but lacks gas exchange and plant support.

Manure has a high cation exchange capacity which serves as a reservoir for nutrients. In addition, it is a good source of nutrients, and micronutrient deficiencies rarely occur when manure is used. As a matter of fact, micronutrient deficiencies present a serious problem. Manure also contains low levels of nitrogen, phosphorus, and potassium as listed in Table 1. Because large quantities of manure are used in media, a significant part of the total requirement of these three macronutrient is meeting. Manure also has a high water-holding capacity, a basic requirement of greenhouse root media.

Peat moss perhaps is being the closest to manure in the functions that it serves in root media and, indeed, has been the component substituted for manure. Often, as in the case of poultry manure, the high ammonia content causes root and foliage injury to the plant. Rotted cow manure is the best type to be used in the greenhouse. Cow manure is incorporated into media at the volume rate of 10–15%. The media is then pasteurized with steam or chemicals. This is necessary in order to rid the medium of harmful disease organisms, insects, nematodes, and weed seed. Following pasteurization, it is very important that each time water is required, a sufficient quantity is applied to ensure leaching so that a buildup of ammonium nitrogen originating from

Table 1 Primary fertilizer nutrient content of some sources of animal manure

Type of manure	Nutrient content (% of dry weight) Nitrogen (N)	Phosphorus (P_2O_5)	Potassium (K_2O)
Cattle (cow)	0.5	0.3	0.5
Horse	0.6	0.3	0.6
Sheep	0.9	0.5	0.8
Chicken	1.0	0.5	0.8
Swine	0.6	0.5	1.0

the manure does not occur. A buildup of ammonium nitrogen contributes to the total soluble-salt content of the root medium and can be detected readily by a soluble-salt test.

4.3 Solar Energy in Environmental Control

Recent interest in sustainability and green buildings has led to an increased focus on solar energy devices for their nonpolluting and renewable qualities. Replacing fossil fuel with domestic, renewable energy sources can also enhance national security by reducing dependence on imported energy.

Rational energy use is fundamental since energy accounts for a substantial proportion of total production costs. Average energy use accounts for 10–30% of total production costs, depending on the region.

Increase in production per unit of energy (energy efficiency) can be achieved through reduction of energy use and/or improvement of production. The major challenge in greenhouse operation is to find ways to contribute to improved energy efficiency combined with an absolute reduction of the overall energy consumption. The optimizing production efficiency is as follows: autumn/winter – maximize the radiation quantity and minimize the energy loss; spring/summer – reduce high temperatures.

For rational use of energy (or fossil fuels) and reduction of greenhouse energy consumption, greater investment is required in order to achieve efficient use of energy (i.e., the amount of product per input of energy), reduction of energy requirement, and replacement of fossil fuels by more sustainable sources.

Rational use of energy depends on efficient energy greenhouse environmental control, which requires knowledge of the physiological processes (photosynthesis and transpiration, crop growth and development), in relation to the various environmental factors (temperature, light, humidity, and carbon dioxide).

However, to achieve the maximum benefits of energy-efficient environmental control, it is essential for the greenhouse itself and the control equipment (heating and ventilation systems, carbon dioxide supply, and lighting) to be properly designed and frequently checked (at least at the start and once during the growth season). For example, optimized designs of heating systems may prevent uneven temperature distribution and subsequent loss of energy and crop yield.

Solar radiation is the first climate parameter to be evaluated, in particular, year-round availability. Day length and solar radiation intercepted by a horizontal surface during daytime hours are measured to determine total daily solar radiation. Another basic climate parameter is ambient temperature.

The type of greenhouse adopted depends on the prevailing climatic characteristics and suitable climate for grown crops.

There are some differences between air temperature and plant temperature as well as between parts of the plant, especially during daytime, depending on the solar radiation intercepted, the water transpiration from plants, and the air movement. Plant root temperature is assumed to be the same as the soil temperature.

A greenhouse is built and operated to produce crops with a high quantity and quality and return a profit to the grower. Latitude angle is the main factor in influencing greenhouse temperature control; solar radiation available inside the greenhouse (sunlight) is the limiting factor in production, especially during winter season. Therefore, greenhouses should be provided for optimum use of available sunlight. The amount of solar radiation available to plants inside the greenhouse is affected by the following factors: structural frame (Quonset, modified Quonset, or gable-even-span), glazing materials (plastic sheets, fiberglass-reinforced plastic or glass), orientation of the greenhouse (east-west or north-south), and surrounding topography (mounts, buildings, or trees), while the amount of solar radiation available outside the greenhouse is affected by the following factors: latitude angle of the location, time of the year (solar radiation in summer is higher than that in winter), time of the day (solar radiation at and around noon is higher than that after sunrise and prior to sunset), sky covering, and clouds (water vapor and dust affecting the solar radiation).

A greenhouse cover with high transmissivity for solar radiation can produce temperature that is higher than desired in the crop zone. Most surfaces within a greenhouse have a high absorptivity for short-wave solar radiation and, thus, convert incoming short-wave solar radiation into long-wave (thermal radiation) resulting in an increase of the thermal trapping. Heat energy exchange during the daylight time is plotted in Fig. 3.

Transmissivity is the percent of short-wave solar radiation transmitted when the sun's rays strike the glazing surface at a right angle to the surface, while emissivity is the ratio of the total solar radiation emitted by a body to the total radiation emitted by a black body of the same area for the same time period.

Total solar radiation flux incident on a surface roof (glazing) of greenhouses is mainly affected by several factors: the tilt angle of the wall surface (vertical and tilted or curved walls), type and number of greenhouse glazing materials, and orientation of the greenhouse.

4.3.1 Crop-Based Environmental Control

Operational control should not aim at control individual environmental factor (e.g., temperature, humidity, and carbon dioxide) but for energy-efficient crop production

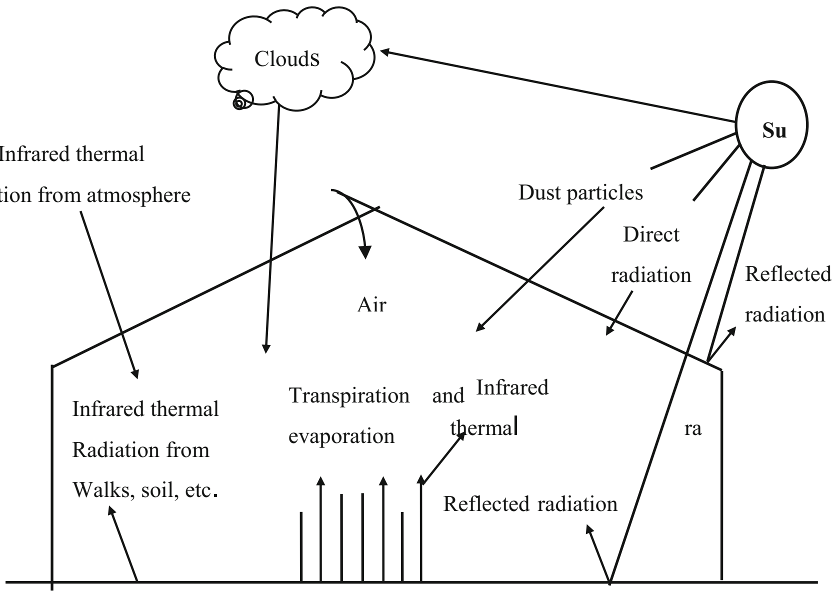

Fig. 3 Energy exchange between a greenhouse and the surroundings

and quality control, taking into account the impact of control actions on both crop yield and energy use.

4.3.2 Evapotranspiration Rate

Evapotranspiration rate of the plants in a greenhouse is mainly affected by the solar radiation received by the leaves of the plant and the stage of plant growth. The ratio of solar radiation to the evapotranspiration for actively growing plants in a greenhouse ranged between 48 and 52% depending upon the total surface area of the plant leaves with an average of 50% (i.e., about one-half of the solar radiation received by the leaves is functioned to evaporate water).

This means that during the first stage of crop growing, the total surface area of leaves is smaller; accordingly, the smaller ratio can be used, whereas the higher ratio can be used during the last stage of growth when the total surface area of leaves is greater. The evapotranspiration rate (q_{ev}) is computed from the following equation [14]:

$$q_{ev} = RFI_{Tg} \text{ W} \tag{6}$$

where R ratio of solar radiation to evapotranspiration, decimal, F ratio of floor surface area cover by plants to the total area, decimal, I_{Tg} total solar radiation flux incident inside the greenhouse

4.3.3 Energy Conservation

Any system functioned in the greenhouse that will reduce heat loss will decrease heating fuel use. A compromise may be necessary to satisfy the light requirement for plant growth while reducing heat loss. For example, the second layer of light-transmitting material will reduce conduction and convection heat loss by about 50%, while the light transmission will decrease by about 10% of a single layer. Movable insulation (thermal screen) can be installed, that is, stores heat energy during daylight time (mainly from the solar radiation) and encloses that heat energy in the crop volume at nighttime. A properly installed double glazing layer or thermal blanket will also reduce air exchange between the crop and outdoor air.

4.3.4 Energy Reduction in Practice

The reduction of the energy need is related to the grower's strategic options in relation to greenhouse construction, covering material, and environmental control equipment in terms of heating system, ventilation, cooling, screens, etc. Increased investment is required and needs to be considered in terms of return rate on investments.

4.3.5 Rational Energy Use in Practice

While the introduction of new modern environmental control technologies will increase energy use efficiency, major advances can be made by enhancing the hardware design of heating and ventilation systems to increase the accuracy and the frequency of controls of the sensor network. Thus, the major applied recommendations for rational energy use mainly depend on the grower's operational control of the available hardware in terms of heating, ventilation and cooling systems, screens, etc.

4.3.6 Replacement of Fossil Fuel by Other Sustainable Sources

As carbon dioxide emission is directly related to the use of fossil fuels for heating and cooling greenhouses, alternatives (e.g., solar and geothermal energy, biomass, and waste heat) can significantly help achieve the reduced carbon dioxide emission targets. Using waste heat and carbon dioxide supply from combined heat and power generators (CHP) and feeding the electricity to the national grid can save a significant fraction of the fuel. While energy is not directly saved at greenhouse level, CHP reduces greenhouse gases emission at the national level by reducing the carbon dioxide emission of the central power plants. However, the economically feasible application of CHP mainly depends on the local situation. Sometimes it is not allowed or is not technically feasible to feed electricity into the national electricity grid, or the price of electricity is too low. Standalone use of CHP (for electricity used at greenhouse farm level) is only an option in large-scale greenhouses and requires smart solutions for the imbalance between the unsynchronized heat and power use at the farm level, for example, using heat storage systems.

Biomass and anaerobic digestion are a good alternative option for fossil fuel, but the availability and massive quantities needed as well as uncertainty about the energy content are major drawbacks for large-scale application. For example, 1 MW of electricity may require up to 2,500 tons of dry mass per year. This not only requires significant investments but also logistic solutions and the availability of biomass in the surrounding area. Furthermore, the continuity of the biomass supply may be a problem as the storage of required amounts of gas is almost impossible. With regard to carbon dioxide from this gas, special attention should be paid to pollution aspects after burning components like SO_2/SO_3 and NO_x may seriously damage the crop. However, for small-scale application and stand-alone greenhouses, they are performing well without connection to energy infrastructure.

5 Greenhouse Heating

Greenhouse heating is essential even in Egypt with a temperate climate, in order to maximize crop production in terms of yield quantity and quality. Heating cost is not only directly connected to profitability, but in the long term, it may determine the sustainability of the greenhouse industry. In addition to the costs of high energy consumption, heating is associated with environmental problems through the emission of greenhouse gases.

Heating of greenhouses accounts for 30–35% of the total cost of production of most protected cropping, and any increase in the price of fuel has a large proportionate effect on production costs.

The requirements for heating a greenhouse reside in the task of adding heat at the rate at which it is lost. Most heat is lost by conduction through the glazing materials (aluminum sash bars, polyethylene, and asbestos-cement curtain walls) of the greenhouse.

The designs and sizes of greenhouse structures used in commercial production influence the indoor air temperature and air circulation patterns, due to the high air temperature that is mainly accumulated in the greenhouse ridge. The heat loss at nighttime in a polyethylene-covered greenhouse represented almost 39% of the total heat loss, providing no condensate was present. The presence of condensate on a polyethylene cover has been reported to decrease heat loss by 10–15%. Infiltration of cold air through improperly fitted ventilation, louvers, and cracks in the cover all contributes to increased heat requirements (heat energy losses up to 16% through the chimneys).

The major heat loss is through the greenhouse structure and covers. Heat energy exchange between indoor and outdoor environments is illustrated in Figs. 4 and 5. Heat energy exchange between the greenhouse indoor and outdoor air is the sum of heat energy available from all sources such as solar radiation heat, furnace heat,

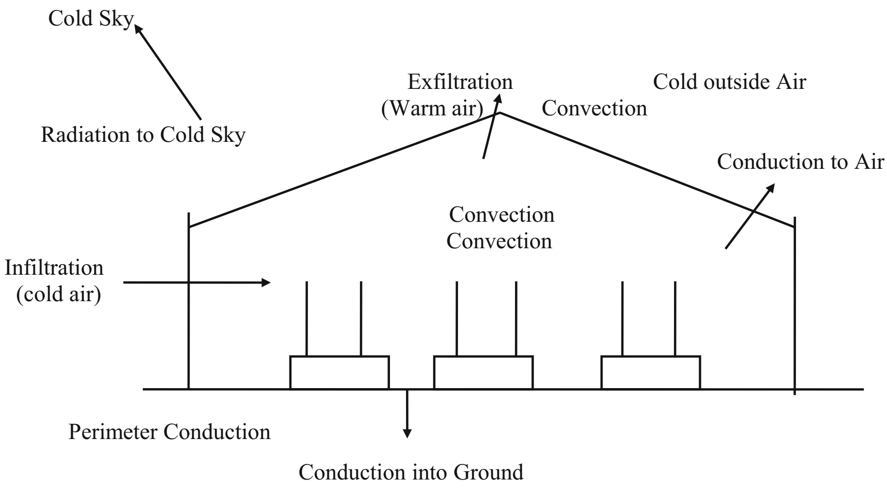

Fig. 4 Heat losses from a greenhouse

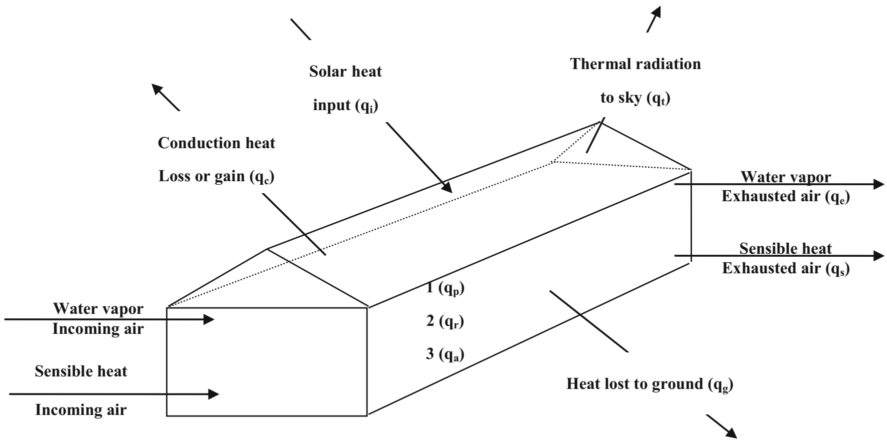

Fig. 5 Heat energy quantities considered in the greenhouse heat energy balance [14]

lighting heat, electric motor heat, etc. and the rate of heat energy loss from the greenhouse. The heat energy balance equation is as follows:

$$q_{\text{input}} = q_{\text{output}} \tag{7}$$

q_{input} = solar radiation + furnace + electric motors + lighting, q_{output} = heat loss by conduction through the greenhouse shell + heat loss by air exchange between indoor and outdoor air + heat loss by thermal radiation to the sky + heat loss by evaporating water

Furnace heat energy is estimated for nighttime heating when there is no solar radiation, and the heat energy from electric motors and lighting and its use in evaporating water may be ignored due to their small values.

During daylight time, the energy balance equation can be written as follows:

$$q_i = q_c + q_e + q_t + q_s \tag{8}$$

where q_i solar heat energy input

$$q_i = R\tau_s A_f \tag{9}$$

q_c = conduction heat energy loss or gain, q_e = water vapor loss by exhausted air (evapotranspiration rate)

$$q_e = FRq_i \tag{10}$$

q_t = thermal radiation to the sky

$$q_t = \varepsilon_i \tau_1 A_f \sigma \left(T_{ai}^4 - T_{sky}^4 \right) \tag{11}$$

$$T_{sky} = 0.0552 (T_{ai})^{1.5}\ ^\circ\mathrm{K} \tag{12}$$

q_s = sensible heat energy loss by exhausted air.

5.1 Computing Heating Requirements

The heat energy requirements for most greenhouse structures are based on the total heat energy loss from the greenhouse and of heat energy at the rate of which it is lost. Heat energy loss from the greenhouse is much higher than from modern conventional housing. This is due to the high rate of heat transfer through the light-transmitting cover, usually plastic or fiberglass. Many factors contribute to heat energy loss (structure frame, covering materials, orientation, and heating systems).

The total heat losses from inside to outside of the greenhouse can be computed from the following equation [14, 22]:

$$q_{Heat} = q_{Loss}\ \mathrm{W} \tag{13}$$

$$q_{Loss} = q_{cl} + q_{inf}\ \mathrm{W} \tag{14}$$

where q_{cl} is the combination of heat losses by conduction, convection, and radiation through the glazing materials and the concrete blocks of the greenhouse. It can be estimated by the following equation:

$$q_{cl} = U_o A_c (T_{ai} - T_{ao})\ \text{W} \tag{15}$$

where U_o the overall heat transfer coefficient, W/m^2/C (Table 2), A_c the total surface area of covering material, m^2, T_{ai} the indoor air temperature, °C, T_{ao} the outdoor air temperature, °C

The heat loss due to air infiltration through the structure (q_{inf}) of outside cold air can be divided into sensible and latent heat. The heat energy quantity associated with having to raise the temperature of outdoor infiltration cold air up to indoor air temperature is the sensible heat component (q_S).

The heat energy quantity associated with net loss of moisture from the space is classified as the latent heat component (q_L). The heat energy required to warm outdoor air entering the greenhouse by infiltration to the indoor air temperature is given by [14, 22]:

$$q_{inf} = q_S + q_L\ \text{W} \tag{16}$$

$$q_S = m_a C_{pa} (T_{ai} - T_{ao})\ \text{W} \tag{17}$$

where m_a mass flow rate of cold air, kg/s

$$m_a = \text{MN}$$

M = greenhouse volume (m^3) × density of air (kg/m^3), N = air infiltration rate, s^{-1}, C_{pa} = specific heat of air.

When the addition of moisture to the indoor air is required to maintain winter comfort conditions, it is necessary to determine the energy needed to evaporate an amount of water equivalent to what is lost by infiltration (latent heat component of infiltration heat loss). This energy may be calculated by

Table 2 Overall heat transfer coefficient for greenhouse cover materials and systems [22]

Greenhouse cover material	Overall heat transfer coefficient (W/m^2 °C)
Single layer glass	5.40
Single layer plastic film	6.80
Single layer fiberglass-reinforced plastic	5.70
Double layer plastic film	3.98
Double layer acrylic	2.84
Double layer plastic film over glass	2.84
Single layer glass plus internal thermal blanket	2.84
Double layer plastic film plus thermal blanket	2.27
Standard concrete blocks, 20 cm thick	2.90
Poured concrete, 15 cm thick	4.26
Perimeter, non-insinuated	4.54
Perimeter, insulated	2.27

$$q_L = m_a h_{fg}(W_i - W_o) \text{ W} \tag{18}$$

where h_{fg} latent heat of vaporization of water, 2,454 × 10^3 J/kg, W_i humidity ratio of the greenhouse indoor air, kg/kg_{dair}, W_o humidity ratio of the greenhouse outdoor air, kg/kg_{dair}

5.2 Heating Equipment

A boiler or heater must be provided to supply heat energy to the greenhouse at the same rate at which it is lost by conduction, infiltration, and radiation. A central or localized heating system may be utilized in larger commercial greenhouse ranges. In the central heating system, one or more boilers are situated in a single position, and the steam or hot water generated is piped to the various greenhouse locations. The localized heating system makes use of several heaters, usually forced hot air, each located in the area it heats.

The recent increases in fossil fuel prices have led to the greenhouse industry to seek for alternative fuel sources to provide heat energy and carbon dioxide for crop production. It is chosen alternative energy source such as the use of solar energy, biogas energy, biomass energy, and hybrid heating systems (solar and biomass or solar and biogas energies), for improving its efficacy in sustainable production and productivity of crops. Field residue biomass is a renewable resource that is considered as greenhouse gas neutral when converted into heat energy properly. Nowadays, there are four different types of heating systems that are commonly used for heating the commercial greenhouses: central heating system, localized heating system, solar heating system, and renewable energy system [23].

5.2.1 Central Heating System

A central boiler system is best justified for the greenhouse range which starts out large (4,000 m^2) and makes its expansions in large increments. It was usually located in a boiler room separate from the greenhouse. When the boiler is separated from the greenhouse, considerable heat energy is lost from the boiler jacket, the pipes carrying steam or hot water to the greenhouse, and the return lines carrying condensate or cool water back to the boiler. When the boiler is in the greenhouse, the escaping heat contributes toward the heat requirement of the crop. However, the high humidity results in corrosion and premature breakdown of switches, pump motors, etc.

Hot water has been customarily supplied to a greenhouse at a temperature range from 82 to 95°C in 50.8 mm pipe diameter. To provide an adequate uniform distribution of heat energy generated by the boiler, a heat-distributing coil (heat exchanger) must be functioned. Circulating pumps are required to move the hot water through the heating system.

Placement of heat-distributing coil is very important; if the entire pipe is stacked on the side walls and end walls of the greenhouse, undesirable patterns of airflow will occur. The heat from the side coils of pipe rises along the side wall and part of the roof until it meets a stream of air which is being cooled by the glazing material and is flowing downward under the roof. The two currents mix and drop at this point, part returning to the pipe coil and part moving toward the center of the greenhouse at the plant level, creating a cold spot in the center. In the center of the greenhouse, currents meet from both sides and rise. The growth of plants is delayed where these cold spots occur as shown in Fig. 6.

A continuous pipe is used in a trombone coil (steam system) (Fig. 7). Resistance to flow is not a problem for steam, but the rapid drop in pressure and temperature along the pipe occurs. Steam enters at the top of the coil and passes to the distance end of the greenhouse. It returns to the entry end of the second pipe down and then back to the distance end in the third pipe down. This arrangement continues until at the end of the coil water condensates and steam enters a trap which permits the return of water, but not steam, to the boiler.

Steam or hot water is produced, plus a radiating mechanism in the greenhouse to dissipate the heat (Fig. 8). The typical cost of a central boiler system depends on the number of heat zones and the exact heat requirement.

Unlike the unit heater systems, a portion of the heat from central boiler systems is delivered to the root and crown zone of the crop, resulting in improved growth and to a higher level of disease control. Placement of heating pipes is very important as it is directly related to heat loss; for example, the placement of pipes in the walls resulted in high losses through the sides.

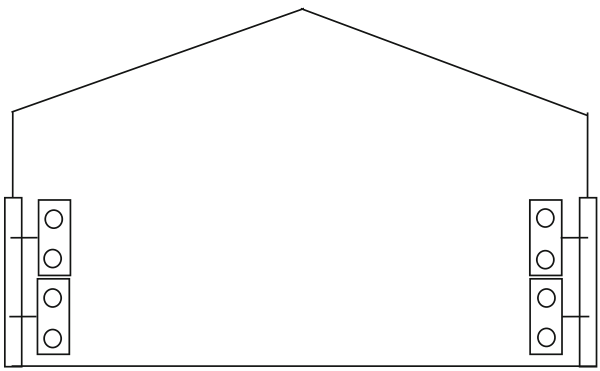

Fig. 6 Heat-distributing system using finned pipe for perimeter of greenhouse

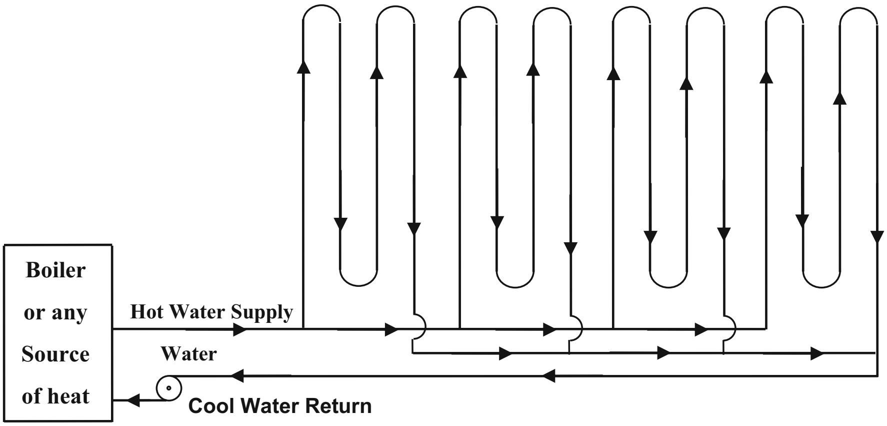

Fig. 7 Heat-distributing coil (heat exchanger) using trombone (series flow) system

Fig. 8 Heating pipes for dissipating the produced heat

5.2.2 Wall Pipe Coils

Perimeter-wall heating can provide part of the additional heat requirement and contribute to a uniform thermal environment in the greenhouse (Fig. 9). Both bare and finned pipe applications are common. Side pipes should have a few centimeters of clearance on all sides to permit the establishment of air currents and should be located low enough to prevent the blockage of light entering through the sidewall.

Fig. 9 Wall pipes

5.2.3 Overhead Pipe Coils

An overhead coil of pipes across the entire greenhouse results in heat loss through the roof and gables. The overhead coil is not the most desirable source of heat, as it is located above the plants; nevertheless, overhead heating systems can provide the additional heat required for winter months. They can also be used to reduce the risk of *Botrytis cinerea* outbreak, a major concern for many greenhouse growers.

5.2.4 In-Bed Pipe Coils

When the greenhouse layout allows it, the in-bed coil is preferable by placing the heating pipes near the base of the plants; the roots and crown of the plants receive more heat than in the overhead system. Air movement caused by the warmer underbench pipe then reduces the relative humidity around the plant. Heat is also kept lower in the greenhouse resulting in better energy efficiency. Such systems are suitable for plants grown on benches, fixed tables, and rolling or transportable tables.

5.2.5 Floor Pipe Coil

Floor heating is more effective than in-bed pipe coil heating. In addition to the advantages of in-bed coils, floor heating has the ability to dry the floor quickly. This is essential when flood floors are used for irrigation/fertilization. In this system, plants are set on the floor, which makes drying the floor difficult. Air movement caused by the warmer floor reduces the relative humidity around the plant.

Such systems are suitable for plants directly grown on the floor, flooded floor areas, or work areas.

5.2.6 Pipe/Rail Heating Systems

These systems maintain uniform temperatures with a positive effect on the microclimate. Air movement caused by the warmer pipe/rail reduces humidity around the plant. Such systems are suitable for vegetable production (see Fig. 10).

5.2.7 Localized Heat System

Numerous heater designs are fit into three basic categories: unit or forced-air, convection, and low-energy radiant heaters.

5.2.8 Unit Heaters

The most common and least expensive is the unit heater system. Unit heaters are often referred to as forced-air heaters. They consist of three functional parts: Fuel is combusted in a firebox to provide heat energy. The heat is initially contained in the exhaust, which rises through a set of thin-walled metal tubes on its way to the exhaust stack. The warm exhaust transfers heat to the cooler metal of the tubes. Much of the heat energy is removed from the exhaust by the time it reaches the stack through which it leaves the greenhouse. A fan in the back of the unit heater draws in greenhouse air, passing it over the exterior side of the tubes and then out the front of the heater to the greenhouse environment again. The cool air passing over the hot metal tubes is warmed. In short, the metal tubes serve as heat exchangers, absorbing heat from the hot exhaust passing through the inside of them and transferring it to the cool greenhouse air passing over the outside of them. Heaters are located throughout the greenhouse, each heating a floor area of 180–500 m^2. Generally the fuel supply

Fig. 10 Pipe/rail heating systems

and fan are connected to a thermostat located in an appropriate area of the greenhouse. Unit heaters come in vertical as well as horizontal designs. This refers to the direction in which the heated air is exhausted from the heater. The vertical heater takes air in from the ridge area of the greenhouse and expels it downward the floor.

These heaters are suspended from the ridge of the greenhouse, well above head height, and are spaced along the length of the greenhouse at intervals equal to its width. Uneven temperatures and drying of the soil sometimes occurred, which resulted in nonuniform growth.

The uneven temperature and drying problems are reduced with horizontal air distribution. It is possible to use fewer but larger heaters, thus reducing the initial cost of the heaters as well as the labor or installation. The horizontal heaters are also adaptable to the newer integrated systems of heating, cooling, and horizontal airflow. Unit heaters (either vertical or horizontal) have an exhaust stack, which is generally run from the heater directly through the roof above the heater (extend 2.4–3.7 m above the firebox).

5.2.9 Convection Heaters

Convection heaters are commonly used in small commercial greenhouses. Fuel of most any type, including wood, coal, oil, or gas, is combusted in a firebox. The resulting hot fumes pass out through an exhaust pipe which is situated along the floor either between floor beds or beneath benches as illustrated in Fig. 11. It is important in all greenhouse heating systems that the exhaust does not contact the crop.

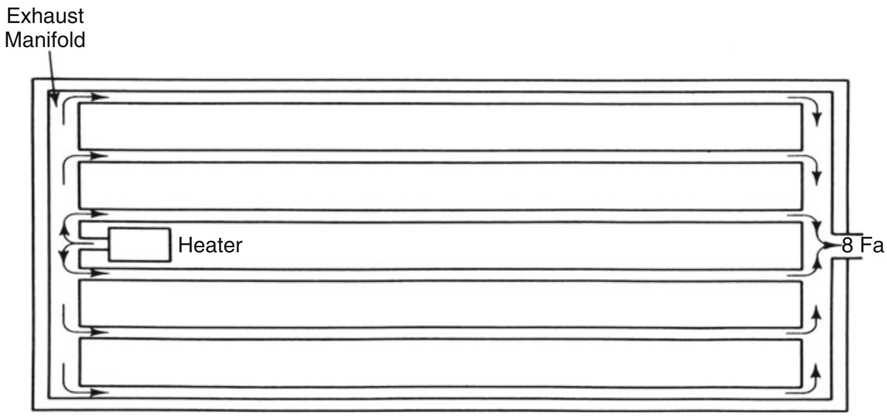

Fig. 11 Exhaust from the convection heater enters a large-diameter stovepipe manifold in which it is distributed to several smaller-diameter stovepipes running along the floor between beds or under benches to the opposite end of the greenhouse

5.2.10 Radiant Heaters

Low-energy, infrared radiant heaters are placed overhead in the greenhouse. They emit infrared radiation, which travels in a straight path at the speed of light (3.8 m/s). Objects (plants, walks, and benches) in the path absorb this electromagnetic energy, which is immediately converted to heat; they in turn will increase temperature of surrounding air. Air temperatures in greenhouses which use infrared radiant heating can be 3–6°C lower than in conventionally heated greenhouses with the same plant growth and production.

Disease is discouraged by the lesser amount of condensation in infrared radiant-heated greenhouses.

The advantage of infrared radiant heat system is the reduction of about 75% in electrical consumption and a 30–50% fuel reduction over a conventional unit heater system. The only motor required in the infrared radiant heat system is in the exhaust fan. Moreover, the selection of heating equipment depends strongly upon the size and type of greenhouse operation, structures and availability, and cost of fuel system components. A system is made up of fuel burner, heat exchanger (heat-distributing coil), and control system.

5.2.11 Solar Heating

Solar heating is an alternative to a fossil fuel heating system. The solar heating system is commonly consists of several components as demonstrated in Fig. 12: solar collector, heat storage facility, heat exchanger to transfer the solar-derived heat to the greenhouse air, backup heater to take over when the solar heating system does not suffice, and set of controls.

5.2.12 Solar Collector

The flat-plate solar collector consists of a flat black plate (aluminum sheet, copper sheet or stainless steel sheet, etc.) for absorbing the maximum possible amount of

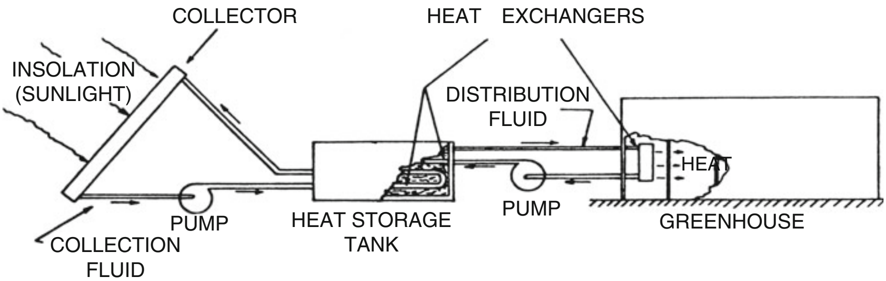

Fig. 12 A typical solar heating system for greenhouses

solar energy. The plate is covered on the sun side by one or more transparent glass or plastic layers and on the back by insulation. The enclosing layers serve to hold the collected heat energy within the solar collector. Water or air is passed through or over the black plate to remove the entrapped heat energy and carry it to the storage facility. Collection of heat energy by flat-plate solar collectors is most efficient when the solar collector is positioned perpendicular to the sun at solar noon. Water collectors require a mass flow rate between 0.4 and 1.2 kg/min per square meter of collector surface area.

A greenhouse itself is considered as a solar collector; some of its collected heat energy is stored in the soil, plants, structural frame, walks, etc. The remaining heat energy can be excessive for plant growth and is therefore vented outdoor. The excess vented heat could just as well be directed to a rock bed for storage and subsequent use during a period of heating (at nighttime).

5.2.13 Storage and Heat Exchanger

Water and rocks are the two most common storage materials for heat in the greenhouse at the present. To store equivalent amounts of heat energy a rock bed would have to be three times as large as a water tank. A water storage system is well adapted to a water collector and a greenhouse heating system making use of a pipe coil or unit heater with water coil contained within. Heated water from the solar collector is pumped to the storage tank during the daylight. As heat is required, warm water is pumped from the storage tank to a hot water or steam boiler or into the hot water coil within a unit heater. Although the solar-heated water will be cooler than thermostat setting on the boiler, heat will be saved, since the temperature of this water will not have to be raised as high to reach the output temperature or steam from the boiler.

5.2.14 Backup Heater

A solar heating system is considerably more expensive than a conventional heating system. A conventional fossil fuel backup system is installed to meet the additional heating needs of the coldest nights. This compromise increases the chances of justifying the cost of a solar heating system. Recently there is a functional possibility of using the stored thermal energy from the hybrid heating system (modern biomass combustion system-assisted flat-plate solar collectors or biogas energy-assisted solar heating system) with a heat exchanger to provide and maintain an optimum level of microclimatic conditions of the greenhouse at nighttime during winter season.

5.2.15 Thermostats and Controls

Various types of thermostat and environmental controllers are available for commercial greenhouse production. Sensing devices should be placed at plant level (at least 1 m above ground) in the greenhouse: thermostats at eye level are easy to read but do not provide the necessary input for optimum environmental control. An appropriate number of environmental sensors are needed throughout the production area. Environmental conditions can vary significantly within a short distance. Thermostats should not be placed in the direct sun rays as this would result in poor readings; they should be mounted facing north or in a protected location. It may be necessary to use a small fan to pull air over the thermostat to get appropriate values. To illustrate typical controls in a solar-heated greenhouse, water system is considered. The first control activates when water in the solar collector becomes 5°C higher than in the storage tank and cuts off when the differential is 2°C. Water is pumped from the solar collector to the top of the storage tank. Cooler water at the bottom of the storage tank returns to the solar collector. A second control might activate the storage tank to the greenhouse heat-exchanger pump when the greenhouse air temperature drops to 16°C and turn it off when 18°C is achieved for most protected cropping. A third control on the backup heater at an air temperature of 16°C in the event that the solar heating system fails to hold the desired temperature.

5.3 Calculation of Greenhouse Heating Needs

1. Measure the first three dimensions of the greenhouse [measure the length, width, and height of the structure (to where the roof begins)].
2. Measure the greenhouse ridge (measure the distance between the ground and the tip of the greenhouse's roof).
3. Measure the greenhouse roof slope (the slope is the distance from the tip of the roof to the bottom of the roof).
4. Determine the surface area of the greenhouse's roof slope and two walls (use the formula: $2(H + S)L$; where $H =$ height, $S =$ roof slope, and $L =$ length).
5. Determine the surface area of the remaining two walls (use the formula: $(R + H)W$; where $R =$ ridge, $H =$ height, and $W =$ width).
6. Determine the total surface area of the greenhouse (add together the results from steps 4 and 5).
7. Calculate the desired temperature difference (determine the best temperature for the interior of the greenhouse, determine the average coldest temperature for the area surrounding the greenhouse, and determine the difference between the two temperatures).
8. Estimate the overall heat loss coefficient (according to the covering material, refer to Table 2) [22].
9. Estimate the heating needs of the greenhouse (multiply steps 6, 7, and 8).

Or, in order to determine the burden of heating requirement, the surface area of an A-frame greenhouse must be divided into four different components, as shown in Fig. 13. These components are: curtain wall, vertical wall, gable end, and gable roof. The areas of each component must be precisely determined in order to calculate the

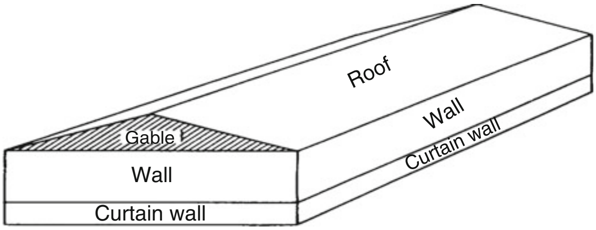

Fig. 13 Schematic diagram of an A-frame greenhouse showing component areas in the determination of heating burden requirement for this greenhouse

heat loss separately from each one. There is also a heat loss from the perimeter of the greenhouse, thus the perimeter must be determined. The heat loss from each area and from the perimeter can be determined by multiplying them by two factors: overall heat transfer coefficient and temperature potential difference between indoor and outdoor air. The burden of heating requirement for greenhouses can be reduced by installing a second covering of polyethylene, by repairing broken glass, by tightening existing glass or sealing the glass laps, by using a windbreak of row of trees to reduce wind velocity, by using high-efficiency heaters and boilers, and possibly by using cool-temperature-tolerant varieties of plants.

6 Greenhouse Cooling

Reducing indoor air temperatures is one of the main problems facing greenhouse management in warm and hot climates. One of the most efficient ways to reduce the difference between indoor and outdoor air temperature is the ventilation system. Natural or passive ventilation system uses very little external energy as opposed to active or forced ventilation, but it increases the complexity of greenhouse structure and makes climate control more difficult. Various technical equipment can efficiently contribute to maintain greenhouse indoor air temperature and relative humidity at acceptable levels during hot periods.

Indoor air temperatures of the greenhouse are frequently 15°C higher than those outdoor in spite of open ventilators. Detrimental effects of high temperatures are typified by loss of stem strength and flower size of carnations and delay of flowering or even bud abortion of chrysanthemums. There are two main cooling systems used for reducing excessive indoor air temperature of greenhouse, natural and mechanical ventilation systems.

6.1 Natural Ventilation Systems

Natural ventilation is the most common method of cooling, and optimizing the geometry of the greenhouse can enhance natural ventilation. Natural ventilation is a direct result of pressure difference created and maintained by wind or air temperature gradients, and it depends heavily on evapotranspiration cooling provided by the crop to maintain acceptable air temperature within the greenhouse. Its suitability as a primary means of cooling must be judged based on local environmental conditions, type of crop grown, and the design of the greenhouse. Natural ventilation may be used to advantage in moderately warm or hot climates, depending on the wind speed. Crops capable of high rates of transpiration should be chosen to maximize evaporation cooling.

Natural ventilated greenhouses are typically provided with vent openings on both sides of the ridge and on both sidewalls. Vent operation should be such that the leeward vents are opened to produce a vacuum at the top of the ridge. Opening of the windward vents produces a positive pressure in the greenhouse which is typically less efficient than vacuum operation. Pressure gradients are typically small so that large vent openings are necessary to provide adequate ventilation. The combined sidewall vent area should equal the combined ridge vent area, and each should be at least 15–30% of the floor surface area; over 30%, the effect of additional ventilation area on the temperature difference was very small [24].

Ridge vents should be hinged and should run continuously to the full length of the greenhouse. The vents should form a 60° angle with the roof when fully open.

Open roof designs may eliminate the need for side or end wall roof vents when more than 50% of the roof area is open. Any natural ventilation system should have the means to open partially or fully in response to indoor air temperature, with automatic control of such systems highly recommended. Incremental opening-closing should also be possible. Automatic vent systems should be equipped with rain and wind sensors to permit closing during periods when crop or ventilator damage might occur.

With roof ventilators, the highest ventilation rates per ventilator area unit are obtained when flap ventilators face the wind (100%), followed by flap ventilators facing away from the wind (67%); the lowest rates are obtained with rolling ventilators (28%).

Shade screens and whitewash are the principal measures taken to reduce incoming solar radiation; greenhouse ventilation is an effective way to remove extra heat through air exchange between the inside and outside (when the outside air temperature is lower). If the outside wind speed is not too low, natural ventilation can be more appropriate, creating a more humid and cooler (albeit less homogeneous) environment around the canopy.

Sufficient ventilation is very important for optimal plant growth, especially in the case of high outside temperatures and solar radiation during the summer in Egypt.

6.2 Insect-Proof Screens for Good Agricultural Practices

Most greenhouses are equipped with ventilation openings to provide suitable microclimate conditions for plant growth. Unfortunately, these vents serve also as a major port of entry for pests, then growers are forced to cover these vents completely and permanently with fine mesh screens net to prevent pest invasion. Since the pests can be very small (e.g., whiteflies and thrips), very fine mesh screens net are required to prevent their entry; these screens impede ventilation and, in some cases, reduce light transmission [10]. Moreover, the targeted insects are most abundant during the warm and hot seasons when effective ventilation is essential for avoiding stressful conditions for both crop plants and workers [25].

Screens are characterized by their porosity (number between openings per inch), mesh size, thread dimension (diameter or thickness), texture (woven, knitted, woven/knitted), color, light transmission/reflection, and resistance to airflow. Most insect-proof screens have square or rectangular openings and are made of monofilament threads.

6.2.1 Effect of Insect-Proof Screens on Ventilation

An important consideration when designing a screen-proof net installation is the effect that screen materials have on airflow through the openings. It has been well documented that screens increase the air pressure drop on the openings, which results in reduced greenhouse ventilation. It is also well known that the air pressure drop on screens is mainly a function of screen porosity (mesh number). For a woven screen made of a monofilament thread and with a simple texture, it is possible to calculate the screen porosity (ε) from the geometric dimensions of the screen:

$$\varepsilon = \frac{(l - d)(m - d)}{ml} \tag{19}$$

where l and m are the distance between the centers of two adjacent weft and warp threads, respectively, d is the diameter of the threads.

Teitel [26] suggested the following correlation to estimate the effect screens on the vents have on temperature difference between greenhouse and ambient air with screens(ΔT_{SW}) and without screens(ΔT_{W}):

$$\Delta T_{\mathrm{SW}} = \Delta T_{\mathrm{W}}(5 - 4\varepsilon) \tag{20}$$

The relationship between the temperature difference with and without a screen is dependent on greenhouse type, crop, weather, and the exact location where the inside air temperature was measured. The value of porosity increases, the ventilation rate increases, and the inside/outside temperature difference decreases.

6.2.2 Removing Insect Screen from Vents When the Risk of Pest Invasion Is Low

Optimal climatic conditions especially air temperature and relative humidity in the greenhouse are often maintained by closing and opening windows and vents. However, insect screens covering windows and vents are not regulated in response to changes in the pest invasion hazards. Greenhouse ventilation is likely to be improved if ventilation openings are uncovered when there is no pest invasion hazards [13]. In the fall, when the whitefly population peaks, over 97% of whiteflies entered the greenhouse between 7.00 and 13.00 h [27]. Thus, the risk of whitefly entering greenhouses in the afternoon and at night is negligible.

The flight of thrips was studied using sticky pole traps and similar traps mounted on wind vanes. For most of the year, about 85% of the thrips were caught in the morning and 10% at dusk [28]. Flight time was correlated with periods of low wind speed, and thrips were seldom caught with wind >10 km/h [29]. Both whiteflies and thrips are not likely to enter protected crops during the hot and windy afternoon hours or at night. Therefore, insect screens may be removed from vents during those times.

6.2.3 Maximizing the Screened Area

Increasing ventilation in multi-span greenhouses with roof openings can be considered a good choice on which screens are mounted to increase the maximum angle at which the flap can be opened. Another openings with preformed concertina-shaped screens can be used that unfold as the ventilators open and then fold up again when they close. Teitel et al. [30] showed that a concertina-shaped screen allows higher airflow (an increase of about 25%) when compared with a flat screen under similar pressure drops across the screen.

6.3 Trends in Natural Ventilation

Efficient ventilation performance is crucial for greenhouse production in both humid winter and hot summer conditions. The ventilation process contributes to optimal control of air temperature, relative humidity, and concentration of gases within the greenhouse. Thus, photosynthetic and transpiration activities of plants are regulated properly and then enhance greenhouse productivity. Given the advantages, low maintenance, low operational costs, and reduced noise, it is the most inexpensive way to keep suitable greenhouse internal microclimate. However, control of airflow with natural ventilation is limited. Therefore, it is necessary to increase ventilation efficiency.

The driving force for natural ventilation is the pressure difference across the ventilation openings caused by wind and/or thermal effects.

Natural ventilation can be achieved by opening windows at the top of the greenhouse and/or at the sidewalls. The number and size of the windows and the mechanisms for window opening vary, with many different arrangements used in glasshouses and plastic-covered houses. Ridge openings can be classified as continuous or noncontinuous, and they are usually on both sides of the ridge, although hoses with openings on one side only are also constructed. Roof vents are either fixed or fully automatic (movable roof vents).

A fixed overlapping vent on a gable ridge provides ventilation while preventing penetration of rain. Movable roof vents may be formed by film rollup from gutter to ridge; ridge hinged arched vents; vertical openings at the center of the arch running the entire length of the roof; vertical roof openings starting at the gutters and extending to a height of about 1 m; or vertical openings at the center of the arched roof running the entire length of the roof. The position and hinging of the vent at the ridge are the basis of a better evacuation of the hot and humid air which builds up at the top of the greenhouse.

Side ventilation is usually achieved by rolling up curtains with a central mechanism operated manually or by an electric motor, mechanisms that open the side vents from bottom to top. Side openings with flaps hinged from the top are also used; however, they are more common in glasshouses than in plastic-covered houses. Flap ventilators are more efficient than rolling ventilators, particularly under moderate wind conditions.

6.3.1 Wind-Driven Ventilation

When the wind blows around a greenhouse, the wind field generates pressure distribution through the greenhouse. Moreover, wind has a fluctuating character that creates a fluctuating pressure difference over the openings; the mean difference in pressure and the fluctuating pressure difference are responsible for the airflow through the greenhouse ventilators [31]. There are claims that air exchange is proportional to outside wind velocity.

6.3.2 Thermally Driven Ventilation

Under calm conditions, buoyancy forces (differences between inside and outside air densities) are the driving mechanism for ventilation, but the effect of thermal buoyancy on ventilation is of fundamental interest when there is almost no wind. Buoyancy-driven ventilation is more important when wind speeds are below 0.5 m/s [32].

6.3.3 Airflow Characteristics Under Wind-Driven Ventilation

Windward ventilation is preferred to leeward ventilation for greenhouses located in warm areas, since windward ventilation clearly increases the ventilation rate [33]. Nevertheless, the internal climate is generally less uniform with windward ventilation, so new greenhouse constructions have larger openings facing the prevailing winds.

6.3.4 Windward Ventilation

The external air is captured by the vent opening of the first span. This results in an internal flow with the same external air direction. The first windward roof ventilator has the most significant effect on the air exchange intensity and internal airflow [34].

6.3.5 Leeward Ventilation

The external wind follows the windward roof of the first span and accelerates along the roof. The external flow separates from the greenhouse structure at the ridge of the first windward span and creates an area of low speed above subsequent spans. Greenhouse air exits the greenhouse through the first roof ventilator, creating an internal flow which is opposite to the external flow. As for windward ventilation, the first ventilator plays the leading role in the air exchange process [35]. Whenever possible, limit greenhouse width to approximately 50 m [34] and leave a separation between adjacent greenhouses to allow hot air to escape.

6.3.6 Sidewall Ventilation

Sidewall ventilation is similar to windward greenhouse roof ventilation with respect to the airflow pattern, since for greenhouse sidewall ventilation the external air also enters the greenhouse through the windward side and passes along the greenhouse width. Kacira et al. [36] showed that the highest greenhouse ventilation rate was achieved when both side and roof vents were used. Without buoyancy effect in the computations, the greenhouse ventilation rate increased linearly with increasing external wind speed. The ratio of the opening of the ventilator area to the greenhouse floor area (9.6%) was found to be small compared with the recommended ratios of 15–25%. Sidewall ventilation may help to reduce the area of the dead zone with high temperatures typical of wide greenhouses.

6.4 Suggestions to Improve Natural Ventilation

6.4.1 Use of Deflectors

Sase [37] suggested a solution to avoid problems in many types of ventilator, that is, the incoming air mainly follows the inner surface of the roof and creates a crossflow above the crop without mixing with the air in the crop area by the use of screens or deflectors to redirect the air stream, while Nielsen [38] offered a method to direct the passing airflow at the hinged ridge vents into the crop space (Fig. 14). Using 1-m-high vertical screen mounted to the ridge, improvements were achieved in the air exchange in the plant zone of about 50% on average. Kacira et al. [39] evaluated the optimization of the traditional vent

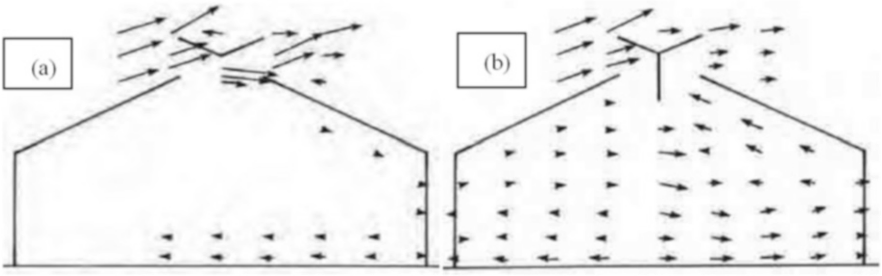

Fig. 14 Effect of a deflector at the roof ventilator on internal air circulation, (**a**) deflector type 1 and (**b**) deflector type 2 [38]

configuration for a two-span glasshouse for better air renewal especially in the plant canopy zone. They evaluated both rollup and butterfly-type side vent openings and various roof vent opening configurations (Fig. 15). The maximum greenhouse ventilation rates were achieved when rollup side vents were used in the sidewalls and both side and roof vents were fully open. The use of the rollup side vent considerably improved the ventilation rate in the plant canopy zone. Thus, the ventilation in the plant canopy zone was considerably affected by the internal airflow patterns caused by different vent configurations.

6.4.2 Changes in the Greenhouse Slope

Increasing the greenhouse roof slope has a positive effect on the ventilation rate. Baeza [34] compared the air exchange rate and internal airflow of greenhouses with roof slopes ranging from 12 to 32°C. According to this study, ventilation sharply increased with increasing roof slopes up to 25°C, after which the increase in ventilation was rather small. The low roof slope does not only affect the ventilation rate but also the air movement inside the greenhouse. Most of the airflow entering through the windward vent on a gentle slope attaches to the greenhouse cover, while with steeper slopes, part of the airflow contributes to the greenhouse ventilation of the first span, and part of it moves on to the following span decreasing the attachment effect observed for lower slopes. Increased roof slope up to 30°C led to increased ventilation rate significantly, and traditional horizontal roof greenhouses are replaced with symmetrical or asymmetrical greenhouses.

6.4.3 Size and Type of Ventilators

Baeza [34] analyzed the effect of ventilator size on greenhouse climate. He increased the flap ventilator size from 0.8 to 1.6 m in the first two and last two spans while maintaining the regular size of 0.8 m in the central spans. For a ten-span greenhouse, the increase in ventilator size had a significant effect on the ventilation rate. Besides, air movement in the crop area was enhanced. As a consequence, the temperature

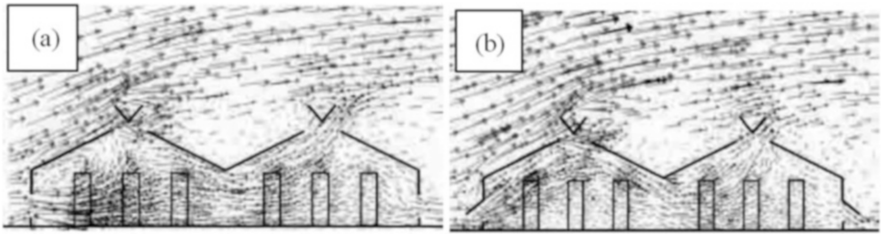

Fig. 15 The effect of side vent configuration on the canopy zone ventilation and air exchange process. (**a**) Rollup side vents and (**b**) butterfly-type side vents [39]

field was more uniform, the temperature difference in relation to the exterior was reduced, and the stagnant air areas were significantly fewer in number and smaller in size. Pérez-Parra [3] compared flap ventilators and rollup ventilators on the greenhouse roof under leeward and windward conditions. Flap ventilators were in all cases more effective at increasing ventilation rate than rollup ventilators. Interestingly, the rollup ventilator's performance was not affected by wind direction, while flap ventilators oriented windward side nearly doubled the air exchange of leeward flap ventilators.

6.4.4 Crop Row Orientation

Sase [40] conducted a ventilation study to compare the effect of the crop rows perpendicular and parallel to the sidewalls. The inside air velocity in the greenhouse with perpendicular rows was nearly twice that of the greenhouse with parallel rows; the crop canopy is a porous medium that offers resistance to the airflow, so it is recommended that the aisle between rows be oriented in the direction of the internal airflow. For roof-ventilated greenhouses, there is strong air movement over the crop area at a higher speed than the air in the canopy zone [35].

6.4.5 New Greenhouse Designs with Improved Ventilation

Upcoming greenhouse models relying on natural ventilation should be narrowed enough (maximum width 50 m) to avoid excessive temperature gradients; furthermore, they should have larger ventilators, especially in the first span facing prevailing winds. They will incorporate screens or deflectors to redirect the airflow toward the crop area producing a homogeneous mixture of the incoming and internal air, to have uniform growing conditions. Effective windward ventilation requires keeping an area between greenhouses free from obstacles. For proper ventilation, future greenhouse designs will not consider a single greenhouse but a group or a greenhouse cluster, since the airflow in a greenhouse is affected by its surroundings.

Natural ventilation is the main method for greenhouse gas exchange, mainly because of the low-energy consumption and low maintenance costs. However, natural ventilation relies on external conditions such as wind speed and wind direction and outside air temperature and relative humidity. Natural ventilation itself may not be sufficient to provide the desired environment. Thus, some other cooling techniques such as shading, mechanical ventilation, or evaporative cooling are used combined with natural ventilation [41–44].

6.5 Mechanical (Fan) Ventilating and Cooling Systems

Mechanical cooling (fans, heat pumps, and heat exchangers) can maintain the same greenhouse temperature as does natural ventilation; it can further reduce the temperature, especially under high ambient temperatures or high radiation levels. With high cooling capacity, it is possible to keep the greenhouse completely closed, even at maximum radiation levels.

Traditional cooling alternatives for greenhouse depend upon exhaust fans to remove excess heat energy. As outdoor air is brought into and then through the house, its energy level rises due to sensible heat gain from the canopy, ground, and surrounding structure. The volume of air required to maintain a given air temperature rise, ($T_{ex} - T_{inlet}$), may be estimated using the following approximate energy balance [14]:

$$(1 - E)R_i A_f = U_o A_c (T_{ai} - T_{ao}) + \left[\frac{q_v A_f C_{pa}}{V_{ex}}\right](T_{ex} - T_{inlet}) \tag{21}$$

where E evapotranspiration coefficient, dimensionless, R_i solar radiation flux incident inside the greenhouse, W/m^2, A_f floor surface area, m^2, U_o overall heat transfer coefficient, W/m^2 °C, A_c surface area of covering material, m^2, T_{ai} indoor air temperature of the greenhouse (the average of the inlet and outlet air temperatures), °C, T_{ao} outdoor air temperature of the greenhouse, °C, q_v ventilation rate, m^3/s m^2 of floor surface area, C_{pa} specific heat of air exhausting greenhouse, J/kg °C, V_{ex} specific volume of air exhausting greenhouse, m^3/kg, T_{ex} temperature of exhaust air leaving the greenhouse, °C, T_{inlet} temperature of air entering the greenhouse, °C

The principle of using forced ventilation is to create airflow through the greenhouse. Fans force air out on one side, and openings on the other side permit air in. Forced ventilation by fans is the most effective way to ventilate the greenhouses, but it consumes electricity energy.

Fine mesh screens obstruct the airflow, resulting in reduced air velocity and higher temperature and humidity, as well as an increase in the thermal gradients within the greenhouse [45].

6.6 Ventilation Cooling and Shading

Removal of heat load can be achieved by reducing incoming solar radiation; removing extra heat through air exchange; and increasing the fraction of energy partitioned into latent heat.

Natural or forced ventilation is generally not sufficient for extracting the excess energy during sunny summer days [46]; even other cooling methods must be used in combination with proper ventilation. The penetration of direct solar radiation through the greenhouse covers into the greenhouse enclosure is the primary source of heat gain. The entry of extra radiation can be controlled by shading or reflection.

6.6.1 Shading

Shading to reduce the solar energy flux into the greenhouse during periods with an excessive radiation level is a common way of achieving passive cooling. Mobile shading systems which installed inside or outside have a number of advantages, such as the improvement of air temperature and relative humidity, quality, and a clear increase in water-use efficiency.

Shading can be achieved in several ways: paints, external shade cloths, nets (of various colors), partially reflective shade screens, and applying water film over the roof and liquid foams between the greenhouse walls. Shading is the last resort to reduce greenhouse air temperature during summer season, because it affects productivity; however, shading can in some cases result in improved fruit quality. A method widely adopted by growers because of its low cost is white painting, or whitening, of the cover material. The use of screens has been progressively accepted by growers and an increase in the area of field crops cultivated under screenhouses [47].

Roof whitening, given its low cost. Baille et al. [48] reported that whitening on glass material enhanced slightly photosynthetically active radiation proportion of the incoming solar irradiance. Therefore, reducing the solar infrared fraction entering the greenhouse is a potential advantage compared with other shading devices with high solar radiation during summer. Another advantage of whitening is that it does not affect ventilation, while internal shading nets adversely affect the performance of greenhouse roof ventilation. Whitening also significantly increases the fraction of scatter irradiance, which is known to enhance radiation use efficiency.

Screens mounted inside the greenhouse also contribute to decreasing the inside air speed, thus lessening the leaf boundary layer and restraining the availability of CO_2 near the leaf surface. It is not clear whether shading nets are best used throughout the growth cycle or only during the most sensitive stages when the crops have a low leaf area and the canopy transpiration rate cannot significantly contribute to the greenhouse cooling [49].

Specific materials which absorb or reflect some wavelengths or contain interference or photo or thermochromic pigments may be used to bring down the heat load, but mostly these materials also reduce the photosynthetically active radiation (PAR) level. Materials reflecting part of the sun's energy not necessary for plant growth [near-infrared (NIR)] show promising results (e.g., [50]) and may be applied either as greenhouse cover or as screen material.

6.6.2 Evaporative Cooling Systems

Evaporative cooling systems is the common technique for reducing sensible heat load by increasing the latent heat fraction of dissipated energy and used to aid greenhouse cooling in warm climates by lowering the dry-bulb temperature of the inlet air. One of the most efficient solutions for alleviating high-temperature conditions is to use evaporative cooling systems, based on the conversion of sensible heat into latent heat through evaporation of water supplied directly into the greenhouse atmosphere (mist or fog system, sprinklers) or via using evaporative pads. Evaporative cooling allows simultaneous lowering of temperature and vapor pressure deficit, and its efficiency is better in dry environments. The advantage of using mist or fog systems over wet pad systems is the uniformity of conditions throughout the greenhouse, eliminating the need for forced ventilation and airtight enclosure.

Direct evaporative cooling by fogging/misting and indirect evaporative cooling (pad and fan) are most likely the result of the positive effects of lower temperature and higher relative humidity resulting in better growth and production, at least with major fruit and vegetables. Therefore, direct evaporative cooling by misting, wet pad, and fan cooling still gives the best economic results and increases energy efficiency primarily through the positive impact on production.

6.6.3 Fog System

Water is sprayed as small droplets (in the fog range, 2–60 nm in diameter) with high pressure into the air above the plants in order to increase the water surface in contact with the air. Free fall velocity of these droplets is slow, and the air streams inside the greenhouse easily carry the drops. This can result in high efficiency of water evaporation combined with keeping the foliage dry.

Fogging is also used to create high relative humidity, along with cooling inside the greenhouse. According to Arbel et al. [51], increased efficiency in the cooling process in relation to water consumption can be expected if fogging is combined with a reduced ventilation rate. Furthermore, the efficiency of fog systems is often limited by insufficient natural air convection, in the absence of wind, and by the risk of wetting the plants when water droplet evaporation is not complete. Fog cooling efficiency increases with spray rate and decreases with ventilation rate [42, 43].

6.6.4 Fan and Pad Cooling

The evaporative cooling system is based on the process of heat absorption during the evaporation of water. The fan-and-pad cooling system is most commonly used in horticulture (Fig. 16). Along one wall of the greenhouse, water is passed through a pad. The pad may be placed vertically in the wall, or it may extend horizontally out from the wall. It is a cross fluted cellulose material somewhat similar in appearance to corrugated cardboard. Exhaust fans are placed on the opposite wall. Cooling pads and air inlets are sized to maintain the face velocities in which inlet air temperature can be expected to reduce to within 2.0°C of the outside wet-bulb temperature at pressure drops through the pads not exceeding 0.015 kPa. Higher face velocities typically result in reduced cooling efficiency.

Water in the cooling pads, through the process of evaporation, absorbs heat from the surrounding pad and frame as well as from the air passing through the cooling pad.

The air entering the greenhouse can be as much as 15–20°C cooler than the outdoor air temperature if the outdoor air relative humidity is lower than 35%.

Outside air is blown through pads with as large a surface as possible and which are kept permanently wet by sprinkling water. The water from the pads evaporates and cools the greenhouse air; relative humidity of outside air must therefore be low. There are basically two systems of fan-and-pad cooling: the negative-pressure system and the positive-pressure system.

- The negative-pressure system consists of a pad on one side of the greenhouse and a fan on the other. The fans suck the air through the pad and through the greenhouse. The pressure inside the greenhouse is lower than the pressure outside; hot air and dust can therefore get into the greenhouse. There is a temperature gradient from pad to fan.
- The positive-pressure system consists of fans and pads on one side of the greenhouse and vents on the another side. The fans blow the outside air through the pads into the greenhouse. The air pressure inside the greenhouse is higher than outside; dust cannot get into the greenhouse.

Fig. 16 Fan and pad cooling system. (*Left*) Exhaust fan located on the leeward side of the greenhouse, (*right*) cross fluted cellulose pads placed vertically in the opposite wall of exhaust fans

In order to achieve optimal temperature during summer, the greenhouse should be shaded. The water flow rate, water distribution system, pump capacity, recirculation rate, and output rate of the fan-and-pad cooling system must be calculated carefully and designed to provide a sufficient pad wetting and to avoid deposition of material.

There are numerous considerations when designing a fan-and-pad cooling system. First, cooling efficiency should provide inside air relative humidity of about 85% at the outlet; higher air relative humidity slows down the transpiration rate of the plants. Plant temperature can then increase above air temperature. It is important that the pad material have a high surface, good wetting properties, and high cooling efficiency. It should cause little pressure loss and should be durable. The average thickness of the pad is 100–200 mm. It is essential that the pad be free of leaks through which air could pass without making contact with the pad.

The pad area depends on the airflow rate necessary for the cooling system and the permissible surface velocity over the pad. Average face velocities are 0.75–1.5 m/s. Excessive velocities may cause problems with drops entering the greenhouse. The pad area should be about 1 m^2 per 20–30 m^2 greenhouse area. The maximum fan-to-pad distance should be 30–40 m.

Pads may be positioned horizontally or vertically. Vertical pads are supplied with water from a perforated pipe along the top edge. In the case of horizontal pads, the water is sprayed over the upper surface. The water distribution must ensure even wetting of the pad. Pads have to be protected from direct solar radiation to prevent localized drying out: salt and sand might clog them if they become dry. The pads have to be located and mounted in a way which allow easy maintenance and cleaning. They should be located on the side facing the prevailing wind direction.

Fans should be placed on the lee side of the greenhouse. If they are on the windward side, an increase of 10% in the ventilation rate will be needed. The distance between fans should not exceed 7.5–10 m, and fans should not discharge toward the pads of an adjacent greenhouse less than 15 m away. All exhaust fans should be equipped with automatic shutters to prevent air exchange when fans are not used and also to prevent back-draught when some are not being used.

When starting the cooling system, the water flow through the pad should be turned on first to prevent the pads from clogging. Fans should not be started before the whole pad has been completely wetted. When stopping the cooling system in the evening, the fan should be turned off before the water flow through the pad. It is recommended to operate the cooling system by a simple control system depending on the inside air temperature. The airflow rate depends on the solar radiation inside the greenhouse – that is, on the cladding material and shading – and on the evapotranspiration rate from the plants and soil. The airflow rate can be calculated by an energy balance. Generally, a basic airflow rate ranged from 120 to 150 m^3/m^2 greenhouse area per hour will allow satisfactory operation of an evaporative cooling system.

There are two main considerations in the evaporative cooling system: the rate at which warm air is to be removed and the area of the cooling pads.

6.7 Rate of Air Exchange

The rate of air removal from the greenhouse must increase as the elevation of the greenhouse site increases. Air decreases in density, becoming lighter with increasing elevation. The ability of air to remove solar heat from the greenhouse depends upon its weight (not its volume) and the light intensity inside the greenhouse (as the light intensity increases, the heat input from the sun increases, requiring a greater rate of air removal from the greenhouse). Solar radiation that penetrated the greenhouse covering material warms the air as it passes from the cooling pads to the exhaust fans. Usually a 4°C rise in indoor air temperature is tolerated across the greenhouse; to reduce the rise in air temperature, it will be necessary to raise the velocity of air movement through the longitudinal direction of greenhouse.

The cooling pads and fans should be located on opposite walls. These walls may be the ends or the sides of the greenhouse. The distance between cooling pads and fans is 30–40 m. The distance <40 m requires expensive equipment, while in the distance >30 m, the cross-sectional velocity of air movement becomes lower, and the air often develops a clammy feeling (it compensated by increasing the velocity of air movement, and this increases the cost of the system).

The exhaust fans should be evenly spaced along the end of the greenhouse, at plant height if possible, to guarantee a uniform flow of air through the plants.

The cooling pads should extend the entire length of the wall in which it is mounted, and this wall should be opposite the wall where the extracting fans are located. The necessary height of the cooling pads is determined by dividing the total area of the pads by the length of the pads.

The cross fluted cellulose cooling pads have the appearance of corrugated cardboard. The cellulose pads are impregnated with insoluble anti-rot salts, rigidifying saturates, and wetting agents to give it its lasting quality, strength, and wettability.

The main disadvantage of cooling pad systems is the creation of large air temperature gradients inside the greenhouse, from pads on one side to extracting fans on the opposite side. The factors mainly affected the air temperature distribution along the greenhouse as follows: ventilation rate, crop transpiration and soil evaporation, percentage of shading, water evaporation from the cooling pads, and the overall heat transfer coefficient of the covering material. The efficiency of evaporative cooling system (η) can be computed by the following formula:

$$\eta = \frac{T_{\mathrm{ao}} - T_{\mathrm{pad}}}{T_{\mathrm{ao}} - T_{\mathrm{oaw}}} \qquad (22)$$

where T_{ao} dry-bulb temperature of the outdoor air, °C, T_{pad} air temperature just leaving the cooling pads, °C, T_{oaw} wet-bulb temperature of the outdoor air, °C

6.8 Temperature Gradients in Greenhouse

The main drawback of evaporative cooling systems for greenhouses based on cooling pads and extracting fans is the thermal gradient developed along the airflow direction. High air temperature gradients of this type can markedly affect plant growth, and growers should combine cooling pads with shading. To predict the air temperature gradients along a greenhouse, a simple climate model is proposed which incorporates the effects of ventilation rate, roof shading, and crop transpiration. In order to calibrate the proposed model, measurements should be performed in a larger greenhouse (commercial) equipped with a complete evaporative cooling system using pads and fans and shaded by black plastic screen. The energy balance equation combines five factors which mainly affect the temperature distribution along the larger greenhouse length. The model can be expressed as

$$T_{\mathrm{ai}}(X) = T_{\mathrm{ao}} + A_1 + \left[\left(T_{\mathrm{pad}} - T_{\mathrm{ao}} - A_1\right)\exp(-A_2 X)\right] \tag{23}$$

where X distance, at which the air temperature was measured, m, and the two coefficients A_1 and A_2 are given by

$$A_1 = \frac{R_{\mathrm{i}} A_{\mathrm{f}}(1 - E)}{q_{\mathrm{v}} \rho C_{\mathrm{p}}}\ {}^{\circ}\mathrm{C} \tag{24}$$

$$A_2 = \frac{U_{\mathrm{o}} P}{q_{\mathrm{v}} \rho C_{\mathrm{p}}}(1/m) \tag{25}$$

where ρ air density, kg/m^3, P perimeter of greenhouse, m

7 Water Requirements and Irrigation Management

Plants require adequate moisture for optimum growth and maximum crop production. Water is the medium by which different nutrients are absorbed by the plants. Water absorbed by root system moves through the roots and xylem into branches and leaves. Water vapor is then transpired through stomates in the leaves into the atmosphere surrounding the plant. For each 28 g of dry matter produced by the plant, as much as 7.5 l of water moves through the plant. An adequate and properly regulated supply of moisture will help control plant growth, flowering, and productivity.

Water use by greenhouse plants is directly related to available sunlight. However, less than 2% of the water that enters the roots remains in the plant. Most water passes through the water-conducting tissue and evaporates into the air. Most of the variables in growing plants have been measured and controlled to varying degrees, and optimum levels of air temperature, relative humidity, nutrients, and light are known for most commercial crops. These can be measured and then adjusted with acceptable accuracy. Rooting medium moisture measurement and control information can be installed. Various methods of indicating soil moisture are used, but, to date, no one method is in general use throughout the country. The following are methods used to indicate the moisture content of the soil:

1. Appearance or feel: growers usually water when the soil mix will crumble easily when compressed in the hand. Examination should be made at several soil depths.
2. Tensiometers: this device consists of a porous cup attached to a vacuum gauge. The cup is inserted in the soil and the apparatus filled with water. As soil dries, water leaves the cup, and the resulting tension (vacuum) is recorded on the gauge. Limitations are lack of soil uniformity and variation in the porous cup. Tensiometers must be calibrated for different soil types.
3. Weight of soil moisture: one pot plant on a bench is used as a control. It rests on a scale that is adjusted to trip a switch when the moisture level drops below a certain level. The setting has to be adjusted as the plant grows to compensate for the added plant weight.
4. Light accumulators: this device utilizes a photoelectric cell and counter to activate a solenoid valve when a predetermined quantity of light has been received. It is based on the idea that increased light causes increased evaporation. It does not take into account air movement or variations in soil mix.
5. Evaporation simulators: a stainless steel screen is used to simulate a leaf. It is placed among the plants and receives the same amount of water as the plants. The screen is attached to a switch which activates a solenoid valve when the water that has collected on the screen evaporates. This device is limited to use with misting or overhead irrigation systems.
6. Soil moisture conductivity: several devices relate soil moisture to electrical conductivity. When the soil dries to a preset level, the electronic circuit activates the solenoid valve. Most of the above devices use a timer to shut off the water supply after a predetermined length of time.

7.1 Water Requirements of Greenhouse Crops

The amount of water required is affected by the type of soil mix and the size and type of container or bed. Proper watering should provide 10% more water than is necessary so that leaching will reduce salts and good fertilizer distribution will occur. Frequent light sprinklings induce shallow rooting and may increase soluble-salt concentrations.

A simple formula for use with bench crops in order to determine the liters of water needed per square meter to thoroughly water a bench and provide 10% leaching can be determined as

$$\text{Amount of water required} = \frac{\text{Bench area}\,(\text{cm}^2) \times \text{Depth of wetting}\,(\text{cm})}{1,000} \tag{26}$$

A correctly designed water system will supply the amount of water needed each day of the year. The amount will depend on area to be watered, crop grown, weather conditions, time of the year, and whether a heating or ventilating system is operating. The maximum amount of irrigation water needed varies from 10 to 60 l per square meter per watering. During a hot summer dry spell, application may be needed on a daily basis. The greenhouse water system should be able to supply the total daily needs in a 6-h period, so that plants can be watered during the morning and early afternoon and the foliage has time to dry before sunset. Peak use rate is the maximum flow rate during this 6-h period. Peak use rate is needed to determine pump capacity, pipe size, type of distributing system, and storage tank size.

7.1.1 Components of Crop Water Requirements Within Greenhouses

Crop water requirement is the total amount of water that a crop needs to maintain optimal rates of crop evapotranspiration (ET_c); it is calculated as the difference between crop evapotranspiration (ET_c) and water obtained from rainfall and soil water. Technically, the water required to maintain sufficient irrigation water is the "net crop water requirement," with the "gross" crop irrigation requirement taking into account additional irrigation to consider salinity and application uniformity. In this case, crop water requirements are "net crop water requirements." Since no rainfall enters greenhouses and seasonal soil water extraction is negligible [52], because the soil is continuously close to field capacity from high-frequency drip irrigation, it can generally be assumed that the crop water requirement of greenhouse-grown crops is equivalent to crop water requirements.

7.1.2 Crop Evapotranspiration of Greenhouse Crops

The ET_c values for substrate-grown crops have been calculated by subtracting drainage from irrigation volumes. Generally, these values are similar to those for equivalent crops grown in soil [53]. Compared with equivalent vegetable crops grown outdoors with irrigation, the seasonal ET_c of greenhouse vegetable crops is appreciably lower due to the reduced evaporative demand inside the greenhouse [54]. The evaporative demand is lower inside than outside due to the decrease in penetrated solar radiation (40% on average) and the greatly reduced wind speeds of 0.1–0.3 m/s or less [55]. The evaporative demand inside the greenhouse can be 60% of that outside [56, 57].

7.1.3 Crop Evapotranspiration and Greenhouse Cooling

Whitewash (suspension of calcium carbonate) is commonly applied to the greenhouse roof and walls during warmer periods to relatively lower crop water requirement values. The whitewash reduces the amount of solar radiation entering the greenhouse and therefore also the air temperature inside the greenhouse; consequently, there is a reduction in crop evapotranspiration which is proportional to the thickness of applied whitewash. The transmissivity to solar radiation of greenhouse plastic cladding is usually about 60%; commonly used whitewash application rates reduce this to 20–30% during July.

Other cooling techniques affecting water needs for crop, such as misting and shading screens, are currently used by only a small percentage of growers [58]. Values for the reduction in radiation and consequently in crop water requirement as a function of applied whitewash are given in [56].

7.1.4 Determination of Crop Evapotranspiration for Greenhouse Crops

The FAO method estimates crop evapotranspiration (ET_c) as the product of reference evapotranspiration (ET_o), equivalent to the evapotranspiration of a grass crop and which quantifies the effect of climate on crop water demand, and the crop coefficient (K_c), which quantifies the effect of crop species and stage of development [45, 59].

7.1.5 Determination of Reference Evapotranspiration for Greenhouse Crops

Penman-Monteith method as a standard for estimating ET_o from climatic data, in both arid and humid climates, uses radiation, air temperature, atmospheric humidity, and wind velocity data. Inside plastic greenhouses, Penman-Monteith equation estimates ET_o compared with a standard grass crop when using a fixed value of aerodynamic resistance of 295 s/m as follows [54, 59]:

$$\mathrm{ET_O} = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(0.34U_2)} \quad (27)$$

where ET_O reference evapotranspiration (mm/day), R_n net radiation at the crop surface (MJ/m^2/day), G soil heat flux density (MJ/m^2/day) (=0 for daily calculations), T mean daily air temperature at 2 m height (°C), U_2 wind speed at 2 m height (m/s), e_s saturation vapor pressure (kPa), e_a actual vapor pressure (kPa), $(e_s - e_a)$ saturation vapor pressure deficit (kPa), Δ slope vapor pressure curve (kPa/°C), γ psychrometric constant (kPa/°C).

FAO24 pan evaporation method estimated ET_o as follows [54]:

$$\mathrm{ET_O} = K_P \times E_o \quad (28)$$

where K_P pan coefficient ($K_P = 0.79$), E_o pan evaporation (mm/day)

Hargreaves equation estimated also ET_o as follows [53 and 59]:

$$\mathrm{ET_O} = 0.0023R_a\tau(T_{max} - T_{min})^{0.5}(T + 17.8) \quad (29)$$

where R_a extraterrestrial radiation (mm/day), τ ratio inside and outside solar radiation, T, T_{max} and T_{min} mean, maximum, and minimum greenhouse air temperatures, respectively.

Almeria radiation method estimated ET_o as follows [60]:

$$ET_O = (0.288 + 0.0019JD)^{R_O\tau} \quad JD \leq 220 \tag{30}$$

$$ET_O = (1.339 + 0.00288JD)^{R_O\tau} \quad JD > 220 \tag{31}$$

JD = Julian days, R_O = daily solar radiation outside the greenhouse (mm/day), τ = ratio between inside and outside solar radiation (transmissivity of greenhouse cover).

In greenhouses, solar radiation is the climatic parameter that most influences evaporative demand. Hargreaves equation and the FAO-radiation equation provide accurate estimation of ET_o. Given their limited climatic data requirements and relative simplicity (compared with the Penman-Monteith equation), these two methods are recommended for practical estimation of ET_o in plastic greenhouses under Mediterranean climatic conditions [54].

The Almeria radiation method calculates daily evapotranspiration within a greenhouse from values of the daily sum of external solar radiation and the transmissivity percentage of the greenhouse cladding. The value of transmissivity depends on greenhouse design, cover material, and management practices used to reduce greenhouse temperature during summer season [54, 55, 60, 61].

The major advantage of the Almeria radiation method is that calculation of ET_o – and consequently of irrigation requirements – considers relevant characteristics of individual greenhouses, including greenhouse construction (structure, cladding materials, age of plastic, etc.) and practical greenhouse management (whitewashing, use of shading materials, etc.). In consideration of these factors and given its simplicity and accuracy, the Almeria radiation method has been used for both extension and scientific purposes.

7.1.6 Determination of Crop Coefficient Values for Greenhouse Crops

Crop coefficient (K_c) values have been determined for the main greenhouse-grown vegetable crops. The crop coefficient values vary according to species, development stage, and crop management practices. Measured maximum crop efficient values for crops that are not vertically supported is essential. Orgaz et al. [62] suggested explanation for the relatively high maximum K_c values of supported greenhouse crops is that there is more uniform light penetration within the canopies, thereby providing relatively higher ET rates than for unsupported greenhouse crops and open field crops which tend to be shorter with denser canopies. Uniformity of light penetration increases with the following [62]: tall and open structure of the supported crops, regular pruning forming more open canopies, high leaf area indices, and high proportion of diffuse radiation inside the greenhouse.

For vegetable crops under greenhouses, planting dates and lengths of crop life cycles can vary appreciably in response to market prices, weather conditions, and farm management considerations. The standard FAO method of calculating ET_c, using three constant crop coefficient values, each for a fixed length crop stage is normally used [55, 61, 62].

Two approaches based on thermal time data have been developed to estimate K_c values during the crop development stage. For crops that are only slightly or not pruned, leaf area index (LAI) is estimated from thermal time, and K_c values are then determined from a linear relationship between K_c and LAI. For frequently pruned crops, an empirical linear relationship between K_c and thermal time has been determined for each species.

7.1.7 Irrigation Volumes Applied by Growers to Greenhouse Crops

According to [63] a survey of total irrigation volumes (crop irrigation supply) applied to vegetable crops grown in commercial greenhouses, indicated that values of annual irrigation applications are higher than the crop irrigation supply since many greenhouse growers produce two crops per year.

Values of annual irrigation applications are higher than the crop irrigation supply since many greenhouse growers produce two crops per year.

The ratio of crop irrigation supply (total volume applied to a crop) to crop water requirements is known as relative irrigation supply (RIS) and is an indicator of the adequacy of irrigation practices [64]. RIS values were determined for the main vegetable species by dividing crop irrigation supply values, determined in the survey, by crop water requirements [61]. There was very large variability in RIS values between crop species and within cropping cycles for individual crops [64].

In general, RIS values for individual crops were 2–5 during crop establishment and then progressively declined [64]. The high RIS values during crop establishment reflect the practice of applying excessive irrigation to ensure the survival and establishment of transplanted or seedlings, which initially have small root systems.

Thompson et al. [65] also compared measured crop irrigation volumes with the crop water requirements; in general, the results were similar to those reported by [64]. Thompson et al. [65] suggested that the high variability in RIS values between greenhouses with the same crop and the high values in certain parts of the crop cycles was evidence of the scope to improve irrigation practices and crop water use for soil-grown crops.

7.2 Irrigation Scheduling of Greenhouse Crops Grown in Soil

Irrigation scheduling (IS) determines the amount and frequency of irrigation based on technical criteria related to crop irrigation need. The main approaches used for IS are water balance method based on determining crop irrigation requirements from collected climatic data and use of soil moisture or plant sensors.

7.2.1 Irrigation Scheduling with Climatic Data

For greenhouse-grown crops, the calculation of crop irrigation requirement considers neither rainfall nor soil water – the latter because the soil is constantly maintained at close to field capacity. Consequently, the applied amount of a single irrigation event is equivalent to the cumulative ET_c for the period between irrigations plus additional irrigation to consider soil or water salinity and irrigation emission uniformity. For vegetable crops under greenhouse receiving high irrigation frequency, irrigation frequency is usually every day under hot temperature conditions and every 3–4 days under cooler conditions. Soil moisture sensors, in particular tensiometers, are an effective method for determining frequency.

ET_c-real is calculated from actual daily values of solar radiation and maximum and minimum daily air temperature measured inside the greenhouse for that particular day [60].

The lookup tables are effective and user-friendly tools for preparing irrigation plans for individual crops; the software is able to prepare a more tailor-made plan. In practice, such plans can be supplemented with the use of soil water sensors, such as tensiometers, to assist in determining irrigation frequencies and to adjust volumes. This combined approach (an irrigation plan based on estimated ET_c together with sensors) is an effective way to ensure optimal irrigation of greenhouse-grown crops.

7.2.2 Irrigation Scheduling with Sensors

The use of sensors to monitor soil moisture or plant water status offers the potential to irrigate in accordance with the characteristics of individual greenhouses and cropping conditions (e.g., variations in greenhouse characteristics, crop management and cycles, and soil characteristics). Additionally, these sensors offer the potential for a fine degree of crop management, such as applying controlled stresses for product quality considerations, and control of drainage for salinity or environmental management. Soil water and plant water status sensors can be used on their own as “stand-alone” methods; the two approaches can be combined; they can be used with the FAO method for estimating crop water requirements [45]; and they can be used as a supplement to irrigation management based on experience.

7.2.3 Irrigation Scheduling with Soil Water Sensors

Soil water sensors measure volumetric water content of soil ($\Theta\nu$) and soil matric potential (Ψm).

The $\Theta\nu$ is the ratio of soil volume occupied by water. The Ψm measures the force of retention of soil water by the soil matrix (particles) and indicates the availability of soil water for crops. Whereas interpretation of Ψm data for irrigation management is straightforward, interpretation of $\Theta\nu$ for practical irrigation management requires site-specific experience [66]. Soil water sensors can be read manually or with continuous automatic data collection; continuous recording allows more detailed information of the dynamics of water use by the crop and its movement in soil.

Soil water sensors can be used with different configurations depending on crop type, irrigation system, cost, and mounting of sensors on probes [66]. One sensor should be placed in the zone of maximum root concentration; additional sensors can be placed at different depths (e.g., below the roots to control drainage, to the side of the plants to control the size of wetting bulbs from drip irrigation). The most commonly used sensor configurations are one sensor within the zone of major root concentration and one sensor within the zone of major root concentration complemented by one or more deeper sensors. Irrigation management with soil water sensors is based on maintaining soil water between two limits [66]: lower limit (drier value), indication of when to start watering, and upper limit (wetter value) – indication of when to stop watering. The difference between the two limits is an indication of the volume of irrigation required. The lower limit most commonly chosen permits depletion of soil water without stressing the plant; it can also be used to impose controlled deficit irrigation. The upper limit is normally chosen to prevent excessive drainage from the root zone. It can also be reduced when controlled deficit irrigation is required. The simplest way to determine the volumes to be applied using soil water sensors is to use the selected lower and upper limits to valuate irrigation (based either on experience or on the use of the FAO method) and then to adjust the applied volumes so that irrigation is maintained within the two limits.

7.2.4 Soil Matric Potential Sensors

In non-saline conditions, soil matric potential (Ψm) is a good approximation of the total soil water potential (Ψs). In saline conditions, osmotic potential may contribute significantly to soil water potential (Ψs). The Ψm generally provides a useful measure of the availability of soil water to plants. When using Ψm, the contribution of salinity to Ψs should be considered separately [67], and equipment manufacturers have indicated the upper and lower limits based on soil water potential. These limits depend on crop species, crop developmental stage, soil texture, and the evaporative conditions.

The two types of matric potential sensors most suitable for protected horticultural crops are tensiometers and granular matrix sensors. Tensiometers are cheap, simple, and easy to use. They require preparation and proper maintenance to provide accurate and reliable data [66]. There are three types: manual tensiometers, data are obtained from the visual reading of a vacuum gauge; manual tensiometers, a switch directly activates the irrigation equipment when it reaches a predetermined value; and electric tensiometers, pressure transducers provide continuous measurement and can be used to directly activate irrigation. Granular matrix (GM) sensors measure the electrical resistance between two electrodes in a porous matrix [66, 68].

The electrical resistance between the two electrodes is a function of the soil matric potential. The water within the sensor matrix equilibrates with that of the soil. A handheld reader is used to supply the current and read the values. Data can be recorded on data loggers or input to an irrigation controller. An internal factory calibration, in the handheld reader, is used to relate measurement of electrical resistance to soil matric potential. GM sensors are cheap, simple, and easy to install and have few preparation and maintenance requirements. They have a wider measurement range than tensiometers, and they tend to be less reliable in wet soils and have a slower response in soils that dry very quickly, while they are somewhat less accurate than tensiometers but require appreciably less attention [69].

7.2.5 Irrigation Scheduling with Plant Sensors

Three kinds of plant sensors can be used for irrigation management [69]: stem diameter sensors, sap flow sensors, and sensors of leaf/crop canopy temperature.

Stem diameter sensors measure both stem contractions occurring during the day in response to transpiration and stem growth; both parameters are very sensitive to water stress. Furthermore, their sensitivity to detecting water stress in greenhouse-grown vegetable crops decreases during winter conditions of low evaporative demand [69].

Sap flow sensors that directly measure plant transpiration. They have been mostly used in research with limited use for irrigation management of horticultural crops because of their high cost and technical complexity.

The temperature difference between the leaf or the crop canopy and the environment is a sensitive indicator of plant water stress. Indicators proposed for irrigation based on this measure include the CWSI (crop water stress index).

Plant sensors have less practical application for irrigation management than soil moisture content sensors, particularly for vegetable crops.

7.2.6 General Considerations Regarding the Use of Sensors for Irrigation

When soil moisture sensors are used for irrigation management, there are two important practical considerations: replication, with a minimum of 2–3 sensors per crop, and location of the sensors, which should be representative of the crop. There are other practical considerations including cost, ease of use, preparation and maintenance requirements, technical support, ease of data interpretation, and availability of irrigation protocols [66].

In general, there is appreciably more use of soil moisture sensors for irrigation management. The most used soil moisture content sensors for irrigation management are tensiometers and capacitance sensors. Two important considerations with capacitance sensors are the cost and sensitivity of some models to changes in salinity. Tensiometers are very suitable for greenhouse vegetable crops in soil because of their low cost, simplicity, and reliability; they are not affected by salinity, and their narrow working range is not usually a limitation in greenhouse soils that generally remain moist.

7.3 Water System Components

The complete water system used in supplying water to the greenhouse consists of a pump, pressure tank, and piping. The following sections presents some details about these equipment and its selection for different systems.

7.3.1 Pump

Many types and sizes of pumps are available for supplying water. The type of pump most commonly used in greenhouse watering systems contains an impeller connected to the motor shaft. When selecting a pump to supply water to a greenhouse system, consider the capacity of water source; if the source is a pond, capacity is usually adequate for maximum use rate. If the source is a well or brook, the yield rate in m^3/h must be determined. Power required by pump to move the required flow rate is as follows:

$$\text{Pump power} = \frac{\text{Water flow rate (L/min)} \times \text{Total head required (m)}}{6.1162 \times \text{pump efficiency}}, \text{W} \quad (32)$$

7.3.2 Commonly Used Pump Terms

Suction Head

The vertical distance from pump to water surface is measured in meter. If a well has low yield rate, water surface in the well may drop rapidly if demand is consistently great, which can affect centrifugal pump capacity by increasing suction head. Pump capacity should be matched to well yield.

If the water source is a well, the diameter of the casing will determine the equipment size that can be installed and the well's reserve capacity. Always specify a 15.24 cm or larger casing for new wells.

Pressure head: pressure required at point of delivery (m).

Friction head: pressure lost in overcoming friction between water and pipes or fitting (m).

Elevation head: vertical distance between pump and point of delivery (m).

Total head: sum of all heads against which a pump must delivery water.

Pumps should supply water under sufficient pressure to provide required flow rate and coverage. The total pressure against which a well pump must work is made up of four parts: (1) suction lift, or vertical distance water, is lifted to the pump by suction, (2) vertical distance from center line of the pump to the point where water is to be delivered, (3) required pressure at the outlet, and (4) friction in the piping system between the pump and the outlet. These values can be given in meter of water.

7.4 Fertilizer Injector

Fertilizer injector is a mechanical device that introduces concentrated fertilizer solution into the supply pipe used for crop watering. Two basic types of injectors are available. One type uses the venture principle to create a pressure difference between the fertilizer container and the water supply line, causing a flow of solution into the irrigation water. The other system uses a positive displacement pump, either water-powered or electrical, that injects fertilizer solution into the irrigation water. Each system can be adjusted to vary the ratio of solution to irrigation water.

When selecting an injector, consider the following:

System Capacity Usually rated in liters of water that can be treated per minute. Systems are available from five to several hundred liters per minute. Select a size that will handle the capacity of the distribution system.

Distribution Ratios Injectors are commonly manufactured with dilution ratios of from 1:15 to 1:2,000. The lower the ratio, the more dilute the fertilizer solution must be. Too high dilution ratio may create problems in dissolving enough fertilizer in the solution tank. A common ratio for greenhouse crops is 1:2,000.

Mobility A portable unit usually works best for an operation having individual greenhouses. The injector is moved between greenhouses when feeding is necessary. Fixed installations with piping used to carry injected water to the growing area are used in ridge furrow ranges. Where automatic watering is provided, a fixed installation for fertilizer irrigation is best.

Alternate Uses Although used primarily for fertilization, injectors can be used to apply other water-soluble materials, such as fungicides and insecticides.

7.5 Distribution Systems

In the greenhouse, two types of watering systems are in common use today: a low-pressure system operating on a water pressure of less than 7 N/cm^2 and a high-pressure system operating above 7 N/cm^2.

7.5.1 Low-Pressure System

This type of system is commonly known as trickle irrigation. Moisture is supplied to the root zone of a plant through drip tubes or soaker hoses. Water is dripped continuously or intermittently into the root zone around the plant. Soil between row crops and out of the plant area does not receive water. Although the water is applied to a small area around the plant, lateral transmission of water takes place through the root system. Major advantages of trickle irrigation are that plant foliage remains dry and water application efficiency is high.

Two methods of supplying water to this system are commonly used. One method uses an elevated mixing tank which is filled from a high-pressure water source. Water should go through a 100–200 mesh strainer before entering the tank. The tank can be any size, but a 1–2 m^3 capacity is adequate for most installations. The tank should have an opening in the top large enough to add and mix fertilizer into the water and should be elevated so that the correct pressure for the distribution system is obtained.

For the second method, the distribution system is connected to the pressure tank. A pressure reducer is placed in the line to lower the pressure to the level needed for the trickle tubes. A backflow preventer should also be used for systems that supply drinking water.

PVC pipe is most commonly used because it is inexpensive and easy to install. Gate valves should be placed at the tank and in supply lines to control water flow to various sections of greenhouse benches. Drip tubes, also known as leader or spaghetti tubes, are widely used for pot watering. This system consists of small diameter plastic capillary tubes connected to a plastic line. "Drop-in" weights are attached at the other end.

Some weights are available with a shutoff so that water flow to individual pots can be stopped when the pot is removed. The diameter and length of the tube determine its water flow rate. Tubes are available from 1 to 2 mm diameter and from 30 to 180 cm long. Low-flow porous or perforated hoses are designed for watering greenhouse benches, beds, capillary mats, outside planters, and beds. Water oozes from seams or tiny holes in the hoes under low pressure.

7.5.2 High-Pressure Systems

Fixed Spray Heads Originally developed for lawn irrigation, fixed spray heads may be used to irrigate small containers such as packs. Heads that spray water in various patterns, square full circle, partial circle, and rectangular, are available, as are stationary and pop-up heads. Sprinkler head spacing is usually 50–75% of the spray's diameter.

Rotating Impact Sprinklers Impact sprinklers rotate slowly, about 1–2 rpm. Rotation is caused by the impact of an arm that oscillates in and out of the nozzle jet. For large areas and containers up to the 7.5 l in size, impact sprinklers are the most efficient form of irrigation. Full or partial circle sprinklers are available from a number of manufacturers to fit various pipe sizes. Interchangeable nozzles are available for all models. Some nozzles have devices (baffle or screw) to break up the spray.

Whirling rotating sprinklers spin rapidly. Rotation is caused by reaction to a jet of water discharged from the nozzles, which are attached at an offset angle on the rotating arm. Sprinklers with single or double arms for either low or high volume discharge are usable on small, closely spaced containers. These sprinklers are used mostly in greenhouses or shade structures because of small area covered by each sprinkler. Some of them discharges fine droplets of water that reduce soil splashing from the pot.

Nozzle lines may be either overhead or along the ground. Both systems are similar in that each uses a pipe with fixed nozzles placed at regular intervals. Overhead lines require rigid pipe. Either jet or fan nozzles may be used and generally are placed at 1.0 m intervals. Lines may be rotated manually automatically to apply water to different areas. Overhead nozzle lines are generally used only in greenhouses or shade structures where the pipe supports will not interfere with movement of machinery, labor, or materials.

7.6 Irrigation Water Performance Indicator (IWPI)

Characterizing water use and management in irrigated agriculture is a prerequisite for conserving agricultural water. Population growth, coupled with economic growth and increased awareness of environmental needs, is now subjecting existing freshwater resources to considerable pressures. Given that irrigation worldwide uses about two-thirds of the water diverted for various uses, there are increased societal demands for an effective accountability of irrigation water use.

7.6.1 Irrigation Water Use Efficiency (IWUE) of Greenhouse Crops

In greenhouse vegetable crops, the irrigation water-use efficiency (kg/m^3, IWUE), expressed as the ratio between marketable crop production and total crop irrigation supply, is higher than in open field crops due to the low evaporative demand inside the greenhouse that reduces water requirements and the higher productivity of greenhouse-grown crops.

In unheated plastic greenhouses, IWUE was similar between crops grown in soil and increased under the following conditions: improved greenhouse structure, increased length of growing season, and recirculation of nutrients in grown crops [63].

Performance evaluation of irrigated areas is thus an activity that is needed, not only to propose improvements in irrigation management but also for assessing the productivity of water at various scales. For each greenhouse, a set of two essential indicators for irrigation water use are calculated as follows:

Irrigation water-use efficiency can be calculated by two main methods [63]:

The Annual Irrigation Water Productivity (AIWP) Computes as Follows:

$$\text{AIWP} = \frac{\text{Total value of crop productivity(kg)}}{\text{Total irrigation water consumption } (\text{m}^3)}, \ \text{kg/m}^3 \qquad (33)$$

AIWP values of greenhouse crops are generally much higher than for open field crops due to the low water use and particularly to the high economic value of vegetable crops grown out of season.

The Annual Irrigation Water Financial Return (AIWFR) Computes as Follows:

$$\text{AWFR} = \frac{\text{Total value of marketing price (LE)}}{\text{Total irrigation water consumption } (\text{m}^3)}, \ \text{LE/m}^3 \qquad (34)$$

8 Conclusions

The protected horticulture crops as well as using soilless culture techniques in Egypt as well as developing countries are facing a number of important issues relating specifically to absence of local advanced modern technology, lack of the well-trained technician, limited number of qualified advisors, lack of food safety of products, and absence of advanced knowledge about crop management for soilless culture under commercial conditions. For soil-grown crops, there is no immediate solution to some, if not all these problems such as soil-borne diseases and nematode, and it is considered that the situation will not improve unless alternative solutions are considered such as using soilless culture system. In this respect, especially as most of the problems arise because the crop is in effect an intensive crop rotation, an obvious solution is to move out of the soil into some form of soilless production. There is already very little vegetable production in Egypt using soilless systems, two of the primary advantages being that they have better food safety for products and are less labor-intensive compared to conventional horticulture production.

There are many trials related to the use of soilless culture, and new technology by many Egyptian scientists is applicable to use with some vegetable crops such as cucumber, tomato, pepper, eggplant, and Chinese cabbage and potentially some ornamental crops. But, these efforts can't compare with the new technology in developed countries such as the Netherlands and Spain. Furthermore, there is a big national project for cultivating 100,000 acres of greenhouses in Egypt during next the few years. This big number of greenhouses considers a revolution in this sector. This project needs to improve the local manufactory to produce devices, materials, and supplies for modern greenhouses. And, such big number of greenhouse will need qualified technician advisors and properly trained staff in many critical issues such as integrated pest and diseases management, irrigation, fertilization, packing, food safety issues, etc. This chapter mentioned most of the technical and scientific information needed to improve the awareness of the agriculture graduated, agriculture engineering, researcher, extension people, and investors about how to manage the greenhouse from select farm location till manage the crops inside the greenhouses with respectable scientific background.

Moreover, there is a vital need to complete this work by improving the marketing of the products via innovative way to ensure the sustainability of the greenhouse production.

Producing vegetables and ornamental from greenhouses in developing countries such as Egypt is considered as a crossroad in starting a new area of development, the main challenges related to food security (enhance the productivity) and food safety (enhance quality of products). However, the amount of fertile arable land devoted accounts for merely 55% of the total cultivated land because of urbanization. This chapter concludes that there is a vital need for improving production from greenhouses for different crops; it would be economically more efficient to produce crops based on an advanced greenhouse system, which represents profitable business with sustained supply for foreign markets. For Egypt's economy true costs are relevant, reflecting the shortage of natural resources such as land, water, and fertile soil. For the long-term strategic vision, greenhouse sector that needs better-equipped facilities to deliver sustainable production system due to crop quality improvements will gradually improve the net return per ton of production with increase quality of product. However, in conventional greenhouse system (without modern technology), the input increased over time to maintain the same output with stable product prices. This will cause higher cost per ton of production with almost the same outcome. In general, good-quality vegetable products have better prices for their products especially in the foreign markets. In addition to that, high-quality products are better for farmer's health due to the avoidance of misuse of chemical and in general create more employment opportunities. This chapter also considers a guideline book for the different stakeholders' work in greenhouse sector, the sufficient scientific background with details which can help to improve the capacity building of the greenhouse sector. We can conclude that greenhouse design, materials, facilities, and the growing system are based on many factors such as availability of water, availability of suitable land, availability of good locations, climatic factors, soil factors, etc. Select the right option of greenhouse design, constructions, growing system, and the proper crops and species depend on market capacity, market needs, availability of liquid money for establish greenhouses, availability of the experts, etc. The technical and scientific information mentioned in this chapter could help as a guide to select the suitable options for the growers and companies. We can conclude from this chapter that working in the greenhouse is a package of procedures that should be respected starting from select greenhouse location, select proper crop and species, greenhouse design, etc.

9 Recommendations

This chapter recommends many of good agricultural practices related to greenhouse sector from the beginning of select the proper site, proper water quality, proper greenhouse design, and proper management for different crops under the greenhouse by using soilless culture and conventional agriculture. This paper recommends complete package related to greenhouse management, and proper tools could be used depending on the purpose of the establishing greenhouse in particular site or location. The current work related to technical information with scientific background about greenhouse management. Additional work should be done in parallel related to the economic consideration of using different options such as selecting the greenhouse cover materials; the cost of greenhouse polyethylene cover has a big difference with the option you select such that dust-free polyethylene cover is more expensive than regular polyethylene cover by 60% or more. To decide all these options (e.g., greenhouse design, greenhouse material, using heating and cooling systems, etc.), the economic study should be done to determine the return of using each option. This chapter also draws a roadmap of greenhouse management to develop this sector. The next recommendation is the most important recommendation we can extract from the abovementioned.

1. Local small farmers can develop his own greenhouse by the use of proper and cheap greenhouse design (wooden greenhouse), select proper greenhouse cover, and improve the ventilation of the greenhouse.
2. Food safety of greenhouse products needs collaboration between the different stakeholders; the collaboration starts from the supplier of seed and rootstock that should supply resistant seed for major pest and diseases; producers should follow restricted integrated pest management program; and irrigation and fertilization program can help to make the plant more resistant for infections of pest and diseases. Finally, the farmers should know when he should spray pesticides, what is the right pesticides, and how to use pesticides.
3. Participatory approach between the European countries and Egypt for producing high-quality products; the European countries have the technology and target market with a good price, whereas Egypt has the suitable climate conditions, manpower, and production inputs. Participatory approach to transfer the technology and some high technology production inputs such as high-quality seeds and rootstocks, modern technology of greenhouses, and soilless culture systems can improve the quality and quantity of products as well as improve the vegetable and ornamental supply from Egypt to the European countries. Maybe participatory should be done in the beginning between Egyptian and European companies, and then these techniques can transfer for smaller farmers.
4. The greenhouse in Egypt during the last 20 years achieved many success related to provide the local market especially during winter season with sufficient vegetable crops such as cucumber, pepper, green beans, tomato, strawberry, and cantaloupe. Development of this sector to continue this success and increase the export volume of these crops can enhance national economy.

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Improving Agricultural Crop Yield and Water Productivity via Sustainable and Engineering Techniques

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Abstract Of the many problems and challenges facing all arid regions, the shortage of water sources is the most important. Egypt is one such arid region. The total volume of Egypt's water resources is 72 billion m^3/year. The Nile River contributes 55.5 billion m^3/year to this total. Recently, the water volume of the Nile River was threatened by the construction of a mega dam by Ethiopia near the border of Sudan. Irrigation consumes 70–80% of Egypt's water resources. To prevent Egypt suffering from a severe water shortage and due to the increasing population and various external and internal challenges facing Egypt at present, very low per capita water limits have been introduced. To alleviate the suffering resulting from the water limits, all water users must apply all possible techniques to improve water use efficiency in these arid conditions. Examples of sustainable techniques that have been proven to show positive impacts on improving crop yield and water productivity and are also environmentally friendly include: (1) biofertilizers, (2) organic mulching, and (3) compost application. Egypt must apply all possible techniques to improve water use efficiency, starting from the mouth of the El-Rayah, passing through main canals then branch canals until the irrigation water reaches the plant. Examples of engineering techniques that have resulted in improved water productivity include: (1) laser land leveling, (2) new design of drip irrigation system, and (3) pulse irrigation.

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Contents

1 Introduction

In arid conditions, sustainable agricultural techniques must be followed to mitigate water stress, increase the crop productivity, and protect the environment. Drought is a worldwide problem that severely limits crop quantity and quality. Recent global climate changes have made this situation more serious [1, 2]. In many regions of the world, drought stress is one of the most critical factors that decrease agricultural crop production [3]. Worldwide, the percentage of drought-affected land doubled from the 1970s to the early 2000s [4]. About 33% of wheat fields worldwide and about 55% of wheat fields in the developing countries are experiencing drought stress. Water deficit influences all developmental stages of wheat from germination to seed formation and finally yield [5]. During the last two decades, because of the negative environmental impact of chemical fertilizers and their increasing costs, application of soil microorganisms in various parts of the world has increased, as shown in Fig. 1.

Plant growth-promoting bacteria (PGPB) are a diverse group of soil microbes capable of increasing crop yields. Most bacterial strains investigated belong to the genera *Pseudomonas*, *Azospirillum*, *Azotobacter*, and *Bacillus*; however, some are members of *Enterobacteriaceae* [7]. When present in plants in adequate amounts, these PGPB stimulate the density and length of root hairs, increase the rate of appearance of lateral roots, increase root surface area, improve plant growth under water stress conditions, produce growth regulators, fix nitrogen, and solubilize inorganic phosphates [8]. Some plant growth-promoting fungi (PGPF) (e.g.,

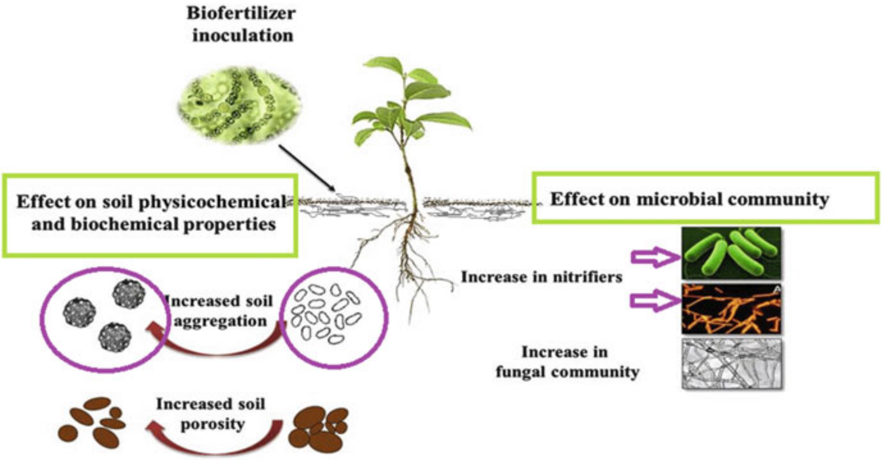

Fig. 1 The importance of biofertilizers [6]

arbuscular mycorrhizal fungi (AMF), which forms a mutual endosymbiosis with plant roots) are essential to help crop plants overcome biotic and abiotic stress. AMF symbiosis alters the microbial population composition quantitatively and qualitatively in the mycorrhizosphere (mycorrhizosphere effect) as a result of altered host physiology and root exudates. These effects cause roots to take up more water and mineral nutrients, resulting in faster plant growth. Under appropriate agronomic conditions, these processes will increase crop yield [9]. Bakry et al. [10] indicated the importance of organic resources for improving productivity and quality of flax. The results confirmed the importance of mycorrhiza, humic acid, and biochar in soil fertility and accumulation of organic carbon. Organic carbon improves the soil quality of sandy soils and improves the water-holding capacity. This consequently increases crop yield and water productivity. Abdelraouf et al. [11–13] summarized the economic views and results of statistical analysis for impact of pulse irrigation and mulching cover systems on the yield, quality properties, and water productivity of soybean. The results indicated that using eight irrigation pulses per day with black plastic mulch resulted in the highest yield, crop quality, and water productivity of soybean. Mitigating CO_2 emission and isolating organic matter to the soil (which improves soil fertility and also sustainability, recycling organic sources) led to an increase in the production of pea plants in addition to protecting the crop from vermin [14]. Maximum values were achieved using drip irrigation (placed 35 cm apart) with the recommended application of compost. No significant differences were observed between the 15-, 25-, and 35-cm spacing with the recommended compost dose. Therefore, the 35-cm spacing was selected to reduce costs and save 10% of the irrigation water [11–13].

2 Sustainable Techniques to Increase Yield and Crop Water Productivity

2.1 Impact of Biofertilizers on Yield and Water Productivity of Wheat

Experimental Design Two split-plot experiments with three replicas each were conducted at the Agricultural Production and Research Station (NRC) in the El Nubaria region, Egypt. These experiments were undertaken during two winter of 2010/2011 and 2011/2012. The aim of the experiments was to study the impact of biofertilizer inoculation (without biofertilizer or with biofertilizer) and irrigation requirements (IR) (100% IR, 80% IR, 60% IR, and 40% IR) on the yield of wheat and water productivity in arid conditions. Biofertilizer inoculation and irrigation treatments were allocated in the main and subplot, respectively. Grains of the wheat cultivar Sakha-93 were sown by manually drilling the seeds 20 cm apart at the rate of 60 kg/fed. (feddan (fed.) = 4,200 m^2). The sowing dates were 17 and 20 November in the first and second season, respectively. Sprinkler irrigation was applied (3/4-in. diameter and discharge was 1.2 m^3/h at 2.5 bar operating pressure and 12 m service radius).

Microbiological Biofertilizer Used The biofertilizer used in this study consisted of two parts. The first part was a bacterial mixture of PGPB: *Azospirillum brasilense*, *Azotobacter chrococcum*, *Bacillus megaterium* var *phosphaticum*, and *Pseudomonas* sp. The second part was arbuscular mycorrhizal fungi (AMF), which is a plant growth-promoting fungus (PGPF). The microorganisms were obtained from the Agricultural Microbiology Department, NRC [15]. Each bacterium strain was grown in the appropriate liquid medium until 105–106 CFU/ml was reached. AMF conidia were extracted from soil by wet sieving and sucrose density gradient centrifugation according to Syliva et al. [16]. The AMF conidia were then added to vermiculite (commercial clay mineral), which acts as a carrier. There were 100–150 mycorrhizal spores/g vermiculite in the AMF inoculums and this was determined by binocular stereo microscope (Olympus SZ). To produce the biofertilizer mixture, 10 ml of each liquid medium containing the PGPB was added to 1 kg of vermiculite and then mixed with 1 kg of AMF inoculum and 200 ml of 1% Arabic gum solution (adhesive agent). Wheat grains (cultivar Sakha-93) were mixed with the biofertilizer immediately before sowing.

Estimations of Total Water Irrigation Total water irrigation (m^3/feddan/season) for the district was estimated according to the meteorological data of the Central Laboratory for Agricultural Climate (CLAC) using the Penman-Monteith equation. As shown in Fig. 2, the seasonal water irrigation applied was found to be 2,060 m^3/feddan (100% IR), 1,648 m^3/feddan (80% IR), 1,236 m^3/feddan (60% IR), and 824 m^3/feddan (40% IR). Normal growing practices for wheat were followed for this experiment.

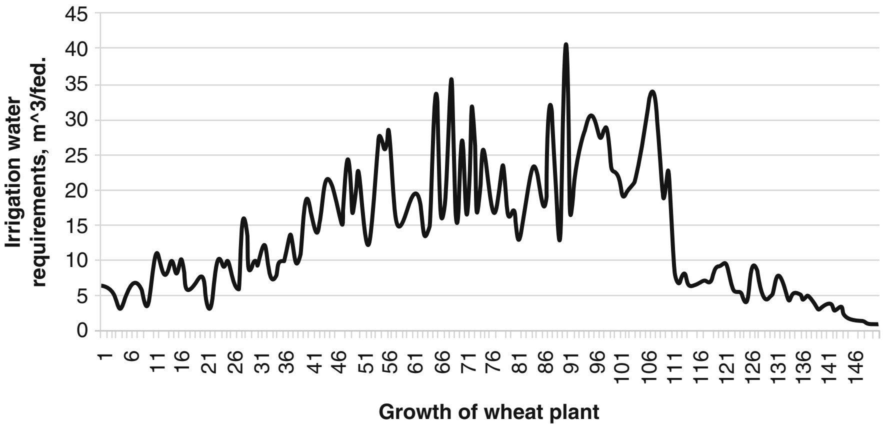

Fig. 2 The relationship between the growth of the wheat plant (days) and irrigation water requirements (m^3/fed.), Abdelraouf et al. [11–13]

Evaluation Parameters

Yield and yield attributes: At harvest, a random sample square of 50 cm by 50 cm was taken from each plot to determine spike length (cm), number of spikes/m^2, number of spikelets/spike, and seed index. The grain, straw, and biological yields (ton/feddan) were determined from the whole area of the experimental unit and then converted to yield per feddan.

Water productivity (WP): The WP was calculated according to James [17] as follows: WP (kg/m^3) = Total yield (kg/fed) /Total applied irrigation water, (m^3/fed/season).

Statistical analysis: The analysis of variance of the split-plot experiment was carried out using MSTAT-C Computer Software Program [18]. Since the trend was similar in both seasons, Bartlett's test and the combined analysis of the two growing seasons were completed. To compare mean treatments, the least significant difference test was applied at 0.05 probability level.

Effect of Interaction Between Drought Stress and Biofertilizer Inoculation on Yield and Yield Attributes of Wheat Data presented in Table 1 show the interaction between biofertilizer inoculation and reduced irrigation on the yield of wheat. Biofertilizer inoculation +100% IR surpassed other treatments with significant differences except for biofertilizer inoculation +80% IR without significant differences between the two treatments except, number of spikelets/spike. Biofertilizer inoculation +100% IR recorded the highest values of different studied characters followed by biofertilizer inoculation +80% IR, while 40% IR without biofertilizer inoculation recorded the lowest values of different studied characters. Decreasing IR from 80 to 40% with biofertilizer inoculation showed significant differences in some studied traits, i.e., number of spikes/m^2, grain, and biological yield/feddan. Okon [19] reported that as a consequence of the increase in plant root

Table 1 The interaction between biofertilizer inoculation and reduced irrigation requirements on the yield of wheat [11–13]

Treatment		Spike length (cm)	Spikelet/ spike	100 – seed weight (g)	Spikes (m^{-2})	Yield (ton $fed.^{-1}$)		
						Biological	Straw	Grain
With biofertilizer	100% IR	11.33	19.00	5.20	497.00	5.40	2.80	2.60
	80% IR	10.34	15.67	4.80	495.34	5.53	3.20	2.33
	60% IR	10.35	15.66	4.57	473.00	5.73	3.43	2.30
	40% IR	10.00	15.34	4.46	452.00	4.57	3.50	1.07
Without biofertilizer	100% IR	10.67	15.67	4.40	485.00	4.20	1.93	2.27
	80% IR	9.67	15.00	4.20	480.00	4.17	2.17	2.00
	60% IR	9.34	12.67	4.21	474.00	3.47	1.93	1.53
	40% IR	9.00	13.00	4.13	462.00	3.80	3.03	0.77
LSD at 5% level		NS	2.24	NS	4.33	NS	NS	NS

IR irrigation requirements, *LSD* Least Significant Difference, *NS* not significant

surface area, inoculated plants showed enhanced mineral and water uptake, which in turn could benefit crops growing in water-deficient soils.

Effect of Interaction Between Drought Stress and Biofertilizers on Water Productivity of Wheat Figure 2 illustrates the effect of the interaction between biofertilizer and irrigation requirements on water productivity where no significant differences among treatments was observed. The treatment biofertilizer +60% IR recorded the highest water productivity followed by the treatments biofertilizer +80% IR, biofertilizer +100% IR and biofertilizer +40% IR, respectively. The absence of biofertilizer in the different irrigation combinations recorded the lowest irrigation water productivity values. Inoculation enhanced plant dry matter in wheat genotypes tested under both well-watered and water stressed conditions. Enhanced growth effects on inoculated plants have been attributed to improving water relations resulting from enhanced P nutrition, Ruiz-Lozano et al. [20] (Fig. 3).

2.2 *Impact of Organic Mulching on Yield and Crop Water Productivity*

"Mulch" has probably been derived from the German "*molsch*," which means soft to putridity, which refers to the use of straw and leaves by gardeners as a cover on the

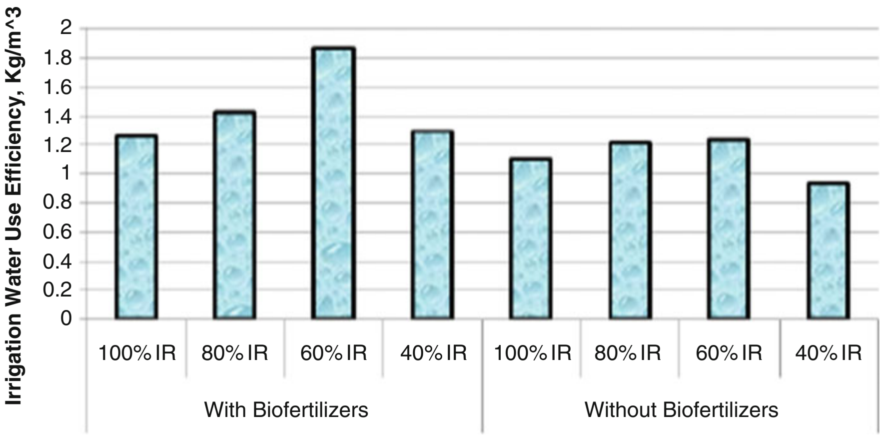

Fig. 3 Interaction between drought stress and biofertilizers on water productivity of wheat, Abdelraouf et al. [11–13]

ground [21]. Different types of mulch are used for many reasons in agriculture. To save water is an essential objective, particularly in arid and semi-arid regions. Other reasons for using mulch include modification of soil temperature, weed control, conservation of soil and organic matter after decomposition to add nutrients to the soil, increasing crop productivity, and improving the soil structure. Mulching reduces weed infestation and water evaporation. It also adds nutrients to the soil and enhances the vegetative growth and yield of field crops [22]. Mulch can efficiently minimize water vapour loss, soil erosion, weeds, and nutrient loss [23]. Different kinds of materials are used as mulch (e.g., rice straw, wheat straw, rice husks, plastic film, wood, grass, oil layer, sand) [24, 25].

Types of Organic Mulching Materials There are many organic mulches that come from plant residues and animal materials such as straw, peanut hulls, hay, leaf mold, sawdust, compost, wood chips, wood shavings, and animal manure. Figure 4 provides some examples of organic mulch types. The mulch must be applied after crop germination or transplanting at 5 ton ha^{-1} to achieve optimum benefits from the organic mulch. Organic mulch is very effective for reducing nitrate leaching, improving soil physical characteristics, supplying organic matter, preventing soil erosion, regulating soil temperature, increasing water retention, improving the balance of nitrogen in the nutrient cycle as well as increasing the biological activity [26]. Organic materials can not be easily spread on growing crops and require considerable human labor [27].

Effect of Organic Mulching on Soil Moisture Conservation The conservation of soil moisture through mulching is due to an increase of favorable micro-climatic conditions in the soil. Covering the soil surface with organic mulch prevents the growth of weeds, increases infiltration of rainwater, and reduces evaporation [28]. Crop residue materials or organic mulch on the soil surface provides shade, is a

Fig. 4 Examples of organic mulch (https://www.slideshare.net/mulchpro/what-is-mulch-in-los-angeles-california)

vapor barrier against moisture loss from soil, causes slow run-off, and conserves water in the soil for better development of crops [29]. Higher water productivity was caused by lower evaporation in *Rosa indica* by using a black polythene sheet (0.18 mm thick) as mulch [30]. Thakur et al. [31] observed that different mulch materials such as lantana leaves, grass, and plastic, helped increase Bell Pepper production (*C. annuum* cv. California Wonder) to perform better at 25% to 75% water deficits. The plastic mulch resulted in the highest water productivity. Hatfield et al. [32] reported a 34–50% reduction in the soil water evaporation as a result of using crop residues as a mulch. Mulch slows down the evaporation rate and therefore reduces the irrigation requirement [33]. Chawla [34], Khurshid et al. [24], and Muhammad et al. [35] indicated that mulching improves the ecological environment of the soil and prevents a decrease in the soil water levels. Reducing infiltration rate: The presence of crop residues as an organic mulch has a direct impact on the infiltration of rainwater and evaporation. Mulch reduces surface run-off and holds rainwater at the ground soil surface thereby giving it more time for infiltration into the soil [24]. Mulching is one of the management practices used to increasing water productivity in crop fields [36].

Add Organic Matter The benefits of organic mulch include: returning organic matter and nutrients to the soil and plants and improving chemical, physical, and biological characteristic of soil after decomposition, which in turn increases crop productivity. Soils covered with mulch remain loose, friable, and lead to the best environment for root penetration. Organic mulching not only conserves soil moisture but also increases soil nutrients through the addition of organic matter [22]. Lal et al. [37] indicated that there is a decrease in bulk density with straw mulch (1.42 g cm^{-3}) compared with bare soil (1.50 g cm^{-3}). Saroa and Lal [38] and Khurshid et al. [24] found that organic matter was significantly higher when more mulch was applied. A higher organic carbon content of soil was recorded with sunhemp mulch (0.71%) followed by silkworm bed waste (0.68%), paddy straw (0.66%) mulched plots, and least organic carbon content (0.48%) in non-mulched plot [39].

Impact of Organic Mulching on Plant Growth and Development Mulching provides a favorable environment for growth, which results in vigorous and healthier plants that may be more resistant to pest damage [26]. Organic mulches induced early flowering and fewer days to fruit and harvest in tomato crop when compared to the control [40]. Mulch results in improved soil environment conditions, moderated soil temperature, increased soil porosity, increased water infiltration rate, controled run-off, and suppressed weed growth [41–44].

Improve Quality and Yield Mulch helps keep fruit off the ground, reduces soil rot, fruit cracking, and blossom end rot. Fruit tends to be smoother with fewer scars. Marketable crop yield (cultivated in a mulched plot) was significantly higher than the crops produced with bare soil. This difference may be due to moisture conservation, higher soil temperatures, weed control, and increasing the mineral nutrient uptake [45]. Gollifer [46] indicated that application of organic mulch at 40 ton ha^{-1} produced 2.5 ton ha^{-1} of chilli dry fruits. Hassan et al. [47] found that organic mulch provided a higher crop yield of bell peppers than the control treatment. The yield of potato was the highest under paddy straw mulch (27.9%) and also starch content was highest in paddy straw mulch (18.18%) than unmulched plot [48]. Thakur et al. [31] experimented with different mulches on *Capsicum annuum* L. under reduced irrigation (75%). Lantana mulch resulted in the highest fruit yield compared to unmulched plots. Gangawar et al. [49] found that paddy straw mulch on mulberry crops resulted in maximum leaf yield compared to sorghum and blackgram mulching compared to the control. Gao et al. [50] reported that paper mulching promoted flower bud differentiation, improved yield, and fruit quality in tomatoes compared to plastic mulch or no mulching. Gandhi and Bains [51] reported that tomato crops under straw mulch produced a higher number of branches, fruit weight, and total yield when compared to no mulch. Shashidhar et al. [39] reported that the total leaf yield of mulberry was found to be highest in paddy straw mulched plots (15.20 ton ha^{-1}) when compared to control plots (11.78 ton ha^{-1}). Manyatsi and Simelane [52] found that the growth rate and yield of spinach plants grown on the treated sewage sludge mulch and organic compost mulch were better than without mulch.

Role of Mulching in Weed Management Mulching reduces germination and nourishment of weeds [53]. Covering the soil surface can prevent weed seed germination. Waste materials such as bark, straw, and composted green waste can provide effective and efficient weed control [54]. Sawdust is a soil improver and weed suppressor as it conserves the soil moisture content, increases infiltration rate and deep percolation, decreases run-off, and decreases the evaporation process. Weed growth can be substantial under clear mulch [55]. Clear or white mulch and green coverings had little impact on weeds, whereas black, brown, blue, or white on black films prevented emerging weeds [56]. Ossom et al. [57] observed significant differences in weed control between mulched and non-mulched plots of eggplant.

2.3 Impact of Application Compost on Yield and Water Productivity

Adugna [58] indicated that intensive cultivation and the misuse and excessive use of chemical fertilizers might lead to a loss of soil organic matter, adverse effects on the environment, threaten human and animal health, and negatively impact food safety and quality. Fertilizers are needed for high yields, particularly in nutrient-poor soils. With increasing fertilizer prices and limited resources, organic additions (e.g., compost and manure as a source of nutrients and organic matter) are considered an economical and environmentally-friendly alternative. Compared to plant residues and manure, compost releases nutrients more slowly and has longer-lasting effects. The slow decomposition of compost is more effective in increasing soil organic matter content of the soil, which plays a crucial role in soil fertility by retaining nutrients, maintaining soil structure and holding water. Compost has other advantages such as using and recycling municipal solid wastes and reducing material going into landfill. Caution must be exercised when generalizing the effects of compost on soil health, fertility, and crop nutrition due to the variable nature of different compost and their interactions with climatic, edaphic, and crop properties. The general effects of compost application on soils have been well-documented (e.g., increasing soil structural stability, improving water-holding capacity and plant water availability, decreasing leaching of nutrients and reducing erosion and evaporation). However, the effect of compost on soils is likely to be strongly dependent on compost composition, which depends on feedstocks, composting conditions, and age of compost. Also, some studies have indicated that the effects of compost application on soil and plant nutrients may be modulated by soil type. Hence, the interactions between compost type, soil properties, tillage, and rotation remain unclear. Furthermore, organic manure discharges nutrients very slowly to the plants and these nutrients are not directly absorbed by the plants. Therefore, plants are unable to access a number of nutrients in the critical yield-forming period. Hence, an integrated approach combining the application of compost with inorganic fertilizer is a good strategy for increasing crop productivity. This will reduce the cost of inorganic fertilizer and improve soil fertility, as shown in Fig. 5.

Amlinger et al. [59] summarized the literature and current knowledge on the effect of compost fertilization on the soil-plant system. Most of the investigations resulted in positive yield effects when compared to unfertilized treatments, and in longer-lasting experiments and also mineral-fertilized control plots. Crops with extended growth periods experienced better responses than those with short growth periods. Many experiments indicate that at typical application rates (ca. 7–10 Mg day month year^{-1}), a positive yield effect occurs only after 3–6 years. In other words, field trials of less than 3 years are not recommended as they do not allow sufficient time for the crop to respond to the fertilizer.

In addition to the above sustainable techniques (i.e., biofertilizers, mulch, compost), some engineering techniques are applicable to sandy soils to increase the crop yield and the water use efficiency. These techniques are presented in the next sections. The results obtained from an experimental case study are also presented.

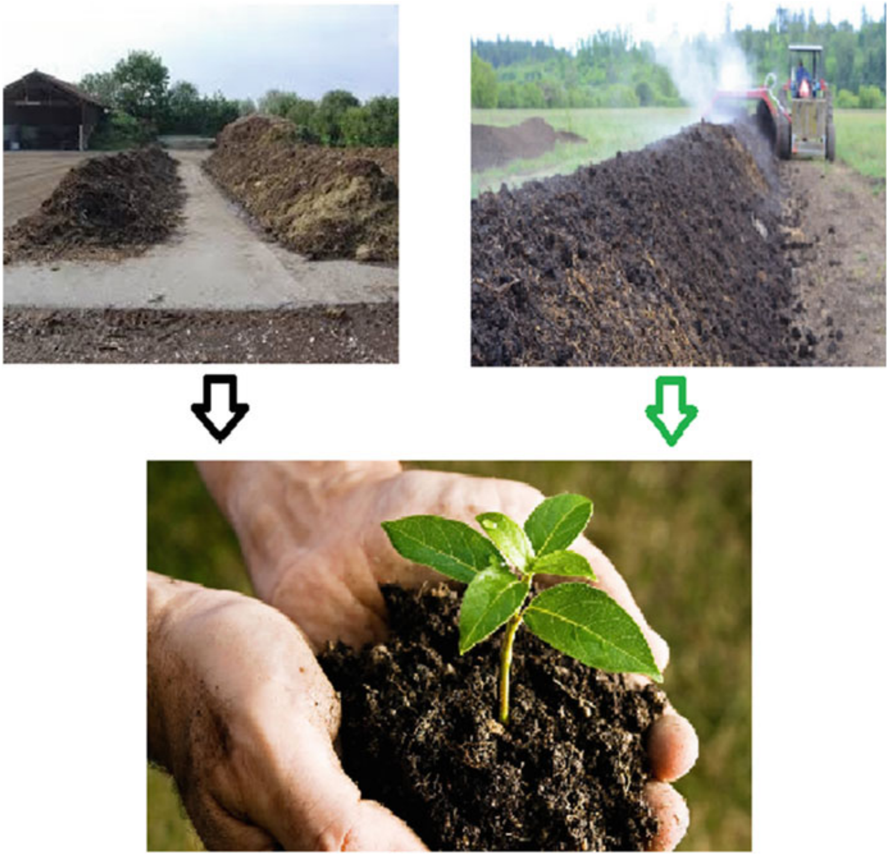

Fig. 5 Production of compost

3 Review of Engineering Techniques in Sandy Soils

Water scarcity is a global problem. As cities grow and populations increase, the problem worsens as the need for water increases in households, industry, and agriculture. How the available water is used, managed, and conserved determines if there is enough to meet household, agricultural, industrial, and environmental demands [60]. Climate change has also contributed significantly to the water scarcity problem. Rising temperatures increase the rate of evaporation from land and surface water resources; this has caused reductions in river run-off in several areas. The rise in temperatures has also greatly affected areas that rely on snowmelt and mountain glaciers as a water source. Water scarcity does not only occur in arid and semi-arid areas but also in areas that receive ample rainfall and/or have abundant fresh water resources.

to the total volume of Egypt's water resources is 72 billion m^3/year with 55.5 billion m^3 of this from the Nile River, in accordance with the 1959 Agreement between Egypt and Sudan. Irrigation uses 70–80% of Egypt's water resources. To conserve water, Egypt has limited the per capita share of water per year.

Maximizing water productivity is a common idea used by irrigation managers. Water use efficiency and crop yield are the main criteria used to evaluate the effectiveness of irrigation systems. Increasing competition for diminished water resources has led to the application of advanced techniques to maximize water productivity and improve crop yields and quality, particularly in arid and semi-arid regions [61].

Laser land leveling improves irrigation application and distribution efficiencies, which ultimately leads to higher water productivity. A significant reduction in water use and marked improvement in water productivity in a rice-wheat cropping system was recorded due to precision land leveling compared to traditional leveling. Jat et al. [62] found that with similar fertility levels and land configurations, the water productivity of rice and wheat increased from 0.55 kg grain m^{-3} and 0.82 kg grain m^{-3} to 0.91 kg grain m^{-3} and 1.31 kg grain m^{-3} water, respectively. Raised bed planting further improved the productivity of wheat in laser-leveled fields.

The pulse irrigation technique refers to short bursts of irrigation and no irrigation and repeating this on-off cycle until all of the irrigation water is applied [63]. If drip irrigation is used, irrigation might need to occur more than once a day to meet the peak water needs. If the drip system drains out after every irrigation and to reduce losses from drainage, use the longest pulses possible. Redesign the irrigation system if the wetted area is too small (limiting) [64].

Based on reports from different soil types, the size of the wetted zone can be increased if irrigation is pulsed [63]. For most crops, the soil in the root zone should be kept near field capacity at all times. This means that irrigation should be frequent and the amount of water applied each time should be equal to the amount used by the plants since the last irrigation. In general, short irrigation cycles with high application rates help promote the lateral movement of water, resulting in better wetting patterns for light soils. Pulse irrigation, where the system is operated several times a day for short durations, can further widen the wetted pattern. Long pulses at a low application rate results in better infiltration of water in heavy (high clay content) soils. El Saidi et al. [65] indicated that, in drip irrigation, high irrigation frequency is one of the most important factors. Due to differences in the soil moisture and wetting patterns, crop productivity may be different when the same quantity of water is applied at different high irrigation frequencies. High irrigation frequency might provide desirable conditions for water movement in soil and uptake by roots [66]. Applying irrigation water in stages or pulses rather than all at one time can save water by giving the soil time to moisten from the first pulse of water thereby allowing it to absorb subsequent irrigation more readily and reducing the total amount of water required [67]. The benefits of pulse irrigation have been documented by different researchers and include: reducing surface soil water evaporation, decreasing fertilizer leaching, enhancing yield, etc. If soil is over-irrigated with drip irrigation, valuable nutrients may be leached out of the root zone and become unavailable for the plants while contaminating the groundwater [68].

The main objective of this chapter is the introduction of engineering techniques to increase water use efficiency under arid conditions. Examples of these techniques to improve yield and water use efficiency of crops include: (1) laser land leveling, (2) applying pulse irrigation, and (3) innovative drip irrigation design.

The methods to apply these three engineering techniques are presented below in Sect. 3.1 and the results and discussions are presented in Sect. 4.

3.1 Materials and Methods

3.1.1 Site Description

There were three field experiments, two of which were conducted during two winters (2010/2011 and 2011/2012) at the experimental farm of the National Research Center, El-Nubaria, Egypt (latitude 30.8667 N, and longitude 30.1667 E, mean altitude 21 m above sea level). The experimental site experiences arid weather with hot summers and cool winters. The data of relative humidity and the maximum and minimum temperatures were obtained from the local weather station in El-Nubaria farm. There was no significant rainfall during the two winters. Wheat and maize crops were cultivated in El-Nubaria. The third crop (potato) was cultivated during two summers (2006 and 2007). The potato crop was farmed in the Abo-Ghaleb region, 60 km from Cairo.

3.1.2 Estimation of Water Requirements for Wheat, Potato, and Maize Crops

Wheat Seasonal IRs for wheat were estimated. The seasonal IR was found to be 2,304 m^3/fed./season for the sprinkler irrigation system by Eq. (1) as follows:

$$\mathrm{IRg} = (\mathrm{ET_O} \times \mathrm{Kc})/\mathrm{Ei} - \mathrm{R} + \mathrm{LR} \tag{1}$$

where IRg = Gross irrigation requirements (mm/day), ET_O = Reference evapotranspiration, mm/day (estimated by the meteorological data from the Central Laboratory for Agricultural Climate (CLAC) according to the Penman-Monteith equation), Kc = Crop factor [69, 70], Ei = Irrigation efficiency = Ea × EU where Ea = (Ds/Da) × 100 where Ds = Average water stored in root volume; Da = Average water applied; EU = Coefficient reflecting the uniformity of application, R = Water received by plant from sources other than irrigation, mm (e.g., rainfall), LR = Amount of water required for the leaching of salts (mm).
The seasonal IR applied for wheat was 2,304, 1,843, 1,382, and 922 m^3/fed. for 100%, 80%, 60%, and 40% IR, respectively.

Potato The total irrigation water for potato was estimated according to the meteorological data from the CLAC. The volume of applied water increased with the growth of the plant and then declined at the end of the growth season. The seasonal IR applied was 3,476 m^3/fed./season.

Maize Seasonal IRs for maize were estimated. The seasonal IR applied was 2,400 m^3/fed./season for 2014 and 2,500 m^3/fed./season for 2015 (drip irrigation system) by Eq. (2) as follows:

$$IRg = (ET_O \times Kc \times Kr)/Ei - R + LR \tag{2}$$

where IRg = Gross irrigation requirements (mm/day), ET_O = Reference evapotranspiration (mm/day) (estimated by the meteorological data of local station in El-Nubaria farm and according to the Penman-Monteith equation), Kc = Crop factor [69, 70], Kr = Ground cover reduction factor, Values of Kr suggested by different authors [71], Ei = Irrigation efficiency (%), R = Water received by plant from sources other than irrigation (mm) (e.g., rainfall), LR = Amount of water required for the leaching of salts (mm).

3.1.3 Soil and Irrigation Water Properties

El-Nubaria Region Soil characteristics at the El-Nubaria site were 0.43% (organic matter), 8.9 (pH) and 0.37 ds m^{-1} electrical conductivity (EC). The soil texture was sandy. The saturation point, field capacity, wilting point, and available water were 20.6%, 12%, 4.9%, and 7%, respectively. The pH, EC and Sodium Adsorption Ratio for the irrigation water were 7.35, 0.41 dS m^{-1}, and 2.8% respectively.

Abo-Ghaleb Region The soil at the experimental site was sandy. The field capacity, wilting point, and bulk density were 9.75%, 3.38%, and 1.56 g/cm^3 respectively. While for pH, EC, and organic matter, the values were 7.64, 3.32 dS m^{-1}, and 1.6% respectively. The pH and EC for irrigation water were 7.55 and 1.9 dSm^{-1} respectively.

3.1.4 Experimental Designs

Laser Land Leveling Experiment with Wheat Experimental design included a split plot with three replications. Land leveling and deficit irrigation were used in the main plots and sub-main plots, respectively. The treatments were IR (100%, 80%, 60%, and 40% IR) and land leveling (conventional and laser).

Pulse Irrigation Experiment with Potato The experimental design was a split-split plot with three replications. Irrigation systems, water regime treatments, and pulse irrigation treatments were used in the main plots, sub main plots, and sub-sub main plots, respectively. Three different irrigation systems were selected: surface drip irrigation (SDI) with 30 cm spacing between emitters, polyethylene driplines with diameter of 16 mm and 70 cm spacing between driplines, and subsurface drip irrigation (SSDI) with 15 cm depth [72]. Three water application rates were applied: 50, 75, and 100% from actual water requirements (WRa). Three types of pulse irrigation were used:

two times per day, three times per day, and four times per day. The time-off between pulses was 30 min. This was compared with continuous drip irrigation (once per day). All details are shown in Figs. 6 and 7.

Innovative Drip Irrigation Design with Maize The experimental aim was to evaluate an innovative design (ID) for a drip irrigation system compared with two traditional designs (TD). The TD1 was a standard drip irrigation system (control system) while the TD2 was a drip irrigation system with partial root drying (PRD)

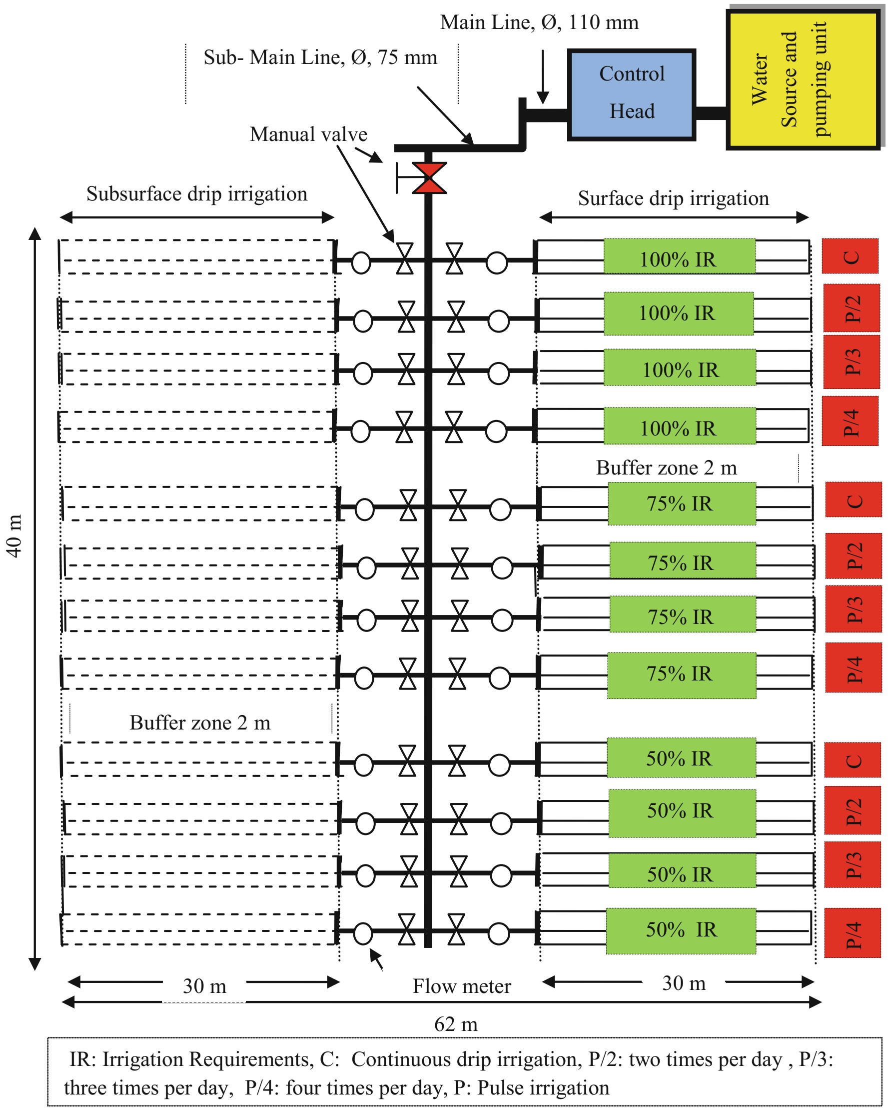

Fig. 6 The layout of the irrigation system used in the experimental design

Fig. 7 Applying the experimental design to the experimental plots

technique. The PRD consists of one emitter irrigating one part of the root system and other emitters irrigating the other half of the root system with the same direction for main lines and laterals. The ID was a drip irrigation system with PRD technique but with opposite water direction in the main lines and laterals. The distance between laterals was 35 cm [11–13]. More details for all three designs are shown in Figs. 8, 9, and 10.

3.1.5 Evaluation Parameters

Soil Moisture Distribution Soil moisture distribution was determined according to Liven and Van Rooyen [73]. The soil moisture content was measured by a profile probe device, 2 h after irrigation at equal 100-cm intervals along 1,200 cm, the distance between each sprinkler line. All the measurements were taken at 15-cm intervals to a depth of 90 cm at each point. Using a contouring program (Surfer version 8), a contouring map for different moisture levels, distances, and depths was created.

Application Efficiency Application efficiency is the actual storage of water in the root zone to meet the crop's water needs in relation to the water applied to the field. Application efficiency (AE) [74] was calculated using Eq. (3) as follows:

$$\mathrm{AE} = \mathrm{Ds}/\mathrm{Da} \tag{3}$$

where AE = Application efficiency (%), Ds = Depth of stored water in root zone (cm) where:

$$\mathrm{Ds} = (\theta 1 - \theta 2) \times d \times \rho \tag{4}$$

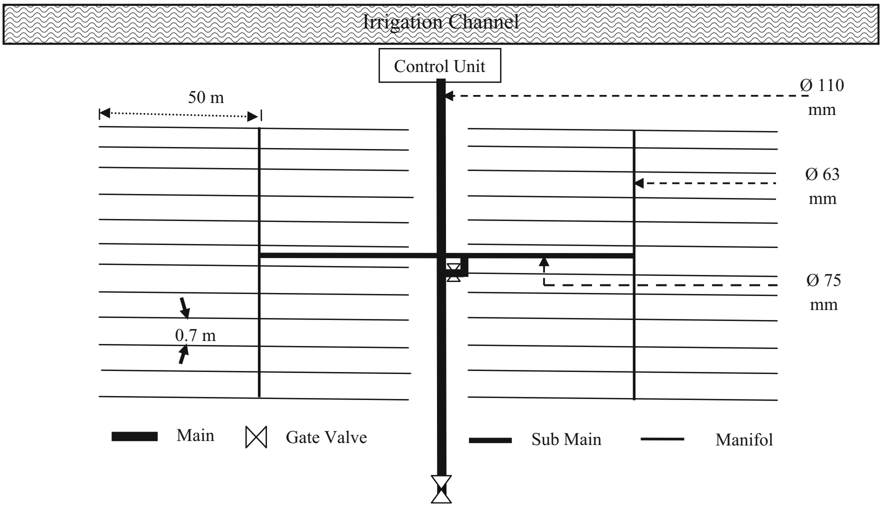

Fig. 8 Layout of design 1: drip irrigation system (control)

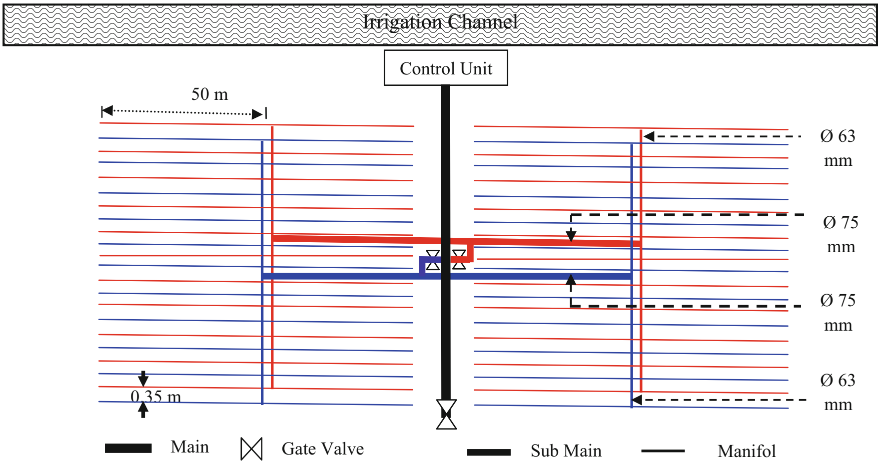

Fig. 9 Layout of design 2: drip irrigation system with PRD technique with the same direction for manifolds and laterals

Da = Depth of applied water (cm), d = Soil layer depth (cm), $\theta 1$ = Soil moisture content after irrigation (%), $\theta 2$ = Soil moisture content before irrigation (%), ρ = Relative bulk density of soil (dimensionless).

Yield At harvest, a random sample of 100 × 100 cm was taken from each plot to determine yields for wheat, potato, and maize and this sample yield was then converted to a total yield (ton/fed.).

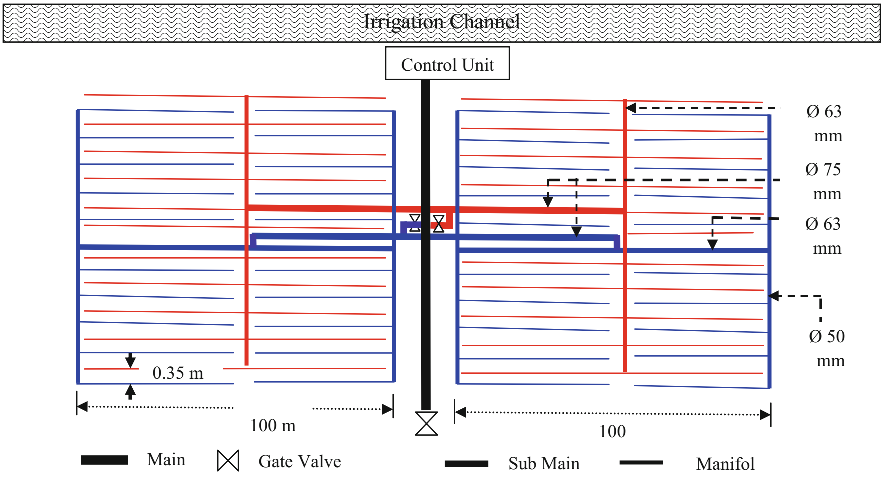

Fig. 10 Layout of innovative design: drip irrigation system with PRD technique with opposite direction for manifolds and laterals

Water Productivity (WP) The WP of wheat, potato, and maize was calculated according to James [17] as follows:

WP (kg/m^3) = Total yield (kg/fed.)/Total applied irrigation water (m^3/fed./season).

3.1.6 Statistical Analysis

Combined analysis of the data from the two growing seasons was carried out according to [75], and the values of least significant differences (LSD at 5% level) were calculated to compare the means of different treatments.

4 Results and Discussion

4.1 Impact of Laser Land Leveling Under Irrigation on Yield and Water Productivity of Wheat

A rotational irrigation system was usedIn this system, the water exists in the irrigation channel for 3 days per week and the channel is empty for the other 4 days (3 days on and 4 days off). By using laser land leveling and deficit irrigation techniques under rotational irrigation, conditions to decrease the water run-off was decreased and this effect on yield and water productivity of wheat (WP_{wheat}) was measured.

Soil Moisture Distribution Soil moisture distribution (SMD) in the root zone and wetted soil volume (WSV) (more than or equal to 100% of field capacity) was measured at maximum IR. Both SMD and WSV improved under laser land leveling compared to conventional land leveling at 100% IR, 80% IR, 60% IR, and 40% IR. The laser land leveling leads to more uniform moisture distribution in the root zone. This is more suitable for growing roots and lowers drought stress. Figures 11 and 12 show examples of contouring maps (bold hashed line in contouring maps = field capacity).

Yield of Wheat Table 2 shows that the highest significant wheat yields were achieved by preparing the soil surface by laser technique when compared to preparing the land by the conventional method. This may be due to improvement in the SMD in the root zone, which creates optimal conditions for root growth. Wheat yield decreased with decreasing amounts of irrigation water. This may be due to the increase in soil moisture content in the root zone and also removing the salts from root zone by increasing leaching process. The grain yield (ton/fed.) decreased by 52.79% when the irrigation water was dropped from 2,304 m^3/fed./season to 922 m^3/fed./season. These data are presented in Fig. 13. Table 2 indicates the interaction between land leveling techniques and deficit irrigation on the wheat yield. The highest grain yield was achieved by using laser land leveling technique under

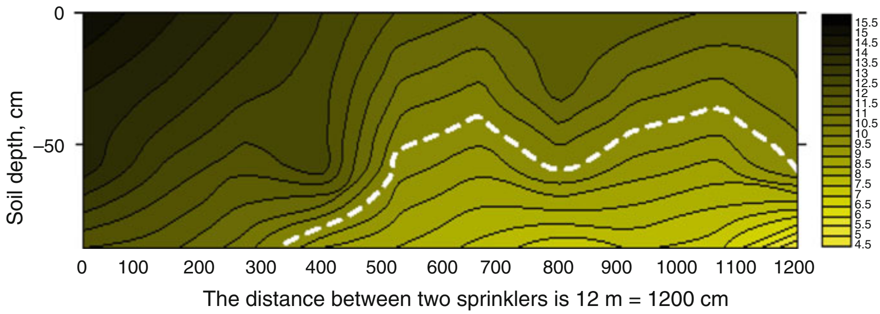

Fig. 11 Soil moisture distribution at 100% irrigation requirements for conventional leveling

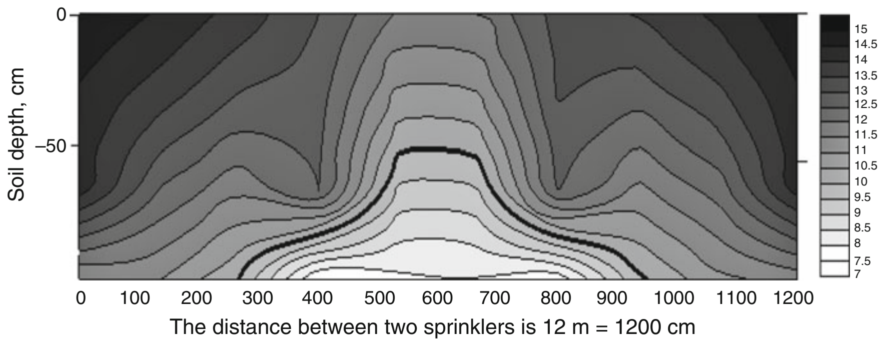

Fig. 12 Soil moisture distribution at 100% irrigation requirements for laser land leveling

Table 2 Effect of interaction between study factors on yield and water productivity of wheat (average of two seasons)

Leveling land system	Deficit irrigation (m^3/fed./season)	Grain yield (ton/fed.)	WP (kg/m^3)
Laser land leveling	100% IR = 2,304	3.03	1.32
	80% IR = 1,843	2.77	1.50
	60% IR = 1,382	2.73	1.98
	40% IR = 922	1.50	1.63
Conventional land leveling	100% IR = 2,304	2.70	1.17
	80% IR = 1,843	2.43	1.32
	60% IR = 1,382	1.97	1.42
	40% IR = 922	1.20	1.3
LSD at 5% level		0.35	0.23

LSD least significant difference, *IR* irrigation requirements

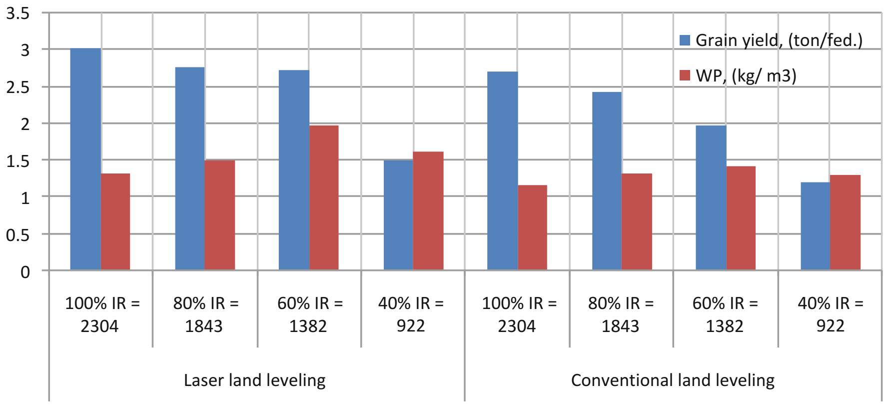

Fig. 13 Effect of laser leveling versus conventional leveling under deficit irrigation (IR: Irrigation Requirements) on yield and water productivity of wheat. FI (full irrigation) mean WR (water requirements)

100% IR (2,304 m^3/fed./season). However, the statistical analysis indicated that no significant difference was achieved between 100 and 60% IR, in the grain yield. This means that by using 60% IR, 40% irrigation water was saved.

Water Productivity of Wheat The WP_{wheat} in the different water regimes and thetwo land leveling techniques is presented in Table 2. The highest WP_{wheat} (1.98 kg/m^3) was obtained using 1,382 m^3/fed./season (60% IR) with the laser land leveling technique. From the viewpoint of water conservation, using 2,304 m^3/fed./season (100% IR) is not efficient. Therefore, the efficient water regime is 60% IR with the laser land leveling technique, because there were no significant differences of grain yield between 60, 80, and 100% IR. Consequently, 40% of the irrigation water could be saved for irrigating other crops.

4.2 Impact of Pulse Irrigation on Yield and Water Productivity of Potato

Abdelraouf [76] stated that the pulse drip irrigation technique has many positive effects. Soil moisture content (SMC) in the root zone and wetted soil volume (more than or equal to 100% of field capacity) in root zone increased by increasing the number of irrigation pulses. Increasing the number of pulses causes increases in water movement in a horizontal direction instead of a vertical direction. In addition to the increase of SMC in the root zone, increasing the number of pulses also increased the SMD inside the root zone and increased the wetted soil volume (higher than or equal to 100% field capacity (FC)) ($WSV_{\geq 100\%FC}$). The best results were determined by the highest values of $WSV_{\geq 100\%FC}$ (Figs. 14, 15, 16, and 17).

The Yield of Potato (PY) The maximum PY was 6.57 ton/fed. under the following conditions: 100% from WRa with four pulses under SSDI. While the minimum PY was 1.56 ton/fed. under the following conditions: 50% from WRa with four pulses under SDI. The PY increased by increasing the number of pulses, especially at 100 and 75% WR. The PY increased due to the increase in the available nutrients in the root zone. These nutrients became more available to the plant by increasing the wetted soil volume (more than or equal to 100% of the field capacity) and moisture content in the root zone. These results are in agreement with those obtained by Zin El-Abedin [68], Feng-Xin et al. [78], Segal et al. [66], Beeson [79], and Nosenko et al. [80]. Very high AE values of 50% from WRa under the surface and subsurface

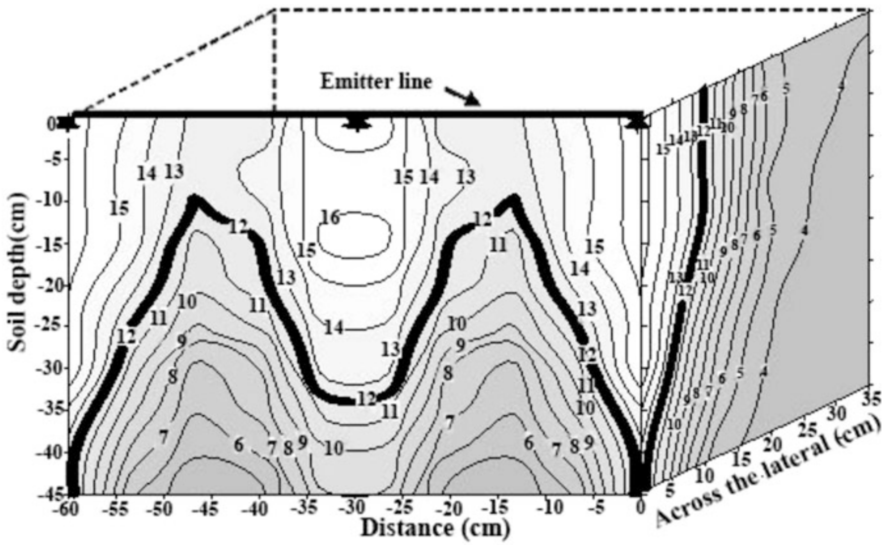

Fig. 14 Three-dimensional soil moisture distribution and wetted soil volume (more than or equal to 100% of field capacity) for sandy soil under surface drip irrigation at 100% from peak actual water requirements under continuous drip [77]

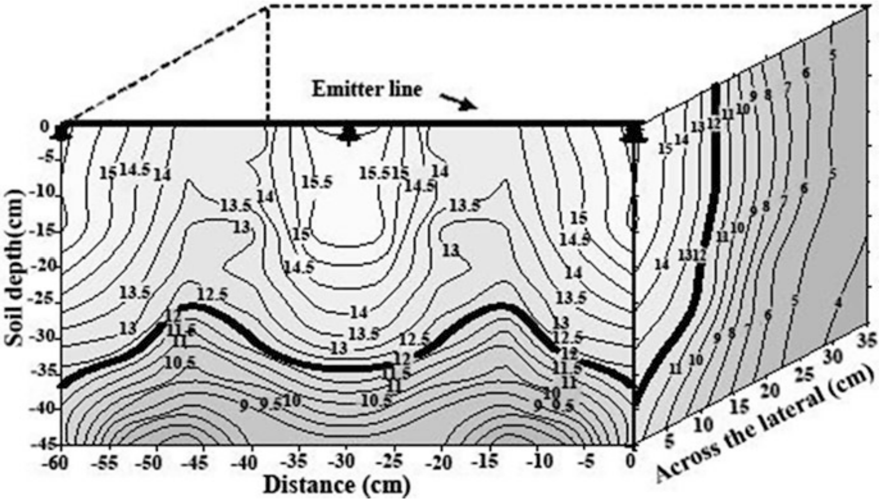

Fig. 15 Three-dimensional soil moisture distribution and wetted soil volume (more than or equal to 100% of field capacity) for sandy soil under surface drip irrigation at 100% from peak actual water requirements on four pulses [77]

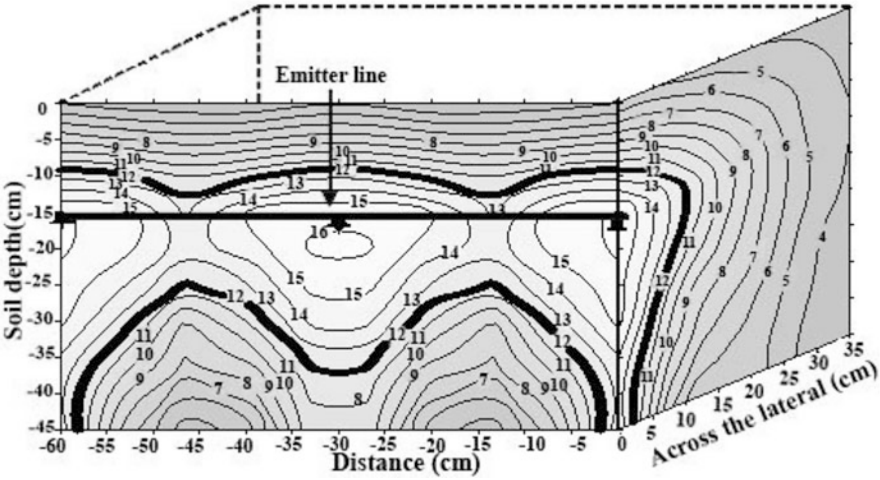

Fig. 16 Three-dimensional soil moisture distribution and wetted soil volume (more than or equal to 100% of field capacity) for sandy soil under subsurface drip irrigation at 100% from peak actual water requirements under continuous drip [77]

drip irrigation, but the depth of water stored was too deep for growing potatoes. A small volume of water irrigated by many pulses with increased time-offs, resulted in concentrated salts in the soil around the plant, which increased the osmotic potential. This increases the probability of plasmolysis (loss of water through osmosis is accompanied by shrinkage of protoplasm away from the cell wall). Consequently, the PY is decreased, especially under SDI as shown in Fig. 18. The PY increased by

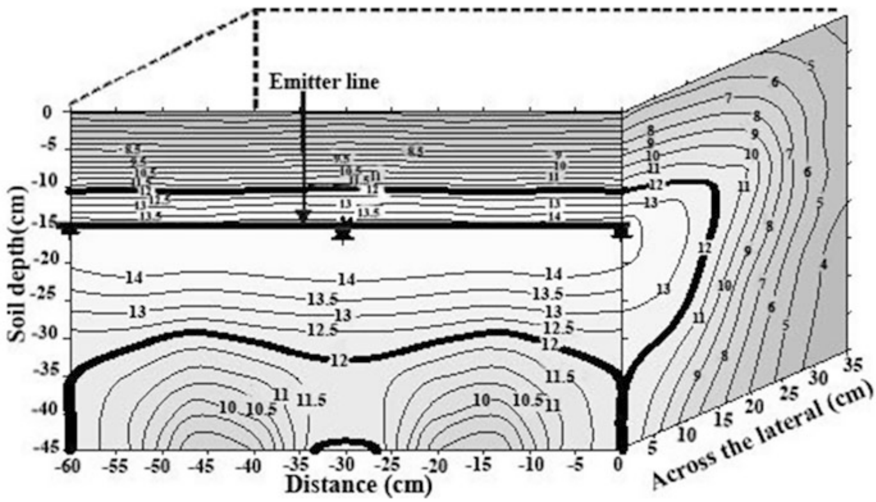

Fig. 17 Three-dimensional soil moisture distribution and wetted soil volume (more than or equal to 100% of field capacity) for sandy soil under subsurface drip irrigation at 100% from peak actual water requirements on four pulses [77]

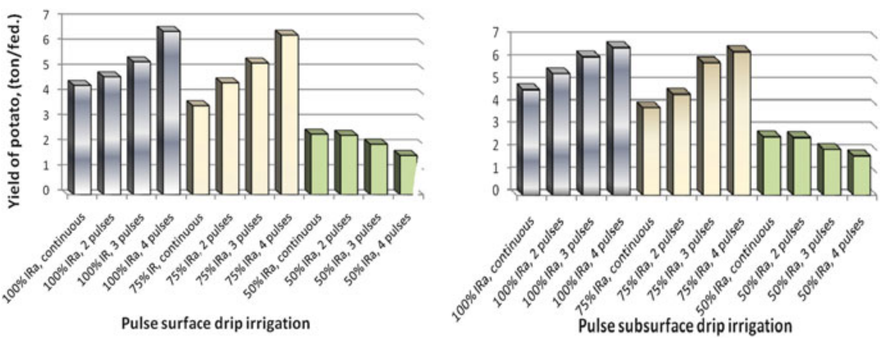

Fig. 18 Effect of pulse drip irrigation on yield of potato

increasing number of irrigation pulses, especially at 100% and 75% WR. PY increased from 4.70 ton/fed. under SDI to a maximum value of 6.57 ton/fed. after applying four pulses at 100% WR under SDI. No significant differences occurred between the maximum PY and 6.50 ton/fed. and 6.39 ton/fed. under the conditions 100% WR with four pulses under SDI and 75% WR with four pulses under SSDI, respectively.

Water Productivity of Potato (WP_{potato}) The maximum WP_{potato} was 2.36 kg/m^3 attained under the following conditions: 75% WR with four pulses under SSDI. The minimum WP_{potato} was 0.80 kg/m^3 under the following conditions: 50% WR with four pulses under SDI. In general, there are significant differences between 2.36 kg/m^3 under 75% WRa with four pulses under SSDI and 1.89 kg/m^3 under 100% WRa with

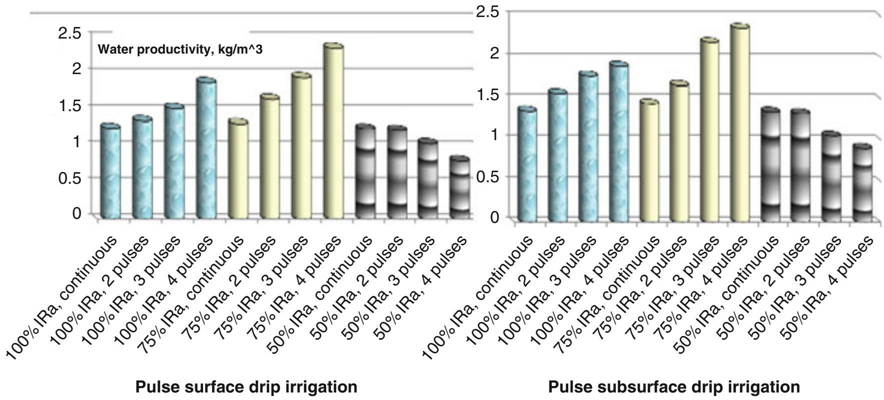

Fig. 19 Effect of pulse drip irrigation on water productivity of potato

four pulses under SSDI. This may be due to the reduced amounts of water applied that did not change the soil moisture significantly. Yields for both treatments were similar. These results are in agreement with those obtained by Kenig et al. [81] and Segal et al. [66]. Using statistical analysis for WP_{potato}, there are significant differences between pulse drip irrigation and continuous drip irrigation (LSD at 5% level was 0.08). WP_{potato} increased by increasing the number of pulses, especially at 100 and 75% WR. WP_{potato} increased from 1.44 kg/m^3 under SDI to the maximum value of 2.36 kg/m^3 after applying pulse technique with four pulses at 75% WR under SSDI, recording an increase of 63.9%. This means that the pulse technique and SSDI system can save 25% of the irrigation water per season, which amounts to 769 m^3, as shown in Fig. 19.

4.3 Impact of New Drip Irrigation Design on Yield and Water Productivity of Maize

Abdelraouf [82] reported that maximizing water productivity should be used in Egypt due to limited water resources. The performance of the innovative design (ID) for the drip irrigation system was compared with two traditional designs (TD1 and TD2) to maximize water and fertilizer use efficiency under arid environment conditions. The following parameters were studied to evaluate the effect of the different irrigation designs: (1) application efficiency, (2) yield of maize, and (3) water productivity of maize (WP_{maize}). Statistical analysis indicated that the maximum values of yield and WP_{maize} were detected under the ID system with the PRD technique with opposite direction for manifold lines and laterals, as shown in Figs. 20 and 21.

The Yield of Maize The main goal of any development in agriculture is to increase the yield. The yield of maize was studied under three drip irrigation system designs. Data in Table 3 represent the grain yield of maize under these designs. The maximum yield occurred under the innovative design.

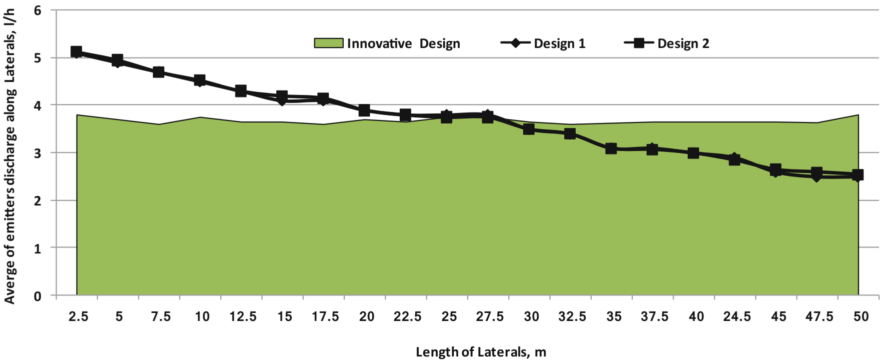

Fig. 20 Impact of innovative design on average of emitters discharge along laterals

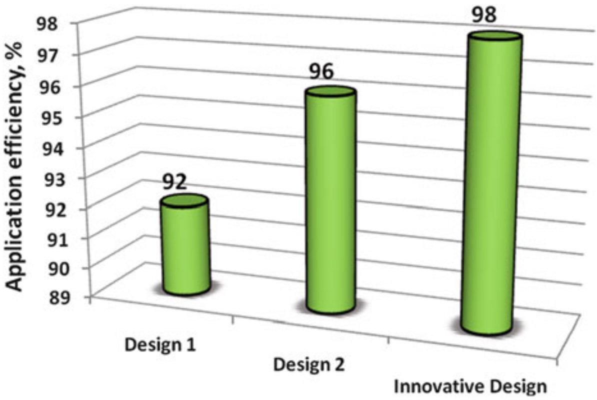

Fig. 21 Impact of the three experiment designs (ID, TD1, and TD2) on application efficiency

Table 3 Effect of innovative design for drip irrigation system on grain maize and water productivity "WP maize"

Designs	Grain yield (ton/fed.)	Water productivity of maize (kg/m^3)
TD1	2.27[a]	1.25
TD2	3.00[b]	1.66
ID	3.97[c]	2.19

TD1 traditional design 1, *TD2* traditional design 2, *ID* innovative design
[a]Lowest value of yield
[b]Second value of yield and there are significant difference between b and a
[c]Highest yield and there are significant difference between c and b

Water Productivity of Maize Water productivity (WP) is an indicator of the efficient use of irrigation water for increasing crop yield. WP maize was calculated by dividing the total yield by total applied irrigation water during the growth season of a maize plant. With the same amount of irrigation water used for the three designs, the maximum value of WP maize was found in the innovative design.

5 Conclusions

5.1 Sustainable Techniques

Biofertilizer technology uses integrated nutrient management to biologically fix N. Biofertilizers may also be used for improvement of phosphorus availability to field crops. The advantages of inoculants varies with inoculant type, formulation, crop species, soil nutrient level, the existence of relevant microbes in the soil, soil pH/type, and weather conditions.

Many farmers and researchers have experienced the beneficial impacts of organic mulches for field crop production. The literature provides robust and widespread evidence that compost fertilization results in multiple benefits for the soil-plant system, including: improving and stabilizing soil functions and properties, improving long-term productivity (including plant health, soil biodiversity and transformation capacity), improving soil physical properties, and improving the soil's ability to fix carbon in soil.

Mulch has many useful benefits for crop production during periods of water and soil conservation, including enhancement of soil bio-activity and improvement of chemical and physical characteristics of the soil. Organic mulching has many beneficial impacts on crop production in arid and semi-arid areas. The positive impacts include increasing in the soil moisture content, reducing water evaporation, reducing weed growth, maintaining the soil temperature, increasing plant growth and development, increasing the quality of crops produced and yield, promoting the earlier harvest of crops, and reducing fertilizer leaching.

5.2 Engineering Techniques

The Yield of Wheat The highest significant values of wheat yield were achieved by preparing the soil surface using the laser technique instead of the conventional method. This may be due to improvements in the soil moisture distribution in the root zone, which creates optimal conditions for root growth. The statistical analysis indicated that no significant difference in the grain yield was achieved between 100 and 60% IR, therefore 40% of the irrigation water could be saved.

Water Productivity of Wheat The highest WP_{wheat} (1.98 kg/m^3) was obtained using 1,382 m^3/fed./season (60% IR) under the laser land leveling technique. From the viewpoint of water conservation, using 2,304 m^3/fed./season (100% IR) is not efficient to irrigate wheat. Therefore, the efficient water regime is 60% IR with the laser land leveling technique, because there were no significant differences of grain yield of the wheat crop between 60, 80 and 100% IR. Consequently, 40% of the irrigation water could be saved for irrigating other crops.

The Yield of Potato (PY) The maximum PY was found with 100% WR with four pulses under SSDI. PY increased by increasing the number of pulses, especially at

100 and 75% WR. This is due to the increase in available nutrients in the root zone. These nutrients will be more available for plants roots by increasing the wetted soil volume (more than or equal to 100% of field capacity) and moisture content in the root zone. A small volume of irrigation water irrigated with many pulses and withlong time-off periods will lead to concentrated salts in the soil around plants roots, which increases the osmotic potential and therefore increases the probability of plasmolysis. This can decrease the yield of potato, especially under surface drip irrigation. There were no significant differences between the maximum PY and values of 6.50 ton/fed. and 6.39 ton/fed. resulting from 100% WR with four pulses under SDI and 75% WR with four pulses under SSDI, respectively.

Water Productivity of Potato The maximum WP_{potato} was achieved under the following conditions: 75% WR with four pulses under SSDI. Applying the pulse technique with four pulses at 75% WR under SSDI recorded an increase of 63.9% in WP_{potato}. This means that 25% of the water requirements can be saved per season, which is 769 m^3 of irrigation water.

The Yield of Maize The maximum yield occurred under the innovative design with significant differences to the other designs. The same volume of irrigation water and fertilizers were fed along the laterals in all of the three irrigation designs, therefore the innovative design increased the yield when compared to the traditional designs.

Water Productivity of Maize With the same the amount of irrigation water used for the three designs, WP maize followed the same trend in water productivity where the maximum value of WP maize was found under the innovative design.

6 Recommendations

Limitation of water sources is one of the most critical challenges facing Egypt and arid regions. Examples of engineering techniques that have increased crop yields and water productivity values in arid regions and sandy soils include: (1) laser land leveling, (2) pulse irrigation, and (3) innovative drip irrigation system design.

The highest significant values of wheat yield and water productivity were achieved by preparing the soil surface with the laser land leveling technique instead of the conventional method. The laser technique can be applied to all intensive crops.

The potato yield increased by increasing the number of pulses, especially at 100 and 75% WR. The increase in PY is due to the increase in the available nutrients in the root zone. However, avoid using pulse irrigation with a small amount of water (50% WR) because negative effects were experienced with a small volume of irrigation water and longer time-off periods. A small volume of irrigation water with many pulses with an increase in the time-off periods will concentrate the salts in the soil around the plant roots.

The maximum maize yield occurred with the innovative drip irrigation design.

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Mega Agricultural Projects in Egypt

Dia El Din El Quosy

Abstract The ancient Egyptian drawings in their temples indicate that the River Nile was used for transportation and inland navigation, for the raising of fish and livestock, and for the production of grain and other food commodities through agriculture. The central power of the state at that time was mainly concentrated in the hands of the Pharaoh or the king who was the donor of the land, the facilitator of optimum production, and the recipient of part or all the crops harvested from the land. The story of Prophet Joseph and the ruler of Egypt which was narrated in almost all holy books shows that Egypt was the place from which all surrounding countries obtain their stocks of grain and other food commodities (legumes, beans, lentils, onions, garlic, etc.).

Egypt, therefore, is not only the gift of the River Nile, but the country is also devoted, since the early days of history for the production of food and fiber, and the Egyptians are all born with their feet in the mud, i.e., they are all born with farming skills.

Throughout history, Egypt changed several times from small-scale farming to medium-sized farms and eventually to mega agricultural projects.

This chapter follows the rout of agricultural development in Egypt during the last 200 years until the present time; the mega projects will have more emphasis especially those established during the last 20–30 years.

Keywords Climate, Crop management, Economics, Farmers, Integrated, Soil management, Water management

Contents

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1 Introduction

The size of land ownership in Egypt was always subject to the political situation in the country. The first ruler of Egypt after the evacuation of the French occupation (1798–1802), Mohamed Ali Pasha, handed over millions of feddans (1 feddan = 0.42 ha) to the head of mighty families all over the country. It was free of charge to get their political support on one hand and to get their support in implementing his national development agenda represented by the construction of the Summer Canals and the Delta Barrages on the other hand.

Cropped land during the rule of Mohamed Ali (1805–1845) increased from 2.5 million feddans at an intensity of less than 100% (less than one crop per year) to 5.0 million feddans at a cropping intensity of more than 150% (more than 1.5 and less than 2 crops per year).

Obviously, Mohamed Ali allocated the best parcels of land to the royal family. His successors followed the steps of their father and grandfather.

Khedewi Ismail, the grandson of Mohamed Ali and the ruler during the period 1855–1870, was behind the successful excavation of the Suez Canal and was also behind the successful excavation of Ibrahimia Canal (in the name of his father, Ibrahim Pasha). Ibrahimia Canal is fed from the Nile close to the city of Assiut (400 km south of Cairo) and was designed to serve 600,000 feddans of sugarcane 60 km north of the offtake on the boundary between Assiut and Minya provinces.

The ownership, therefore, during the age of the Alawy Monarchy (1805–1952) was mainly with the royal family and large capitalists.

The July Revolution (23 July 1952) put the Agricultural Reform Law under application. The law confiscated the ownership of everybody in the country except 300 feddans as a maximum for a family and no more than 100 feddans for an individual. The confiscated land was divided into 5 feddans (about 2 ha) parcels and distributed among landless farmers. The philosophy of Mohamed Ali is if the land is priced, the landholder will not be able to develop it due to a shortage of funding. Therefore, the landholder was given specified period, to spend on the fallow land and bring it fast to commercial cultivation.

The law stated that to stop any further split of this small ownership, this land should not be divided anymore. However, since heritage of belongings is explained in the holy books, this act of the law was not implemented, and the ownership kept fragmenting until it reached few square meters in some cases at present.

After 50 years of the July 1952 revolution, the country realized that land fragmentation was an appropriate social policy because it promoted the social grade of the landless farmers to landlords; however, the policy was not proper because it brought the production of the land to an unexpected level of degradation.

Following the construction of the High Aswan Dam, preparation of land reclamation schemes was at full swing. The debate on how this newly reclaimed land is going to be allocated was raised. The conclusion was that landless farmer should have a bite of the cake of 2.5 feddans. High school and university graduates were given larger parcels of 5–10 feddans. Small investors were given 20 feddans, while large investors were given 100 feddans. On the other hand, cooperatives were given up to 1,000 feddans, and agricultural companies were given 1,000 to 5,000 feddans.

However, only in very few cases, more than 500 feddans were allocated to an individual or to an entity.

In the 1980s, President Sadat adopted the principle of "Land for the Reclaimer" which meant that whoever reclaims a piece of desert land, he will be the owner and the state will give him the title over this land. A large number of investors rushed into the business of land reclamation particularly on groundwater aquifers, and the situation in some locations became out of the authorities to control especially when these investors or some of them changed agricultural development into tourism or housing enterprise.

Eventually, the state realized that small-scale farming is not the right solution to the country's food production and food security. Gigantic projects of huge size could attract large investors, bring about hi-tech, train young engineers and technicians, and employ people especially in the locations where unemployment is high.

2 The 1997–2017 Plan

In the year 1997, the Prime Minister, Dr. Kamal El Ganzoury, announced four plans 5 years each covering the period from 1997 to 2017. In this plan, a number of regional projects were introduced including the Cairo Metro, East Port Said, South the Gulf of Suez, and the South Valley and Al Salam Canal Agricultural Projects.

One of the most essential components of the 1997–2017 plan was the horizontal expansion in an area of 3.4 million feddans. Part of the area is served by Nile water; the other is served by deep, nonrenewable fossil groundwater (see Fig. 1) [1].

This was the first time Egypt used the terminology of gigantic, giant, or mega agricultural projects. The reasons for the deviation from small-scale farming on the microlevel to ultra-mega projects were:

1. To avoid the inefficient management of water, soil, and crops on the microscale
2. To attract big international investors capable of implementing integrated development represented by numerous activities (farming, agro-industry, mining, tourism, communication, roads network and transportation, energy, etc.) but each activity is complementing the others in the meantime
3. The transfer of high technology that will be utilized by the influential investors

Fig. 1 Horizontal expansion plan in an area of 3.4 million feddans up to the year 2017 [1]. Green: projects completed up to October 1998 (360,000 feddan). Red: projects under implementation (1.9 million feddan). Yellow: projects to be implemented up to 2017 (1.3 million feddan)

4. To employ as many as possible of skilled and non-skilled labor
5. To use the most critical two resources of the country, land and water, in the most efficient manner
6. To secure the less inhabited quarters of the country on the east, west, and southern boundaries against possible smuggling (of weapons, drugs, and people)
7. To reduce the extremely high population density locations and slumps, redistribute population, and create a new demographic map for the country

The 1997–2017 plan was so ambitious and caused a big row over the possibility of its application. Indeed the economic situation of the country at the beginning of the millennium was at its highest level which gave the impression that the plans can be implemented only to catch up with the fast-growing population which was at the 2.1% level at that time.

The major agricultural projects of the 1997–2017 are shown in Table 1 [2]. The plan will be discussed in the following section showing the merits and limitation of each project.

Table 1 Details of the 1997–2017 horizontal expansion plan [2]

Water source	Area served (million feddans)	Location
• Surface water and reuse of agricultural drainage water	1.2 0.5 0.55 0.05	Remaining to be reclaimed Sheikh Zayed Canal South Egypt West Delta
• Groundwater in the desert and Sinai	2.3 0.5 0.1	Western oases, east of Owainat and Darb El-Arbeen Sinai
• Sewage water in greater Cairo and Alexandria	0.6 0.2 0.05	Greater Cairo, in the areas lying between Ismailia and Suez desert roads and the areas right and left Cairo-Alex desert road till the southern boundaries of Sadat City
• Water available after termination of Jonglei Canal Project	0.25 0.25	Middle Sinai

3 The South Valley Development Project (SVDP)

The SVDP was mainly initiated in the upper part of the Nile Valley where development is generally far behind the Nile Delta area. The per capita share of land is less than the Delta, and due to harsh climatic conditions, crop yields are also lower. Poverty levels are apparently more in the south than those in the north.

The idea behind SVDP was to almost double the area of cultivated land by increasing this area from the existing level of 2.5 million feddans (about 1 million ha) to be 4.5 million feddans. The additional 2 million feddans were supposed to be from the following spots:

- The wadis east and west of the River Nile in the distance between Aswan and Qena governorates, namely, Wadi Al Sa'yda, Al Nokra, Al Lakita, Al Kobbania, and Wadi Kom-ombo; all the wadis area is about 500,000 feddans to be irrigated directly from the River Nile.
- East Owainat, Darb El Arbien, and the West Desert Oasis (Baris, Kharga, Dakhla, Farafra, Baharia, and Siwa); the total area to be irrigated is again about 500,000 feddans served by groundwater abstracted from deep nonrenewable aquifers in the west desert depressions.
- Toshka project designed to irrigate 540,000 feddans from a large size pumping station constructed on the western side of Lake Nasser, 220 km south of Aswan High Dam, close to the historic city of Abu-Simbel.

Unfortunately, the three parts of the project were not completed due to the following reasons:

1. The high cost of land reclamation under extremely high variable soil characteristics conditions

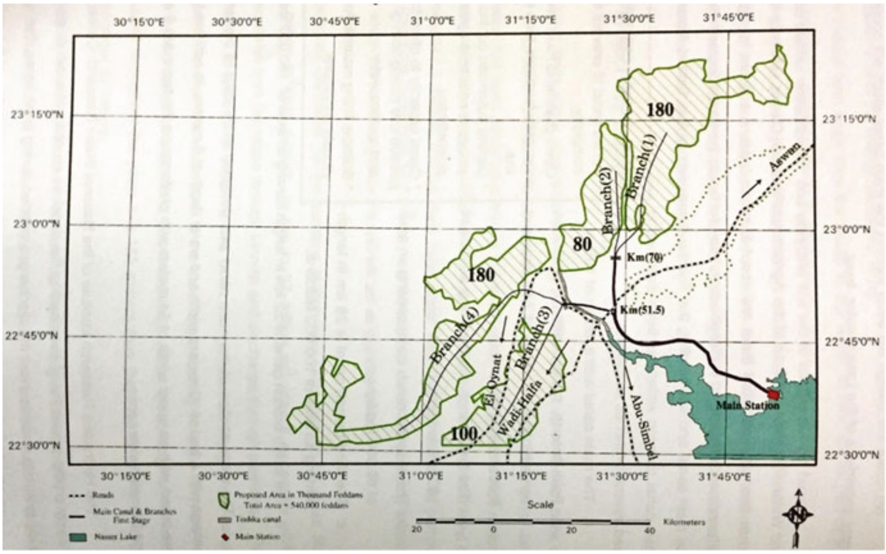

Fig. 2 Central layout of Sheikh Zayed Canal of South Valley Development projects [3]

2. The harsh weather conditions with hot spells exceeding 50°C in summer
3. The movement of sand dunes and sand and dust storms
4. The high crop water requirements
5. The large area of land allocated to private investors (100,000 feddans in Toshka project)
6. The long distance between the projects and the nearest markets and the high cost of safe transportation of crops through cool trucks or by air
7. The worldwide recession which hit most of the surrounding countries

Generally, the mega projects exercise was not as successful as it was anticipated.

Figure 2 shows the location map of the SVDPs [3], and Fig. 3 shows details of Toshka project served by Sheikh Zayed Canal [2].

4 Al Salam Canal Development Project (SCDP)

The idea behind Al Salam Canal project is not as new as the Toshka project. It goes back to the late 1970s when it was suggested to have a large reclamation project in the Eastern Delta and Sinai Peninsula. It was planned to irrigate them partly by drainage water from Bahr Hadous and Lower Serw drains and partly by the freshwater remaining in Damietta Branch immediately before it meets with the Mediterranean close to the city of Farskour. The freshwater is diverted upstream of Farskour Head Regulator located near the end of Damietta Branch.

Fig. 3 Details of Toshka project and Sheikh Zayed Canal [2]

The amount of water to be mixed is almost 4 billion m^3/year, divided equally between the two sources (drainage and freshwater) at a mixing ratio 1:1. This amount of water was at the time of project design suitable for irrigation at a salinity of no more than 1,000 mg/L (ppm) and sufficient to irrigate about 620,000 feddans at a water duty of almost 6,000 m^3/feddan/year. This amount is enough to meet the evaporative demand plus the leaching requirements in the area.

The project area is divided into two parts:

1. 220,000 feddans west of Suez Canal concentrated in South Salhia, South Port Said, and Bahr El Baqar area.

2. 400,000 feddans on the coastal plain of Sinai Peninsula divided into five parts, namely, Tina Plateau, southeast Qattara, Rabaa, Beer El Abd, and El Sir and Al Qwarir Plateau.

Development of the land west of the Suez Canal was carried out at a reasonable rate despite the effort of leaching the high salt content and planting the suitable crops under these abnormal environmental conditions. However, work in Sinai Peninsula was not as easy. The main reason was the late arrival of irrigation water which was transported from the east through a huge five meter diameter syphon constructed under the bed of the Suez Canal. This project was completed late in the 1990s.

The Tina Plateau of an area of 65,000 feddans contains highly saline heavy clay underlain by a very shallow extremely salty groundwater table. Almost all the attempts to bring this type of soil to commercial cultivation failed. It was, therefore, reasonable to think about the conversion of this plot from agri- to aquaculture. This matter is still debatable.

The Sir and Qwarir Plateau of about 135,000 feddans area required the lifting of water at the end of the feeding canal for about 150 m. This was considered to be an uneconomic lifting head. Eventually, this part was taken out from the irrigated area.

The actual reason behind the elimination of the last portion (El Sir and Al Qwarir) was also because the discharge of drainage water from Bahr Hadous and the Lower Serw drains decreased with time due to the massive withdrawal of farmers from both drains before their end points. Again, due to the high-demand upstream, the flow in the Damietta Branch became less. Therefore, the elimination of the last part of the area was the right decision at the right time.

The remaining three plots of the project were more or less completed concerning their infrastructure. However, some social and security reasons caused the long delay of the project which is still underdeveloped until the present time. Figure 4 shows the layout of Al Salam Canal Development Project [1].

5 West Delta Irrigation Improvement Project (WDIIP)

The WDIIP was planned to serve three primary objectives:

1. To convert 255,000 feddans from groundwater to Nile water irrigation. This area was served by groundwater recharged from the Rosetta Branch and its tributaries. This recharge was only sufficient for the irrigation of 70,000 feddans. However, the uncontrolled expansion brought the area to 255,000 feddans.

   Obviously, over-pumping of the aquifer caused severe drawdown and salination of the groundwater which put the whole area with all the capital investment in billions of Egyptian pounds under high pressure. At this point, the Government of Egypt sought the assistance of the World Bank and started looking at alternative supply from the Rayah Nasseri which is a tributary of the Rosetta Branch.

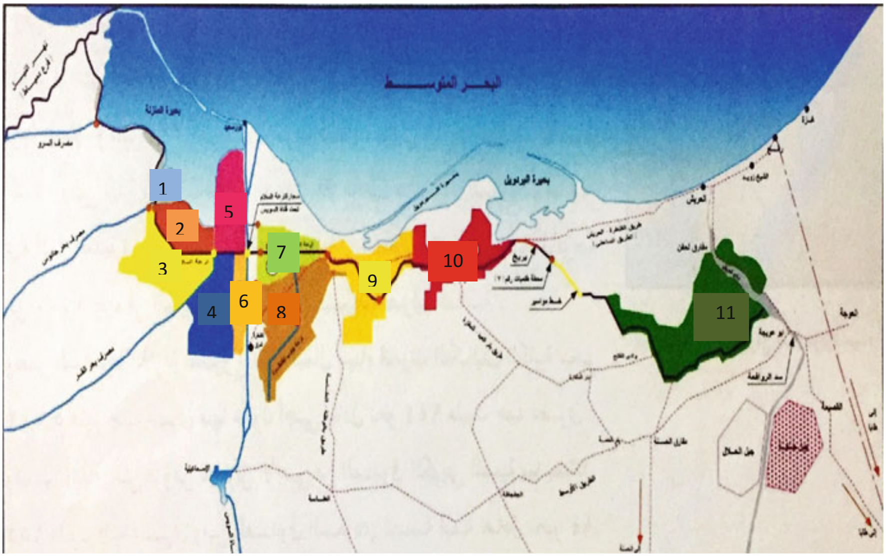

Fig. 4 Al Salam Canal Development Project [1]. 1. Atawy and Mataria (13,000 feddans), 2. North Husienya (30,000 feddans), 3. South Husienya (64,000 feddans), 4. South Port Said (47,000 feddans), 5. South Port Said Plateau (45,000 feddans), 6. Om El Reesh (31,000 feddans) [total (west of Suez Canal) = 220,000 feddans], 7. Tina Plateau (50,000 feddans), 8. Southeast Kantara (75,000 feddans), 9. Raba (70,000 feddans), 10. Beer El Abd (70,000 feddans), 11. Sin and Qwareer (135,000 feddans) [total (east of Suez Canal) = 600,000 feddans]

2. To reclaim an additional area of 100,000–200,000 feddans in the Wadi El Natrun Region.
3. To improve the irrigation in an area of 700,000 feddans further north by the provision of an extra supply of Nile water to compensate for part of the pressure caused by short water supply especially during high water requirement demand periods.

   Unfortunately, this vital project was not implemented due to administrative and logistic affairs, and the area is still suffering tremendous losses to the extent that some users started desalinating their irrigation water. Figure 5 shows the preliminary plan of the West Delta Development Project [1].

It should be noted here that the 1997–2017 plan was mainly focusing on areas outside the boundary of the Nile Valley and Delta. This is because the existing capacity of the River Nile and its major branches cannot actually bear any extra areas that need irrigation. Therefore, the development of more lands on the fringes of the Valley and the Delta became impossible.

In other words, the country has to change at this moment from the development by creeping east and west of the River Nile to what is so-called frog development, i.e., by jumping out of the Valley and Delta Systems to the Western Desert (SVDP) and to Sinai Peninsula (SCDP).

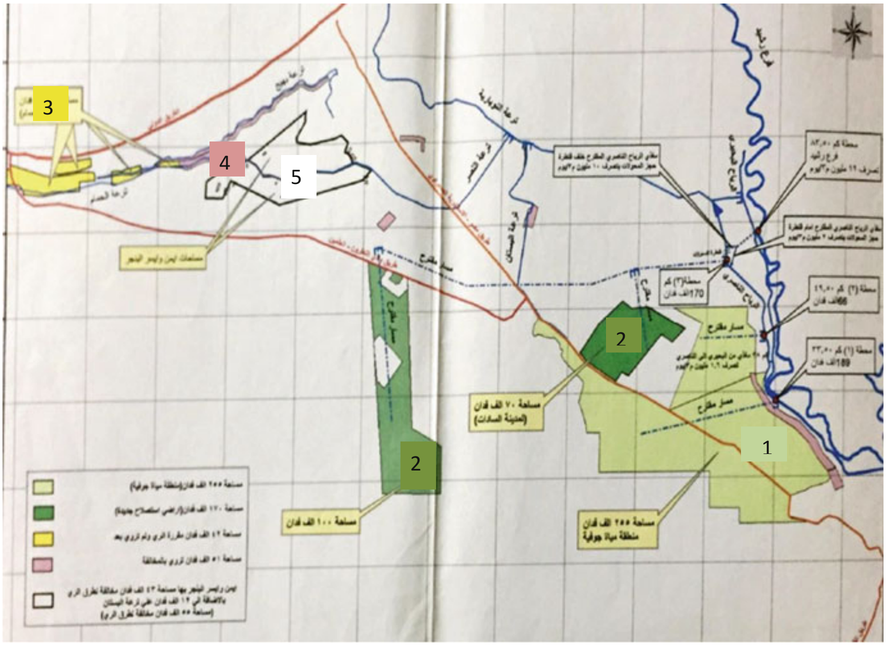

Fig. 5 West Delta Development Project [1]. 1. Groundwater irrigation (255,000 feddans), 2. new reclamation area (170,000 feddans), 3. new reclamation area (42,000 feddans), 4. encroachment area (51,000 feddans), 5. sugar beets area (55,000 feddans)

Moreover, following the exhaust of almost all the Nile water resources, deep and nonrenewable groundwater was targeted in the Western Desert, while renewable groundwater has to be supplemented by Nile water in the WDIIP to bring 255,000 feddans back to economic production.

6 The 4 Million Feddans Development Project

Following two successive revolutions in no more than 3 years, Egypt realized that time is running faster than the rocketing population growth which increased the number of Egyptians from almost 60 million at the beginning of the millennium to more than 104 million at the end of 2017. This number is expected to go up 130 million by 2030 and to 150 million by 2050.

However, the lessons learned from the 1997–2017 plans were well comprehended by the post-revolution planners.

The theme of the 4 million feddan project was to optimize the socioeconomic return, to minimize the environmental impacts, and to make sure that development is sustainable. The project was divided into three phases: (1) phase I in an area of 1,018 million feddan, (2) phase II in an area of 942,000 feddan, and (3) phase III in an area of 2,060 million feddan.

Details of phase (I) are as follows:

- Leftover areas in Toshka Project are 108,000 feddans to be irrigated as other areas in the project from Nile water.
- An area of 30,000 feddans in Toshka project located along Sheikh Zayed Canal (the main canal feeding the project downstream the project main pumping station); this area will be irrigated by groundwater.
- South and southeast Qattara Depression to be irrigated by groundwater; the area is 100,000 feddans.
- New and old Farafra 300,000 feddans – groundwater irrigation.
- Extension of Dakhla Oasis 50,000 feddans – groundwater irrigation.
- North of Siwa Oasis 30,000 feddans – groundwater irrigation.
- West – West El Minya 200,000 feddans – groundwater irrigation.
- Extension of East Owainat 50,000 feddans – groundwater irrigation.
- Al Moghra 150,000 feddans – groundwater irrigation.

The total area in phase I is 1,018 million feddans. The project is facing many challenges. Some of these challenges are as follows:

- Most of the project area is dependent on deep, nonrenewable groundwater. Deep wells are very costly to dig, large head pumps are expensive, the cost of energy to operate the pumps is high, and after all if the water is not used rationally, the water table will go deeper, and the water quality may deteriorate.
- Climate change may cause a temperature increase, high consumption for domestic purposes, and high water requirements for crops. This will speed up to the process of pumping vulnerable groundwater reserves.
- In some of the groundwater aquifers, groundwater is brackish (West-West El Minya). In others, water is saline (Al Moghra). These two locations from almost one-third of the total (200,000 feddans in El Minya and 150,000 feddans in Al Moghra aquifer).
- The high cost of water exploitation; the increase of abstraction with time reduces the expected economic return.
- Availability of conventional energy sources in the area is very slim, and, therefore, the generation of highly expensive solar or wind energy may be the only solution.
- The infrastructure needed for the development of new communities in the project area does not exist, and therefore the project has to cover the cost of roads, factories, ports, ziloses, housing, public buildings, schools, hospitals and clinics, etc.
- Sustainability under the prevailing circumstances of the high cost of water abstraction and high expenses of agricultural activities cannot be guaranteed.
- In the case of establishment of new inhabited communities and the buildup of a number of individuals and families, the situation in the case of sudden or gradual water shortage would be disastrous by all means.

- Groundwater in these nonrenewable aquifers should be kept as a strategic reserve for coming generations, especially with the existing hazard of reduced supply from the River Nile due to the actions taken by some upstream countries.
- From the institutional perspective, the large number of ministries, organization, and institution involved could create unforeseen problems and difficulties.
- The existing laws and regulations cannot be applied to the condition of the establishment of new communities in desert areas. Special logistics should be formed to apply under these conditions.
- The project was not introduced in the appropriate standard shape with a definite time schedule.

The above challenges caused the project to be faced with intense debates questioning its ability to achieve the targets and goals of spending large sums of capital investment with no clear vision on how the outcome will be.

7 Concluding Remarks

As Egypt is looked as one of the countries that are suitable for small and even minute industries, the country is again suitable for small-scale farming. Large-scale farms were not accepted socially due to the vast gap between extremely large landlords and impoverished majority of small-scale farmers. Attempts to attract capital investment (local or foreign) appear to be not very much satisfied. The main reason for that is the fact that agricultural enterprise is a long-term, modest return business. In the meantime, 50% of the population of Egypt is connected in one way or the other to agriculture. They have to have jobs available or to sit unemployed.

Mega agricultural projects have not yet proved to be successful. Maybe in the coming days will the application of Hi-tech be proved otherwise.

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Role of the Participatory Management in Improvement of Water Use in Agriculture

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Abstract Engagement of the stakeholders, fairness, and transparency are among the basic rules of the governance. Egypt started in 1986 to develop its irrigation systems via the so-called irrigation development project to apply the governance rules on the level of small irrigation called mesqa and on the level of branch canal too. To engage all stakeholders in the irrigation and agriculture system in Egypt, several water user associations were developed, and the farmers were trained. Demonstration irrigation canals owning to WUAs is being used to apply the activities of on-farm water management to demonstrate the benefits of good agriculture practices (GAP) to them. The final aim is to apply the best irrigation and agricultural practices to improve the productivity, incomes, and livelihood of WUAs that accomplished as a result of participatory management which increases agricultural production, water saving, and water productivity that reflects on national domestic production improvement performance. Different important aspects including legal status of water user associations on the branch canal, operation and maintenance of the sub-branch in partnership with water user associations, organizing (roles, responsibilities, and authorities) of water user associations to the branch canal, and training/technology transfer/communications and financial aspects are considered while applying the participatory irrigation management system. This participatory management model as an active cooperation between citizens and the governmental department is better achieved with close engagement of various agencies of Ministry of Water Resources and Irrigation (MWRI) and Ministry of Agriculture and Land

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Reclamation (MALR) with the farmers. This chapter presents the success story of the participatory management system which was achieved through the implements of the irrigation development project and beyond.

Keywords Adoption technologies, Farmers, On-farm water management, Participatory management, Water user associations

Contents

1 Introduction

1.1 Brief Overview of Irrigation Water Supply System

The Egyptian irrigation system is one of the oldest systems, if not the oldest, in the world. Good cooperation between the farmers and the concerned authorities is always present. The Ministry of Water Resources and Irrigation (MWRI) is the primary governmental agency which is responsible for water resources management in Egypt. Therefore, it is mandated to plan, construct, operate, manage, and maintain the irrigation and drainage network in Egypt. The MWRI distributes irrigation water to Egypt's "old lands" by diverting water at various points on the Nile River to principal canals, which, in turn, feed a complex network of main canals. Most of the irrigation main system operates based on gravitational flow. Water is supplied below the surrounding farm ground level, which means that farmers must use pumping devices to lift water from the watercourse supplying their farms. Exceptions include the Fayoum Oasis and some canal commands in Upper Egypt, where delivery farm turnouts are by gravity flow [1].

1.2 Background of Private Water User Associations

Several historical precedents plus impacts of the Egyptian Water Use Management Project (EWUP) limited WUA experiments under the Regional Irrigation Improvement Project in 1986 to 1988, and lessons learned since 1989 provide background for the present WUA program in Egypt.

The historical context of informal water user group in Egypt provides some potential for building strong formal private water user associations. MWRI provide a number of established principles and concepts which have been used in initiating the first formal private WUAs in Egypt. For example, the traditional "sakia rings" or water lift systems from belowground level mesqas have been privately owned and operated in formal organizations for many years. They used the principle of allocating water to land and shared costs of the said maintenance and repairs. Rapid mechanization has resulted in many of these principles being transferred to the popular diesel power mobile pumping units. By law, mesqas (irrigation canals) are private property, and water users are responsible for their operations and maintenance [2].

Another historical precedent is found in the Fayoum Governorate where water is delivered to farmer's fields from gravity mesqas. The mesqa organizational unit is known as "Ra' is El Munawaba system." This informal system has a "Mowwaz El Fatha" who is chief or leader of the local organization which allocates water to land based on minutes per feddan. The leader draws up the list of water users, their responsibilities related to the scheduling of turns, and other operational and maintenance tasks and issues and sanctions and collects fees and fines. He also arbitrates conflicts which may arise and works with the heads of smaller units known as "tarafs" for mesqa cleaning and maintenance. The well-known "Haq El Arab" or "right of the Arabs" concept used in decision-making and conflict resolution though weakened through the years still operates in some degree in all canal command in Egypt [3]. This and the "Munawaba system" are being tested under the irrigation management project (IIP) on one large demonstration mesqa at Bahr El-Gharaq Canal Command in Fayoum Governorate where a new IIP established buried pipeline system with over 40 alfalfa valves being tested.

1.3 Brief Background of WUA Formation and Development Initiatives in Egypt

In 1981, MWRI initiated the Irrigation Management Systems Project (IMS) with USAID funding. The IMS project was amended in 1984 to take advantage of the 7-year Egyptian Water Use Management Project (EWUP) [4], an interdisciplinary project implemented by MWRI.

The regulations (instructions) to farmer participation in irrigation management include:

(a) Farmers should be involved in improvement to the water delivery system.
(b) Farmers should play a role in ensuring more efficient operation, improved maintenance, and protection of physical works.
(c) Farmers should become involved in the management of water.
(d) There is a need for a well-trained cadre of Irrigation Advisory Service (IAS) professionals to provide farmers with services related to water delivery and water use and effectively organize mesqa-level (irrigation canal) WUAs.
(e) Continued farmers' involvement is essential for improved operation, water scheduling, mesqa improvements, and renovations of branch canals.

2 Sustainable Private Water User Associations

There are a number of internal factors impacting irrigated agriculture directly which include a radical restructuring of agriculture creating free market prices, deregulation and the removal of large government subsidies, and controls and efforts to lessen the dependence on imports of food. Some of the internal factors impacting irrigation directly are the following:

1. Increased water requirements of agriculture
2. Industry and urban areas with expected water shortages
3. Water users' demands for improved water control
4. Reliability inadequate: land reclamation
5. Drainage system improvements
6. Groundwater development
7. Recycling of water and the working out of a strategy to improve irrigation system performance into the next century [5]

2.1 Major Roles of WUAs

Private WUAs are defined as "organization owned, controlled and managed by members for their benefits in achieving increased water control for increased production possibilities through improved irrigation system performance."

The WUAs have specific tasks to perform after they have organized. It is important that water users build up their own skills and capabilities for fulfilling various tasks [6]. The IAS role is to facilitate WUAs, providing training and special services aimed at making them capable, self-sufficient, and sustainable. The IAS does not do the work for WUAs; they are to support them in ways that make them independent [7]. Major WUA tasks after organization and election of their officers include:

(a) Participating actively in planning, designing, implementing, and accepting of improved mesqa systems after an investigation walk-through

(b) Operating, maintaining, and managing the mesqa and branch canal of WUAs
(c) Developing and implementing operational plans for irrigation scheduling, purchasing, operating, and maintaining WUA pumps and implementing regular mesqa maintenance
(d) Improving mesqa water delivery and decreasing return flow and drainage problems on mesqas and drains and improving water use management through improved irrigation scheduling and other useful irrigation practices
(e) Developing roles and responsibilities of mesqa and branch canal WUA council members and rules required for the WUA and local rules for resolving complex water-related conflicts
(f) Developing and maintaining close coordination and good working relationships with organizations for essential services such as banks, equipment firms, public and private laser and leveling firms, local village councils and their leaders, and the agricultural extension service

In addition to the above, the following are essential [8]:

(a) Building and maintaining good relationships with influential local political educational and religious leaders
(b) Developing and maintaining good two-way communications with WUA members
(c) Participating organizations (irrigation departments) and other organizations related to irrigated agricultural improvement
(d) Developing a formal functional linkage with the irrigation departments through branch canal federations, special demonstrations, training programs, seminars, and workshops
(e) Mobilizing and managing finances for pumps, equipment, and mesqa maintenance
(f) Federation of WUAs to the branch canal level and functional linkages with the irrigation departments in improving system performance through maintaining continuous flow that improved operations, maintenance, and projection of canal facilities [9, 10].

The present initiatives of WUAs developing their own contracts for the pump and mesqa repairs; building or improving pump houses, mesqas, or other structures; mobilizing funds; cooperating with other mesqas; etc. will continue. As WUAs become more mature, it is expected they will take more significant role in a number of activities which will be identified in the future.

2.1.1 Performance Criteria for WUA-Managed Technology

The performance criteria which serve as guides and standards for IAS and the WUAs are essential for building sustainability. These are built into the irrigation improvement areas and the IAS monitoring programs which provide documentation for revising and improving the program of WUA organizational development [11]. They are as follows:

Reliability How timely, adequate, and predictable are water supplies? Variables to measure: continuous flow in canals and mesqa water deliveries.

Equity How fair are the allocation and distribution of water throughout the branch canal and mesqas? Variables to measure: water delivery at head and tail reaches of branch canals and delivery efficiencies at mesqa head and tail reaches.

Productivity What is happening over time to crop yields, cropping intensities, and crop quality? Variables to measure: mesqa cropping patterns and crop yields.

Financial Viability How cost-effective is the new mesqas in terms of labor savings, and saving of money is costs of pumping and maintenance? Does the WUA have a financial plan, and are they collecting adequate funds for O&M plus a reserve fund for major repairs and pump placement? Are the accounts available for WUA members to examine at any time? Variables to measure: saving, fee collection, balances in the WUA bank account, and WUA openness to records.

Manageability How well is the WUA in managing its affairs in relation to irrigation scheduling and handling major issues? Variables to measure: adequacy of irrigation scheduling and conflicts which WUA cannot manage or resolve and special initiatives WUAs take in solving such problems as damages to pipelines, raised lined mesqas, alfalfa valves, gates and business agreements with local firms, etc.

Physical Sustainability How well are the structures and technology kept in favorable operating conditions over time to assure that the system is functional enough to meet operational objectives? Variables to measure: maintenance of gates, mesqas, and pumps using a rating scale.

Organizational Sustainability Are continuous flow and the WUA organization sustainable over time? Variables to measure: continuous flow levels over time, specific benefits to water users, ability to resolve WUA problems, balances in WUA reserve funds, and the degree to which WUAs are taking their own initiatives in doing things not planned by the IAS [8–10].

Environmental Impacts What are the impacts of the WUA-managed and WUA-operated mesqa on the physical environment? Variables to measure: closure of old mesqas, changes in water flow going to drains, salinity, and other water quality measures [11, 12]. Particular attention to be given to improved branch canals and mesqas which run through populated or settled areas.

Reliability How widely are the new technology and its management being disseminated on the canal command? Has the technology been accepted and implemented by any private farmers of the area who are not in the improvement areas? Variables to measure: dissemination of fully operational mesqa technology over a specified period and demands for the new technology or implementation in areas by private farmers outside the improvement areas using their own finances.

2.2 Secondary-Level Organizations (Federations) for Water Users

2.2.1 Roles and Responsibilities of the District Engineer in Supporting BCWUA Work

The following are among the roles and responsibilities of the district engineer to support BCWUA activities:

- Identify technical problems, and propose solutions to BCWUA Executive Council.
- Provide the Executive Council with technical data required for sound decision-making.
- Assist Executive Council members in setting the Annual Work Plan.
- In the event of varying opinions on technical matters on the branch canal, the view of the district engineer will predominate.

2.2.2 Roles and Responsibilities of the Irrigation Advisory Service in Supporting BCWUA Work (IAS Engineers)

The following are among the roles and responsibilities of the irrigation advisory to support BCWUA activities:

- Coordinate the organizing process and establishment of BCWUAs.
- Increase farmer awareness about BCWUAs.
- Develop awareness among Executive Council members as to BCWUA roles and responsibilities, and provide necessary technical consultation.
- Provide orientation and training to Executive Council members and branch canal manager.
- Participate in BCWUA meetings.
- Regularly collect data on BCWUA performance and problems, evaluating activities. Report problem issues to MWRI Irrigation authorities.
- Assist the BCWUAs in organizing mesqa-level WUAs (in non-improved areas), as well as the technical package of improvements.
- Assist the BCWUA, and mesqa-level WUAs prepare for the mesqa improvements.
- Coordinate with MWRI Water Communication Unit to develop awareness of building programs among farmers and field staff (prepare fliers, news bulletins, posters, publications, etc.).

- Coordinate with Agriculture Extension Service and other related agencies in the Ministry of Agriculture to strengthen BCWUAs and WUAs.
- Facilitate the establishment of communication linkages between BCWUA and different ministerial agencies.

2.2.3 Role of the MWRI Action Team in BCWUA Program Development

The following are among the roles and responsibilities of the MWRI action team to support BCWUA program development:

- Follow up work on the formation of the BCWUAs.
- Monitor the Annual Work Plan activities of the BCWUA.
- Hold regular monthly meetings.
- Keep MWRI and other agencies apprised of plans for establishing new BCWUAs, and prepare reports accordingly.
- Help in the establishment of an IAS information database on WUAs.
- Meet with BCWUA Executive Council members, as needed.
- Assist IAS in setting up a BCWUA monitoring and evaluation plan.
- Advise the MWRI in drafting the legal amendments to institutionalize BCWUAs formally.
- Help MWRI identify local and international sources of financial and technical assistance to support the BCWUA concept.
- Advise MWRI in the preparation of a training plan for MWRI staff and BCWUA leaders.
- Advise and assist MWRI agencies in conducting workshops and seminars on BCWUA activities and programs.
- Advise MWRI in expansion plan for BCWUA programming.

3 Key Organizations and Stockholders

The following are the type of organizations and stockholders involved in building and maintaining successful private WUAs. The primary stockholders in establishing successful WUAs are water users and ministry of irrigation and water resources. Other key actors include the following:

(a) Mesqa and branch canal construction firms with an emphasis on private firms
(b) Private and MALR precision land leveling organizations
(c) Private and public firms for clearing and maintaining branch canals
(d) Private firms dealing with pump sets and their maintenance
(e) Agricultural cooperatives and credit banks
(f) Agricultural extension service of the MALR
(g) Local village councils

(h) Irrigation department of MWRI
(i) Drainage Authority of National Water Research Center, MWRI

In addition to these above key organizations, there are a number of other organizations as well as influential leaders and the leaders of political as well as nongovernmental organizations located in the improvement areas. WUAs as private organizations can initiate new activities with any organization if it decides to do. There is a need to involve all organizations and leaders in communication and other programs. In some areas, IAS staff has made a significant impact in local schools and other organizations where they have participated in activities to promote the irrigation improvement areas and WUAs. The IAS will continue to improve its linkages with all organizations in the area whether they are major or minor stockholders. Now and in the years ahead, there will be many more volunteer organizations in rural areas and private firms with which it will be essential to establish and maintain good linkages [12].

4 Guidelines for Removing the Existing Constraints and for Improving Irrigation Extension and Advisory Services in the Country

4.1 The Challenge: Ensuring Adequate Water Supply

This requires further development of Egypt's Water Management Organization, to achieve fully integrated management of water resources. The government of Egypt expressed its commitment to the development of not only integrated water management but also to the more intensive participation of the end users (i.e., the farmers) in water management [13].

Concerning scarce water resources and growing demand, any policy development and implementation should consider the following principles, guidelines, and warnings:

- Achieve an optimum integration among different sources and types of water for the different fields of water use.
- Maximize the economic return per unit of water, without causing negative environmental side effects.
- Develop the legal and administrative framework and its implementing rules and regulations, which have to be rooted in the historical and social-cultural environment.
- Promote the active participation of the water users and develop the appropriate mechanisms to impart to them the critical value of water resources.
- The present overall water use efficiency of the Nile irrigation system is about 75% (including reuse of drainage water) [14]. This is one of the highest water use efficiency in the world. Unfortunately, the scope of further improvement is

limited because a sufficient fraction of Nile water has to be discharged to the sea, to evacuate natural salts and polluted domestic and industrial effluent [13].

5 The Action Program

5.1 The Role of the Ministry of Water Resources and Irrigation (MWRI)

The MWRI is responsible for the proper management of all water resources of Egypt, both concerning water quantity and quality, whether surface water or groundwater. The MWRI is the only competent body that can authorize the use of water resources and which is charged with the control of water quality. The MWRI is also responsible for the construction, operation, maintenance, and rehabilitation of the entire irrigation and drainage systems, up to the tertiary (mesqa) level, where the farmers take over the responsibility. The MWRI is organized along four main departments (Irrigation, Mechanical-Electrical, Planning, and Finance) and four authorities (Drainage, High Aswan Dam, Coastal Protection, and Survey). The MWRI's research and specific studies are done by the National Water Research Centre and its 11 specialized institutes. By law, the MWRI is charged with the ultimate water resources development, water allocation and distribution over the various categories of users, control of water quality, and supervision of all water resources. Besides the MWRI there are seven other ministries involved in water resource management. These are Agriculture and Land Reclamation, Transport and Tourism, Housing, Health, Power, and Industry. Several Inter-Ministerial Committees at various levels facilitate the coordination between the involved parties and enhance the horizontal communication and information exchange [15, 16].

5.2 The MWRI's Responsibilities Concerning the Water Sector

The MWRI's responsibilities concerning the Water Sector are categorized as follows:

- Optimization of the use of available freshwater resources. This includes the operation of Lake Nasser reservoir, the flow regulation of the River Nile, the sustainable management of groundwater reservoirs, the reuse of drainage water for irrigation, and the temporary storage of seasonal excess freshwater.
- Improvement of irrigation systems and operation. This encompasses reduction of system losses, improvement of irrigation efficiency and effectiveness, improvement of distribution equity, and rehabilitation of irrigation systems.

- Improvement of drainage conditions. This includes the application of modern technology and materials in the construction of subsurface drainage systems, construction and O&M of drainage pump stations, O&M of subsurface drains, weed control and channel maintenance of open drains, and rehabilitation of drainage systems.
- Environmental management. Specialist agencies of the MWRI are responsible for monitoring and control of water quality; assessment and mitigating adverse impacts of desert reclamation; monitoring and controlling groundwater exploitation; and monitoring and curtailing negative effects of industrial, municipal, and agricultural pollution.
- Reclamation of desert areas for agriculture. This includes planning, design, and implementation of appropriate irrigation systems for desert areas, development of sustainable groundwater utilization, and installation of drainage networks in newly reclaimed lands.
- Human resource development in the Water Sector. This includes not only the staff of the MWRI but also the water users. The training center of the MWRI and the drainage training center provide a wide variety of courses to the different staff levels within the MWRI. The Irrigation Advisory Service and the Drainage Advisory Service provide extension programs and specific training to water users groups.

6 Strengthen the Participation of the Farming Community

The following measures and activities are considered to strengthen the participation of the farming community:

- Target groups (including women's groups) recognize and accept the benefits of establishing and/or strengthening organizations that represent their interests and participate in empowering them for better on-farm soil, water, pest, and waste management.
- Target groups participate and cooperate in the identification of concerns related to the environmentally sound management of water, soil, pest, and waste. They can formulate solutions in cooperation with other entities (water user associations, irrigation advisory service, Government of Egypt ministries, voluntary groups) as required in order to optimize the management of soil, waste, pest, and water at the farm level.
- Replication of those results which have been validated and formulated with input from the farming community.
- Effective and ongoing participatory rural appraisal (PRA) by Egyptian entities.
- Mechanisms in place and functioning efficiently, giving the agricultural community access to policymakers and researchers and providing a feedback loop from policymakers and researchers to farmers, including required information on market trends and prices.

- Mechanisms allowing farmers (men and women) to have input in applied research and development proposals in areas that affect them and have that input communicated to the responsible MALR entities.
- Farmers can identify existing services and goods in the private sector and/or nongovernmental organizations and are able to contract and/or access them.
- Financing mechanisms, which will provide credit to farmers (including small farmers and women) and allow them to purchase required goods and services from private sector enterprises.

7 Develop the Capacity to Provide Advisory Services for On-Farm Water and Soil

The following measures and activities are considered to develop the capacity and provide advisory services for on-farm water and soil:

- The government of Egypt institutional capabilities and agricultural extension services training needs to be identified in relation to providing environmentally sound water, soil, waste, and pest management practices at the farm level. Given that water management is a new activity for agricultural extensionists, training programs will have been developed for on-farm water management [17]. Whereas, training programs will have been strengthened for on-farm soil, waste, and pest management.
- Training capacity of various institutions (local and other) in the area of water, soil, waste, and pest management and related topics identified and revisited on an ongoing basis.
- Course and syllabi developed and taught at selected institutions, reflecting that on-farm water management is a new discipline.
- Courses and syllabi strengthened and taught at selected institutions to supplement current on-farm soil, waste, and pest management training to include environmental and social implications, e.g., better management of agrochemical, pesticide, and waste.
- Capacity developed for non-formal training in related local nongovernmental organizations and the private sector.
- A trained cadre of subject-matter specialists (SMS) and extension agents (men and women) can provide advisory services for environmentally sound on-farm water, soil, pest, and waste management to the agricultural community within the pilot area and beyond which were relevant for replication purposes.
- Dissemination of training materials and research results to the subject-matter specialists (SMS), extensionists, and others.
- The Agriculture Research Centre and the Central Administration for the agricultural extension service can design, develop, and implement extension programs reflecting environmentally sound management of water, soil, pest, and waste management as a pilot on the project site.

- The systemic framework in place, allowing for ongoing training and placement of extension workers and SMS and follow-up and monitoring of the effectiveness of training and replication.
- Ministry of Agriculture and Land Reclamation (MALR) research institutes have developed mechanisms which transfer research results from the lab to the field.
- The government of Egypt and pertinent stakeholders formulate a replication strategy, acceptable to the target groups and with input from them, and implement validated results from the pilot site elsewhere in Egypt as soon as these become available.
- Effective and ongoing participatory rural appraisal (PRA).
- A mechanisms was established and is now functioning, allowing farmers (men and women) to identify problems and concerns on matters pertaining to water, soil, waste, and pest management, communicate them to the responsible Government of Egypt (GOE) entities, and receive feedback.
- Mechanisms established and functioning, allowing farmers to have input in applied Research and Development Proposals in areas that affect them and have that input communicated to the responsible GOE entities.
- Mechanisms strengthened and functioning, allowing GOE to efficiently communicate with farmers regarding market, policy and regulatory trends, and service and product standards.
- Information loopback mechanisms between the Government of Egypt and the agricultural community to allow for a sustainable exchange of water, soil, pest, and waste input and information.

8 Optimize On-Farm Water Management [17]

The following measures and activities are considered to optimize the on-farm water management:

- A trained cadre of SMS and extension workers and others, who were applicable for replication and provide on-farm water management advice, including training in the application of the guidelines.
- MALR capacity established to address and respond to requirements of environmentally sound water management at the farm level.
- Demonstrations and pilot studies carried out in concert with the farmers (men and women) aimed at physical improvement of marwas (irrigation canals) and generating guidelines for cropping patterns and water use.
- Guidelines and practices established with the participation of farmers on water management practices: results reflected in reports, extension, and replication materials.

- The validity of guidelines adopted by farmers (men and women).
- Guidelines applied by farmers (men and women): farmers provide feedback and guidelines to be updated accordingly, resulting in reduced water usage and improved water quality.
- Catalytic support provided to MALR with the formulation of a replication strategy which includes feedback from the farming community concerning the application of the guidelines.
- Active and ongoing participatory rural appraisal.
- Functional and sustainable linkages established between farming organizations and the irrigation services.
- Active replication of validated results beyond the pilot site.

9 Adopted Technologies and Acceptance by Farmers

The demonstration fields have been used to serve WUAs in 248,000 acres (1 feddan = 1.03784 acres, 1 acre = 0.9635 feddan, 1 acre = 4046.856 m^2, and 1 feddan = 4,200 m^2) in El-Behira and Kafr El-Sheikh Governorates. About 131,000 acres are located in El-Behira Governorate, and 117,000 acres (75,000 acres at El-Wasat and 42,000 acres at El-Manaifa) are located in Kafr El-Sheikh Governorate. The field demonstration aimed to help WUAs to follow and apply the up-to-date package of recommendations of both ministry of agriculture and land reclamation and ministry of water resources and irrigation. This package included the following items:

(a) Suitable seed-bed preparation for each crop including suitable ploughing kind and depth and laser land leveling
(b) Suitable furrow length with suitable border size for more efficient and more uniform irrigation application and distribution
(c) Suitable time of planting, suitable seed rate, and hence better plant population using the up-to-date high yielding varieties
(d) Applying suitable different fertilizers in terms of when and how much and applying suitable pest control in terms of when and how much
(e) Suitable time of crop harvesting

Applying agricultural technologies depends on effective extension activities which provide the farmers with the knowledge needed and teach them how to apply this knowledge. Extension efforts have been exerted to convince farmers that it is necessary to follow the agricultural and irrigation practices which rationalize the use of water in irrigation. Among such activities were the demonstration plots (fields), where technologies and recommended packages are applied (precision land leveling, long furrow and border, new promising crop varieties, etc.). To increase the educational effectiveness of the demonstration fields (aggregates), field and harvesting days, meeting and field visits have been implemented in the irrigation improvement areas of Kafr El-Sheikh and El-Behira Governorates by researchers and extension workers in cooperation with farmers and water user associations. Much efforts have been made to evaluate the educational effect of such demonstration fields on the irrigation improvement areas to know the following:

(a) The extent of the farmer's knowledge of the technologies used for each crop
(b) To find out the growers attitudes toward practices of water management
(c) To identify the farmer's adoption of water management practices
(d) To be aware of the farmer's reasons for using too much water in irrigation
(e) To know their suggestions for controlling the use of irrigation water [18, 19]

9.1 Adoption of Water Management Practices

Figure 1 showed adoption of low precision land leveling (43%) because Leazer units are not available and the growers need to level their fields in short time, along with smallness of farm size for the majority of farmers. Also, the findings showed low adoption of the long furrow (29%) and dry planting of berseem (11%) because these practices are considered new for growers, so it needs a long time for adoption. Also, the findings showed low adoption of drilling planting of wheat (17%), because the majority of wheat growers do prefer to plant wheat heratii (dry seed in wet soil) [19, 20].

As for grower's information sources on water management, the extension workers are the first source for the demonstration aggregates and field's growers, and local leaders in the village came in the second arrangement. Growers of the demonstration aggregates and fields came in the first source for the control field's growers. This result showed the effect of the demonstration aggregates and fields on the diffusion of new knowledge among growers.

Regarding reasons for farmers' consumption to large quantities of water in their fields concerning management, Fig. 2 showed that the reasons for using too much water in irrigation were non-precision land leveling (118 farmers or 39.6%), salt accumulation (67 farmers or 22.5%), low awareness about importance of water regime (46 farmers or 15.4%), planting crops that need too much water like rice (45 farmers or 15.1%), and on-off rotation of irrigation water (22 farmers or 7.4%).

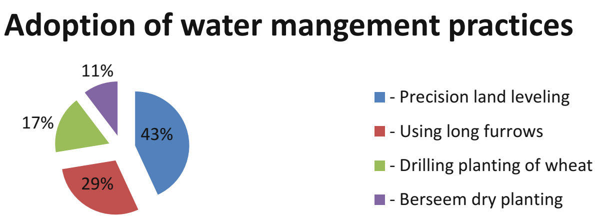


Fig. 1 Adoption of water management practices

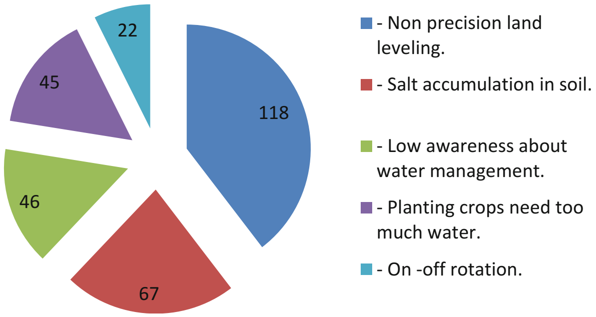


Fig. 2 Reasons of using large quantities of water in their fields by farmers

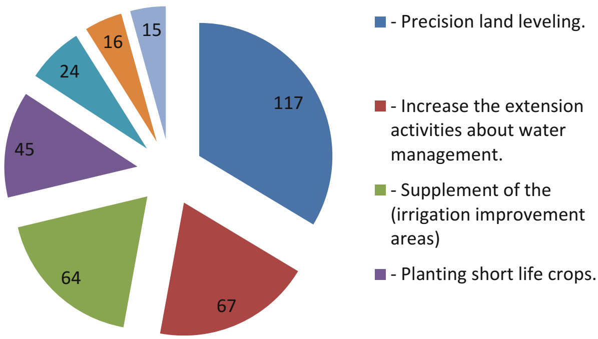
Farmers' suggestions for good water management were precision land leveling (117 farmers or 33.6%), increase in awareness of water management (67 farmers or 19.3%), a supplement of the irrigation improvement areas (64 farmers or 18.4%), planting short-lived crops (45 farmers or 12.9%), and 15.8% in other minor factors as shown in Fig. 3.

Finally, the different activities of on-farm water management component achieve its goals toward teaching the farmers new technologies and raising their awareness about good water management in their fields to obtain the highest production and increasing the water use efficiency. Furthermore, they enrich the cooperation between village extension workers (VEW) and irrigation advisory engineers (IAS) [20–22].

10 Conclusions and Recommendations

Increased user participation in planning, operation, maintenance, and management of branch canal irrigation unit was the desirable goal. The achieved results since the implementation of WUAs until now proved that the goal was achieved. The formation and establishment of water user associations at the branch canal level have proven to be a viable, highly desirable means of intensifying farmer participation in irrigation management for water use and agriculture. Management capabilities and capacities at this level have to be supported and improved as water supplies become more constrained and the innovation of continuous flow availability is advanced to larger areas of the system. Willingness on the part of users to assume part of the operation and maintenance costs, in the form of time, labor, and finances, is shown to reduce government costs in operations and maintenance and will affirm that eventual management transfer can be successful in the future. It is recommended to extend the improvement of the irrigation practice by applying the rest of the governance principles to the irrigation and agricultural management.

Fig. 3 Farmers' suggestions for good water management



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Part VIII
Quantity and Quality of Water in the Egypt's Water Resources Bank

Development of the Rating Curves for Egypt's Water Resources Bank

Mohamed Elsahabi, Abdelazim M. Negm, and Kamal A. Ali

Abstract Water resources in Lake Nasser supply Egypt with about 97% of its freshwater needs. It is the water resources bank of Egypt. Estimating the amount of water in the storage reservoirs (lakes) from time to another is essential. The most straightforward and cheapest way is the rating curves. In the present chapter, the authors used the remote sensing and GIS along with the available water levels observations for the years 1992, 2000, 2006, 2009, and 2012 and the previously developed 3D profile of the lake to develop the rating curves for Lake Nasser. Lake Nasser is the water resources bank of Egypt and it supplies Egypt with about 97% of its freshwater needs. The estimated capacities using the present approach were compared with the those measured by the Aswan High Dam Authority (AHDA) and were found accurate enough with the root mean square error values ranging between 4–5% and 2–3% for volume/level relationship and surface area/level relationship, respectively, with underestimation of 2% for the entire period from 1992 to 2012. Consequently, the developed rating curves (and equations) could be used to estimate the water volume (capacity) of Lake Nasser instead of the costly measurements. However, field measurements by AHDA and NRI are needed to update such equations.

Keywords 3D profile, GIS, Lake capacity, Lake Nasser, Rating curve, Remote sensing, Water resources

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Contents

Nomenclature

AHD	Aswan High Dam
AHDA	Aswan High Dam Authority
AHDR	Aswan High Dam Reservoir
amsl	Above mean sea level
Bm^3	Billion cubic meters
GIS	Geographic information systems
km^2	Square kilometer
MAE	Mean absolute error
Mes	Measured
NRI	Nile Research Institute
RBF	Radial basis function
RMSE	Root mean square error
RS	Remote sensing

1 Introduction

It is challenging to maintain a continuous record of reservoir capacity unless there is a simple way to estimate the capacity via the water level. Such relationship is called the rating curve. Developing the storage reservoir rating curves via the manual computationally labor-intensive methods needs an extensive field measurement and consumes time, effort, and money [1–3]. Developing of the rating curves for Lake Nasser is, therefore, of utmost importance. The remote sensing (RS) and the geographical information systems (GIS) approach for the development of the rating curves almost succeeds to give volume/level and area/level relationships accurately.

Moreover, this approach (RS/GIS) can overcome most such problems when generating the rating curves and estimating the capacity of Lake Nasser.

To developing rating curves, various techniques have been proposed including artificial neural network technique [4, 5], genetic algorithm with model tree [6], spreadsheet approach [7], combination of remote sensing (RS) and digital elevation model data approach [8], integration between RS and in situ measurements technique [9, 10], RS/GIS approach [3], numerical hydrodynamic models [11], and combination of RS satellite imagery and altimetry data method [12]. The present chapter tested the applicability of using the RS/GIS to develop the rating curves of the portion of Lake Nasser (which has water level measurements) compared to the used traditional method adopted by AHDA.

2 Study Area and Data Collection

2.1 The Study Area

Lake Nasser, which is considered the water resources bank of Egypt, is located between latitudes 22° 00′ 00″ N (upstream the AHD) and the AHD in the north. The measurements (hydrographic survey data) cover only the distance that extends from the end of Reservoir Nubia in Sudan to km 123 upstream the AHD in Egypt (behind which no significant sedimentation is observed) [13]. The study area is selected within Lake Nasser, from latitude 22° 00′ 00″ N to km 123 upstream the AHD where measured data are available, as presented in Fig. 1.

2.2 Collected Data

The used data in the present study include the following.

2.2.1 Hydrographic Survey Data

The hydrographic survey data presented by easting, northing, and elevation (E, N, and Z) are used to describe the geometry of Lake Nasser study area for years 1992, 2000, 2006, 2009, and 2012. These data were collected using the echo sounder measurements system provided by AHDA and NRI [14].

2.2.2 Satellite Images (Remote Sensing Data)

Table 1 shows the specifications of the acquired eight Landsat ETM+ images which are used in this study to extract the lake boundaries. These images were downloaded

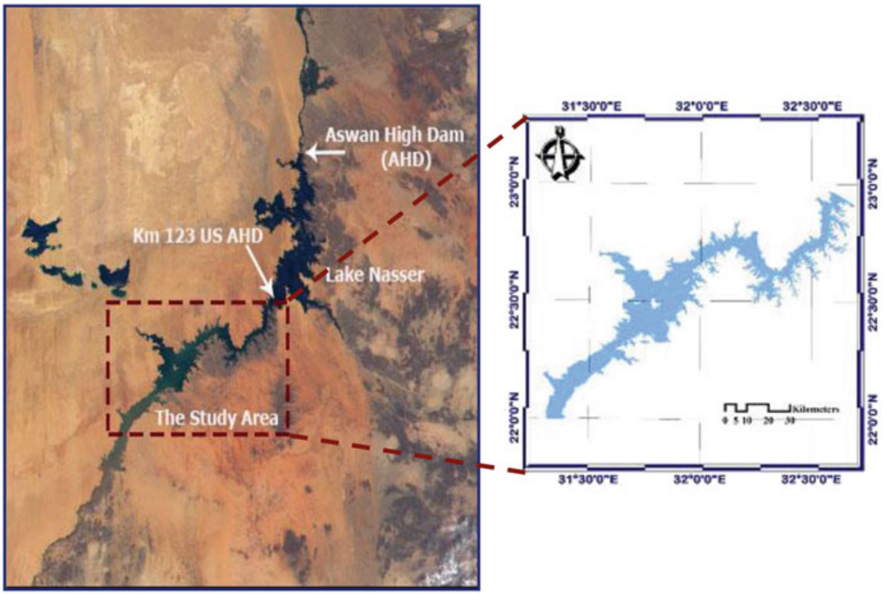

Fig. 1 Location of the study area in Lake Nasser. Source: Earth Observatory. NASA https://earthobservatory.nasa.gov/IOTD/view.php?id=975

Table 1 The specifications of the acquired RS data [1]

Satellite	Sensor	Path/row	Date	Spatial resolution (m)	Water level (m)
Landsat-7	ETM+	175/045	September 2000	30	178
		175/045	March 2006		173
		175/045	March 2009		176
		174/044	March 2005		174
		174/044	November 2001		180
		175/044	September 2000		178
		175/044	April 2006		172
		175/044	March 2009		176

freely from the Global Land Cover Facility (GLCF) website [15]. Three scenes are needed to completely cover the study area with path/row = 175/045, 174/044, and 175/044 in GeoTIFF (systematic correction) product. Consequently, the collected images are free from geometric, radiometric, and noise errors. These images were geo-referenced by USGS using the world reference system (WGS-84 datum) to Universal Transverse Mercator (UTM) system, zone 36 North projection.

2.2.3 Water Levels Data

The daily recorded water levels by AHDA gauge stations [16] were collected to help in detecting the water surface levels of the study area at the dates of acquiring the satellite images.

3 Methodology

To develop the rating curves of the study area, several tasks should be achieved. All these tasks are presented in the flowchart of Fig. 2.

A brief description of the methodology tasks is provided herein.

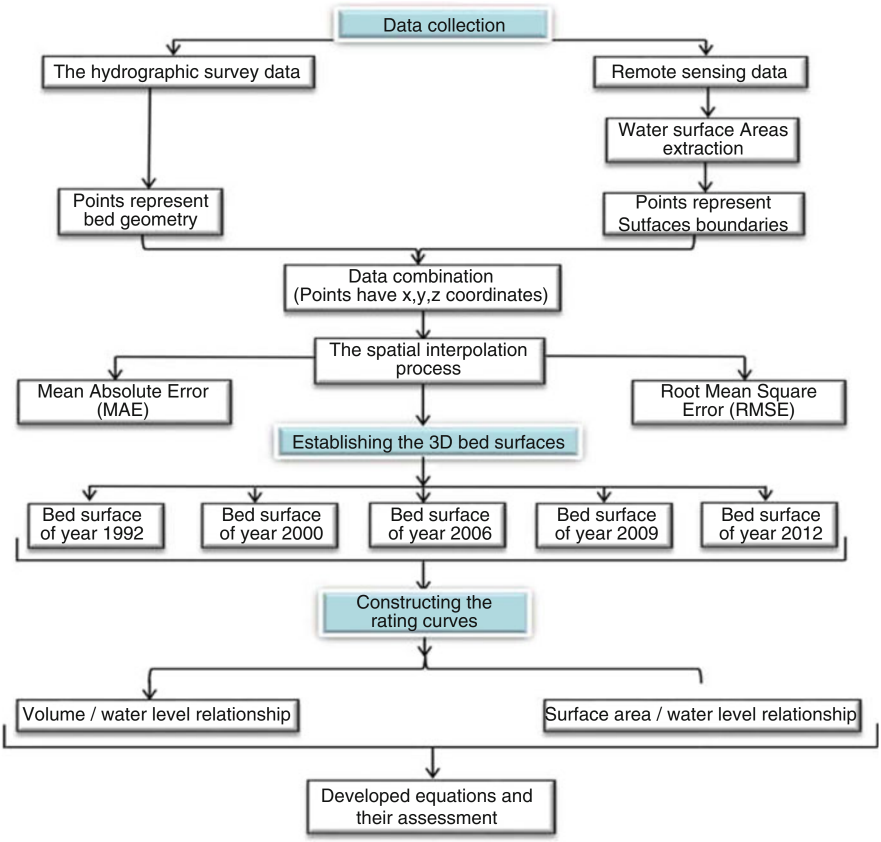

Fig. 2 Flowchart of the procedures adopted in this study to develop the rating curves of Lake Nasser [1]

3.1 Extraction of Water Surface Areas

The unsupervised classification technique was performed to extract the water boundaries of the study area. It is considered the best technique for water areas recognition using Landsat images [17–19]. The shape of the lake surface was formed by using the extracted lake boundaries obtained from the satellite images. Then, a group of scattering points (*x*, *y*, *z*) using the WGS84, UTM Z36N as a defined projected coordinate system, is formed. These points are used in combination with the hydrographic survey points in the generation of the 3D bed surface of the study area for the selected years from 1992 to 2012 [1].

3.2 Spatial Interpolation Process

In order to generate continuous knowledge about the bed levels of the study area, it is necessary to approximate the level values in areas that are not included with measurements (levels points). This is done using the most used three interpolation methods, namely, inverse distance weighting (IDW), radial basis function (RBF), and ordinary kriging (OK). For more information on the theoretical background of these methods, interested readers can review the help topics of ArcGIS software [1, 20].

The mean absolute error (MAE) and the root mean square errror (RMSE) were computed to assess the accuracy of the interpolation methods.

3.3 Creation of the 3D Bed Surfaces

The developed 3D profiles for the years 1992, 2000, 2006, 2009, and 2012 were obtained using the spatial interpolation technique with the best performance. They were used to compute the storage capacity (volume) and surface area variations with the water level changes for Lake Nasser study area for the selected years from the year 1992 to the year 2012.

3.4 Constructing the Developed Rating Curves

The values of the two parameters of the lake (water volume/surface area) are estimated from the generated 3D profiles of the lake at different water levels by using 3D analyst tool in ArcGIS software [20]. These values are computed in order to establish the rating curves which represent volume/level relationship and area/

level relationship for all selected years from 1992 to 2012 individually and collectively.

3.5 Rating Curve Equations and Their Validation

The equations of the developed rating curve volume/water level, water surface area/ water level, and volume/area are conducted to estimate the storage capacity and the surface area of Lake Nasser study area at any stage (level) and to monitor the lake morphological changes efficiently.

Both the root mean square error (RMSE) and coefficient of determination (R^2) (Eqs. 1 and 2) were used to assess the fitness of the developed relationships.

$$\mathrm{RMSE} = \sqrt{(\mathrm{Mes} - \mathrm{calc.})2/N} \tag{1}$$

$$R^2 = \sum (\mathrm{calc.} - \mathrm{avg.Mes})^2 / \sum (\mathrm{Mes} - \mathrm{avg.Mes})^2 \tag{2}$$

4 Results and Discussions

4.1 Generation of the 3D Profiles

The unsupervised technique was used to extract the water surface utilizing all available Landsat images (remote sensing data), then the interpolation process in the GIS was used to generate the 3D profile of the lake. As mentioned above, several interpolation functions were tested, and it was found that the RBF method for interpolation produced the best results (the lowest values for both the MAE and the RMSE) between the other tested methods of interpolation in this study. The MAE for the year 2012 equals 0.31 m, and the RMSE equals 0.73 m indicating the highest accuracy of the interpolation process. The 3D profiles were for the years 1992, 2000, 2006, 2009, and 2012. Typical results are presented in Fig. 3 for the year 2000 and year 2009.

4.2 Rating Curves and Their Validation

The development of the rating curves involves the use of the statistical methods, particularly, least squares method, to final the optimal relationship between the water levels and the water surface areas and the relationship between the water levels and the water capacity or water volume in the reservoir (Lake Nasser). The next subsections present the achieved results in terms of figures, tables, and discussions.

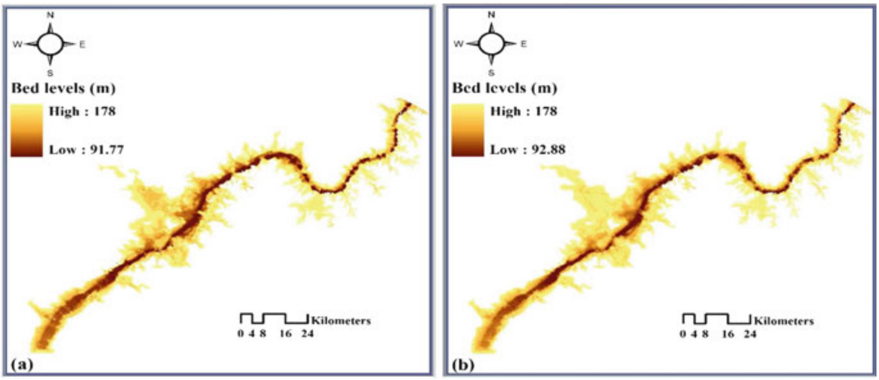

Fig. 3 Sample results of the generated bed surfaces: (**a**) 2000 bed surface and (**b**) 2009 bed surface [1]

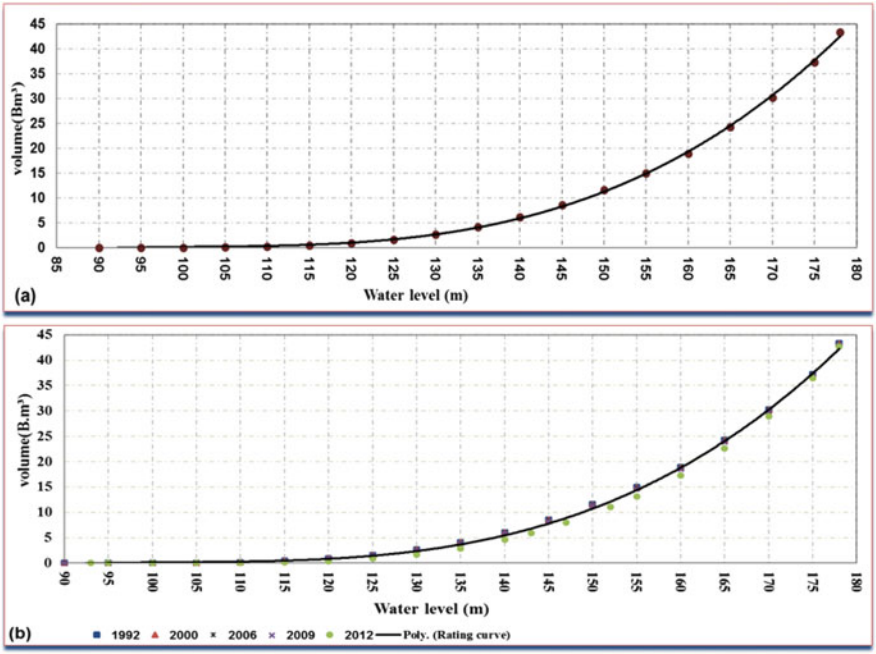

Fig. 4 Typical sample simple results of the rating curves (water capacity/water level): (**a**) 1992 rating curve and (**b**) collective rating curve for the years 1992 to 2012 [1]

4.2.1 Water Capacity (Volume)/Water Level Relationship

Using the least squares fitting, it was found that a third-order polynomial fits well in the relationship between the water capacity (water volume) and the water level in the reservoir (Lake Nasser). Figure 4a, b shows typical relationship between volume and capacity/water level for the year 1992 and collectively for the whole studied period from the year 1992 to the year 2012.

Table 2 indicates the developed third-order equations for the years 1992, 2000, 2006, 2009, and 2012 and for all years 1992 to 2012 as one batch. It is evident that good agreement was obtained with R^2 values more than 0.99, and RMSE varies between 4% to 5%.

As a quantitative indicator for above results, Fig. 5 shows a comparison between the measured and the calculated water volumes from the developed rating curve equations at water level 175 m amsl, as an example. It is clear that the computed and the measured volume values are almost equal which indicate the effectiveness of the developed (volume/level) relationship using RS/GIS approach.

Table 2 Evaluation of the developed relationships between water volume and level for the period from 1992 to 2012, individually and collectively [1]

Period of the estimated rating curve	Number of points	R^2	RMSE (Bm^3)	RMSE (%)	Rating curve equation (y = volume in Bm^3 and x = water level in m)
1992	19	0.999	0.49	4.55	$y = 0.0000939081x^3 - 0.0288x^2 + 2.951x - 101.33$
2000	19	0.999	0.50	4.60	$y = 0.0000943237x^3 - 0.0289x^2 + 2.972x - 102.18$
2006	19	0.999	0.48	4.45	$y = 0.0000954247x^3 - 0.0294x^2 + 3.027x - 104.38$
2009	19	0.999	0.47	4.40	$y = 0.0000960099x^3 - 0.0296x^2 + 3.057x - 105.56$
2012	20	0.999	0.38	3.83	$y = 0.0001178181x^3 - 0.0380x^2 + 4.083x - 146.31$
1992–2012	96	0.998	0.54	5.14	$y = 0.0001000332x^3 - 0.0311x^2 + 3.241x - 112.78$

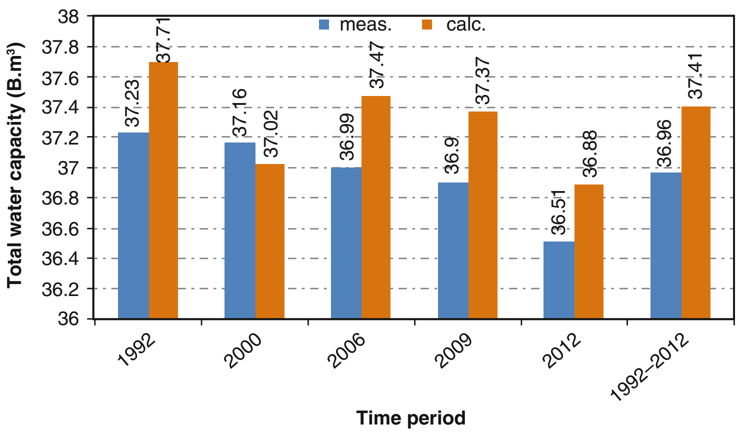

Fig. 5 Typical total water capacities computed from the individual and collective rating curves at water level (175 m amsl) [1]

4.2.2 Area/Level Relationship

Several fitting functions were tested to fit the relationship between the water level and water surface area in the reservoir (Lake Nasser). It was found that a second-order polynomial relationship fits well the available data. Typical samples of the developed relationships are presented in Fig. 6a, b for the year 1992 and collectively for all years from the year 1992 to the year 2012.

Similarly, Table 3 presents the developed rating curve equations between water levels and the surface area for Lake Nasser for the years 1992, 2000, 2004, 2006,

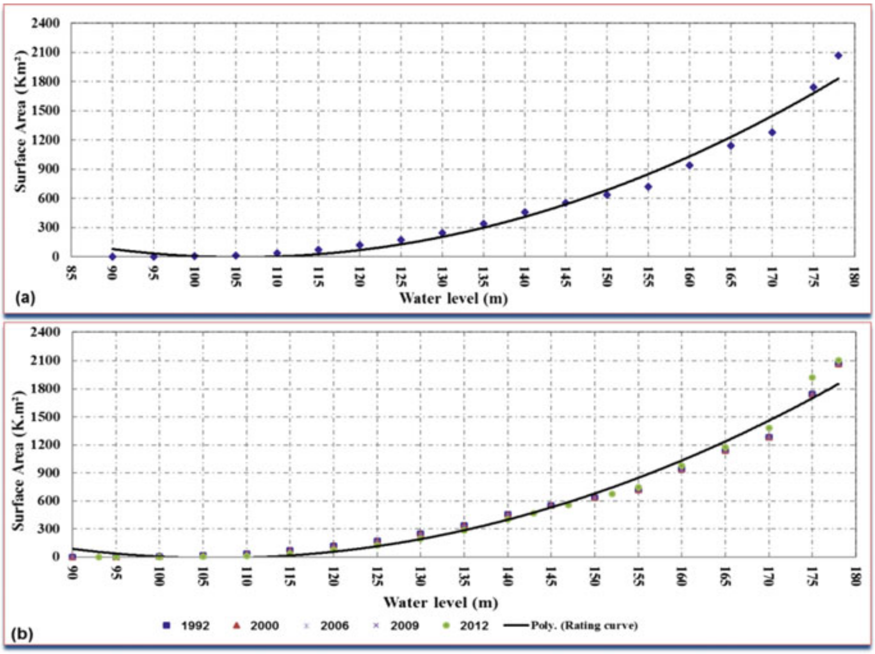

Fig. 6 Sample results of the rating curves (surface area/water level): (**a**) 1992 rating curve and (**b**) collective rating curve for the years 1992 to 2012 [1]

Table 3 Evaluation of the developed relationships between water surface area and level for the period from 1992 to 2012 [1]

Period of the estimated rating curve	Number of points	R^2	RMSE (km^2)	RMSE (%)	Rating curve equation (y = surface area in km^2 and x = water level in m)
1992	19	0.9791	13.42	2.42	$y = 0.3491x^2 - 73.685x + 3{,}882.6$
2000	19	0.9790	13.56	2.45	$y = 0.3496x^2 - 73.826x + 3{,}891.7$
2006	19	0.9793	13.07	2.37	$y = 0.352x^2 - 74.482x + 3{,}932$
2009	19	0.9794	12.94	2.35	$y = 0.3532x^2 - 74.798x + 3{,}951.6$
2012	20	0.9856	10.64	1.91	$y = 0.4164x^2 - 90.74x + 4{,}913.5$
1992–2012	96	0.9787	15.51	2.80	$y = 0.3638x^2 - 77.435x + 4{,}109$

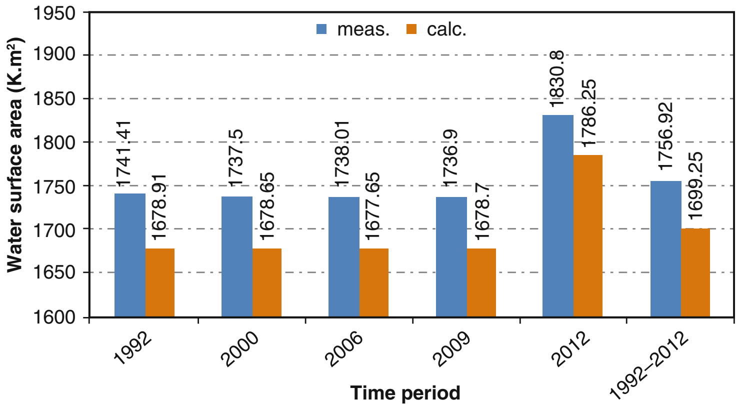

Fig. 7 Water surface area computed from the individual and collective rating curves at water level (175 m amsl) [1]

Table 4 Comparison of results between the present approach and the traditional method for estimating the water capacity of Lake Nasser study area for 2 years that have maximum errors [1]

Year	Estimated water capacity using the developed rating curves (Bm^3)	Estimated water capacity by AHDA method (Bm^3) [14]
2000	37.02	37.46
2012	36.88	37.48

2008, 2010, and 2012 and collectively for the period from 2000 to 2012. The values of R^2 are more than 0.97, while RMSE ranged between 10.64 and 15.51 km^2. The computed values of both R^2 and RMSE imply that the developed rating curves are reliable enough for detecting the water surface area changes from the level variations. The predicted surface area values using the developed equations are compared with the measured values as shown in Fig. 7 for the lake water level of 175 m.

4.3 Comparisons with the Reference Method

Table 4 presents a comparison between the results of the present approach and that used by AHDA and NRI (concerning authorities) for the years 2000 and 2012.

The results presented in Table 4 indicated that there is an underestimation of about 1.5% for the year 2000, while it is about 1.6% for the year 2012. Overall, the underestimation for the period from 1992 to 2012 is about 2% which indicated that the developed relationships are accurate enough to estimate the capacity of the reservoir (Lake Nasser).

5 Conclusions

The available water level observations for the years 1992, 2000, 2006, 2009, and 2012 were used to develop rating curves for Lake Nasser using the RS/GIS techniques. The developed relationships have good accuracy with underestimation of 2% for the whole period 1992–2012. Moreover, the value of the coefficient of determination, R^2, is more than 0.99 for volume/level relationship and is more than 0.97 for area/level relationship. The obtained results indicated that RS/GIS techniques has an excellent potential applicability and high efficiency in developing rating curves for the reservoirs similar to Aswan High Dam reservoir or Lake Nasser. However, such relationships need an update from time to another, and consequently, field measurements are necessary from time to another to collect the needed data to update these developed equations. The authors are recommending the application of RS/GIS to develop the rating curves for the whole lake.

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Investigating the Water Quality of the Water Resources Bank of Egypt: Lake Nasser

Mohamed E. El-Mahdy, Mohamed S. Abbas, and Hassan M. Sobhy

Abstract This chapter aims to analyze the water quality of Lake Nasser in Egypt for irrigation and drinking purposes according to Egyptian and World Health Organization (WHO) standards. Water samples were collected from eight sampling locations. Water quality variables were measured in the lake in a field trip occurred in March 2014. The samples were analyzed for electrical conductivity (EC), total dissolved solids (TDS), magnesium content (MC), sodium percent (SP), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), and permeability index (PI). The minimum value of total dissolved solids was found in sample no 6 with a concentration of 192.90 mg/l, and the maximum value was found in sample no 8 with a value of 354.47 mg/l, which was taken from a sub-branch canal. The minimum EC was recorded in the sample no 6 with a value 190 μmho/cm, and the maximum EC was recorded in sample no 8 with a value of 705 μmho/cm, and the sodium percent values of Lake Nasser were 58.48–81.98. These values are high, so gypsum can be added to the soil to reduce the effect of high percentage of sodium in irrigation water. Study of all these characteristics indicated that the lake water quality is suitable for both drinking and irrigation purposes because of adequate values of total dissolved solids, EC and SP.

Keywords Analysis, Irrigation, Lake Nasser, SAR and RSC, Water quality

Contents

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1 Introduction

Concern about water quality for drinking and irrigation is not new; criteria and standards for its evaluation have spread since the late 1800s [1, 2]. Currently, there is much concern about the aesthetic qualities of our natural waters and the presence of extremely small amounts of potentially harmful substances in them. Legislative bodies are moving to set criteria and standards of water quality for water users. The more extensive use, man will make of natural waters in the future, will magnify present-day problems of water quality. The various users of water domestic, industrial, and agricultural have different quality requirements and will likely be competing for the same water supplies. There is little question, then, that a need exists for adequate criteria and standards for evaluating the suitability of waters for irrigation and drinking [3].

Water Resources Bank of Egypt (Lake Nasser) is studied by many researchers. Since the lake is the main source of Egyptian surface water, it was subjected to many studies covering many aspects [4–10]. Toufeek and Korium [11] conducted a study about the physicochemical parameters variation, such as turbidity, total dissolved solids (TDS), electrical conductivity, dissolved oxygen, temperature hydrogen ion concentration (pH), and major anions. The study was done during the year 2005. The results showed some variations in the physicochemical parameters concentration between bottom and surface layers of the lake during summer season. On the other hand, the variation range is narrow during winter. Rashed [12] assessed the pollution of water, fish, aquatic plant, and sediment with heavy metals in Lake Nasser. The study showed that heavy metals in different parts of fish differ with the fish growth and extraction rate of these elements from water, aquatic plant, and sediment. The study concluded that heavy metal concentration in the edible parts of the studied fish species was in the permissible range for human use. Ibraheim et al. [8] investigated the concentrations of radionuclides in surface soil and sediments of Lake Nasser. The concentrations have been measured by both gamma spectrometry (GS) and neutron activation analysis (NAA). The study found that concentration range was from 25 to 68 Bq kg^{-1} for ^{238}U and 8.4–59.3 Bq kg^{-1} for ^{232}Th. The study indicated the possibility of a state of disequilibrium within the ^{238}U series but not in the ^{232}Th series. Moalla [10] studied the phase association and distribution of Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn, and organic matter in the sediments of Lake Nasser. The study found that very small concentrations of all studied heavy metals were found in aqueous phase, which is bioavailable. Between aqueous phase and the metal phases that are not bioavailable, there exist many geochemical phases. These phases may release their associated metals under some change in environmental conditions as redox and pH. Negm and Armanuos [13] studied the groundwater quality of the aquifer of the western Nile Delta. The study presented the suitability of groundwater for both drinking and irrigation purposes. The World Health Organization and Egyptian standards were used as reference standards for the suitability of water for drinking purposes. The study evaluated groundwater suitability for irrigation. The calculated water quality data index (WQI) showed that 45.37% and 66.67% of wells water samples are good for drinking based on WHO and ES, respectively. With respect to the values of SAR, RSC, TDS, and PI, more than 58.83% of wells are suitable for irrigation.

This chapter discusses some important factors that must be considered in assessing the suitability of waters for irrigation and drinking; then it presents the results and discussion of water sample analysis and, finally, conclusions and recommendation followed by references.

2 Criteria of Drinking and Irrigation Water Quality

The suitability of waters for drinking could be assessed using the World Health Organization (WHO) and Egyptian standards (ES) as a reference to determine the suitability of water for drinking purposes [14]. The suitability of waters for irrigation should be evaluated by criteria indicative of their potentials to create soil conditions hazardous to crop growth or animals or humans consuming the crops. The prevailing criteria of irrigation water quality and their associated potential hazards to crop growth are:

Salinity: the general salt effects on crop growth thought to be mostly osmotic and related to total salt concentration rather than to the individual concentrations of specific salt constituents. These effects are evidenced by retarded growth, producing smaller plants with fewer and smaller leaves [15].

Sodicity: the effect of an excessive amount of exchangeable sodium in the soil on soil permeability, soil structure deterioration, and a direct toxic effect of exchangeable sodium on plants specially sensitive to sodium. The soil effects are evidenced by puddling and by a reduced rate of water intake. Sodium toxicity is evidenced by leaf bum and defoliation [16].

Toxicity: the specific ion effects of solutes (other than sodium) of a nutritional nature, especially those of chloride and boron. These effects are evidenced by leaf burn and defoliation [17].

3 Considerations in Assessing Drinking and Irrigation Water

Drinking water quality should achieve the standards prescribed by World Health Organization and Egyptian standards. The physiochemical characteristics have to be in the permissible limit [18].

Irrigation waters may contain from 0.1 to 4 metric tons of silts per thousand cubic meters and are applied to soils at annual application rates of 10 to 15 thousand cubic meters per hectare, from 1 to 60 metric ton of salt per hectare may be added to irrigate soils annually. The concentration of soluble salts in soils increases because most of the applied water is removed by evaporation and transpiration, leaving the salt behind. Without leaching, salt constituents will accumulate in the soil waters with successive irrigations until the solubility limit of each salt is reached [19].

The solubility of many salts, such as the chlorides and sulfates of sodium, magnesium, and potassium, are above the salinity tolerance limits of most plants [20]. The relatively low solubility of calcium and magnesium carbonates and calcium sulfate limit their accumulation in soil waters to levels below those that are harmful to plant growth [21]. With leaching, the accumulation of salts in soil water is lessened, but not eliminated. The first increments of leaching are more effective and efficient in this regard than latter increments [22].

Interest in the quality of irrigation water dates back to about the 1800s. In contrast, the quantity of water available for irrigation has always been of primary concern [15].

Although there are differences between the several schemes for the classification of irrigation waters, there is reasonable agreement with respect to criteria and limits. This makes it possible to anticipate, with considerable confidence, the effect of water on soils and plants. However, the successful use of water may not depend on quality alone but other factors including the drainage characteristics of the soil [23].

For all practical purposes, pure water is considered to be which has low dissolved or suspended solids and obnoxious gases as well as low in biological life. Such high quality of water may be required only for drinking purposes, while for other uses like agriculture and industry, the quality of water can be quite flexible, and water polluted up to certain extent in general sense can be regarded as pure [3, 24].

4 Sampling

This study was performed at eight locations starting from Garf Hussein, Al-Luhaa farm, Thomas and Affia, Wadi El-Allaki, Amada and El-Soubou, Kostol and Adindan, Al-Raghey farm, and Holding company farm. The sampling locations cover the lake from its north to the southern border of Egypt.

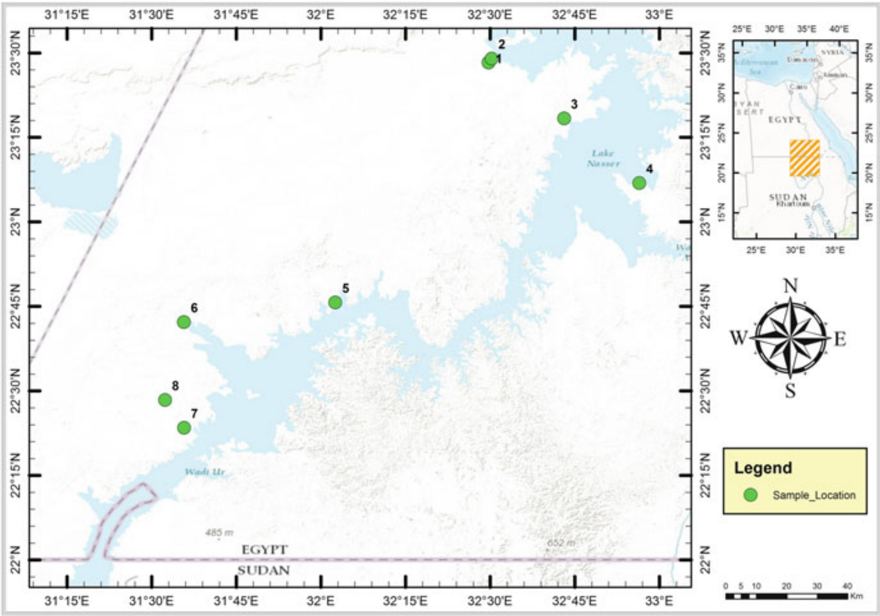

Fig. 1 Map of sampling sites

Drinking water and irrigated agriculture is dependent on adequate water supply of usable quality. In water quality evaluation, the emphasis is placed on the chemical and physical characteristics of the water [3, 25, 26]. Here, an attempt has been made to assess the drinking and irrigation water quality for Lake Nasser area. The quality characteristics studied in the present investigations were as follows: total dissolved solids (TDS), electrical conductivity (EC), pH, magnesium content (MC), sodium percentage (SP), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), and permeability index (PI).

5 Experimental Setup

Eight water samples were collected in the field trip from eight points as described before, since they cover almost all the lake in Egypt and are located at populated area, as shown in Fig. 1. Water samples were collected in plastic gray canes on March 13–17, 2014. Water samples were analyzed by standard methods on March 20, 2014. MC, SP, SAR, RSC, and PI were calculated as follows:

5.1 Magnesium Content

Magnesium content of water is considered as one of the most important qualitative criteria in determining the quality of water for irrigation. Magnesium content is calculated by the following formula [3].

Mg content = $[Mg^{2+}/(Mg^{2+} + Ca^{2+})] * 100\%$

(Concentrations are in mg/l)

5.2 Sodium Percentage (SP)

The sodium percentage is calculated by the following formula [27].

$Na\% = [(Na^{+} + K^{+})/(Ca^{2+} + Mg^{2+} + Na^{+} + K^{+})] * 100\%$

(Concentrations are in mg/l)

5.3 Residual Sodium Carbonate (RSC)

The concept of residual sodium carbonate (RSC) is employed for evaluating high carbonate waters and is calculated by the formula given below [28].

$RSC = (CO_3^{2-} + HCO_3^{-}) - (Ca^{2+} + Mg^{2+})$

(Concentrations are in mg/l)

5.4 Permeability Index (PI)

Permeability index is calculated by the method suggested by Domenico and Schwartz [29].

$PI = [(Na^{+} + HCO_3^{-})/(Ca^{2+} + Mg^{2+} + Na^{+})] * 100\%$

PI is used to evaluate the sodium hazards of irrigation water.

6 Results and Discussion

The results obtained from chemical analysis of water samples of Lake Nasser are shown in Table 1, and the calculated water characteristics are shown in Table 2.

Table 1 Water chemical analysis results in Lake Nasser

Sample no	Lat.	Long.	pH	EC (μmhos/cm)	Mg^{+2} (ppm)	Ca^{+2} (ppm)	Na^{+} (ppm)	K^{+} (ppm)	CO_3^{-2} (ppm)	HCO_3^{-} (ppm)	Cl^{-1} (ppm)	B^{-1} (ppm)	$SO4^{-2}$ (ppm)
1	23.4712	32.4955	8.38	200	9.94	11.91	75.98	7.93	0.00	48.80	42.60	0.02	14.35
2	23.4827	32.5042	8.53	196	9.33	9.19	77.49	6.73	0.00	24.40	35.50	0.13	42.83
3	23.3060	32.7183	7.79	239	9.79	19.29	71.88	4.98	0.00	61.00	42.60	0.08	2.34
4	23.1147	32.9405	7.32	240	8.77	17.84	73.40	5.22	0.00	24.40	42.60	0.04	38.22
5	22.7614	32.0422	7.37	210	7.63	16.32	71.93	4.29	0.00	48.80	35.50	0.11	15.86
6	22.7192	31.5053	7.67	190	8.12	19.14	65.60	3.53	0.00	48.80	42.60	0.11	4.99
7	22.3908	31.5955	7.67	219	8.32	20.23	67.05	4.39	0.00	61.00	78.10	0.07	0.00
8	22.4727	31.5395	6.85	705	14.23	59.35	99.24	4.41	0.00	61.00	63.90	0.03	52.32

Table 2 Water characteristics in Lake Nasser

Sample No	Lat.	Long.	TDS (ppm)	MC (%)	SP (%)	SAR	RSC	PI (%)
1	23.4712	32.4955	211.53	45.49	79.34	22.99	26.95	127.55
2	23.4827	32.5042	205.59	50.37	81.98	25.47	5.88	106.13
3	23.3060	32.7183	211.97	33.66	72.55	18.85	31.92	131.62
4	23.1147	32.9405	210.48	32.96	74.71	20.12	−2.21	97.79
5	22.7614	32.0422	200.44	31.86	76.09	20.79	24.86	125.92
6	22.7192	31.5053	192.90	29.79	71.71	17.77	21.53	123.19
7	22.3908	31.5955	239.15	29.15	71.45	17.75	32.45	133.95
8	22.4727	31.5395	354.47	19.34	58.48	16.36	−12.58	92.72

6.1 *Total Dissolved Solids (TDS)*

Water can vary significantly in quality depending upon the quantity and type of dissolved solids. Salts originate mainly from weathering of rocks and soil, including dissolution of gypsum, lime, and other slowly dissolved soil minerals [30]. Dissolved solids are carried with water to wherever and whatever it is used. For drinking water, if the TDS level exceeds a specific limit, it will harm both humans and animals. In the case of irrigation, the salts are applied with water, as water evaporates; salts are deposited in the soil, if not consumed by the crop. A salinity problem emerges if salt accumulates in the root zone to a concentration level that causes a yield loss. Crop yield loss occurs when the salt concentration in the root zone becomes high to such an extent that the crop is not able to get sufficient water from the soil. If water uptake is reduced, the plant growth rate is reduced. Water with TDS less than 500 mg/l is considered good, while that with greater than 2000 mg/l is unsuitable for both drinking and irrigation purposes [31].

In the present study, the minimum value of total dissolved solids, as shown in Fig. 2, was found in sample no 6 with a concentration of 192.90 mg/l, and the maximum value was found in sample no 8 with a value of 354.47 mg/l, which was taken from a sub-branch canal. The low concentration of TDS in all samples except for sample no 8 is due to low pollution sources around the lake, while the concentration in sample no 8 can be returned to the fact that the sub-branch canal, where the sample was taken from, is polluted by the agriculture activity. These results are slightly higher than the results found by Toufeek and Korium [11]. The concentration of TDS of all samples is adequate for irrigation and drinking purposes.

6.2 *Electrical Conductivity (EC)*

Electrical conductivity (EC) is the most influential water quality guideline on crop productivity. The primary effect of high EC water on crop productivity is the inability of the plant to compete with ions in the soil solution for water (physiological drought) [3]. The higher the EC value, the less water is available to plants. Water

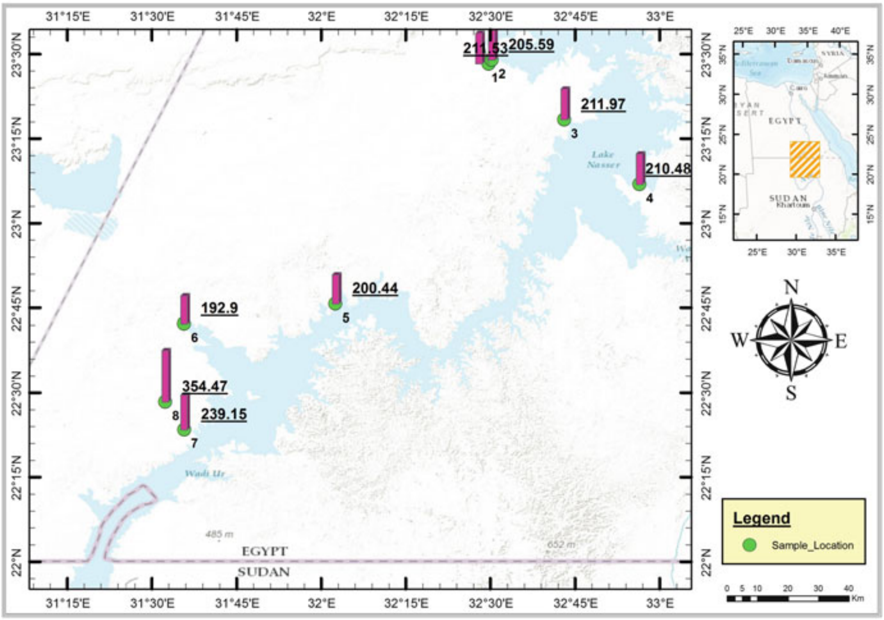

Fig. 2 TDS values at each sampling site

with EC less than 250 μmhos/cm is considered good and that with greater than 750 μmhos/cm is unsuitable for irrigation [32]. Same as TDS, the minimum EC was recorded in the sample no 6 with a value 190 μmho/cm, and the maximum EC was recorded in sample no 8 with a value of 705 μmho/cm, as shown in Fig. 3. The results of EC are almost the same as the results of Toufeek and Korium [11]. The values of EC of all samples are good and suitable for irrigation.

6.3 Magnesium Content (MC)

Magnesium content of water is one of the most critical factors in determining the water quality for irrigation and drinking. Calcium and magnesium maintain a state of equilibrium in water. The presence of more magnesium in water affects adversely crop yield, because the soils become more alkaline. In the present study, the magnesium content of the water of Lake Nasser varies from 19.34 to 50.37 mg/l, as shown in Fig. 4. So, water is suitable for irrigation and drinking purposes in terms of magnesium content.

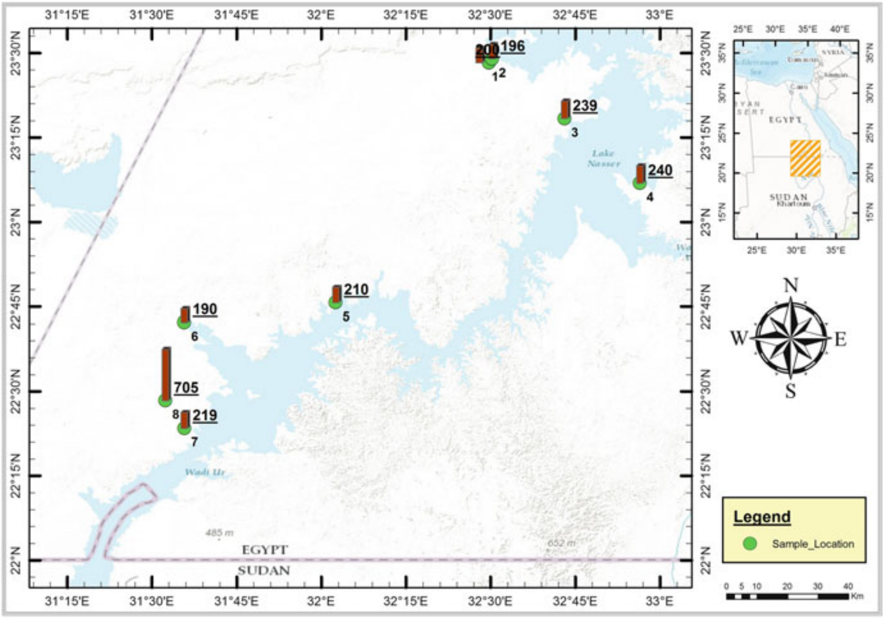

Fig. 3 EC values at each sampling site

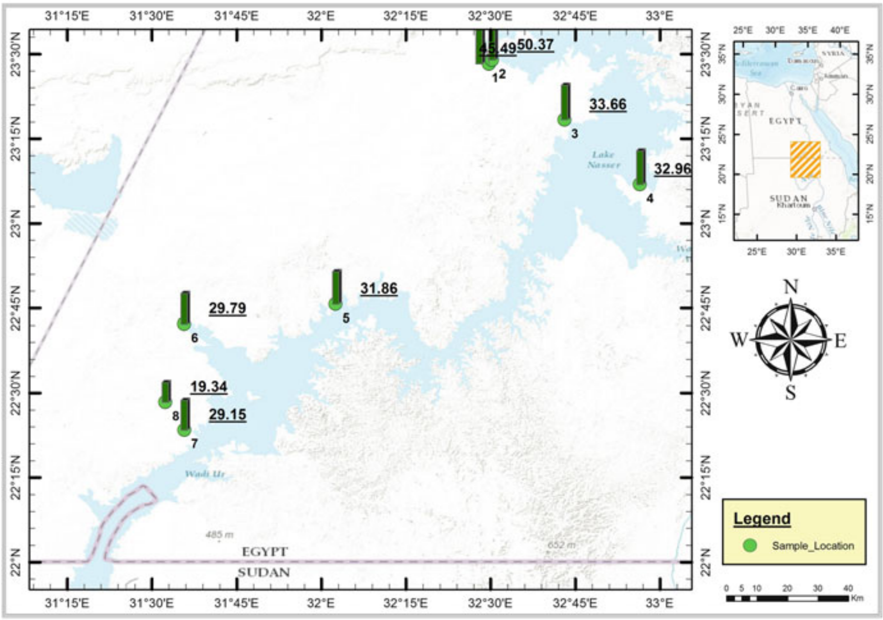

Fig. 4 MC values at each sampling site

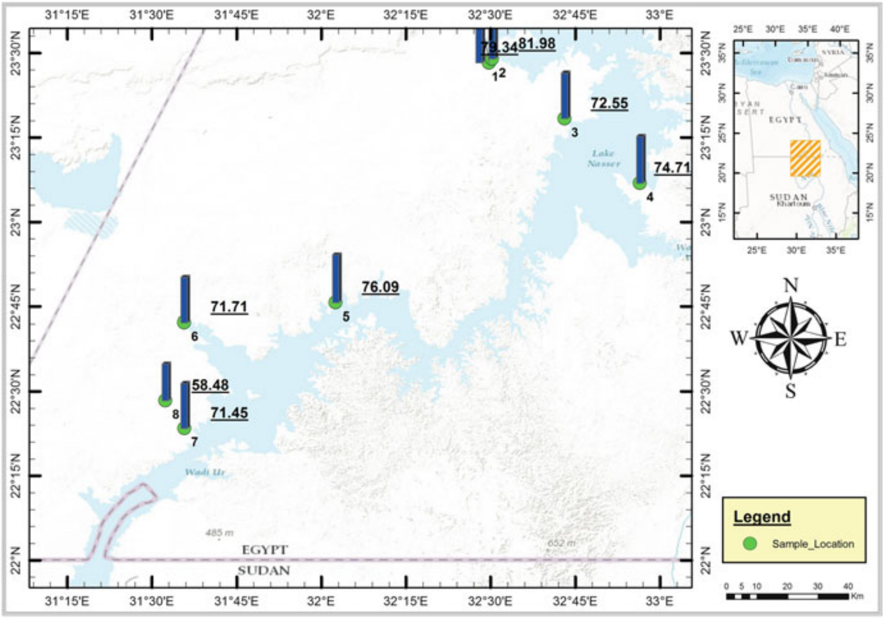

Fig. 5 SP values at each sampling site

6.4 Sodium Percent (SP)

Sodium hazard is studied by sodium percent. It is calculated as the percentage of sodium and potassium to all cationic concentration. It is used for testing the quality of water used for agricultural purpose. High concentration of sodium in irrigation water affects the plant growth negatively. Sodium reacts with soil to reduce its permeability. Usually, little or only minor problems occur when SP values are less than 15%. When SP $>$ 15%, reduced permeability will occur. The finer the soil texture and the higher the organic matter content, the higher the impact of sodium on water infiltration and aeration [33]. The sodium percent values of Lake Nasser were 58.48–81.98, as shown in Fig. 5. These values are high, so gypsum can be added to the soil to reduce the effect of high percentage of sodium in irrigation water.

6.5 Residual Sodium Content (RSC)

The concentration of bicarbonate and carbonate also influences the suitability of water for irrigation purpose. One of the empirical approaches is based on the assumption that all Ca^{2+} and Mg^{2+} precipitate as carbonate. Considering this hypothesis, residual sodium carbonate (RSC) concept is used for the assessment of high carbonate waters. The water with high RSC has high pH, and land irrigated

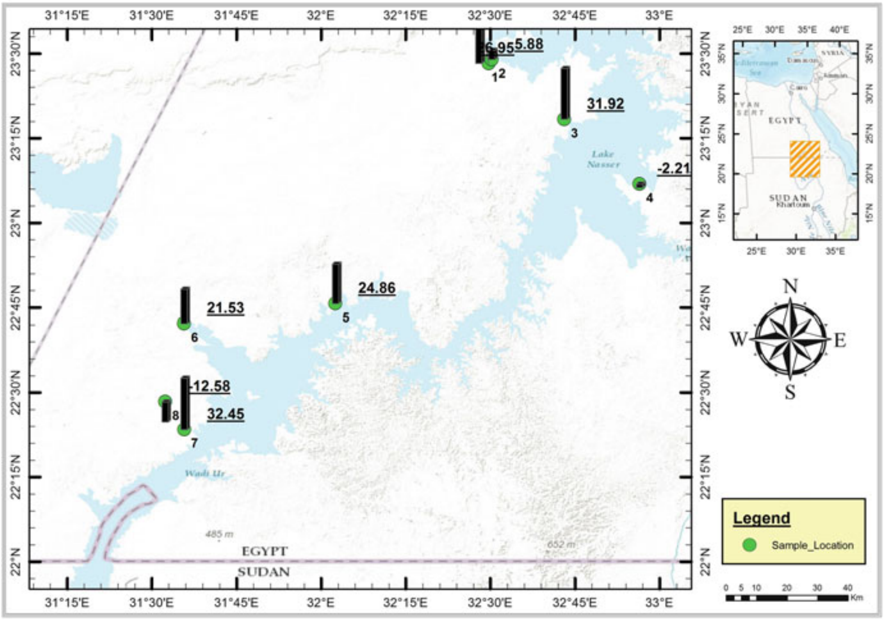

Fig. 6 RSC values at each sampling site

with this water becomes infertile owing to deposition of sodium carbonate, as known from black color of the soil. In the present study, RSC values are below 33 ppm at all sampling stations, as shown in Fig. 6, so the water of Lake Nasser can be considered safe for irrigation purpose.

6.6 Permeability Index (PI)

Sodium, calcium, magnesium, and bicarbonate content of the soil influence the soil permeability, which is affected by long-term use of irrigation water [34]. introduced a criterion to assess the suitability of irrigation water based on the permeability index. Waters can be classified according to this criterion as Class I, Class II, and Class III orders. Class I and Class II waters are categorized as good for irrigation with 75% or more maximum permeability. Class III water is unsuitable with 25% of maximum permeability. In the present study, the minimum value of PI is 92.72. Hence, water of Lake Nasser is of good quality, as shown in Fig. 7.

In the present study, TDS, MC, SP, RSC, and PI were found to be within permissible range. Hence, water quality of Lake Nasser was found to be good for both drinking and irrigation uses.

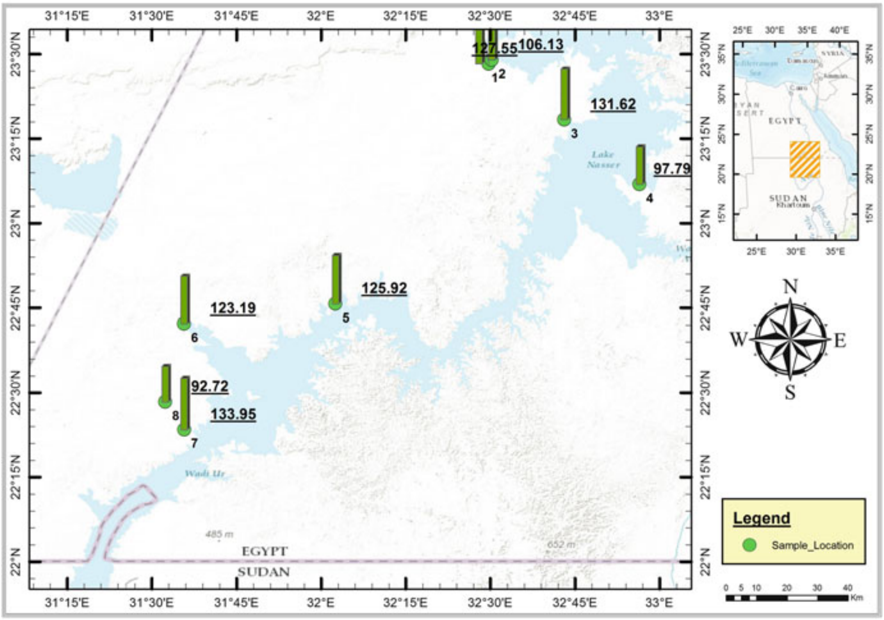

Fig. 7 PI values at each sampling site

6.7 Correlation Coefficient Matrix

Correlation coefficient matrix as shown in the Table 3 puts in hand some strong relations between different parameters. There is a strong relationship between pH and two cations, Ca^{+2} and K^{+}. While pH has a negative correlation with Ca^{+2}, it has a positive correlation with K^{+} and strong relationship with SP and SAR. pH has a very strong relation with MC. These results are consistent with many researches [35, 36]. This relation is strong due to the strong calcic properties of sodium ions. EC has very strong relation with Mg^{+2}, Ca^{+2}, Na^{+}, TDS, and SP, which is logic since the major cations affect directly on TDS and EC [37, 38]. Also, $SO4^{-2}$ has very strong relation with RSC and PI, although the equations of both RSC and PI have nothing to do with SO_4^{-2}. The strong relationship can be explained as reverse ion exchange process over SO_4^{-2} [39]. The strong relation between TDS, MC, and SP is because of the common item, sodium, which is a major parameter in the three Equations [40].

Finally, the very strong relation between RSC and PI can be returned to the fact that both of them are depending on sodium concentration [41].

Table 3 Correlation coefficient matrix between different parameters in Lake Nasser water

	pH	EC	Mg^{+2}	Ca^{+2}	Na^{+}	K^{+}	$CO3^{-2}$	$HCO3^{-}$	Cl^{-1}	B^{-1}	$SO4^{-2}$	TDS	MC	SP	SAR	RSC	PI
pH	1																
EC	−0.660	1															
Mg^{+2}	−0.358	0.922**	1														
Ca^{+2}	−0.755*	0.977**	0.849**	1													
Na^{+}	−0.395	0.918**	0.942**	0.815*	1												
K^{+}	0.739*	−0.232	0.099	−0.406	0.122	1											
$CO3^{-2}$	[a]	[a]	[a]	[a]	[a]	[a]	[a]										
$HCO3^{-}$	−0.351	0.371	0.313	0.485	0.128	−0.390	[a]	1									
Cl^{-1}	−0.388	0.445	0.333	0.530	0.203	−0.323	[a]	0.581	1								
B^{-1}	0.301	−0.468	−0.550	−0.441	−0.453	−0.285	[a]	−0.241	−0.398	1							
$SO4^{-2}$	−0.235	0.613	0.613	0.471	0.789*	0.211	[a]	−0.487	−0.100	−0.201	1						
TDS	−0.600	0.973**	0.903**	0.954**	0.879**	−0.189	[a]	0.439	0.617	−0.511	0.542	1					
MC	0.936**	−0.642	−0.361	−0.781*	−0.303	0.820*	[a]	−0.594	−0.574	0.274	−0.007	−0.623	1				
SP	0.825*	−0.867**	−0.695	−0.951**	−0.601	0.605	[a]	−0.612	−0.622	0.400	−0.227	−0.855**	0.911**	1			
SAR	0.802*	−0.519	−0.296	−0.684	−0.144	0.797*	[a]	−0.690	−0.634	0.289	0.205	−0.523	0.952**	0.874**	1		
RSC	0.430	−0.687	−0.630	−0.597	−0.757*	0.015	[a]	0.410	−0.011	0.261	−0.951**	−0.602	0.235	0.419	0.052	1	
PI	0.383	−0.625	−0.582	−0.527	−0.715*	−0.027	[a]	0.484	0.049	0.240	−0.955**	−0.536	0.171	0.347	−0.011	0.996**	1

*Correlation is significant at the 0.05 level (2-tailed)
**Correlation is significant at the 0.01 level (2-tailed)
[a]Cannot be computed because at least one of the variables is constant

Table 4 WHO and ES allowable limits for drinking water [13]

Parameters	WHO allowable limit	Egypt standards allowable limit	Samples fulfilling standards no	Samples not fulfilling standards
TDS	1,000 mg/L	500 mg/L	All	–
pH	8.5	7.0–8.5	1, 3, 4, 5, 6, 7, 8	2
EC	1,500 μs/cm	–	All	–
Ca	75 mg/L	75 mg/L	All	–
Na	200 mg/L	200 mg/L	All	–
Mg	30 mg/L	50 mg/L	All	–
K	10 mg/L	–	All	–
CL	200 mg/L	200 mg/L	All	–
CO_3	100 mg/L	–	All	–
SO_4	200 mg/L	400 mg/L	All	–
HCO_3	100 mg/L	–	All	–

6.8 Suitability of Water for Drinking

Suitability of water for drinking is decided according to the limit of WHO and ES [13]. From Table 4, all water samples achieved the limits of both WHO and ES, except for sample no 2. The study found that Lake Nasser water is of high quality and could be used safely for drinking. These results support the results of many researchers [6, 42].

7 Conclusion and Recommendations

Water quality for irrigation as well as drinking is of extreme importance. While the water quality for drinking is very important, it is substantially treated before use by humans. But for irrigation purposes, the water from Lake Nasser are used directly and does not need any treatment. Criteria and standards for irrigation water evaluation have spread since the two centuries. Currently, there is much concern about the quality of our natural waters and the presence of extremely small amounts of potentially harmful substances in them.

In the present study, EC, TDS, MC, SP, RSC, and PI were found in the permissible range for Lake Nasser water, both for irrigation and for drinking. Some strong to very strong significant relations were found between parameters, which verify the results of analysis and calculations.

Finally, continuous monitoring of Lake Nasser water quality is very necessary. The more detailed and sustainable investigation of the water quality, especially for drinking purpose, would be of great importance and is highly recommended.

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Part IX
Conclusions

Update, Conclusions, and Recommendations for Conventional Water Resources and Agriculture in Egypt

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Abstract Water resources in Egypt are limited. The Nile River is the main water resource. Agriculture is the main water consumer of water resources. It consumes about 80–85% of all available water resources. The rapid growth of the population and the expected impacts of climate change on water resources and agriculture threaten current and future food security in Egypt. Policymakers and expertise give important attention to these challenges where so many efforts were done long time ago (and still doing) to enhance delivery and on-farm water use efficiencies. Egyptian policymakers pay special attention on the agricultural sector for its importance in ensuring food security to the rapidly growing population through the vital activities. These activities include (but not limited to) better utilization of agricultural resources, using drainage water reuse, reusing of treated wastewater, improving water use efficiency, managing groundwater resources, and developing a horizontal expansion area through reclaiming new lands. In addition, many irrigation improvement projects were conducted to increase water productivity. This chapter focuses on conventional water resources and sustainability of agricultural environment in Egypt

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that was documented during the book project. This chapter summarizes the critical conventional water resource challenges (in terms of conclusions and recommendations) of the existing main agri-food system and offering perceptions resulting from the cases in the volume. In addition, certain update and findings from a few recently published research work related to the conventional water resources covered themes are presented.

Keywords Agriculture, Food security, Governing water resources, Greenhouses, Irrigation development, Productivity, Socioeconomic impacts, Water qualities, Water resources, Water use

Contents

1 Introduction

Egypt is a pioneer in agriculture and irrigation management thousands of years ago until now. Agriculture in Egypt is currently a significant source in the Egyptian economy. Agricultural production in Egypt depends on irrigation, using surface water coming from the River Nile. Irrigation development projects in Egypt started in the dawn of history with the Egyptian Stone Age man changing from a nomadic life to settled farming.

Future projections have shown challenges in conventional water resources, such as water shortages, pollution, and deterioration of aquatic ecosystems, further aggravated by urbanization, climate change, and increasing demands for food production and hydropower. Egypt needs to restructure and reform agriculture-related policies to produce more food and to achieve an advanced degree of food security, which can be achieved in crops such as lentil, bean, sugar, maize, and oilseed and in particular wheat. In 2050, the Egyptian population is projected to be 135 million, and the water shortage will reach 75 BCM; thus food insecurity is expected to be more than 75% of the total essential needed food. Water resources management must change to deal with urgent issues and protect aquatic ecosystems and their services while addressing the demand for water from the competing claims for cities, agriculture, industry, energy, and transport. The successful sustainable use of water resources is a multifaceted, long-term, and often decentralized process, requiring new engagements between the biodiversity community, water managers, and the various sub-sectors analyzed in this volume. Sustainable use of water resources will require more awareness and knowledge, experimentation, and experience sharing but has high potential for upscaling and implementation across scales. The required innovation, nature-based infrastructure and novel applications of high and low technologies, will offer great opportunities for business and development of new solutions by engineering and consulting companies alongside public authorities. Support of public authorities in the long term will be an important lever, as is the inclusion of major stakeholders [1]. Climate change is likely to cause higher temperatures and alterations in precipitation patterns, with potential impacts on water resources [2]. In the context of climate change, salinity intrusion into rivers has been, and will be, one of the most important issues in water resources management. A combination of changes, including increased temperature and change in regional rainfall, especially sea level rise related to climate change, will have significant impacts on this phenomenon [3].

The confounding effect of all these components represents the main challenge for researchers and policy planners and makers in Egypt. So agriculture production has to increase by 70% within 2050 to keep pace with this rapid population growth. This should be implemented, in a way that preserves the environment, to reduce the vulnerability of agriculture to climate changes which tend to hinder agricultural production by lowering crop yields, often quite substantially. So this chapter focuses on conventional water resources and sustainability of agricultural environment in Egypt that was documented during the book project. To this end, we identify eight main contribution areas, which include:

- History of irrigation and irrigation projects.
- Key features of agriculture, administrative and legal framework.
- Land resources for agriculture development.
- Water shortage, food insecurity, and climate change.
- Assessment of water resources for irrigation and drinking purposes.
- Impacts of GERD and Tekeze Dams on Egypt's water resources.
- Sustainable use of water resources and future of irrigation projects.
- Key requirements of Egypt's Water Resources Bank.

The Government of Egypt has continuous programs for vertical and horizontal expansion through the added new reclaimed land, reuse of drainage water, and maximized use of conventional water resources. Also, other programs for horizontal expansion are developed through maximizing the usefulness of the unit of land and water. Recently, Egypt has established a national mega project for the establishment of 100,000 acres of greenhouses during the next few years, which will contribute to food security and export of some vegetable crops. On the one hand, the proper use of the remote sensing and GIS, as powerful techniques, on a large scale is necessary. On the other hand, use of digital maps and their attribute tables assist in decision support systems and may result in sustainable development project planning. All these and others are presented in this volume, and the most important findings and recommendations are presented in this chapter.

2 Update

Egypt is facing increasing water demand to satisfy rapidly growing population, increased urbanization, a higher standard of living, and an increase in the agricultural production to assure food security for the growing population. The increasing Egyptian population rate, with the decrease in natural land resources, threatens the balance with available food resources. The main objectives of Egypt's agricultural development plans target the increase and conservation of productivity, in addition to desert land reclamation. Implementation of successful sustainable agriculture requires the availability of accurately documented data for soil resources. Integrated remote sensing and GIS techniques are the most suitable means for inventory monitoring and documentation of natural resources, as they are characterized by high resolution and multispectrally. Also, distribution of the natural resources and detection of their changes is accessible by the multi-temporal nature of remote sensing data.

The following are the major update for the book project based on the main book theme:

History of Irrigation and Irrigation Projects Three-point of view were identified for irrigation projects history in Egypt. The first point is related to the irrigation system in Egypt. The irrigation system in Egypt, which was developed throughout thousands of years, can be described as evolutionary (i.e., gradually created and improved with time). Over time, new ideas were introduced, and irrigation technology was developed. Egyptians were pioneers in leading the whole world toward novel techniques and the introduction of irrigated agriculture. Estimation of the extent of the River Nile water level change with time was an essential issue throughout history. It was very early in history (before Dynasty 4300 BC) when the clergy were praying for a normal water level during the peak of the flood. This level was estimated at 16 ziraa (1 ziraa = 55 cm). To measure the water level, 20 nilometers were established as the distance between Aswan and Cairo. The nilometer consists of a well (stilling basin) which is equipped with a vertical marble gauge. On the top of the well, two copper eagles, one male and the other female, were installed. If the male eagle started whistling first, this was an indication of high flood; otherwise, the flood was low.

The second opinion is related to major irrigation development projects, which started in Egypt in the dawn of history. Remains of Stone Age man indicated that the change from continuously moving nomad tribal life to settlement family-like residential communities started far south in locations like Toshka and Owainat. This type of change was accompanied by domesticating animals as farm aid rather than killing them for meat, fats for fuel and lighting, and hides for clothing and tents and making household and farm tools from their bones. Instead, farming and production of food and fiber became more popular. The first move toward perennial irrigation, i.e., raising more than one crop on the same piece of land every year, was to store water from the time of abundance to use during shortages. Mohammad Ali was the first ruler to plan for disciplined, modern, and economical agriculture in recent history in Egypt. The momentum of modern irrigation continued over the second-half of the nineteenth century after the end of Mohammad Ali Rule. However, during the period 1859–1869, the country was busy preparing for different hydraulic projects of various shapes and scales. One of these projects included the excavation of the Suez Canal. It all started with the construction of the Aswan Dam (1898–1902) followed by a set of "Grand Barrages" which continued over the twentieth century. Since that date, development projects on irrigation and drainage systems expanded.

Key Features of Agriculture, Administrative, and Legal Framework Two potential key features were identified related to the administrative and legal framework of water resources policy in Egypt. First, formulation of Egypt's water resources policy for the twenty-first century requires a major shift from the classical pattern used in water resource planning and management to a new innovative paradigm. Dynamic interrelationships among water resource system components impose the integrated approach on policymakers. The Egyptian government prepared its first national policy after the construction of the Aswan High Dam in 1970. Since then, several water policies were formulated to accommodate the dynamics of the water resources and the changes in the objectives and priorities. The latest policy was issued in January 2005. It included several strategies to ensure satisfying the demands of all water users and expanding the existing agricultural area through reclaiming new land. It also gave farmers the chance to share in the different responsibilities concerning the water distribution system and drainage water reuse besides choosing their own crop pattern. In fact, the agricultural sector plays a central role in the Egyptian economy, contributing 14.5% to GDP of output; and it is the largest employer as it accounts for more than 30% of the workforce [4].

Second, the management of water resources and agriculture has legally and administratively passed through many stages. This necessitated severe attention to the management of water resources, which have developed over different periods up to the present moment. The Ministry of Water Resources and Irrigation plays a nearly sole role in terms of legal responsibility for the planning and management of all water resources in Egypt. There are some local units that play complementary roles; they participate in one form or another in the regulation of water and sanitation. Beginning with the water policy of 1975, the Ministry of Water Resources and Irrigation started to assess the water supply and demand situation to assess the likely parity between supply and demand in the future. In 1981, a major water plan was issued to develop plans to meet water requirements for agricultural development and to study nonagricultural water requirements. The most recent water policies, entitled "Key Features of the 2017 Water Policy," were issued in January 2000. There is an extensive set of legislation and legal procedures governing agriculture in Egypt, where most agricultural laws such as the Agrarian Reform

Law and the Agriculture Law No. 53 of 1966 have been issued as mentioned above. However, there are many legislative limitations and legal challenges facing the agricultural sector in Egypt. The agricultural policies that were applied before the revolution of 25 January 2011 are still the same. As for the reflection of political and economic events on the water and agriculture issue, the strong and cohesive state at the domestic level has a stable capacity and effectiveness at the external (international and regional) level and vice versa which is the main issues Egypt suffered from during the period 2011–2014.

Land Resources for Agriculture Development Two potential approaches were identified to survey and monitor land resources for agriculture development in Egypt. First, integrated remote sensing and GIS techniques are the most suitable means for inventory monitoring and documentation of natural resources, as they are characterized by high resolution and multispectrally. Also, distribution of the natural resources and detection of their changes is accessible by the multi-temporal nature of remote sensing data [5]. The Egyptian Academy of Scientific Research and Technology, in cooperation with international organizations, has invested funds to produce the soil maps of Egypt. Three major projects funded include the High Dam Soil Survey [6], the Soil Map of Egypt [7], and the Land Master Plan (LMP) of Egypt [8]. The LMP is an international collaboration between the Arab Republic of Egypt (ARE) and Kingdom of the Netherlands. Moreover, many M.Sc. and Ph.D. theses and research papers, dealing with mapping soil resources, are available in the academic libraries. The nature of the past available data, in an analog format, makes it difficult to manipulate and upgrade their information. Following different land classification and mapping schemes led to a contradiction in estimating the cultivated areas and crop acreage. The detailed outline of the objectives is as follows:

1. Establishing a basic reference database including the previous studies and research work related to the Egyptian agricultural land resources at the scale of 1:100,000.
2. Using the previous studies as a base for establishing the GIS land resources numerical database for the agricultural use of sustained arable land.
3. Use of remote sensing for updating the existing data and detecting multi-temporal environmental changes.
4. Use of GIS technology in storing, documenting, retrieving, and analyzing land resources data, including the tabulated geographic attributes (e.g., physical and chemical soil properties).
5. Employing the created database in mathematical modeling for assessing land capability, land degradation hazard, and urban sprawl on account of cultivable land.

Second, Egypt's land and water resources are finite and under pressure from a growing population as well as climate change. These resources are central to agricultural development, as well as degradation of quality and quantity. Innovative technologies, such as remote sensing (RS) and geographic information systems (GISs), have an immense role to play [9, 10]. RS techniques were used for land

and water assessments over large and inaccessible areas. Visual image interpretation can by used in monitoring the geographic distribution of land and water resources. Vegetation varieties can serve as an indication of approximate groundwater depth. Three major paleolakes were defined in Sinai in which the largest lake occupied an area of at least 337 km^2 and contained approximately 10.7 km^3 of water when filled during pluvial phases. Abuzied [11] took a holistic approach to assessing groundwater locations in the Wadi Watir area, Egypt, based on RS (e.g., Radarsat 2000 and ground penetrating radar) to define the favorable zones of groundwater occurrences.

Food Insecurity due to Water Shortage and Climate Change Three approaches were identified related to water shortage, food insecurity, and climate change in Egypt. The first approach is the impacts of climate change on the agricultural sector. Climate change impacts on the agricultural sector include production (in terms of quantity and quality), species types, environment, and land use changes. The integration of all these confounding components represents the main challenge for researchers. Africa is likely to be highly impacted by these adverse direct effects due to their high agricultural dependency and limited capacity to adapt. Egypt is also vulnerable to climate change because of its large traditional agricultural practices and the limited source of water from the Nile River as the main water source. Also, the coastline of the Nile is already suffering from erosion and intensifying development. Climate change may affect agricultural production in Egypt especially the Nile Delta region. This region is characterized as one of the most vulnerable regions in the world to climate change in particular soil and water degradation, sea level rise, undiversified crop patterns, pests and disease severity, yield reduction, irrigation, and drainage management. Agriculture plays a vital role in Egypt's economy contributing roughly 15% of the gross domestic product (GDP) and employing about 30% of the national workforce. Smallholder farmers represent the majority of Egypt's farming sector [12]. Thus, adaptation strategies to climate change are vital for sustainable agriculture and food security in Egypt.

Second, a change in climate state can be identified by detecting changes in the mean and/or the variability of its properties, and that continues for an extended period, typically decades or longer [13]. Climate change is likely to increase the stress on currently stressed resources, especially in the developing world. Studies have shown that most systems are sensitive to both of the magnitude and the rate of climate change. However, the vulnerability of a system to the expected change depends on the economic strength and existing infrastructure as well as overall country resilience to cope with different risks. Most developing countries, such as Egypt, are generally more vulnerable and less able to adapt. In order to reduce the expected impacts of climate change, it is necessary to both reduce (mitigate) emissions of heat-trapping pollution and build resilience (adapt) to the impacts of climate change. However, even with strong programs to reduce greenhouse gas emissions (which proved to be a very difficult process), the effects of climate change will persist due to the longevity of certain greenhouse gases in the atmosphere and the absorption of heat by the oceans. Therefore, adaptation has a major role to play in reducing the impacts of climate change on people, businesses, and society.

Third, food security can be looked at three levels: the global, national, and household levels. Food security on a global scale is the level to set out from for analysis of general trends and to gain an understanding of the possible impacts of, e.g., climate change on agriculture. This is of importance since these trends have an effect on the worldwide level of agricultural prices and influence the decisions made by producers. Food security on a national level is where most of the decisions on food security are taken, for example, on how many financial resources are available for the national agricultural policy. Central elements of adaptive strategies in response to crises and disasters are defined at a national level. Food security at the household level: Without a detailed examination of the impacts on the household level, it would not be possible to gain an understanding of the specific needs of each individual with regard to food security. Such knowledge is key to the support groups most threatened by food insecurity in the event of a crisis. These distinctions show that food security for a country as a whole cannot always be equated with food security at the regional level or at the household level, and this information is vital in the event of a crisis.

Assessment of water resources For irrigation and drinking purposes. Three potential methods were identified for assessment of water resources in Egypt. First is the evaluation of water resources quality for agriculture irrigation. Irrigation water quality parameters were classified into individual parameters and integrated parameters. Salinity, sodium chloride, RSC, pH, and alkalinity hazards are considered as individual parameters. The integrated parameters include Welcox's classification, US Salinity Laboratory Staff Classifications, and irrigation water quality (IWQ) index. The water samples are mostly situated in IWQ moderate suitability range for irrigation and very satisfactory to satisfactory for all classes of livestock and poultry.

Second, water pollution monitoring programs are essential procedures to discover the environmental problems before turning into big threats. The regular monitoring of physicochemical parameters is common but has limitations and not enough for having the complete ecological status. Biological analysis including phytoplankton monitoring is also necessary [14]. Sometimes, algal analysis can be used to get a deep understanding of the degree of eutrophication and pollution of aquatic ecosystems better than the instantaneous information that can be understood through regular physicochemical monitoring. Moreover, the blooming of certain *Cyanobacteria* because of previous high eutrophication level may lead to severe damage if the water is used directly in drinking stations without suitable treatment to remove toxins [15, 16].

The third method is related to groundwater assessment for agricultural irrigation in Toshka area. Toshka project is a part of the mega project "Developing Southern Egypt." It is located in the area of Toshka depressions, but independent of them. It is a large-scale project of surface irrigation, using pumped water from the High Dam Lake to irrigate 216,000 ha (540 feddan) by 2017. According to the Landsat image of September 24, 2017, the total cultivated area was 24,000 ha (60,000 feddan), representing only 11.1% of the target. The Egyptian government prepares in its current strategy to reclaim 1.6 million ha (4 million feddan) from the desert in 4 years through four stages starting from June 2014. The first stage was to reclaim 1 million feddan, raised to be 1.5 million feddan in August 2015. About 90% of the 1.5 million feddan depend on nonrenewable and deep groundwater through 5,000 water wells. The new reclamation project will be carried out in three sub-phases in nine areas of the Western Desert, including Toshka, Farafra Oasis, Dakhla Oasis, Bahariya Oasis, Qattara Depression (Moghra), West Minya, and East Owainat. In addition to the 540,000 feddan in Toshka, about 100,000 feddan depending on surface water and 32,000 feddan depending on groundwater (through 102 wells) are included in the "1.5 Million Feddan Project."

Impacts of GERD and Tekeze Dams on Egypt's Water Resources Two potential scenarios of GERD and Tekeze Dams impacts on Egypt's water resources were identified. First, Bastawesey et al. [17] presented hydrological scenarios of GERD to estimate the water storage for its lake to assess the impact of the dam on the net annual discharges downstream. They mentioned that the anticipated negative impacts of the GERD on downstream would be more pronounced for Egypt as it mostly relies on the Nile water. They concluded that the completion of this project could occur over a short duration and during low-flood seasons. Consequently, the net annual discharge of the Blue Nile downstream could be minimal, and the Nasser Lake would struggle to sustain the necessary water for all the Nile Valley and its Delta in Egypt. Ramadan et al. [18] quantified using a hydrological model, the shortage of water in the active storage of Nasser Lake due to impounding of GERD reservoir. Different scenarios of impounding were considered as 6, 3, and 2 years under different inflow conditions. Their results indicated that the negative impacts on Egyptian water resources were severe especially if the filling period is shorter than 6 years and their results agreed well with the results obtained by Mulat and Moges [19].

Second, Ethiopia is the main water tower in East Africa, where water flows in all directions to the five neighbor countries: Sudan, South Sudan, Kenya, Somalia, Djibouti, and Eretria. It is endowed with a substantial amount of water resources, with average annual precipitation of 848 mm/year, and an annual 936 km^3 [20], while Egypt is ranked last in Africa regarding average annual rainfall 51 mm/year [21]. The internal renewable water resources in Ethiopia comprise 122 km^3/year in 12 basins, 9 of which are transboundary and 3 are located in the Eastern Nile Basin (the Blue Nile or Abay, Atbara or Tekeze, and Sobat or Baro-Akobo). About 75% of the total water resources drain to neighboring countries [22], and no perennial flows cross into the Ethiopian lands [23]. More than 80% of the Ethiopian surface water resources are generated by four river basins in the western part of the country. They are Blue Nile (Abbay), Sobat (Baro-Akabo-Pibor), Atbara (Tekeze), and Omo rivers, covering about 40% of the Ethiopian landmass.

Sustainable Use of Water Resources and Future of Irrigation Projects Six potential factors were identified for sustainable use of water resources in Egypt. First, the major limiting factors controlling ETo are water availability, amount of energy, and wind speed. These factors depend on many other quantities such as soil moisture, land surface temperature, air temperature, vegetation cover, vapor pressure, and wind speed, which vary according to the latitude of the region, the season of the year, time of day, and cloud cover. It requires daily data to provide an acceptable estimation of crop water requirements. Numerous models, which varied in complexity, were used to calculate ETo. Penman-Monteith method is one of the most accurate models to estimate ETo. Recently, the modified FAO Penman-Monteith equation presented in the FAO paper 56 has been widely used to estimate both the hourly and daily ETo from climatic data, either measured in the field or official meteorological records. Many studies investigated the potentiality of remote sensing data in crop monitoring, yield prediction, weed control and pest management, and crop water requirements [24–29]. Remote sensing technique is a powerful, economic, and efficient tool for estimating ETa. The irrigated farms and crop-coefficient (Kc) curves may be monitored and developed through remote sensing techniques.

Second, water requirements for various crops depend mainly on evapotranspiration, which is affected by weather parameters, management, and environmental factors. Also, water requirements for the same crop differ from one place to another depending on the agro-metrological zone, irrigation system, variety, and management. Application efficiency reached 80% at farm level according to Elbably [30]. Irrigation efficiency mentions to the amount of water removed from the source of the water that is used by the crop. This value is determined by water distribution characteristics, management of irrigation system, crop water use rates, soil, and weather conditions (http://passel.unl.edu/pages/informationmodule.php?idinformationmodule=1130447144). Ideal water efficiency for crop irrigation means reducing losses as evaporation, runoff, or subsurface drainage, however, increasing production. Utilization efficiency for water resources in Egypt is very low. Large amounts of irrigation water are being lost during water transmission from Aswan High Dam to fields. The recorded data indicated that the irrigation water at the Aswan dam has increased by about 20% from 2000 to 2009. However, losses during the transferring irrigation water from Aswan High Dam to fields due to evaporation and transpiration have increased by 30.90% and 35.46% in 1985 and 2005, respectively, and reached 33% in 2010. The efficiency of the field irrigation system is about 50% (http://iwtc.info/wp-content/uploads/2013/11/167.pdf).

Third, greenhouse production helps to meet the local market needs from the vegetables and ornamental plants. Besides supplying the local markets, the production of the greenhouse should be much valued for its export potential to play an essential role in the foreign trade balance of several national economies in Egypt. However, the intensification of greenhouse crop production has created favorable conditions for many devastating pests and diseases. This has significantly increased the need for pesticide applications. At the same time, legislative measures and standard requirements regarding the food safety of vegetables have become increasingly demanding. Food safety issues are the main barriers to export of produce to European Union countries according to the GLOBALGAP legislations (http://www.fao.org/3/a-i3284e.pdf). Over the last two decades, use of solar agricultural greenhouses has globally increased notably in developed countries. The primary objective of a greenhouse is to produce high yield and good quality yields during the non-cultivation season, which is possible by providing and maintaining optimal levels of light intensity, air temperature, and relative humidity at every stage of the crop growth. An appropriate air conditioning including heating and cooling systems can be equipped with the greenhouse for this purpose. These, as a result, will have significant impacts on the cultivation time, quantity, and quality of the products.

Fourth, biofertilizer technology has been in view promise for integrated nutrient management through biological N fix. (BNF). Biofertilizers may also be used for improvement P availability to field crops. The advantage of inoculants varies with inoculant type, formulation, crop species, soil nutrient level, the existence of relevant microbes in the soil, soil pH/type, and weather conditions. Many farmers and researchers have more widely discussed the beneficial impacts of organic mulches for field crop production. The literature provides robust and widespread evidence that compost fertilization contributes to multiple benefits to the soil-plant system. It improves and stabilizes soil functions and properties as there are long-term productivity including plant health, soil biodiversity, and transformation capacity and soil physical properties with all positive side effects of water and air household and contributes to a better performance in sequestering carbon in soil.

Fifth, following the construction of the High Aswan Dam, preparation of land reclamation schemes was in full swing. The debate on how this newly reclaimed land is going to be allocated was raised. The conclusion was that landless farmer should have a bite of the cake of 2.5 feddan. High school and university graduates were given larger parcels of 5–10 feddan. Small investors were given 20 feddan while large investors were given 100 feddan. On the other hand, cooperatives were given up to 1,000 feddan, and agricultural companies were given 1,000–5,000 feddan. However, only in very few cases, more than 500 feddan were allocated to an individual or to an entity. In the 1980s, President Sadat adopted the principle of "Land for the Reclaimer" which meant that whoever reclaims a piece of desert land, he will be the owner and the state will give him the title over this land. A large number of investors rushed into the business of land reclamation particularly on groundwater aquifers, and the situation in some locations became out of the authorities to control especially when these investors or some of them changed agricultural development into tourism or housing enterprise. Eventually, the state realized that small-scale farming is not the right solution to the country's food production and food security. Gigantic projects of huge size could attract large investors, bring about hi-tech, train young engineers and technicians, and employ people especially in the locations where unemployment is high.

Finally, Egypt started in 1986 to develop its irrigation systems via the so-called irrigation development project to apply the governance rules on the level of small irrigation called Mesqa and on the level of a branch canal too. To engage all stakeholders in the irrigation and agriculture system in Egypt, several water user associations on Mesqa and Branch Canal levels were developed, and the farmers (users) were trained. Demonstration irrigation canals owning to WUAs are being used to apply the activities of on-farm water management to demonstrate the benefits of good agriculture practices (GAP) to them. The final aim is to apply the best irrigation and agricultural practices to improve the productivity, incomes, and livelihood of WUAs that were accomplished because of participatory management, which increases agricultural production, water saving, and water productivity that reflects on national domestic production improvement performance. Different important aspects including legal status of water user associations on the branch canal, operation and maintenance of the sub-branch in partnership with water user associations, organizing (roles, responsibilities, and authorities) of water user associations to the branch canal, and training/technology transfer/communications and financial aspects are considered while applying the participatory irrigation management system.

Key Requirements of Egypt's Water Resources Bank
Lake Nasser is the main and the most important source of surface water for Egypt. In fact, it is the water resources bank of Egypt. Two main issues could be regularly measured, the quantity stored in the Lake and the quality of the water in the Lake.

For the quantity, the rating curves for the lake should be developed accurately. However, developing storage reservoir rating curves via the manual computationally labor-intensive methods needs an extensive field measurement and consumes time, effort, and money [31, 32]. Developing of the rating curves for Lake Nasser is, therefore, of utmost importance. Remote sensing (RS) and geographical information systems (GIS) approach for the development of the rating curves almost success to give volume/level and area/level relationships accurately. Moreover, this approach (RS/GIS) can overcome most such problems when generating the rating curves and estimating the capacity of Lake Nasser. In developing rating curves, various techniques have been proposed including artificial neural network, genetic algorithm with model tree [6], spreadsheet approach [33], combination of remote sensing (RS), digital elevation model, and in situ measurements technique, numerical hydrodynamic models, and altimetry data method.

The quality of the water in the Lake could be easily identified by monitoring the water quality parameters regularly at several locations and comparing the values by the Egyptian standards for irrigation water and for drinking water and could be also compared with the WHO standards. The chapter preceding this chapter presents the results of monitoring the water quality of the lake at several locations.

3 Conclusions

Throughout the development of the current book scheme, the editorial teams were able to draw several conclusions. Besides methodological insights, the chapter originates key lessons from the cases in the book, in particular, the promising characteristics of both the historical and current local food system. These conclusions are focused on conventional water resources and sustainability of agricultural environment to increase sustainable food supply in Egypt. These are discussed in the following in no particular order.

3.1 History of Irrigation and Irrigation Projects

Since the dawn of history, the Egyptians are always concerned about how to develop their irrigation system and how to improve this system to meet the ever-increasing demand for food and natural fiber. The last 200 years witnessed large alteration, promotion, and upgrading of the irrigation system through the introduction of new irrigation development projects. The Summer Canals Project was first implemented in increasing the storage capacity of floodwater as well as to replenish groundwater reservoirs by downward percolation. The construction of the Delta Barrages marked an important step toward the introduction of modern management. Although the excavation of the Suez Canal appears to be an essential transportation project, yet, it was accompanied by the vital water conveyance open channel to transport Nile water to the site of the Suez Canal Project.

The cultivation of land, the irrigation in soils, and the raising of the same crops for such an extremely long period without being affected by salinity, alkalinity, water logging, or any serious damages or injuries pose a very important question, that is, how can this happen? The answer would always be: this was only due to the application of the appropriate management of the water, soil, and plant systems and suitable but excellent prevailing climatic conditions.

The available water levels observations for the years 1992, 2000, 2006, 2009, and 2012 were used to develop rating curves for Lake Nasser using the RS/GIS techniques. The developed relationships have good accuracy with underestimation of 2% for the whole period 1992–2012. Moreover, the value of the coefficient of determination, R^2, is more than 0.99 for (volume/level) relationship and is more than 0.97 for (area/level) relationship. The obtained results indicated that the potential applicability and high efficiency of the RS/GIS techniques for developing rating curves. However, such relationships need an update from time to another, and consequently, field measurements are necessary from time to another to collect data for the needed data to update these developed equations. The authors are recommending the application of RS/GIS to develop the rating curves for the whole lake.

3.2 Key Features of Agriculture, Administrative, and Legal Framework in Egypt

The Egyptian situation is a special case, where Egyptians rely mainly on Nile water, accounting for more than 96% of Egypt’s total fresh water. Therefore, the Nile River – was and still – represents the backbone of Egyptian development in all its dimensions. Throughout the ages, Egyptians have developed various laws, policies, mechanisms, and institutions to manage water resources and to manage agriculture in Egypt.

The Egyptian government prepared several water policies to accommodate the dynamics of the water resources and crop productivity. The latest policy was issued in January 2005. It included several strategies to ensure satisfying the demands of all water users and expanding the existing agricultural area through reclaiming new land. Also, it gave farmers the chance to share in the different responsibilities concerning the water distribution system and drainage water reuse besides choosing their own crop pattern (http://iwtc.info/wp-content/uploads/2013/11/167.pdf).

In the agriculture sector, the agricultural, irrigation, and drainage investments have tended to increase year after year due to the launch of new land projects. Within this sector, it is clear that the private sector is playing an increasing role in agricultural investments. To provide food for Egypt's growing population, many achievements have been made to improve the agricultural production through technological advances, better utilization of agricultural resources, reusing drainage water, reusing of treated wastewater, improving water use efficiency, managing groundwater resources, reducing the area of rice cultivation, and developing a horizontal expansion area through reclaiming new lands.

3.3 Land Resources for Agriculture Development

Digital mapping of land resources is encouraged by the "progress of geographic information system (GIS) and data provided by satellite images." Such approaches may preserve investment spent in cataloging soil and another thematic mapping, as digital maps are more granted. Updating and manipulating digital thematic maps to be more accessible is also economically effective. Usage of digital maps and their attribute tables assists in decision support systems and may result in sustainable development project planning. The digital format of the soil map facilitates the linkage with the different software; this allows the integration of data for defining the optimum land uses of a studied region. The obtained results, extracted from the created digital Egyptian land resources database, recommend testing land capability and realizing the optimal land use.

One example illustrates that the potential areas for the groundwater development in Sinai were identified based on the aquifer hydrogeological characteristics and groundwater quality. The iso-salinity contour map of the aquifer shows a general increase of groundwater salinity toward the west and the north, with four salinity zones recognized as follows. Zone I have groundwater salinity <1,500 ppm. It occupies the area of the aquifer located south of the main road Joining Sudr El-Heitan, Nakhl, and Ras El Naqb within this zone. Zone II occurs to the east of the line joining Sudr El-Heitan-Nakhl, El-Bruk, El-Menashereh, El-Hassana, and El-Quseima, where the aquifer salinity ranged between 1,500 and 2,000 ppm within this zone and near the folded structures at El-Bruk, Gabal El-Menashereh, and Gabal Arif El-Naga. Salinity appears to be high due to the possible groundwater stagnancy around these highly elevated structures allowing for more dissolution of salts. Zone III is characterized by salinity ranging between 2,000 ppm and 5,000 ppm. It occupies a narrow zone surrounding Zone I and extends to Ayun Musa area in the west and Gifgafa north of Gabal El-Halal in the north. Zone IV occurs to the north of Zone III and has salinity in the aquifer ranging between 5,000 and 10,000 ppm. Zone V occupies the northern and western parts of Sinai where the aquifer has been deeply buried by faulting. The rather high salinity values in this zone (14,000 ppm–19,000 ppm) may be due to ineffective flushing of the formation's saline water by the recharging meteoric water due to the interruption of the groundwater flow paths by block faulting.

3.4 Food Insecurity due to Water Shortage and Climate Change

Climate change can have several kinds of impacts on the agricultural sector and stability of food security in Egypt. Crop production will be affected negatively due to the expected increases in temperature, extreme weather events, drought, plant diseases, and pests. Also, the land use will change due to flooding from sea level rise, seawater intrusion, and secondary salinization. Water resources may be affected due to global warming and decreases in precipitation. Moreover, crop water requirements are expected to increase. The confounding effect of all these components represents the main challenge for researchers.

Developing countries, such as Egypt, are the most threatened by the drastic impact of climatic changes on agriculture and food security. One of the main challenges facing water management in Egypt is the expected impacts of climate change on the Nile flows and the different demands of the water sector. This, in turn, will directly affect the agricultural sector, which is a key sector for the socioeconomic development in Egypt and plays a significant role in the Egyptian national economy. Climate change, population growth, and economic development will likely affect the future availability of water resources for agriculture in Egypt. The demand and supply of water for irrigation is expected to be influenced not only by changing hydrological regimes but also by concomitant increases in future competition for water due to population and economic growth.

The water shortage in Egypt exceeds 30 BCM/year with Egypt's water share per capita being 674 m/year. This severe shortage of water resources and arable land in addition to the growing population are one of the reasons why Egypt is one of the largest food importers in the world. Egypt is the biggest importer of wheat (12 million tons/year), fourth importer of maize at 8.5 million tons/year, and the seventh biggest importer of edible oils in the world, with a gap, which reached 100% of lentil, 70% of broad bean, 32% of sugar, and 60% of red meat, butter, and milk powder. There are several impacts of food and water insecurity and socioeconomic impacts such as the soaring price of food and small and tiny farm. More than 80% of land tenures and ownership are less than 0.8 ha in addition to very low share land per capita not exceed 0.14 acre and continuous increase in the poverty rate, which reached 27.8% at the end of the year 2016. To deal with this food insecurity, Egypt counts on major reclamation projects for an addition of more than 1 million acres as an extension to the present agricultural land located in North Sinai, at Toshka in the southwest valley, and the Oweinat project in the far south of the western desert near the border with Libya.

3.5 Assessment of Water Resources

The present chapter aims to evaluate the groundwater conditions to determine the sustainability of the groundwater resource, the expected changes in groundwater levels, the amount of recharge, and the suitable discharge from the groundwater for irrigation of 25,500 feddan based on the safe yield of 100 years from 102 wells and changes in water quality. Safe water use of groundwater for a 100 years is 1,007 m^3/day from each well working 8.4 h/day at 120 m^3/h, to provide 1,500 m^3/feddan/year for a total 25,000 feddan or 3,000 m^3/feddan/year for 12,500 feddan, etc. This means that the concerning authorities have to decide carefully the area to be reclaimed and crop based on the availability of the water production of the wells taking into consideration the climatic conditions. The expected lowering in the groundwater level after 100 years is 15 m. The salinity ranges from 480 to 1,200 ppm with an average of 648.5 ppm.

The temperature and nutrient availability during the summer seemed to give higher productivity in both irrigation and drainage water. There was evidence for heavy organic pollution through the presence of pollution-tolerant algal taxa; also, there were many species that were tolerant to Eutrophication. In this work, besides the observation of phytoplankton communities' fluctuations, a phytoplankton checklist was established for irrigation and drainage water of the Middle Nile Delta so that it can be used as environmental bioindicators and other probable applications. Palmer index was used to evaluate the organic contamination in the studied water bodies. Organic pollution in summer was higher than that of winter. In general, pollution increased along the water pathways from southern to northern direction.

3.6 Impacts of GERD and Tekeze Dams on Egypt's Water Resources

The construction of water projects in the Nile Basin region in Ethiopia has produced political tensions between Egypt and Ethiopia over the construction of Tekeze in 2009, the Tana-Beles diversion in 2010, and the under-construction Grand Ethiopian Renaissance Dam (GERD) that has started in April 2011. Ethiopia has great potential to generate hydropower electricity, but it faces geological and environmental challenges to establish major water projects especially in the area located within the Nile Basin to store water due to:

1. Spatial and temporal variations of the heavy rainfall. The concentration of as much as 75% of rainfall in a short rainy season (3–4 months) is followed by the dry spell.
2. High evaporation that averages 85%.
3. The dissected nature of the landscape, high relief, and steep slopes.
4. Rock types that are mostly fractured basaltic rocks (50%), Precambrian metamorphic rocks (25%), and soft rocks of jointed cavernous limestone (25%), causing water leakage.
5. Severe water erosion degradation and associated siltation in the surface water reservoirs, decreasing the water storage capacity.
6. Geologic tectonics and common earthquakes due to the activity of the African Rift that bisects Ethiopia.
7. Landslides triggered by heavy rainfall, steep slopes, thick hard rock underlain by clay, fractured rocks, common earthquakes, and deforestation.

Tekeze Dam was built in a canyon surrounded by steep topography; landslide and high rate of sedimentation are already a problem. Analysis of ASTER DEM of the Tekeze River basin showed that it has a dendritic pattern. Tekeze reservoir area is 155 km^2 at 1,140 m amsl with a volume of 9.3 km^3. Egypt and Sudan lost 4 km^3 in 2008 and 2009 in addition to an annual loss estimated at 200–700 Mm^3.

Many scenarios were conducted to predict the optimum filling scenario of the Grand Ethiopian Renaissance Dam (GERD) to minimize these impacts on downstream countries. Simulating results show that the live water storage in AHD will reach its minimum with the minimum water level of 147 m by the end of 5 years of filling period of the full storage capacity of GERD (74 BCM). Scenarios of changing GERD's filling period and GERD filling storage capacity have been conducted, and their effect on agriculture has been sensed. Scenario results show that decreasing the water supply required for agriculture will cause a high loss in income especially in case of 5 years filling period of GERD. Therefore, increasing filling period to at least 10 years is a solution, or the other solution is the reduction of the GERD storage capacity to minimize downstream impacts on AHD. However, this will not eliminate the impacts but will just relief them. The net loss in the return of each crop was computed for all scenarios to enable the decision takes to plan for the future for the different scenarios.

3.7 Sustainable Use of Water Resources and Future of Mega Irrigation Projects

Due to the increasing population that is facing Egypt at present, many challenges lead to the very low per capita water per year. To alleviate the suffering resulting from the limitation of water resources, they must apply all possible techniques to improve water use efficiency under this aridity condition. There are some sustainable techniques proved positive impacts on raising and improving yield and water productivity. Also, these techniques are friendly with the environment including (1) biofertilizers, (2) organic mulching, and (3) application compost. Also, to alleviate water shortages in Egypt, action is needed in order to conserve and manage water resources.

There are many ways to increase water use efficiency, such as improving irrigation canals in old land to increase the conveyance efficiency; using a pressurized irrigation system in new reclaimed lands, in addition to water management practices on farm like laser land leveling; using the raise bed irrigation method, irrigation scheduling, intercropping, crop intensification, and mulching; using soil amendments and organic fertilizers; and using short and drought tolerance varieties. The integrated management for soil, water, and crops is very important to maximize crop yield and water productivity. Therefore, water users should seek to maximize crops yield with minimal water use.

Crop water consumption has to be estimated with a high level of accuracy to save water and to maximize water unit uses. The limitation of water resources and scarcity of water in arid and semi-arid regions put many countries in a critical situation. Dealing with water shortage must be planned, and good models were needed to estimate water consumption. Space-borne technologies are a good and powerful tool but need calibration and validation. Maybe in the future, it may be a stand-alone technology, but in the first, we must deal with it using a new method. It must have its own methodologies.

Increased user participation in planning, operation, maintenance, and management of branch canal irrigation unit was the desirable goal. The formation and establishment of water user associations at the branch canal level have proven to be a viable, highly desirable means of intensifying farmer participation in irrigation management for water use and agriculture. Management capabilities and capacities at this level have to be supported and improved as water supplies become more constrained and the innovation of continuous flow availability is advanced to larger areas of the system. Willingness on the part of users to assume part of the operation and maintenance costs, in the form of time, labor, and finances, is shown to reduce government costs in operations and maintenance and will affirm that eventual management transfer can be successful in the future. It is recommended to extend the improvement of the irrigation practice by applying the rest of the governance principles to the irrigation and agricultural management.

Throughout history, Egypt changed several times from small-scale farming to medium-size farms and eventually to mega agricultural projects. As Egypt is looked as one of the countries that is suitable for small and even minute industries, the country is again suitable for small-scale farming. Large-scale farms were not accepted socially due to the vast gap between extremely large landlords and impoverished majority of small-scale farmers. Attempts to attract capital investment (local or foreign) appear to be not very much satisfied. The main reason for that is the fact that agricultural enterprise is long-term, modest return business. In the meantime, 50% of the population of Egypt is connected in one way or the other to agriculture. They have to have jobs available or to sit unemployed. Mega agricultural projects have not yet proved to be successful.

Egypt has established a national mega project for the establishment of 100,000 acres of greenhouses during the next few years. This project needs a lot of infrastructure, materials, manufacturing, and labor and technicians. Management of 100,000 acres greenhouses will need properly qualified advisors and properly trained staff. There are a limited number of advisors and proper technician in Egypt because many good advisors and technicians left to work for in gulf countries due to better salaries provided. There is an urgent need to prepare a new generation of advisors and technician in a short period.

4 Recommendations

A key aspect of sustainable water resources is the ability to adapt to future challenges. We argue that sustainable systems need built-in flexibility to achieve this goal. Throughout the course of this book project, the editorial teams noted some areas that could be explored to further improvement. Based on the authors' findings and conclusions, this section presents a set of recommendations and suggestions for future researchers in exceeding the scope of this volume.

- More effort should be done to design a cropping pattern map, according to specific crop pattern suitable for the available water.
- Activate the role of water user associations for providing the farmers with the necessary information about water saving, crop water productivity, and technology.
- Support the role of scientific research to introduce new agricultural technologies that have high productivity and low water consumption.
- Encourage horizontal expansion to increase cultivated lands and plant yields within the accessible amount of water resources.
- Shifting to less water demanding crops (e.g., rice and sugarcane areas) and gradually introducing crops consuming less water with the use of genetic engineering to produce crops with lower water requirements.
- Improve the efficiency of the existing irrigation networks in the old and new land to achieve maximum utilization of irrigation water by reducing losses, detecting leakage, and improving irrigation distribution and conveyance efficiency.
- More emphasis should be placed on the importance of selecting new strains and varieties of different crops that tolerate diseases, drought, and salinity.
- Continuation of the policy of reuse of agricultural drainage water for irrigation.
- Enhancement of the private sector in participation in management and operation of the water resources and raising the public's awareness of the water scarcity problems.

- Establish a well-coordinated information system to support decision-makers in water resources management.
- Intensify the government's efforts to reduce the population growth rate.
- Digital mapping of land resources is encouraged by the "progress of geographic information system (GIS) and data provided by satellite images." Such approaches may preserve investment spent in cataloging soil and another thematic mapping, as digital maps are more granted. Updating and manipulating digital thematic maps to be more accessible is also economically effective. Use of digital maps and their attribute tables assists in decision support systems and may result in sustainable development project planning. The digital format of the soil map facilitates the linkage with the different software; this allows the integration of data for defining the optimum land uses of a studied region.
- Studying the dynamic interactions of land and water regionally and globally is necessary to offer more reasonable predictions of both irrigation water efficiency and cost as a function of water scarcity; these studies should include challenges faced by other sectors.
- There is a need for a parallel implementation of adaptation strategies and mitigation actions in order to diminish the negative effects of climate change on human activities and ecosystems. Society must learn to respond to climate change pressure over the approaching decades.
- Collecting regular information about the ecosystem (phonological observations, inventories of land use per species, production statistics, etc.) and their development over the preceding few decades on a large scale is needed to understand the effects of climate change on cultivation and forestry and also to improve our understanding of certain mechanisms.
- Analyzing the comprehensive series of climatic data on national territories over a period extending from the end of the nineteenth century to the present day is an important thing. It is necessary to complement these data by phonological series coming either from observations of the natural vegetation or forest species or from the cultured species, especially the perennial species (fruit trees, vines, etc.). There must be a quick adaptation of cultivation to meet the challenge of maintaining food security. Although there are a countless number of strategies for doing so, one of these strategies is taking the benefit of the extra CO_2 put into the Earth's atmosphere.
- To deal with this food insecurity, Egypt counts on major reclamation projects for an addition of more than 1 million acres as an extension to the present agricultural land located in North Sinai, at Toshka in the southwest valley, and the Oweinat project in the far south of the western desert near the border with Libya. Agriculture-related policies in Egypt should be reformed to plan and advance increased food production especially the essential crops such as wheat, maize, sugar, lentils and broad bean, oilseed, meat, and dairy products. Moreover, Egypt should make serious efforts to find new sources of water to combat water shortage, which may include untraditional sources such as desalination of seawater, treated sewage and treated industry water, and reclaimed agricultural drainage water, and also develop and renovate the whole agricultural system.

- The restructure of agriculture policy in Egypt could perform a great part of food security in Egypt within a short time. Moreover, the projects of land reclamation and agriculture extension which targeted 1.5 million acres could help so much in decreasing food gape in Egypt.
- It became necessary to use the phytoplankton analysis as an environmental monitoring procedure for the organic pollution more than the regular methods. Developing checklists and special indices are required to facilitate the task for the fast analysis and revealing the aquatic environmental crime and the presence of dangerous blooming with harmful toxins.
- Failure of water projects in Ethiopia is mainly due to geological, technical, and lack of studies. Technical and environmental studies should be done before construction. Further studies are required for Tekeze Dam such as leakage of water from its reservoir, the rate of sedimentation, and water quality of the reservoir. The social, environmental, and economic impacts on the downstream countries, Egypt and Sudan, have not been completed yet. East Nile basin countries (Egypt, Sudan, and Ethiopia) should cooperate in the reservoir operation to maximize the benefits for Ethiopia and minimize the harmful impacts of the Tekeze Dam on Egypt and Sudan.
- Crop water consumption has to be estimated with a high level of accuracy to save water and to maximize water unit uses. Space-borne technologies are a good and powerful tool but need calibration and validation. Maybe in the future, it may be a stand-alone technology, but in the first, we must deal with it using a new method. It must have its own methodologies.
- Remote sensing techniques are powerful on the large scale if used after calibration and validation. Developing the old methods of calculation, the irrigation water consumption is necessary for estimation accuracy. Numerous of ET calculation models are so complicated, and it needs to be simplest.
- The expansion of improvement on the surface irrigation system in the old agricultural land through improvement of Mesqas and Marwas. Moreover applying on-farm practices causes an increase in water use efficiency as laser land leveling, raised beds, alternate furrow irrigation, deficit irrigation, surge irrigation, irrigation scheduling, and reducing irrigation water losses during nights and weekends.
- The spreading use of pressurized irrigation systems as sprinkler and trickle in newly reclaimed land and desert. In addition, applying on-farm practices as irrigation scheduling, night irrigation, and partial root-zone drying for drip irrigation.
- Improving water harvested techniques in rain-fed areas in the North West coast area and using these harvested water in supplemental irrigation on critical crops physiological stages.
- The expanding use of non-conventional water resources as desalination of seawater and reusing of drainage water and groundwater under integrated water management for sustainable agricultural.

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