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Deficit Irrigation

A Remedy for Water Scarcity

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We would like to dedicate this work to all our professors who supervised us in our early stages of education and career. These professors guided and assisted us until we reached this stage of our working life. Some of them passed away and the others are still among us generously contributing with their great knowledge to bring out generations of scientific excellence.

Of these professors, we dedicate this work to the souls of Prof. Hamadah Abd El-Maksoud and Prof. Ahmed Said Kamel (both from Agricultural Research Center).

We also dedicate this work to Prof. Hamdy Khalifa (Agricultural Research Center), Prof. Nemet Nour El-Din (Faculty of Agriculture, Ain Shams University), and Prof. Mahmoud Saif Osman (Faculty of Agriculture, Al-Azhar University).

Finally, we dedicate this work to all our colleagues who supported us physically and emotionally.

Preface

Agriculture is the largest freshwater user on the planet. It consumes more than two thirds of total withdrawals. A general perception has been existed worldwide that agricultural water as the major user is often wasteful and has less value, compared to other uses. In addition, freshwater shortage is becoming critical in the arid and semiarid areas of the world. Consequently, freshwater resources available to agriculture will need to be re-rationalized to satisfy the developmental needs of other sectors. Sustainable irrigation water management should be applied using practices that improve crop yield and minimize non-beneficial water losses. Deficit irrigation application could be very useful strategy to reduce the demand for water in the agriculture sector. In this strategy, under-irrigating a crop is deliberately done, where its irrigation water supply is reduced relative to that needed to meet its maximum evapotranspiration. Although this practice normally involves yield losses, it increases water use efficiency.

One might wonder whether application of deficit irrigation can contribute in increasing food availability. Although application of deficit irrigation involves loss in crop productivity, it also secures water to be used in cultivating more lands. However, on national level in Egypt, would the production resulted from the new added area could compensate the yield losses attained by application of deficit irrigation.

In this book, we answer the above question and shed the light on the role of deficit irrigation in securing food under water scarcity. We assessed the potential effect of application of deficit irrigation to four winter crops grown in Egypt, namely, Egyptian clover, sugar beet, onion, and tomato. These four crops have a surplus in their production. We also assessed the possibility of saving an amount of irrigation water from these four crops and use it to cultivate new areas with wheat. Wheat is an important crop in Egyptian daily diet and has the major food production-consumption gap.

Chapter 1 provided an overview on the interrelation between water scarcity and food production. The chapter discussed several concepts related to food production, namely, water scarcity induces water stress, deficit irrigation and water scarcity, climate change, water scarcity and food security, as well as climate change and agricultural soil.

In Chap. 2, we tackled some of the concepts and definitions used in application of deficit irrigation instead of full irrigation as a technology aims at conserving irrigation water. Both water use efficiency and water productivity are important estimators in the assessment of the effect of deficit irrigation. This chapter also reviewed deficit irrigation strategies, which consist of sustain deficit irrigation, regulated deficit irrigation (stage-based and partial root zone irrigation), and subsurface drip irrigation. The hidden role of intercropping systems in irrigation water conservation was also discussed.

Chapter 3 provided an overview of the situation of Egypt with respect to its natural resources. It discussed the climate of Egypt and its relation to the growing season of cultivated crops and water requirements of these crops. It also presented the quantity of water resources, the management of irrigation water, and irrigated agriculture, as well as its food production, and reviewed soil resources in Egypt and population pressure on land and water resources. This chapter also tackled the issue of food gaps in Egypt. In addition, it reviewed the previous research done on the application of deficit irrigation to monocrops and to intercropping systems.

Chapter 4 provides quantification of the effect of the application of deficit irrigation to Egyptian clover and sugar beet cultivated on raised beds to reduce the amount of applied water to raised beds to be lower than full irrigation. Five production alternatives were quantified on governorate level, namely, traditional cultivation, raised beds cultivation, application of deficit irrigation, calculation of production without investing the saved water in adding new area, and calculation of production with investing the saved water in adding new area. Water productivity was calculated under all the suggested alternatives.

In Chap. 5, an assessment of the potential effects of applying deficit irrigation to onion and tomato grown on raised beds on its production was done. Five production alternatives were quantified on governorate level, namely, traditional cultivation, raised beds cultivation, application of deficit irrigation, calculation of production without investing the saved water in adding new area, and calculation of production with investing the saved water in adding new area. In all alternatives, water productivity was calculated.

Chapter 6 tested whether implementing different production alternatives will contribute in increasing wheat national production and increase its self-sufficiency ratio. Data on the cultivated area and productivity of wheat were collected for both old and new lands on governorate level, and weather data in 2017 and water requirements were calculated. Also, Egyptian population data and data on the cultivated area of winter tomato, sugar beet, cotton, fruit trees, and sugarcane were collected. Five production alternatives were quantified on governorate level, namely, traditional cultivation, raised beds cultivation, application of deficit irrigation, implementing intercropping systems with wheat, and using the saved water from application of deficit irrigation to Egyptian clover, sugar beet, onion, and tomato to cultivate new area with wheat. Under all alternatives, self-sufficiency ratio and water productivity were calculated.

In Chap. 7, a review of all the previous climate change studies in Egypt on water resources, crops production, evapotranspiration, seasonal crop coefficients, water consumptive use and water requirements of crops, cultivated soils and areas, suitability of growing area to be cultivated with a certain crop, and food gaps using 67 papers found on the Internet to cover these items is presented.

Chapter 8 assessed the effect of climate change in 2030 on wheat cultivated area and total production under five production alternatives, namely, traditional cultivation, raised beds cultivation, application of deficit irrigation to wheat grown on raised beds, implementing wheat intercropping systems, and using the saved irrigation water from other winter crops to cultivate new lands with wheat. Our aim was to produce more wheat seeds to increase its self-sufficiency.

We spent about 14 months to put this book in its final format. I hope this book will help researchers and policy-makers in their future planning and to be a base for more research to provide more knowledge.

Giza, Egypt
March 10, 2019

Samiha Ouda
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Contents

Chapter 1
Water Scarcity Leads to Food Insecurity

Samiha Ouda and Abd El-Hafeez Zohry

Abstract This chapter provides an overview on the interrelation between water scarcity and food production. A general perception has been existed worldwide that agricultural water, as the major user, is often wasteful and has less value, compared to other uses. Additionally, water scarcity became more acute in many part of the world. Thus, there is a need to manage water resources more efficiently to produce more food with the same amount of water. Although irrigation is important to attain stable food production, over-irrigation is prevailing in many areas worldwide and it has many disadvantages. On the contrary, under-irrigation with less than crop water requirements causes stressful conditions to the growing plants leading to lower yield and consequently food insecurity. One of the effective water management practices is deficit irrigation application. It can use water resources more efficiently in the agricultural sector. It can maintain reasonable levels of production and it could improve yield quality. One might wonder whether application of deficit irrigation could contribute in increasing food availability. Although application of deficit irrigation involves loss in crop productivity, it also secures water to be use in cultivating more lands. However, on national level, will the production resulted from the new added area can compensate the loss attained by application of deficit irrigation. In this book, we answer the above question and shed the light on the role of deficit irrigation in securing food under water scarcity. We also tested whether deficit irrigation practice could positively contribute in reducing the loss in production of crops under the impact of climate change in 2030.

Keywords Water stress · Irrigation water management · Deficit irrigation · Climate change and food production · Climate change and agricultural soils

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1.1 Introduction

Demand for food was increased due to an exponential rise in population between 1961 and 2000 (Keating et al. 2014). In addition, food shortage is a problem facing over-populated developing countries. These countries need to double food production to meet the growing demand of food (FAO 2009). Thus, scientific and technological advances, institutional intervention, government policy, business investment and innovation should joint together to meet the demand for food (Keating and Carberry 2010). A second green revolution targeting nutrients and water use efficiency is one of the proposed solutions to meet the increase in food demand and tackle food scarcity in upcoming decades (Blum 2009). Furthermore, Foley et al. (2011) suggested solutions to food security that taking advantage of the advances in agriculture and reducing waste, whilst addressing shifting diets, enabled a doubling in agricultural production and a reduction in environmental impacts. Food wastage reduction, both food loss and waste, provide an opportunity to capturing more of the food that is produced for human consumption, which will help in increasing food security without increasing the environmental burden of production (Cole et al. 2018).

The concept of food security is based on three main pillars, food availability, food accessibility and food stability. Agriculture is concerned about food production and availability. Consequently, crops production is restricted by the availability of water, where water supply in irrigated agriculture is often the most critical factor limiting crop growth and yield. Maximum or potential crop yield is limited by climate and crop cultivar, assuming all the other factors affecting crop growth and yield are optimal (Karmakar et al. 2016). Consequently, environment deterioration arose as result of increased farm inputs and outputs in their attempts to increase food production. Moreover, farmers often achieve far less than 50% of the climatic and genetic yield potential for a given sowing date, cultivar choice and site (Karmakar et al. 2016)

1.2 Food Production Depends on Water Availability

Although 70% of the surface of the Earth is covered with water (Siddique and Bramley 2014), only about 2.5% is fresh water (Gleick and Palaniappan 2010). The majority of these amounts of water are trapped in glaciers, permanent snow, or aquifers (Farihi et al. 2013). The fresh water is divided in two types of resources: renewable and non-renewable water resources. Groundwater and surface water, such as the average flow of rivers on a yearly basis, are considered renewable water resources, whereas deep aquifers are considered non-renewable water resources (FAO 2003). Agriculture is the largest fresh water user on the planet, consuming more than two thirds of total withdrawals (Gan et al. 2013) and fresh water shortage is becoming critical in the arid and semiarid areas of the world (Forouzani and Karami 2011). A general perception has been existed worldwide that agricultural water as the major user, is often wasteful and has less value, compared to other uses (Jury and Vaux 2006). Furthermore, irrigation consumes a significant amount of energy, compared to other operations (Topak et al. 2010). In addition, rapid urbanization has caused conflict between the need for freshwater in agriculture and other sectors. Consequently, fresh water resources available to agriculture will need to be re-rationalized to satisfy the developmental needs of other sectors (Chai et al. 2016). Increasing the effective use of water resources in many parts of the world is required to enhance food security, where availability of water for food production becomes more acute (FAO 2012). Globally, 40% of annual food production comes from irrigated land, which consumes 70% of all fresh water withdrawals (FAO 2007).

Applying irrigation to cultivated crops is crucial to attain stable agricultural production, where the supply of water to crops done by artificial means. Irrigation also aids crop intensification and diversification in dry land areas thereby permitting multiple cropping per year (two to four crops) (Vlek et al. 2008). Furthermore, other intensification inputs, namely fertilizers and agricultural chemical are provided by irrigation (Kögler and Söffker 2017). Surface irrigation is still the most widely used technique despite its relatively poor application efficiency, which may cause water logging. Water logging is the saturation of the root zone with water that leads to reduced aeration, nutrient uptake, crop growth, and yield, carbon dioxide accumulates to a toxic level results in crop failure (Vlek et al. 2008). Furthermore, current rates of agricultural water use are unsustainable in many parts of the world, generating an urgent need to improve its management strategies (Lopez et al. 2017). Thus, irrigation water management in the current era of water scarcity need to be conducted most efficiently, aiming at saving water and maximizing its productivity (Johnson et al. 2001).

The sustainable water management concept refers to all practices that improve crop yield, and minimize non-beneficial water losses (Johnson et al. 2001). Additionally, improving irrigation water use efficiency, namely the ratio of consumed water to crop yield (Stanhill 1986), and water productivity, namely the ratio of applied water to crop yield (Kumar et al. 2010) are significant to attain the sustainability of water resources. This goal could be achieved through improved management practices on farm level using appropriate methods of irrigation scheduling. Irrigation scheduling is a process used to determine the amount of water applied to the crop and the timing for application; as it determines seasonal irrigation volume and crop yield (Fernandez and Cuevas 2010). Tanner and Sinclair (1983) stated that the primary aim of irrigation scheduling is to minimize wasteful losses of water (percolation beyond what is necessary for salt leaching, surface runoff and evaporation) and maximize transpiration, which is the beneficial loss of water due to its direct link with dry matter production. Thus, efficient irrigation scheduling aims to supply the crop with enough water to ensure optimum production while minimizing water loss and nutrient leaching (Fernandez and Cuevas 2010).

1.3 Water Scarcity Induces Water Stress

Water stress can be defined as the absence of adequate moisture necessary for normal plant growth to complete its life cycle (Zhu 2002). The lack of adequate moisture that leading to water stress is a common occurrence in rain fed areas, brought about by infrequent rains and poor irrigation (Wang et al. 2015). Similarly, in irrigated agriculture water stress could be also induced by water scarcity. Water stress affects every aspect of plant growth, including anatomy, morphology, physiology, and biochemistry (Zhu 2002). Decreasing water availability under drought generally results in limited nutrients uptake (Davari 2016). Another important effect of water deficit is the reduction of nutrient acquisition by the root and its transport to shoots (Farooq et al. 2009). Lowered absorption of the inorganic nutrients could result from interference in nutrient uptake and the unloading mechanism, which reduces transpiration flow (Garg 2003). Influence of drought on plant nutrition may also be related to limited availability of energy for assimilation of nitrate, phosphate, and sulfate (Baligar et al. 2001).

Under water stress, plants close their stomata to prevent dehydration, thus drastic reduction in transpiration rates occur (Taiz and Zeiger 2004), and production of abscisic acid increases by as much as 50-fold in leaves, which decreases leaf area due to lower-turgor-pressure cells, stomatal closure, the induction of senescence and ethylene production (Taiz and Zeiger 2013). Water stress also affects many important biochemical processes such as osmotic adjustment, antioxidant enzyme defense system, abscisic acid production, and lipid peroxidation (Sarto et al. 2016). The increase in Si in the plant can increase the efficiency of water use by some grasses (Sarto et al. 2017).

Under severe stress, the dehydration in mesophyll cells inhibits photosynthesis and water use efficiency decreases as a result (Taiz and Zeiger 2004). A reduction in water availability in plants leads to the reduction of cell solutes thus increasing the solute concentration. This causes the plasma membrane to become thicker, affecting the turgidity processes of cells, reducing the leaf area and causing stomatal closure. This results in a reduced rate of photosynthesis, influencing the plant development (Dias 2008).

At present, nearly 80% of the world's population is exposed to high levels of threat to water security (Bunn 2016). The misuse of water resources (Ouda and Zohry 2018a), and the lack of infrastructures to supply water (Abou Zeid 2002) are some of the main reasons for scarcity of water. Many parts of the world experience acute water scarcity and that requires increasing the effectiveness of agricultural water resources usage and reduces the excessive irrigation for enhanced food security (FAO 2007). To cope with water scarcity without reducing the irrigated area, different options are available. One of these options is better forecasting of soil moisture and requirement of crops for water through combining weather predictions and hydrological modeling, supported by data using new technologies for environmental monitoring and Earth observations from space (Ravazzani et al. 2017).

Another option could be done, namely cultivation of short season crops. In Egypt, this practice was successful in saving large amounts of water, where short season rice cultivars replaced long season cultivars resulted in water saving by 15% (Abd El-Megeed et al. 2016). MacDonald et al. (2017) reported that developing new farming systems could intensify land and water use. Said et al. (2016) indicated that implementing intercropping systems, where two crops share the area and the applied water to one of them is another alternative to cope with water security. Furthermore, reducing non-productive water consumption, through improved crop water management, use of techniques to reduce soil evaporation, capture surface run-off, and improve soil infiltration capacity and efficiency of irrigation systems could help in expanding irrigation and increasing food production (Cole et al. 2018). It is necessary for irrigation management in these areas to shift from emphasizing production per unit area towards maximizing the production per unit of water consumed, which is called water productivity (Rekaby et al. 2016). All that will improve agricultural water practices and lead to gains in global crop production. Not only scarcity in water quantity is becoming obvious, but also in quality, where is become to be obvious in regions where rainfall is abundant too (Capra et al. 2008).

1.4 Deficit Irrigation and Water Scarcity

Deficit irrigation application can be very useful in reducing the demand for water in the agriculture sector. Deficit irrigation is the practice of deliberately under-irrigating a crop, where its irrigation water supply is reduced relative to that needed to meet its maximum evapotranspiration (English and Nuss 1982). Another terminology for deficit irrigation is the application of irrigation below the full crop evapotranspiration, which potentially improve efficiency and maximize profits through a reduction in capital and operating costs (Capra et al. 2008). Kögler and Söffker (2017) indicated that deficit irrigation is a crop cultivation practice allows saving up to 20–40% irrigation water with yield reductions below 10%, leading to more efficient water use. However, conducting deficit irrigation by increasing the duration between irrigation intervals or by omitting one or more irrigation event could causes several negative effects on growth and reduces yield (Zhu 2002). The knowledge of crop water use and its response to water deficits should include identification of critical crop growth stages and the impacts on yield (Oweis and Hachum 2003).

Adopting deficit irrigation principles implies the acceptance of a certain level of reduction in yield level (Hamdy et al. 2005). As long as that certain level of yield reduction is low, there is a high possibility that farmers will adopt it. The saved irrigation water from application of deficit irrigation could be used to irrigate new lands to produce more crops and compensate for the loss in productivity. There are several basic recommended deficit irrigation strategies that minimize yield losses. Sustain deficit irrigation; in which reduced amount of irrigation is applied during all the growing season (Fernandes-Silva et al. 2018) is one of these strategies. Regulated deficit irrigation is another strategy contributes in water saving and low yield losses (Capra et al. 2008). This strategy is divided into stage-base deficit irrigation and partial-root system irrigation (Chai, et al. 2016). Moreover, precise irrigation scheduling is crucial for regulated deficit irrigation, which aims to induce a mild water stress to the plant to save water and improve crop yield (Jones 2004). Maintaining optimum crop yield under water deficit conditions has stimulated researchers to explore new irrigation technology, systems, and strategies to improve water use efficiency and water productivity (Fernandes-Silva et al. 2018).

1.5 Climate Change, Water Scarcity and Food Security

Global and regional climates have already begun changing. Climate change is directly or indirectly attributed to human activity that alters the composition of the global atmosphere, in addition to natural climate variability observed over comparable time periods (Karmakar et al. 2016). The models that describe global climate are mathematical representations of physical and dynamical processes to simulate the interaction within and in between the atmosphere, land surface, oceans and sea ice (Dettinger 2005). IPCC (2007) reported that “the global atmospheric concentration of carbon dioxide, methane and nitrous oxide has increased from pre-industrial era to 2005. The annual carbon dioxide concentration growth rate was larger during the last 10 years’ average (1995–2005, 1.9 ppm per year), than it has been since the beginning of continuous direct atmospheric measurements (1960–2005, average 1.4 ppm per year) although there is year-to-year variability in growth rates”. In order to limit global warning in 2100 to 2 °C above pre-industrial levels, annual emissions from the agricultural sector must be reduced by 1 giga ton of carbon dioxide equivalents per year by 2030 (Wollenberg et al. 2016). Currently available interventions, such as sustainable intensification of dairy production and alternate wetting and drying in irrigated rice to achieve emission efficiencies will be necessary, as well as innovative policies to promote sequestering soil carbon (Cole et al. 2018).

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2013) stated that “the magnitude of stress on water resources is expected to increase as a consequence of climate change, in addition to future population growth and urbanization as a consequence of land-use change”. According to the scenarios described in the IPCC Special Report on Emissions Scenarios, changes in precipitation and temperature may lead to changes in runoff and water availability (Cisneros et al. 2014). Previous research projected that climate change will intensify and accelerate the hydrological cycle, which will result in more water being available in some parts of the world and less water being available in other parts of the world (most of the developing world) (IPCC 2013). Weather patterns are predicted to be more extreme. The regions adversely affected by climate change will experience droughts and/or possible flooding, which could affect food production

(Elsaeed 2012). Moreover, as a result of sea level rise, intrusion of saline water in low coastal areas could occur, which will influence the quality of fresh water aquifers (Bates et al. 2008). The combined effect of higher temperature and the reduction of water availability in regions affected by falling precipitation could result in an increase of crop evaporative demands, following by reduction in crop yield, where temperature restrains crop growth (FAO 2005).

The UNEP (2013) reported that climate change will affect the extent and productivity of both irrigated and rain fed agriculture across the globe, increasing crop water demand and decreasing crop productivity in many regions. FAO (2012) predicted that by 2030, the world population will grow beyond 7.5 billion inhabitants, which will have a significant impact on water usage for food. They also predicted that food demand will increase by 50% and water use in irrigation will increase by 30%. In Egypt, Alkitkat (2017) projected that the Egyptian population in 2030 will increase by 32%, compared to the population value recorded in 2014. Accordingly, the demand for food is expected to increase. For example, the demand for wheat is expected to increase by 53% (Ouda and Zohry 2017), for maize by 40% (Zohry and Ouda 2017a) and for faba bean by 68% (Zohry and Ouda 2017b). Furthermore, de Fraiture and Wichelns (2010) indicated that, under a pessimistic low yield scenario in 2050, water consumption by the crops will increase by 53% and lands needed to achieve food production goals will increase by 38%.

1.6 Climate Change and Agricultural Soil

Soils has a major role in supplying macro and micro nutrients to all kinds of crops grown in it, thus they are important for food security. Because climate is one of the most important factors affecting the formation of soil, climate change could result in soil deterioration (Karmakar et al. 2016) and consequently it has the potential to threaten food security through its effects on soil properties and processes (Pimentel 2006). Increased temperature is likely to have a negative effect on carbon allocation to the soil, leading to reductions in soil organic carbon and creating a positive-feedback in the global carbon cycle (Wan et al. 2011). Increased temperatures lead to increased carbon dioxide release from soils to the atmosphere leads to more increases in temperature (Cole et al. 2018). Rising atmospheric carbon dioxide levels, elevated temperature, altered precipitation and atmospheric nitrogen deposition caused by climate change, affect soil chemical, physical and biological functions (IPCC 2007).

A decline in soil organic matter levels lead to a decrease in soil aggregate stability, infiltration rates and increase in susceptibility to compaction, run-off and susceptibility to erosion (Gorissen et al. 2004). Furthermore, increased salinization and alkalization would occur in areas where evaporation increased or rainfall decreased (Varallyay 1994). Transient salinity increases as capillary rise dominates, bringing salts into the root zone on sodic soils. Increased subsoil drying increases concentration of salts in the soil solution. Conversely, the severity of saline scalds due to secondary salinization may decline as ground water levels fall in line with reduced rainfall (Karmakar et al. 2016). Moreover, salinization can also be a consequence of expected climate change, as the rise of sea level and sea water intrusion occur (Várallyay 2010). Climate change can affect soils build up due to an increase of the evapotranspiration through the increase in air temperature (Várallyay 2004). Higher rate of evapotranspiration will increase capillary transport of water and solutes from the groundwater to the root zone. The degradation cause by climate change was summarized by Várallyay (2010) in increasing soil erosion and that should be balanced by the increasing soil conservation effect of more dense and permanent vegetation.

Avoiding soil degradation under climate change through technologies and farm practices that maintain ground cover to minimize erosion and nutrient runoff will be important (Karmakar et al. 2016). Efficient water management under climate change can reduce soil erosion, thus soil degradation. Sojka et al. (2007) indicated that water management practices, such as monitoring crop water use, increasing application efficiency, timing considerations based on crop needs, soil water storage capacity, as well as water application method and intensity can play a major role in reducing soil erosion under furrow irrigation practice. Furthermore, intercropping with legumes can be an excellent practice for controlling soil erosion and sustaining crop production (Dwivedi et al. 2015). Deep roots of legume crops penetrate far into the soil and use moisture and nutrients from deeper soil layers, whereas shallow roots of cereal crops fix the soil at the surface and thereby help to reduce erosion (Machado 2009). Growing legumes with cereals results in nitrogen fixation in the soil and consequently increase in soil organic content (Hauggaard-Nielsen et al. 2006).

Precision agriculture techniques will enable reduced use of agri-chemicals and water that match supply with demand and limit losses (Cole et al. 2018). Crop rotation can play an important role in reduction of greenhouse gases fluxes from the soil by more efficient management of carbon and nitrogen flows in agricultural ecosystems (Cerri et al. 2004). An emerging approach to reducing fertilizer requirements is by reconstituting the nitrogen fixing function in plant cells. This approach relies on using synthetic biology for direct engineering of nitrogenase into the mitochondrial matrix of plants (Allen et al. 2017).

It is noticeable now that climate change is unavoidable and farmers are already living with its impacts. Farmers practice adaptation to climate change through simple measures, namely changing sowing date, implementing intercropping systems, and changing irrigation schedule (Ouda and Zohry 2018b). However, more transformative changes to farming systems will be required, namely changes to business structure, portfolio management, off-farm investments and geographical diversification (Robertson and Murray-Prior 2016). Advance innovations for increasing photosynthetic potential (Parry et al. 2011), radiation use efficiency or modifying canopy architecture (Robertson and Murray-Prior 2016) could applied to increase yield potential, thus reduce food insecurity.

1.7 Research Question

One might wonder whether application of deficit irrigation can contribute in increasing food availability. Although application of deficit irrigation involves loss in crop productivity, it also secures water to be use in cultivating more lands. However, on national level, will the production resulted from the new added area could compensate the loss attained by application of deficit irrigation. In this book, we answer the above question and shed the light on the role of deficit irrigation in securing food under water scarcity. We assessed the potential effect of application of deficit irrigation to four winter crops grown in Egypt, namely Egyptian clover, sugar beet, onion and tomato. These four crops have a surplus in their production. We also assessed possibility of saving an amount of irrigation water from these four crops and use it to cultivate new areas with wheat. Wheat is an important crop in Egyptian daily diet and has the major food production-consumption. We tested weather application of deficit irrigation to wheat cultivated on raised beds will increase its national production, in addition to implementing intercropping systems for wheat with other crops and used the saved water from the suggested four crops could to irrigate new areas with wheat will increase its production and reduce its food gap.

We also tested whether deficit irrigation application, as well as the other suggested practices could positively contribute in reducing the loss in wheat production under the impact of climate change in 2030.

1.8 Conclusion

There is an urgent need for effective management of water resources used in agriculture to overcome the prevailing situation of water scarcity. Application of deficit irrigation practice is good candidate to attain sustainable use of water resources without sacrificing food production.

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Chapter 2
Deficit Irrigation and Water Conservation

Samiha Ouda and Tahany Noreldin

Abstract In this chapter, we tackled some of the concepts and definitions used in application of deficit irrigation instead of full irrigation as a technology aims at conserving irrigation water. Both water use efficiency and water productivity are important estimators in the assessment of the effect of deficit irrigation. Water use efficiency serves as a key variable in the assessment of plant responses to water stress induced by deficit irrigation. On the other hand, water productivity is a quantitative term used to define the relationship between crop produced and the amount of water involved in crop production. This chapter also reviewed deficit irrigation strategies, which consist of sustain deficit irrigation, regulated deficit irrigation (stage-based and partial root zone irrigation), and subsurface drip irrigation. The hidden role of intercropping systems in irrigation water conservation was also discussed.

Keywords Water use efficiency · Water productivity · Sustain deficit irrigation · Regulated deficit irrigation · Stage-based and partial root zone irrigation · Subsurface drip irrigation · Intercropping systems

2.1 Introduction

Recently, water shortages is prevailing in many parts of the world and threaten its population, where nearly 800 million people lack access to safe drinking water and 2.5 billion have no proper sanitation (Schiermeier 2014). It is expected that this situation will get worse in coming decades, as world's population is anticipated to increase by 30% in 2050 (Godfray et al. 2010). Thus, providing food for the growing population is expected to be more difficult in light of the situation of water shortage. Globally, more than 40% of annual food production comes from irrigated

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land, where 70% of fresh water is withdrawn (FAO 2007). Coupled with the projected climate change, the situation may get worst in the future (De Wit and Stankiewicz 2006).

Irrigation is very important practice to attain high yield potential and increase total production. Because irrigated agriculture is the largest fresh water user on the planet (Gan et al. 2013), irrigation water has been over-exploited and over-used (Chai et al. 2014). Additionally, irrigated agriculture is practice in many parts of the world and water resources conservation and sustainability are not taking into consideration in many developing countries (Fereres and Soriano 2007). Some countries, like Egypt is recently transferred from the situation of water abundant to water deficiency. Egypt has passed the threshold of water scarcity and reached the value of 600 m^3/capita/year (Ministry of Irrigation and Water Resources 2014). This value is expected to reach 500 m^3/capita/year in 2025, as a result of population increase. Rapid urbanization in Egypt has caused conflict between the need for water for agriculture and other sectors.

A strategic change in water resources management is taking place in many parts of the world, where the supply available for irrigation is limited to what is left after all other sectors satisfy their needs (Fereres and Soriano 2007). Under such situations, farmers often receive water allocations below the maximum evapotranspiration needs, and either have to concentrate the supply over a smaller land area or have to irrigate the total area with level below full evapotranspiration (Vörösmarty et al. 2010a). Consequently, water resources available to agriculture will need to be re-rationalized to satisfy the developmental needs of other sectors (Vörösmarty et al. 2010b). Deficit irrigation is one of the most important management strategies. Fereres and Soriano (2007) defined deficit irrigation as an irrigation strategy to maximize yield with a minimum rate of water application.

In this chapter, we tackled some of the concepts and definitions used in application of deficit irrigation instead of full irrigation as a technology aims at conserving irrigation water.

2.2 Consequences of Water Stress on Plants

Water stress initiates a complex pathway, starting with the perception of stress, which trigger a sequence of metabolic responses. Various levels of physiological responses, both metabolic and developmental occur (Sarto et al. 2016). A reduction in water availability in plants leads to the reduction of cell solutes, thus plasma membrane become thicker, affecting the cells turgidity and causing stomatal closure to prevent dehydration (Sarto et al. 2017). The turgor of the guard cells change to control the opening and the closing of the stomata by hydropassive (without energy expenditure) and hydroactive (with energy expenditure) movements resulted in drastic reduction in transpiration rates (Taiz and Zeiger 2004). Reduction of carbon dioxide supply as a result of stomata closure reduces assimilative capacity due to decreasing photosynthesis, thus, translocation of carbohydrates and plant-growth regulators decrease, which disturb nitrogen metabolism (Kramer 1983) and reduces final crop yield (Taiz and Zeiger 2004).

Production of abscisic acid in leaves increases under water stress by about 50-fold, which cause stomatal closure and the induction of senescence and ethylene production (Taiz and Zeiger 2013). Water stress also affects many important biochemical processes such as osmotic adjustment, antioxidant enzyme defense system, and lipid peroxidation (Sarto et al. 2017). However, plants protects themselves from drought by morphological, physiological, and biochemical processes (Sarto et al. 2016). These processes are influenced by the level of CO_2, solar radiation, temperature, and relative humidity (Grant 1992). The increase in Si in the plant can increase the efficiency of water use by some grasses (Sarto et al. 2016). Under severe stress, the dehydration in mesophyll cells inhibits photosynthesis, as well as mesophyll metabolism, and water-use efficiency decreases as a result (Taiz and Zeiger 2004).

2.3 Deficit Irrigation Concept and Definitions

English and Nuss (1982) developed the concept of deficit irrigation and define it as “the practice of deliberately under-irrigating a crop, where its irrigation water supply is reduced relative to that needed to meet its maximum evapotranspiration”. The concept of deficit irrigation was further developed by English (1990) as “the deliberate and systematic under-irrigation of crops during the entire biological cycle with acceptance of a certain yield reduction”. His definition also included an analytical framework to estimate the profit-maximizing level of water use. Fereres and Soriano (2007) stated that deficit irrigation should be defined in terms of the level of water supply in relation to maximum crop evapotranspiration and a maximum yield is not sought. Another terminology for deficit irrigation was developed by Capra et al. (2008) as the application of irrigation below the full crop evapotranspiration, which potentially improve efficiency and maximize profits through a reduction in capital and operating costs. Whereas, Chai et al. (2016) stated that deficit irrigation is considered as an irrigation practice characterized by application of irrigation water below the full required amounts for optimal growth and yield, aiming at improving the response of plants to the certain degree of water deficit in a positive manner, and improving crop’s water use efficiency. Thus, deficit irrigation is looked upon as a key contributor in water saving technology.

Capra et al. (2008) reported that a number of authors, who have adopted the “English definition of deficit irrigation”, dealt only with the physiological and agronomical aspects of deficit irrigation, namely crop response to different irrigation regimes without any economic evaluation, which created some misunderstanding.

2.4 Water Use Efficiency/Water Productivity Under Deficit Irrigation

Water use efficiency serves as a key variable in the assessment of plant responses to water stress induced by deficit irrigation (Chai et al. 2016). It describes the intrinsic trade-off between carbon fixation and water loss, because water evaporates whenever stomata opens for CO_2 acquisition for photosynthesis (Bramley et al. 2013). In plant research, water use efficiency is defined as crop yield per unit of water used (Chai et al. 2014). It can also express the ratio of photosynthesis rate to transpiration rate or the ratio of photosynthesis rate to stomatal conductance of CO_2 (Bramley et al. 2013).

Deficit irrigation increases water use efficiency through increase in application efficiency, consumption efficiency and yield efficiency (Hsiao et al. 2007). Increases in application efficiency occur as a result of lower amount of water applied than full evapotranspiration, thus most or all the water applied remains in the root zone and water lost by run-off and deep percolation decreases (Sepaskhah and Ghahraman 2004). The consumption efficiency is defined as the ratio between the amount of evapotranspired water and the amount of water in the root zone. It may increase due to crops are forced to extract water from deeper soil (Hsiao et al. 2007). Furthermore, the yield efficiency is defined as the proportion of biomass in the harvested products, which may be enhanced due to an excessive vegetative growth of some crop species under full irrigation (Capra et al. 2008). When farmers have less water than the maximum evapotranspiration needs, they practice deficit irrigation, thus increasing application, consumption and yield efficiency, mainly through applying the available water in the root zone, forcing crops to extract more water from the soil and improving harvest index by regulating vegetative and reproductive growth (Hsiao et al. 2007).

Other quantifications of the term of water use efficiency are described by different terms and scales. Photosynthetic water use efficiency is the most basic at leaf level (Fereres and Soriano 2007). Furthermore, other common water use efficiency parameters are: instantaneous water use efficiency and intrinsic water use efficiency. The instantaneous water use efficiency is defined as the ratio between photosynthesis rate and transpiration rate and the intrinsic water use efficiency is defined as the ratio between photosynthesis rate and stomatal conductance of CO_2 (Li et al. 2014).

From an agronomic and genetic viewpoint, it has also been argued that effective use of water is the important determinant of plant production. Effective use of water is defined as maximal soil moisture capture for transpiration, and minimal water loss by soil evaporation under drought stress (Blum 2009). Hsiao et al. (2007) indicated that recycled water in the farmland and canal systems at the farmland, irrigation district, and regional levels, the seepage, water loss represent multiplicative water use efficiency chain. They developed a systematic and quantitative approach to clearly improve the multiplicative water use efficiency chain from reservoir to crop yield to quantify the integrative effects of agricultural water management, engineering, agronomical, and physiological processes.

Similarly, crop water productivity is an alternative term, has been used for the expression of water use efficiency by some irrigation managers (Chai et al. 2016).

Water productivity is a quantitative term used to define the relationship between crop produced and the amount of water involved in crop production (Igbadun et al. 2006). Valipour (2014) defined water productivity as the ratio of yield or marketable product to net income, or to water used by the crop. Optimization of irrigation strategy is necessary to increase water productivity and minimize yearly fluctuations of crop production. Under limited water supplies, the farmer's goal should be to maximize net income per unit water used rather than per unit land (Fereres and Soriano 2007). Water productivity increases under deficit irrigation, relative to its value under full irrigation, as shown experimentally for many crops (Fan et al. 2005).

2.5 Strategies of Deficit Irrigation

2.5.1 Sustained Deficit Irrigation

Fernandes-Silva et al. (2018) defined sustained deficit irrigation as "an irrigation strategy based on the distribution of a reduced water volume, controlled by a water stress indicator or as a percentage of the full water requirements for a crop throughout the whole irrigation season, so that the water deficit is intended to be uniform over the whole crop cycle to avoid the occurrence of severe water stress at any particular moment that might have unfortunate results". Whereas, Sofo et al. (2012) indicated that sustained deficit irrigation distributes a reduced water volume, as percentage of crop evapotranspiration, throughout the whole irrigation season. Many studies assessed the effects of application of sustained deficit irrigation to crops. Noreldin et al. (2015) tested the effect of reducing the applied irrigation water to wheat by 25 and 20% under drip and sprinkler systems, respectively and they found that wheat yield was reduced by 20 and 18%, respectively. Furthermore, Abdelraouf et al. (2013) indicated that application of 75% of wheat water requirements under sprinkler irrigation in sandy soil resulted in only 3% reduction in wheat yield as a result of applying 100% of NPK via fertigation pump, which reduced the leaching of fertilizer, improved plants growth and reduce yield losses under deduction of 25% of the applied irrigation water. In the same token, Taha and Ouda (2016) indicated that application of deficit irrigation to wheat, where 11% saving in the applied water under sprinkler system and fertigation in 80% of irrigation time resulted in 2% yield losses. Whereas, fertigation in 60% of irrigation time resulted in saving the same amount of irrigation water with higher yield losses, namely 8%. Other studies compared irrigation regimes based on different levels of crop evapotranspiration restitution and their influence on fruit and oil quality of different olive cultivars. Berenguer et al. (2006) found that a restitution ranging from 66% to 75% of crop evapotranspiration is enough to obtain good yields similar to those harvested from fully irrigated olive trees. However, Dabbou et al. (2010) indicated that phenolic compounds in oils significantly decreased under the highest irrigation levels.

2.5.2 Regulated Deficit Irrigation

Regulated deficit irrigation was proposed in the first time by Chalmers et al. (1981). This irrigation strategy reduces water supplies during specific periods characterized by a less plant sensibility to water stress with minimal effects on yield. Research on regulated deficit irrigation could also be viewed as research on the crop coefficient in different phenological phases (Capra et al. 2008). Regulated deficit irrigation has been adapted successfully for some tree crops (Girona et al. 2005). It has been also applied to sugar beet (Fabeiro et al. 2003), tomato (Hsiao 1993) and cotton (Snyder 1992). In this strategy, vegetative and reproductive growth are controlled by water stress through water deficits imposed during crop growing phases that are not yield reducing (Girona et al. 2005). Du et al. (2014) reported that there is some potential to practice regulated deficit irrigation on cereal crops in the arid north and northwest of China, where it was shown that regulated deficit irrigation can maintain a similar yield level under mild water stress during earlier stages and it significantly enhanced water used efficiency. Other studies on the effect of regulated deficit irrigation indicated that this practice increases root to shoot ratio (Vandoorne et al. 2012).

Chai et al. (2016) identified three main regulated deficit irrigation approaches in the production of agricultural crops, namely stage-based deficit irrigation, partial root-zone irrigation and subsurface irrigation or infiltration movement as followed.

2.5.2.1 Stage-Based Deficit Irrigation

The principle behind this approach is that the response of plants to regulated deficit irrigation varies with growth stages, where less applied water at non-critical stages cause no yield losses (Hongbo et al. 2005). Assuming that critical growth stages are determined, this approach could cause insignificant negative impact on plant productivity even though it may reduce normal plant growth (Chai et al. 2016). The sensitivity of any plant growth stage to water deficit is affected by many factors, including climatic conditions, crop species and cultivars, where cultivars differ in photosynthetic rate, stomatal conductance, and transpiration rate, thus they express different degrees of responses to water stress (Hongbo et al. 2005). Timing and the extent to which stage-based deficit irrigation is applied plays a critical role in plant recovery from deficit-induced stress (Chai et al. 2016). Stage-based deficit irrigation could help in improving the adaptability of plants to the stress through a stress-induced acclimatization process.

In wheat, the most sensitive growth stage to lack of water is the flag leaf stage, followed by the flowering stage (Kirigwi et al. 2004). Rodrigues et al. (1998) highlighted three critical periods wherein the occurrence of drought most affects the wheat crop: floral initiation and inflorescence development, anthesis and fertilization, and grain formation. Dias (2008) indicated that the greatest reduction in wheat grains yield occur when plants suffer from water deficiency during 15 days before and 5 days after heading. On the other hand, in maize, drought occurring between

2 weeks before and 2 weeks after the silking stage can cause significant reductions in kernel set and kernel weight (Schussler and Westgate 1991). A short duration of water deficit during tasselling stage in maize resulted in reduction in biomass production and grain yield by 30 and 40%, respectively (Çakir 2004). Kamara, et al. (2003) reported that water deficit reduced biomass accumulation by 37% at silking, by 34% at grain filling period, and by 21% at maturity. A comparison was made between maize yield resulted from deficit irrigation applied during the vegetative stage and deficit irrigation applied during the whole growing season revealed that yield increase by 10–20% in the first case, compare to the second case (Domínguez et al. 2012). Furthermore, maize plants that recovered from water stress during seedling-stage were better adapted to soil water deficit occurring later in the life cycle (Siddique and Bramley 2014). Kuşçu et al. (2014) indicated that application of full irrigation until the beginning of the fruit ripening stage and the cessation of irrigation thereafter in tomato resulted in 33% saving in irrigation water and 42% increase in water use efficiency, in addition to 5% yield loss.

2.5.2.2 Partial Root-Zone Irrigation

Partial root-zone irrigation is a strategy of deficit irrigation that involves irrigating only one half of the root zone in each irrigation event, while the other half is allowed to dry, thus both halves are watered alternately (Dry and Loveys 1998). This strategy is divided into two approaches. The first approach is watering and drying of root zone are alternated in a pre-set frequency that allows the previously well-watered side of the root zone to dry down while fully irrigating the previously dried root zones according to water requirements of the crop species, growth stages, and soil water holding capacity at the time of irrigation. The second approach is called fixed partial root-zone irrigation, which depends on irrigation of half of the root system irrigated in a normal amount each time when irrigation is applied, and the remaining half is always exposed to drying soil (Chai et al. 2016). In both approaches, it is assumed that respond of the fraction of the root system under drying soil was done by sending a root-sourced signal to the shoot where stomata may close to reduce water loss through transpiration (Liu et al. 2006). Furthermore, reduction in the applied amount of water to plants cause a small narrowing of the stomatal opening, which helps reduce water loss with little or no impact on plant photosynthesis (De Souza et al. 2005). The performance of partial-root drying strategy is based on the assumption that photosynthesis and fruit growth are less sensitive to water deficit than transpiration, where the production of chemical signals is induced, namely ABA in the root and translocated to leaves causing stomatal closure (Wilkinson and Hartung 2009). Watering alternation between drying and wetting root zones with partial root-zone irrigation allows roots to experience mild water stress first, and then, re-watering provides a compensatory effect in enhancing root activity (Chai et al. 2016).

In a partial root-zone irrigation study for potato, water use was reduced by nearly 50% without reducing potato tuber yield, and water use efficiency was increased by more than 50% (Xie et al. 2012). Furthermore, a partial root-zone irrigation study was done in a semiarid area of Italy by Garofalo and Rinaldi (2015) for sunflower, where small and moderate amounts of irrigation water, namely 150 and 270 mm, respectively ensured an average seed yield, with water saving by 74 and 53%, respectively, compared to the fully irrigated control treatment.

Wang et al. (2012) indicated that maize plants grown under alternate partial root-zone deficit irrigation in a climate controlled environmental study produced 49% more root biomass and increased root to shoot ratio by 54%, compared to the fully irrigated control. Similarly, in cotton, alternate partial root-zone irrigation stimulated the growth of secondary roots (Du et al. 2008). The increased secondary roots, along with increased root to shoot ratio, are beneficial for improving water absorption (Li et al. 2013) and enhancing soil nutrient uptake (Wang et al. 2012). Furthermore, alternate partial root-zone irrigation has been shown to increase root activity in tomato plants by 48–59% compared to the conventional irrigation control (Yang et al. 2012).

2.5.3 Subsurface Drip Irrigation or Infiltration Movement

Subsurface drip irrigation is the third most popular regulated deficit irrigation practice (Chai et al. 2016). It is mostly used in nursery systems and, to a lesser extent, in the production of large scale field crops (Xu et al. 2009). Subsurface drip irrigation has the potential to provide consistently high water use efficiency over traditional methods, including surface drip irrigation while conserving soil, water, and energy (Vyrlas et al. 2014). In this system, irrigation water is supplied to plants by capillary movement from the bottom. The root-zone air space is not immediately filled with water, in contrast with traditional irrigation where water is supplied directly overhead and fill the air space in the soil (Xu et al. 2009). Infiltration movement induces plant hardening or internal physiological regulations caused by mild water stress (Yactayo et al. 2013). A relatively dry soil surface under using subsurface drip irrigation permits farm equipment access and movement during the whole irrigation period, eliminates weed growth, restricts root rot and other soil diseases and prevents crust creation (Sakellariou-Makrantonaki et al. 2000).

2.6 The Hidden Role of Intercropping Systems in Water Saving

The aim of application of deficit irrigation is water saving and increase water use efficiency. Similar outcome could be obtained from implementing intercropping systems. Intercropping systems is an efficient cropping system in irrigation water use because it produces more yields (yield of two crops) by utilizing less water (water applied to one crop). Intercropping is found to play a crucial role in securing food supply and raising the income of farmers in developing countries, thereby, balancing higher food demands and lower water utilization (Yin et al. 2015). Qin et al. (2013) described intercropping as a systematic approach that makes full use of nutrient and water resources, achieves agricultural biodiversity, and increases yield significantly in comparison with crop monocultures. Thus, intercropping increases unit land productivity (harvest two types of crops from the same area), increases water productivity (using amount of irrigation water applied to one crop to irrigate two crops) and increase farmers income (reduce risks from crop failure) (Anderson 2007).

Intercropping with legumes can use moisture and nutrients from deeper soil layers (Machado 2009). Sorghum intercropped with cowpea system reduced runoff by 20–30% compared to sorghum sole planting and reduced runoff by 45–55% compared to cowpea monoculture (Lithourgidis 2011). Rahman et al. (2017) indicated that, in maize-soybean relay intercropping system; soil evaporation and soil water content was reduced, compared to sole planting. Hu et al. (2015) found the wheat and maize intercropping system used more water and enhanced water use efficiency by an average of 26%. In addition, wheat and maize yield was increased by 42 and 23%, respectively over the sole planting. Furthermore, Yang et al. (2011) revealed that wheat and maize intercropping system increased water use by 2–16% compared to sole cropping of wheat and maize. Water use efficiency of wheat was increased by 31–75% and water use efficiency of maize was increased by 33–38%, compared to sole cropping of wheat or maize. Lithourgidis (2011) proved that intercropping sorghum with either cowpea resulted in better productivity and water use efficiency. Coll et al. (2012) indicated that improvement of water productivity of intercropped soybean with maize occurred, compare to the sole planting is due to increase water capture efficiency.

Water equivalent ratio is a measurement used to quantify the amount of water that would be needed in single crop to achieve the same yield as produced with one unit of water in intercrops (Mao et al. 2012). Feng et al. (2016) showed that water equivalent ratio of two peanut-millet intercropping patterns ranged from 1.17 to 1.22, which implied an increase in water use efficiency of the two patterns by 17 and 22%. Furthermore, El-Mehy et al. (2018) indicated that intercropping sunflower with peanut system can utilize irrigation water more efficiently than monoculture of either crop by about 25 and 26%, respectively. Whereas, Ouda et al. (2018) indicated that irrigation water utilization of sunflower and peanut system was higher that the sole cropping by 49 and 50%, respectively.

2.7 Conclusion

Because water shortage is prevailing around the world and irrigated agriculture is the main user of water resources, efficient management of water resources is required. Deficit irrigation practice can play an important role in water conservation under the current situation of water scarcity. Several strategies of deficit irrigation were studied, namely sustained deficit irrigation, regulated deficit irrigation and subsurface drip irrigation. Previous research indicated the efficiency of these strategies in saving irrigation water with low or no yield losses.

Implementing intercropping systems can attain similar outcomes as deficit irrigation, with respect to water saving because two crops are produced with the applied water to one of them.

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Chapter 3
Egypt Faces Water Deficiency, and Food Insufficiency

Abd El-Hafeez Zohry and Samiha Ouda

Abstract This chapter provided an overview of the situation of Egypt with respect to its natural resources. It discussed the climate of Egypt and its relation to the growing season of cultivated crops and water requirements of these crops. It also presented the quantity of water resources, the management of irrigation water, and irrigated agriculture, as well as its food production. It also reviewed soil resources in Egypt and population pressure on land and water resources. This chapter also tackled the issue of food gaps in Egypt. Five food gaps were discussed, namely wheat, maize, faba bean, edible oil crops, and summer forage crops. It also reviewed the previous research on the application of deficit irrigation to mono crops and to intercropping systems.

Keywords Climate · Water and soil resources · Food gaps · Deficit irrigation

3.1 Introduction

Egypt is located on the Northeastern corner of Africa on the Mediterranean Sea between latitudes 22° and 32° N, and between longitudes 24° and 37° E. The total area of Egypt is 1,001,450 km^2, with a land area of 995,450 km^2. The Egyptian terrain consists of vast desert plateau interrupted by the Nile Delta and Valley, which occupy about 4% of the total area of Egypt (Fig. 3.1). The Nile Delta and Valley divided the desert land of Egypt into the western desert (represents two third of Egypt territory) and the eastern desert. In addition, Sinai Peninsula located on eastern part of Egypt represents 6% of the Egypt area. Sinai Peninsula is located in Asia continent, which makes Egypt a transcontinental country (Omran 2017).

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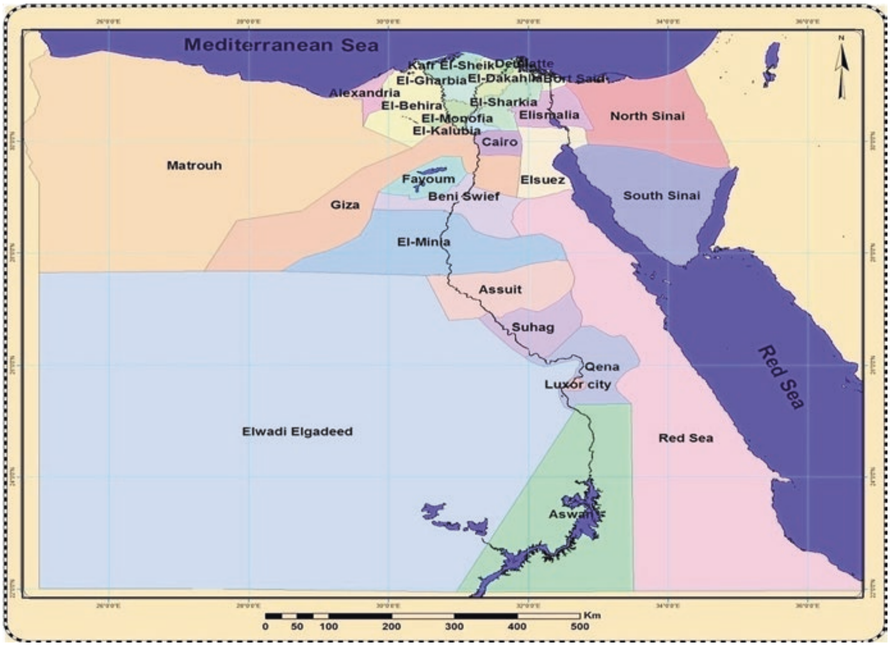

Fig. 3.1 Map of Egypt

Egypt is bordered by Libya in the west, by the Gaza Strip and the Red Sea in the east, and by Sudan in the south. The inhabited area of the country is confined to the Nile Delta and Valley. The Nile Delta covers the area from Cairo to the shoreline of the Mediterranean Sea, between the cities of Damietta in the east and Rashid in the west. A narrow strip from south of Cairo to Aswan represents the Nile Valley (Morsy et al. 2017).

This chapter provided an overview of the situation of Egypt with respect to its natural resources, food production, and population pressure on land and water resources. It also reviewed the previous research on the application of deficit irrigation to crops.

3.2 Climate of Egypt

There are four distinguished seasons in Egypt: winter (from December to February), spring (from March to May), summer (from June to August) and autumn (from September to November). The climate of Egypt is characterized by hot dry summers and mild winters with winter Mediterranean climate. Most of Egypt is a desert and can be classified as arid, with the exception of the slightly wetter Mediterranean coast, which can be considered semi-arid. The rain is relatively low, irregular, and unpredictable, where it is the highest along the Mediterranean, where it average about than 200 mm/year. Precipitation rates drop quickly as one moves away from the coast. It average to 20 mm/year in Middle Egypt to 2 mm/year in Upper Egypt (EEAA 2010).

El-Fandy (1948) stated that mid-latitude weather regime is prevailing during the winter season, which is characterized by the frequent passage of upper westerly troughs associated with surface depressions. Thick layers of low and medium clouds cover the northern part of Egypt and sometimes extend to the south during the passage of these depressions along the east Mediterranean. These cloud clusters are usually associated with torrential rain and in many cases with thunder storms. The minimum value of maximum temperature occurs in the winter, where maximum temperature tends to reach its maximum value of 18 °C over the northern part and 24 °C over the southern part with small gradient of temperature. Minimum temperature during winter could reach 3 °C over middle of Egypt region. Wind speed could reach as minimum as 1.5 m/s in the winter. In addition, the difference between north and south values of downward short wave radiation is large (Morsy et al. 2017).

The main climatic feature within the spring season is the southward shift of the tracks of depressions known as desert or Khamasen depressions. After the passage of the depression, northerly winds prevail over Egypt with possible strong guests that cause rising sand (dust) in open areas especially in Upper Egypt (El-Fandy 1948). Furthermore, there is a gradient of maximum temperature intensifies during spring season over northern part and decline over the rest of Egypt, where it is between 21 °C over the northern part and 36 °C over the southern part. Minimum temperature during spring season is around 12 °C covers most of Egypt (Morsy et al. 2017).

The main forcing during the summer season is the westward extension of the Indian monsoon low pressure, which provides Egypt with hot and humid north easterly surface winds. Occasionally, during the summer season, the Indian monsoon low pressure is weakened and shrinks towards the east, allowing the sub-tropical high pressure. As a consequence, a rather mild and dry north westerly wind invades the northern parts of Egypt (Hasanean and Abdel Basset 2006). The maximum value of maximum temperature occurs in the summer, where its gradient intensifies during summer over northern part and decline over the rest of Egypt. A minimum temperature of 21 °C during summer season is the prevailing over all Egypt, except latitudinal band from 28 to 30 °N. Wind speed could reach a maximum value of 4 m/s in the summer. Additionally, downward short wave radiation has a weak gradient in the summer (Morsy et al. 2017).

During the autumn season, Egypt is under the influence of northward extension of Sudan monsoon along Red Sea with southward extension of upper air trough that cause heavy rain over the eastern part of Egypt (Hasanean and Abdel Basset 2006). Maximum temperature during summer season ranges from 30 °C to 42 °C with maximum core over Upper Egypt. A dominant minimum temperature of 15 °C during autumn season occurs over all Egypt, except north and south east parts (Morsy et al. 2017).

3.2.1 Growing Seasons of the Cultivated Crops

The characteristics of climate of each season determinate crops growth periods and crops water requirements. The relationships between climate, crop, water and soil are complex with many biological processes involved (Rao et al. 2011). There are two main crop growing seasons in Egypt: winter and summer seasons. The winter season starts as early as October and ends in May. Most of winter field and vegetable crops are cultivated in November, with few exceptions. Egyptian clover, legume crops (faba bean, and lentil), sugar beet, pea and strawberry could be cultivated early in October. Fall sugarcane could also be cultivated in September and October and its season length is 16 months (Ouda 2019). Table 3.1 shows planting and harvest dates of some winter field and vegetable crops.

Summer season starts between 15th of April to 15th of May for all crops, except cotton and spring sugarcane. Cotton is cultivated in March and its season length is 7 months. Spring sugarcane is cultivated between February and March and its season length is 12 months. Some summer vegetable crops must be cultivated as early as in February, i.e. watermelon. Whereas, the suitable planting month for fruit trees in Egypt is February (Ouda 2019) (Table 3.2).

3.2.2 Water Requirements of the Cultivated Crops in Egypt

Water requirement of the cultivated crops is influenced by the type of the growing season and the length of its growing season. Water requirements of a crop is defined as the amount of water need to be applied to the growing plants during its growing season to substitute water losses from its surface and from the soil surface, to insure healthy growth and attain optimal productivity. Two main components, in which

Table 3.1 Planting and harvest dates for the selected winter field and vegetable crops

Crop	Planting date	Harvest date	Season length (days)
Faba Bean	25-Oct	25-Apr	152
Clover	15-Oct	1-Apr	169
Flax	15-Nov	13-Apr	150
Lentil	25-Oct	25-Mar	152
Sugar beet	15-Oct	12-Apr	180
Wheat	15-Nov	18-Apr	155
Fall sugarcane	51-Oct	15-Feb of the following year	480
Potato	1-Nov	1-Feb	93
Strawberry	1-Sep	15-May	257
Tomato	1-Oct	1-Mar	152
Peas	1-Sep	30-Nov	91
Onion	15-Nov	15-Apr	152
Watermelon	15-Feb	30-Jun	136

Source: Ouda (2019)

Table 3.2 Planting and harvest dates for the selected summer field and vegetable crops

Crop	Planting date	Harvest date	Season length (days)
Cotton	15-Mar	15-Aug	154
Maize	15-May	1-Sep	110
Rice	15-May	16-Sep	125
Sorghum	15-May	1-Sep	110
Soybean	15-May	25-Aug	103
Sunflower	15-May	15-Aug	93
Wheat	15-Nov	18-Apr	155
Spring sugarcane	15-Feb	14-Feb	365
Cucumber	15-Mar	15-Jun	93
Eggplant	1-Apr	1-Aug	130
Pepper	1-Apr	8-Aug	130
Potato	1-Aug	28-Nov	120
Tomato	1-May	1-Sep	124

Source: Ouda (2019)

crop water requirement depends on them, namely reference evapotranspiration and seasonal crop coefficients.

3.2.2.1 Reference evapotranspiration

Reference evapotranspiration (ETo) is the total amount of water lost from the field by both soil evaporation and plant transpiration (Gardner et al. 1985). It is a key component in irrigation scheduling for crops and water requirement calculation. Various equations have been developed to estimate ETo. The Penman-Monteith equation (Allen et al. 1998) is widely recommended because of its detailed theoretical base and its accommodation of small time periods. It was also indicated that the Penman-Monteith method exhibited excellent performance in both arid and humid climates (Shahidian et al. 2012).

Ouda and Noreldin (2017) indicated that there is evidences of an increasing trend in ETo values calculated from 30-year interval (1986–2015) illustrated by higher mean values of ETo in the 10-year interval (2006–2015), compared to the mean value of 20-year time interval (1996–2015) (Fig. 3.2).

3.2.2.2 Seasonal Crop Coefficients

Seasonal crop coefficients (Kc) takes into account the relationship between atmosphere, crop physiology, and agricultural practices (Snyder et al. 2004). Multiplication of ETo by Kc values results in the value of crop evapotranspiration (ETc, or water consumptive use by the crop). Table 3.3 presents the values of Kc (initial, middle and end season) and ETc value of different crops cultivated in the winter season. The table indicated that spring sugarcane has the highest ETc values as a result of its long

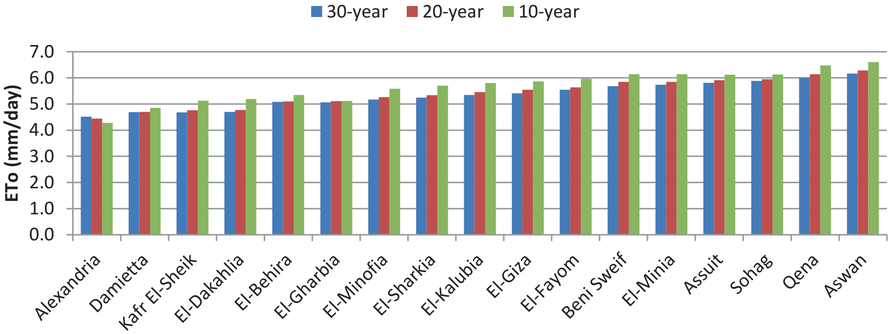

Fig. 3.2 Comparison between averaged values of ETo over 10, 20 and 30 years. (Source: Ouda and Noreldin 2017)

Table 3.3 Crop coefficient (Kc) and crop evapotranspiration (ETc) values for different winter field and vegetable crops

Crop	Kc_{ini}	Kc_{mid}	Kc_{end}	ETc (mm)
Barley	0.29	1.11	0.19	380
Faba bean	0.27	0.99	0.19	411
Clover	0.25	1.15	1.15	635
Flax	0.29	1.10	0.25	589
Lentil	0.22	0.99	0.19	402
Wheat	0.30	1.08	0.18	455
Sugar beet	0.25	1.15	0.95	604
Fall sugarcane	0.83	1.25	0.75	2982
Potato	0.26	1.09	1.24	232
Strawberry	0.20	0.70	0.70	694
Sweet potato	0.23	1.10	0.69	423
Tomato	0.23	1.10	0.64	395
Peas	0.19	0.98	0.98	340
Onion	0.28	1.19	0.54	581
Watermelon	0.26	1.00	0.75	751

Source: Ouda (2019)

growing season, namely 12 months. In addition, the value of ETc of watermelon is ranked second because its growing season started in February and ended in June resulted in high values of ETo. The third highest value of ETc is found for sugar beet as a result of its long growing season, namely 6 months (Table 3.3).

For field crops grown in the summer season, the highest value of ETc is found for rice, sorghum and cotton. Furthermore, three vegetable crops have the highest value of ETc, namely eggplant, potato and cucumber (Table 3.4).

To calculate water requirements of a crop, irrigation application efficiency is considered in the calculation. In Egypt, the common used values of irrigation application efficiency are 60, 75 and 85% for surface, sprinkler and drip, respectively.

Table 3.4 Crop coefficient (Kc) and crop evapotranspiration (ETc) values for different summer field and vegetable crops

Crop	Kc_{ini}	Kc_{mid}	Kc_{end}	ETc (mm)
Cotton	0.27	0.99	0.63	675
Maize	0.21	1.03	0.58	690
Rice	0.34	0.61	0.47	757
Sorghum	0.18	1.06	0.50	717
Soybean	0.21	1.11	0.39	684
Sunflower	0.21	1.09	0.37	616
Wheat	0.23	0.85	0.85	480
Cucumber	0.20	0.91	0.86	728
Eggplant	0.20	0.98	0.83	824
Pepper	0.22	1.10	0.69	546
Potato	0.22	1.10	0.65	788
Tomato	0.23	0.90	0.70	479

Source: Ouda (2019)

3.3 Water Resources of Egypt

3.3.1 Water Resources Quantity

Water resources in Egypt are very limited, where more than 95% of it is received from outside of its international borders. The Nile River is the main water resource in Egypt. Egypt shares the Nile water with nine countries (Sudan, Ethiopia, Eritrea, Tanzania, the Democratic Congo, Uganda, Burundi, Rwanda, and Kenya). Egypt also lies at the end of the Nile's route toward the sea. The annual share of Nile River water was determined in an international agreement by 55.5 billion cubic meters (BCM). The High Aswan Dam is the major regulatory facility on the river. The annual share of the Nile is stored in Lake Nasser. The Nile water is driven from the dam downstream by intensive network of canals through several types of control structure (Ministry of Water Resources and Irrigation 2005).

Groundwater is one of the most important resources after the Nile River. Ground water is the portion of the water beneath the surface of the earth that can be collected with the wells, tunnels, drainage galleries, or that flows naturally to the earth's surface via seeps or springs (Ashour et al. 2009). There are different groundwater aquifers with variable importance for exploitation in the Nile river region. They are ranging from shallow local aquifers, recharged by rainfall, to deep non-replenish aquifers. The first category comprises groundwater in the Nile Valley and Delta system. The second aquifer category is the non-renewable type, which is located in the Western Desert-Nubian Sandstone Aquifer (Abdel-Shafy and Kamel 2016). The current total abstraction of the groundwater is only 2.0 BCM per year as a result of great depth, up to 1500 m in some area (Ministry of Water Resources and Irrigation 2013).

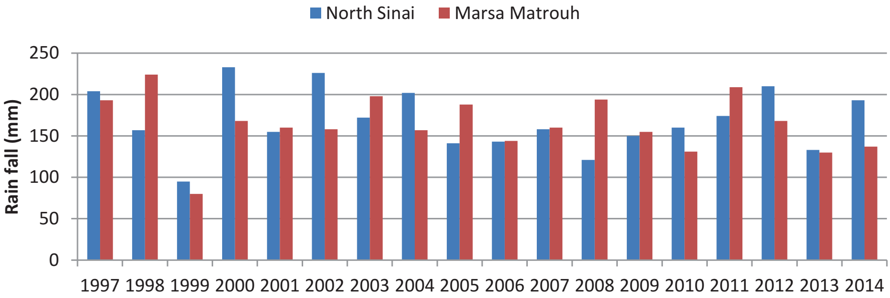

Fig. 3.3 Annual values of rain fall (mm) from 1997 to 2014 in North Sinai and Marsa Matrouh governorates. (Source: Ouda et al. 2016)

Rain is the third important water resource in Egypt. Rain falls in the winter only and its amount in the Egyptian north coast varies ranging from 130 to 150 mm in the northwestern coast and from 80 mm (west of Al-Arish) to 280 mm (at Rafah) in the northeastern coast. This rate decreases after 20 kilometers south of the Mediterranean in both areas. The effective rainfalls on the northern strip of the Nile Delta are calculated by 1.3 BCM/year (http://www.emwis-eg.org). Figure 3.3 showed rain fall values from 1997 to 2014 in North Sinai and Marsa Matrouh located on eastern and western coast of the Mediterranean Sea. The figure showed high temporal and spatial variability in rain fall amounts. Therefore, the rain fall in Egypt cannot be considered as a reliable source.

The total annual water resources in Egypt are 55.5 BCM obtains from the Nile, 2.0 BCM from ground water, 1.3 BCM from rain, which add to 58.8 BCM. The major amount of water consumption come from agriculture, namely about 62.3 BCM. Drinking water uses 8.7 BCM and industry uses about 7.5 BCM. These three amounts add up with total of 78.5 BCM. Thus, there is a gap estimated by about 20 BCM/year between available water resources and the demand for water. This gap is overcome by recycling agricultural drainage water to be used in irrigation (Ministry of Irrigation and Water Resources 2014).

The reuse of agricultural drainage water in irrigation has been adapted as an official policy since the late seventies by mixing it with Nile water (fresh water) in the main and branch canals. However, the reuse of agricultural drainage water is not considered as independent resource. It is only used to fill the gap between water supply and demand.

3.3.2 *Irrigation Water Management*

Agriculture water demand is one of the serious pressures on water sector in Egypt, since 85% of total available water is consumed in agriculture and most of the on-farm irrigation systems are low efficient coupled with poor irrigation management (Abou Zeid 2002). Irrigation water management becomes increasingly important in the presence of the expected low water supplies. In order to avoid the underestimation or overestimation of crop water consumption, knowledge of the exact water loss through actual evapotranspiration is necessary for sustainable development and environmentally sound water management (Shideed et al. 1995). One of the suggestions to attain the sustainable use of water resources is to develop agro-climatic zones. In this procedure, a particular region can be divided into agro-climatic zones based on homogeneity in weather variables that have the greatest influence on crop growth and yield (Doorenbos and Kassam 1979). An agro-climatic zone is a land unit in terms of major climate, superimposed on length of growing period i.e. moisture availability period (FAO 1983). As a result, crops growth periods, water requirements and irrigation scheduling are dependent on weather conditions.

Noreldin et al. (2016) uses 30-year of weather elements to form (1985–2014) to develop agro-climatic zones in the Nile Delta and valley, where the agricultural areas are located. Their results defined seven ago-climatic zones. Although climatic normals (the arithmetic average of a climate element over a 30-year interval) is sufficiently long to filter out many of the short-term inter-annual fluctuations and anomalies (NCDC 2002), variability in weather elements from year to year was observed worldwide, as well as in Egypt. Colder winters and hotter summers were prevailing in the past few years in Egypt. Thus, a rational decision was made by Ouda and Noreldin (2017) to use 20-year and 10-year intervals of weather elements to develop agro-climatic zones in Egypt using data from 1995 to 2014 and it was compared with the values obtained from 30-year interval. The average values of ETo over the three intervals was close to each other, where it was 5.64, 5.43 and 5.36 mm/day for 10-year, 20-year and 30-year values of ETo, respectively. They also found out that using 10-year period of weather elements to develop agro-climatic zones resulted in higher values of ETo in each zone, compared to 20-year ETo values and 30-year ETo values (Fig. 3.4).

3.4 Soil Resources of Egypt

The main soil groups in Egypt are Arenosols and Leptosols represents 26 and 25%, respectively (FAO 2005). According to Hegazi et al. (2005), four agro-ecological zones can be identified based on soil characteristics and water resources, namely the old lands, the new lands, the rain fed and the oases.

The old lands are located in the Nile Valley and Delta Regions. It covers a total area of 2.38 million hectares or about 68% of the total cultivated area. It is characterized by alluvial soils (clay to loamy). As stated by the FAO (2005), available phosphorous is generally moderate, and available potassium (soluble and exchangeable) is high in most of Egyptian alluvial soils. The Nile River is the main source for irrigation in the old lands, where surface irrigation is practiced.

On the other hand, the new lands are located mainly on both the east and west fringes of the Nile Delta and Valley and scattered over various areas in the country, where it covers 1.01 million hectares. Sandy and calcareous soils are prevailing in these areas, where micronutrients are above the critical limits, and levels of available phosphorus, potassium and micronutrients are fairly low (Hegazi et al. 2005). These areas are recently reclaimed and became productive lands. The newly

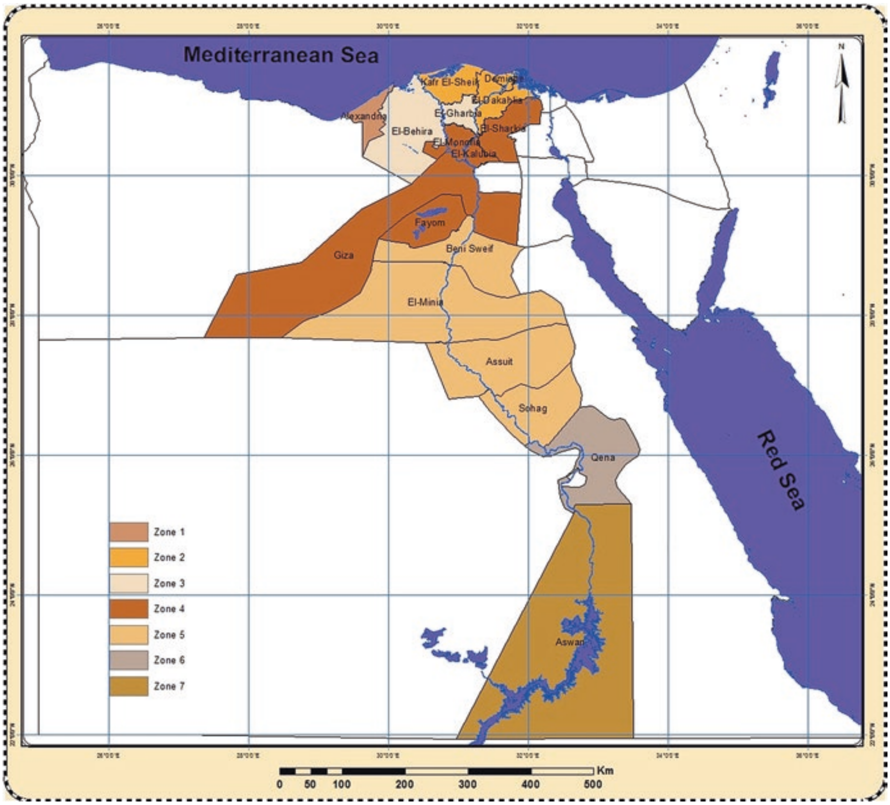

Fig. 3.4 Map of agro-climatic zones of Egypt using 10-year of ETo values

reclaimed lands are viewed as an opportunity for increasing agricultural production and ensuring food security in the country. Groundwater is the source of irrigation water in these areas, where sprinkler and drip irrigation are practiced.

The rain fed areas include approximately 0.13 million hectares of land located in the north coastal areas. About 70% of such area lies in the North Western coastal sub-zone of the country in Marsa Matrouh governorate, while the rest lies in the eastern one in North Sinai. Although these areas may not appear significant in relation to the total agricultural land, they are important for local communities. Finally, the oases are characterized by alluvial, sandy and calcareous soils. They cover a total area of 40,000 hectares. Groundwater is the main source for irrigation.

3.5 Population Impacts on Per Capita Water and Land

Egypt has a total population of 95.2 million inhabitants in 2017 mainly concentrated in the Nile Delta and Valley (CAPMAS 2018). The Egyptian population almost doubled during the last three decades, between 1986 and 2016 (CAPMAS 2017).

Uneven distribution of the population exists in Egypt, where they are living on only 4% of the total area. The recent census statistics revealed that around 43% of the population lives in Lower Egypt (Port Said, Suez, Ismailia, Sharqia, Damietta, Qalyubia, Gharbia, Menufyia, Kafr El- Sheikh, Behira, and Alexandria governorates). In the Greater Cairo (Cairo, Giza, and Qalubia governorates), around 25% of the total population live. Around 22% of the total population inhibit Middle Egypt (Fayoum, Beni Sweif, and Minia governorates), whereas around 16% of them inhibit Upper Egypt governorates (Assuit, Sohag, Qena, Luxor and Aswan). Border governorates, namely Marsa Matrouh, El-Wadi El-Gedid, Red sea, North Sinai and South Sinai have very low population, less than 2% of the total population. Reclamation of new lands provides an opportunity to absorb the increasing population and improving the demographic distribution of the country.

The high population growth rate put high pressure on the government of Egypt to supply clean water for domestic use and for agriculture to produce food. Egypt has passed the threshold of water scarcity and it reached the value of 600 m^3/capita/year (Ministry of Irrigation and Water Resources 2014). Thus, Egypt is recently transferred from the situation of water abundant to water deficiency.

Furthermore, because the Egyptian population is living on only 4% of Egypt area and characterized with high growth rate, arable land per capita was reduced from 0.09 hectare in 1961 to 0.03 hectares in 2016. Land holdings in Egypt are very small, with 89% of land holdings smaller than 1.3 hectares (FAO 2015).

3.6 Irrigated Agriculture and Food Production

Irrigated agriculture is the main contributor in food production in Egypt, which consumed 85% of its water resources. Surface irrigation is the prevailing system in the old lands with 50–60% water application efficiency on farm level. Farmers are used to plant crops in basins, where they broadcast seeds, or they plant seeds on furrows. This practice results in application of a large amount of irrigation water. Under furrow irrigation, water runoff could cause soil erosion and loss in fertility (Sojka et al. 2007). In addition, fertilizer leaching is also a consequence of application of large irrigation amounts, causing groundwater pollution (Abouelenein et al. 2010).

In the new lands, sprinkler and drip systems are prevailing and surface irrigation is prohibited by the law. Small areas of the new lands irrigated using canals originated from the Nile River, but most of the new lands irrigated using groundwater. Nevertheless, the revenue obtained from most of the already reclaimed areas is low compared to its full potential due to inefficient use of land and water resources, inferior or absence of agriculture background, weakness or absence of extension services that deal with the specific needs of the new lands, poor agricultural credit and low input supply. Additionally, other problems exist in the new lands, namely degradation of soils through salinity and alkalinity. The high evapotranspiration rate and/or combination with high groundwater level in some areas cause salinity accumulation, especially in the northern part of the Nile Delta (Mohamedin et al. 2011).

Table 3.5 National cropping pattern in Egypt in 2014/15 growing season and its water requirements

	Cultivated area (ha)	Water requirements (m^3)
Winter crops		
Wheat	1,354,844	8,825,826,373
Faba bean	34,418	178,997,045
Clover	624,741	5,948,296,442
Onion	148,173	1,244,936,988
Tomato	70,173	347,661,962
Potato	102,285	339,729,364
Sugar beet	231,193	1,955,202,088
Other crops	680,278	2,858,335,063
Total	3,246,104	21,698,985,326
Summer crops		
Cotton	100,349	1,264,924,487
Rice	506,249	5,896,134,782
Maize	938,329	9,259,942,383
Soybean	14,130	147,263,643
Sunflower	6585	48,883,220
Potato	53,110	385,322,673
Tomato	89,825	824,943,808
Cowpea	516	1,032,000
Sugarcane	134,656	4,271,214,589
Fruit trees	524,763	9,789,068,856
Other crops	682,329	8,735,940,296
Total	3,050,840	40,624,670,737
Grand total	6,296,944	62,323,656,063

Source: Ouda and Zohry (2018)

The prevailing cropping pattern in both old and new lands contains diversifies number of field, vegetable and medicinal crops, in addition to fruit trees (Table 3.5). Ouda and Zohry (2018) estimated total water requirements for the prevailing cropping pattern in the old lands by 49.5 BCM. Whereas, in the new lands, they reported that water requirements for the prevailing cropping pattern were estimated by 12.9 BCM. Thus, the total amount of irrigation water required to irrigate the old and new cultivated area is 62.3 BCM (Table 3.5).

3.7 Food Gaps in Egypt

The steady increase in the population from year to year, the decline in land productivity due to cessation of the implementation of crop rotation after agriculture liberalization law in 1980s, and the incompatibility of the fertilization regimes with cultivated crops have cause food shortage in many important crops. Additionally, reduced productivity of the cultivated crops obtained by some farmers in both the old and new lands is due to their wrong on-field practices. The typical farmer practices in the old lands includes mono cropping in both growing seasons, low land leveling, furrow cultivation, and application of large amount of irrigation water as a result of using fixed time interval, regardless of crop needs. As a result, fertilizer leaching occurred, as well as loss in soil fertility. Whereas, in the new lands, mono cropping is also practice by the farmers. Although sprinkler or drip systems are used, the farmer depended on his experience to decide the appropriate amount of irrigation water to apply in each irrigation event. The farmer applies irrigation water every 3 days for summer crops and every 4 days for winter crop. Fertilizer is broadcasted on the ground before irrigation, which leads to fertilizer leaching, as a result of applying large amount of irrigation water.

3.7.1 Wheat Production-Consumption Gap

Wheat is very important crop in Egypt, where its production does not fulfil its consumption, which generates a need to increase its production. Egypt was used to be self-sufficient in almost all basic food commodities in the 1960s, with the exception of wheat. Wheat self-sufficiency ratio (domestic production in relation to consumption) was 70% during that time. Between the 1970s and the 1980s, the self-sufficiency ratio declined dramatically for most products, where it was an indication of serious food gaps in Egypt (Metz 1990). Under the current situation of water deficiency, it is crucial to develop improved management package to increase its national production.

Ouda and Zohry (2017) thoroughly assessed solutions to the wheat production-consumption gap using data published in 2014. The study divided Egypt into three regions, Lower, Middle and Upper Egypt (Fig. 3.5).

From their study, Table 3.6 showed that under traditional cultivation of wheat in Lower Egypt had the highest percentage of wheat production, and population consumption. Whereas, Middle Egypt had the lowest percentage of wheat production and Upper Egypt had the lowest percentage of population consumption. Self-sufficiency ratio (total production divided by total consumption) was the highest in Upper Egypt and the lowest in Middle Egypt. Under these conditions, the average wheat self-sufficiency ratio was 51%.

The study also revealed that using improved production package in the old lands to increase wheat total production and could contribute in saving part of the applied irrigation water and use it to cultivate new areas in the new lands. The suggested improved production package included hanging traditional cultivation to raised beds and implementing intercropping systems for wheat, where wheat plants share the cultivated area and the applied irrigation water with other crops, namely with tomato (Abd El-Zaher et al. 2013; Fig. 3.6a). Cotton relayed on wheat system (Lamlom et al. 2018; Fig. 3.6b) was also suggested. Other wheat intercropping systems were suggested, i.e. wheat intercropped with sugar beet system (Abou-Elela

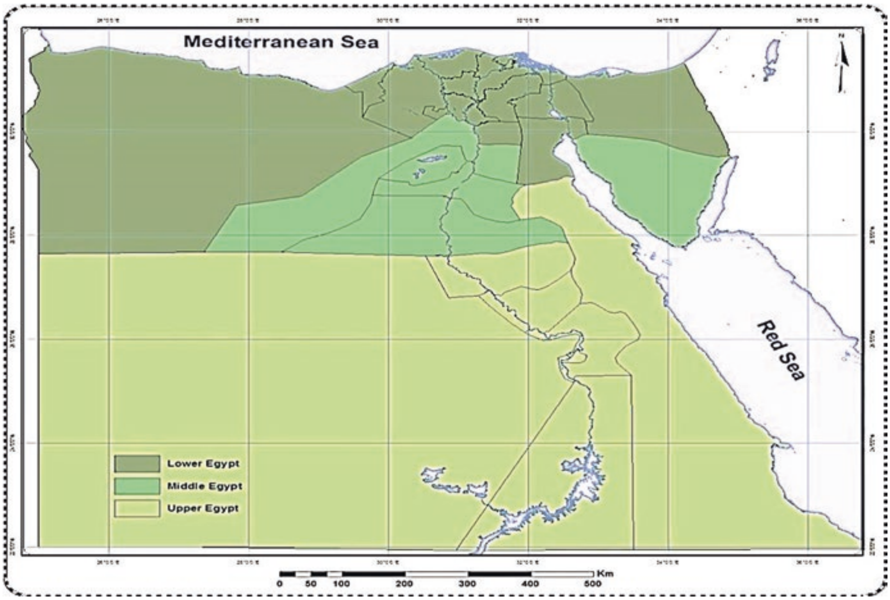

Fig. 3.5 Map of major regions in Egypt

Table 3.6 Percentage of wheat production, population consumption and self-sufficiency on region level in 2014 under traditional cultivation

	Production (%)[a]	Consumption (%)[a]	Self-sufficiency (%)[a]
Lower Egypt	61	61	51
Middle Egypt	19	22	46
Upper Egypt	20	17	61

[a] Calculated by the authors from Ouda and Zohry (2017)

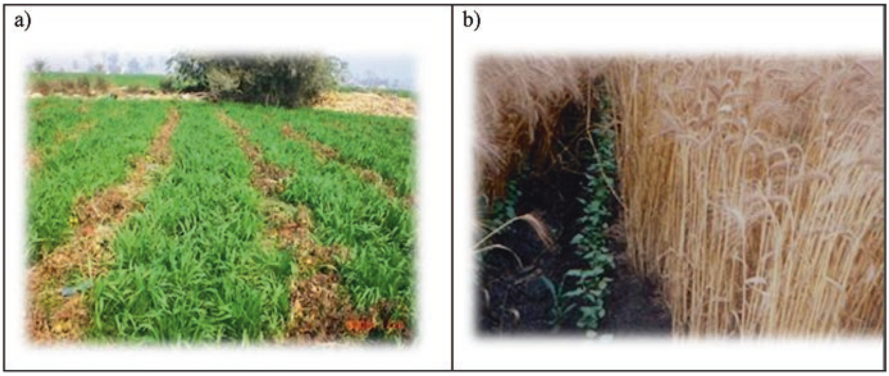

Fig. 3.6 Wheat intercropping system with tomato (**a**) and cotton relay intercropped with wheat (**b**)

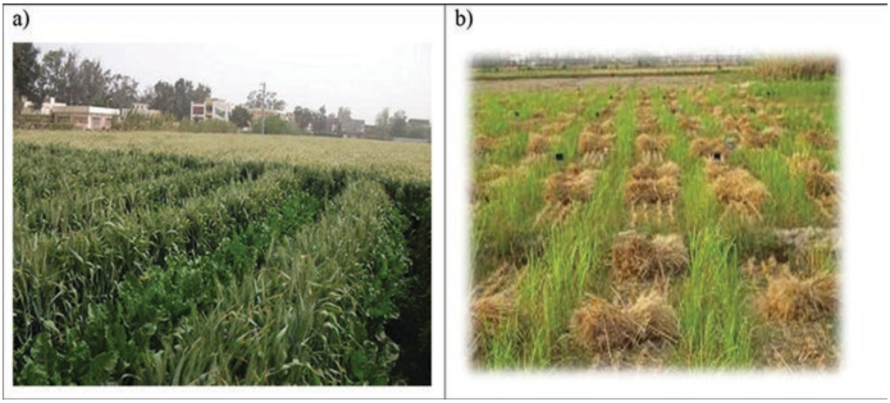

Fig. 3.7 Wheat intercropped with sugar beet (**a**) and wheat intercropped with sugarcane (**b**)

Table 3.7 Percentage of increase in wheat production, and self-sufficiency on region level in 2014 under using improved production package

	Percentage of increase in production (%)[a]	Self-sufficiency (%)[a]
Lower Egypt	64	83
Middle Egypt	58	73
Upper Egypt	40	85

[a] Calculated by the authors from Ouda and Zohry (2017)

2012; Fig. 3.7a), wheat intercropped with sugarcane system (Ahmed et al. 2013, Figure 3.7b), and wheat intercropped under fruit trees.

Table 3.7 showed that total wheat production under these practices could be increased, compared to its value under traditional cultivation, and consequently wheat self-sufficiency ratio could be increased. Thus, total wheat production in Lower Egypt was increased by 64%, whereas it was increased by 58 and 40% in Middle and Upper Egypt, respectively. The average self-sufficiency ratio could be increase from 51% to reach 81% (Ouda and Zohry 2017).

In more recent study done in 2019 for wheat production in 2017, population was increased to 95.2 million inhabitants and wheat production-consumption gap was increased to 57%. The study revealed that implementing improved management practices and wheat intercropping systems could reduce the gap to 35% (unpublished data). Dawoud (2017) indicated that population increase by 1% could result in an increase in wheat consumption by about 1.29% and an increase in the gap by 1.98%. He also reported that an increase in the domestic production by 1% could result in a decrease in wheat consumption by about 0.73% and could cause a decrease in wheat production-consumption gap by about 1.11%.

3.7.2 Maize Production-Consumption Gap

Maize is a dual-purpose crop for food and feed. It has become a very vital component of global food security due to genetic and management practice improvements that increased its yield over the past century (Grassini et al. 2017). There are three main summer crops in Egypt competing for the available arable area, namely maize, rice and cotton. The cultivated area of maize is the highest among these three crops.

Zohry and Ouda (2017a) studied maize production-consumption gap in 2013 in three regions of Egypt under traditional maize cultivation. Table 3.8 revealed that the highest percentage of maize production, and consumption existed in Lower Egypt. On the contrary, the lowest percentage of maize production, and consumption existed in Upper Egypt. The average maize self-sufficiency ratio under these conditions was 53%.

They also indicated that implementing improved production package, as well as intercropping systems for maize, namely maize intercropped with tomato (Mohamed et al. 2013; Fig. 3.8a), maize intercropped with soybean (Metwally et al. 2018a; Fig. 3.8b), maize relay on potato system (Ibrahim 2006; Fig. 3.9a), maize intercropped with cowpea (Hamd-Alla et al. 2014; Fig. 3.9b) and maize intercropped with peanut (Metwally et al. 2018b) resulted in reduction in this gap.

Their results indicated (Table 3.9) that implementing the suggested improved production package could increase total maize production by 64, 66 and 55% in

Table 3.8 Percentage of maize production, population consumption and self-sufficiency on region level in 2014 under traditional cultivation

	Production (%)[a]	Consumption (%)[a]	Self-sufficiency (%)[a]
Lower Egypt	54	61	47
Middle Egypt	28	22	69
Upper Egypt	18	17	56

[a]Calculated by the authors from Zohry and Ouda (2017a)

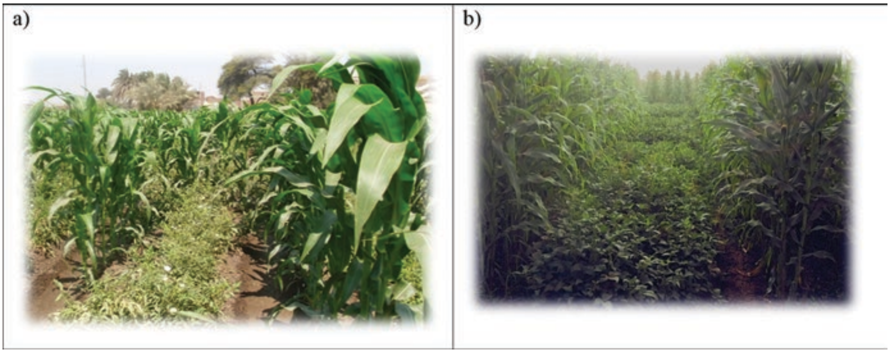

Fig. 3.8 Maize intercropped with tomato (**a**) and maize intercropped with soybean (**b**)

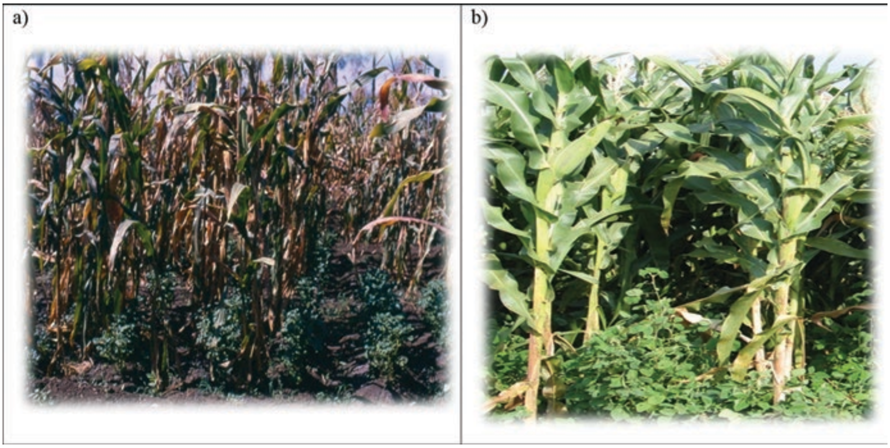

Fig. 3.9 Relay intercropped maize with potato (**a**) and maize intercropped with cowpea (**b**)

Table 3.9 Percentage of increase in maize production, and self-sufficiency on region level in 2014 under using improved production package

	Percentage of increase in production (%)[a]	Self-sufficiency (%)[a]
Lower Egypt	64	76
Middle Egypt	66	115
Upper Egypt	55	86

[a]Calculated by the authors from Zohry and Ouda (2017a)

Lower, Middle and Upper Egypt, respectively compared to its value under traditional cultivation. Table 3.9 also showed that self-sufficiency ratio was increase in the three regions, with the highest value existed in Middle Egypt, namely 115%. The average self-sufficiency ratio was 86%.

3.7.3 Faba Bean Production-Consumption Gap

Faba bean is one of the main cultivated winter pulses seeds in Egypt. It has been very poplar diet for the Egyptians due to its high nutritional value. However, its cultivated area has sharply declined as a result of the expansion in sugar beet cultivation, where sugar beet is more profitable than faba bean.

Zohry and Ouda (2017b) revealed that 90% of faba bean production under traditional cultivation came from Lower Egypt, so was the highest percentage of consumption and the highest self-sufficiency ratio. Both Middle and Upper Egypt produced very low percentage of faba bean and also have the lowest self-sufficiency ratios (Table 3.10). The average faba bean self-sufficiency ratio was 27%.

Table 3.10 Percentage of faba bean production, population consumption and self-sufficiency on region level in 2014 under traditional cultivation

	Production (%)[a]	Consumption (%)[a]	Self-sufficiency (%)[a]
Lower Egypt	90	61	40
Middle Egypt	2	22	3
Upper Egypt	8	17	13

[a]Calculated by the authors from Zohry and Ouda (2017b)

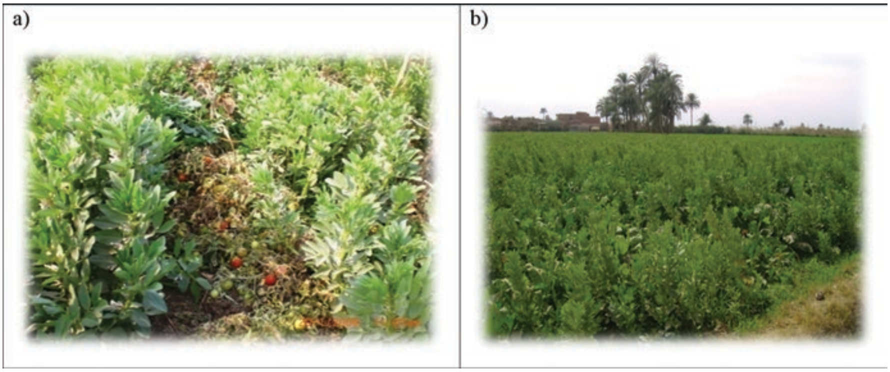

Fig. 3.10 Faba bean intercropped with tomato (**a**) and with sugar beet (**b**)

They also indicated that applying the improved management package and intercropping systems for faba bean increased faba bean national production and could attain self-sufficiency of faba bean. The suggested faba bean intercropping systems are namely faba bean intercropped with tomato (Ibrahim et al. 2010, Figure 3.10a), faba bean intercropped with sugar beet (Abd El-Zaher and Gendy 2014, Figure 3.10b), faba bean intercropped with sugarcane (Farghly 1997, Figure 3.11a) and faba bean intercropped under fruit trees (Figure 3.11b).

3.7.4 Edible Oil Production-Consumption Gap

During the 1960s, the self-sufficiency proportion of edible oil in Egypt was 95% (El-Hamidi and Zaher 2018). This proportion has declined to reach 32% in 2017. Table 3.11 showed the production, consumption and self-sufficiency of five oil crops in 2016, which are the most important edible oil crops in Egypt. These crops are cotton seeds, soybean, sunflower, maize embryos and flax seeds. Cotton seeds used to be the main edible oil crop in Egypt. A decline in the cultivated area of cotton was reported recently as a result of its high production costs. Similarly, declines in the cultivated area of soybean and sunflower were reported due to the preference of the farmers to cultivate either maize or rice to attain more revenue. Whereas, the

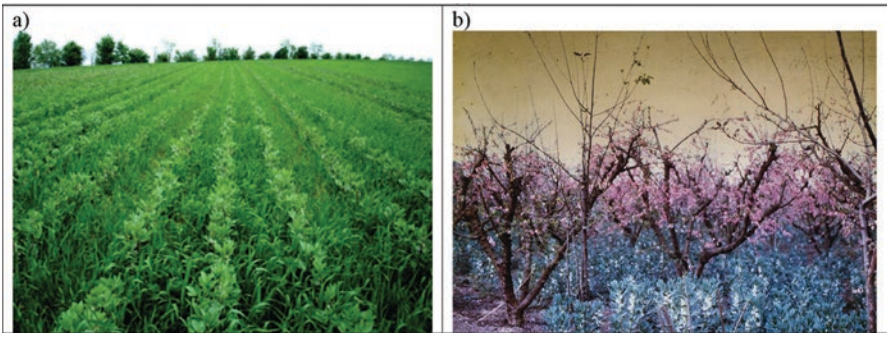

Fig. 3.11 Faba bean intercropped with sugarcane (**a**) and under fruit trees (**b**)

Table 3.11 Production, consumption, and self-sufficiency of major oil crops in Egypt in 2016

Crop	Production (000 ton)	Consumption (000 ton)	Difference (000 ton)	Self-sufficiency (%)
Flax	8	16	−8	50.00
Cotton	83	83	0	100.00
Soybean	47	869	−822	5.41
Sesame	50	64	−14	78.13
Sunflower	22	82	−60	26.83

Source: Central Agency for Public Mobilization and Statistics (2018)

cultivated area of flax is low, as a result of high competition with either wheat or Egyptian clover, where both crops are more important to the farmers.

Hassan and Shafique (2011) suggested solutions to reduce edible oil production-consumption gap using three crops (cotton seeds, sunflower and soybean) in 2007 through increasing its cultivating area, without indicating how they were going to increase its area. They indicated that the cultivated area of cotton could be increased by 145%, the cultivated area of sunflower could be increased by 870% and the cultivated area of soybean could be increased by 495%. The rise in the production of these three crops could increase the self-sufficiency of edible oil from 32% to 84%. In 2007, the total population was 79.5 million inhabitants.

Zohry and Ouda (2018a) indicated that the total cultivated area of cotton, sunflower, soybean, maize and flax could be increase through implementing intercropping systems and cultivation of three-crop sequences. Regarding cotton, it can be relied intercropped with wheat and onion (Lamlom et al. 2018) to increase its production. With respect to sunflower, it could be intercropped with summer tomato, sugarcane and under fruit trees. It could be also relay intercropped with wheat and could be cultivated as early summer crop after sugar beet and faba bean. With respect to soybean, it can be intercropped with maize (Metwally et al. 2018a), it can be intercropped with sorghum (Abou-Keriasha et al. 1993), it can be intercropped with sugarcane (Eweida et al. 1996, Figure 3.12a) and it could be intercropped

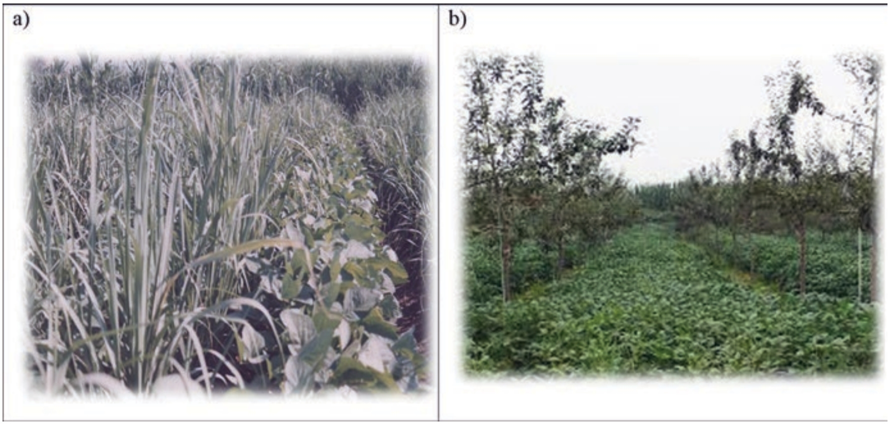

Fig. 3.12 Soybean intercropped with sugarcane system (**a**) and soybean intercropped under apple trees (**b**)

under fruit trees (El-Mehy and El-Badawy 2017, Figure 3.12b). It could also relay intercropped with wheat and it could be cultivated as early summer crop after sugar beet and faba bean. Regarding maize, it could be intercropped with summer tomato, peanut, and sorghum. Finally, flax could be intercropped with sugar beet and faba bean.

Using the data published in 2015 by the Ministry of Agriculture and Land Reclamation in Egypt, they calculated the potential increase in the cultivated area of these five crops, where the actual area was 1,062,495 hectares under traditional cultivation and could became 2,043,618 hectares under the suggested intercropping systems, which represent an increase by 90% of the total cultivated area, compared to its area in 2015. The production of these extra 90% cultivated area could increase the edible oil self-sufficiency from 33% to 62% (Zohry and Ouda 2018a).

3.7.5 Summer Forage Production-Consumption Gap

Zohry and Ouda (2018b) calculated the contribution of intercropping systems and cultivation of three-crop sequences in increasing the cultivated area of summer forage crop, where its production-consumption gap was estimated by 90%. The authors suggested using two legume forge crops, namely cowpea and fahl clover (a short season clover variety) to attain double benefits; increase the supply of forage crops and improve soil fertility. Cultivation of fahl clover as an early winter crop after maize, rice or sorghum crops and before the following winter crop was suggested. Furthermore, implementing intercropping systems of cowpea with maize, sunflower, sorghum and under fruit trees was also suggested. Their results indicated that an increase by 1647% in the cultivated area of both crops could be attained if intercropping systems and cultivation of three-crop sequences will implemented.

3.8 Deficit Irrigation and Crops Production

Several studies have been done in Egypt on the assessment of deficit irrigation effects on crop productivity, as well as the amount of saved irrigation water.

3.8.1 Effect of Deficit Irrigation on Winter Crops

3.8.1.1 Wheat

Skipping the last irrigation event for wheat at flowering stage cultivated in clay soil under surface irrigation resulted in high yield losses fluctuated between 28% for cv. Misr2 and 7% for cv. Misr1 (Elhag 2017). Abdelkhalek et al. (2015) indicated that skipping the last irrigation applied for wheat in loamy clay soil under surface irrigation resulted in 12% saving in the applied water, with 6% yield losses. Ouda et al. (2007) indicated that skipping the last irrigation for wheat at maturity stage reduced yield by 13%, whereas this percentage was reduced to 7% under spraying $MgCO_3$ as an anti-transpirant compound during vegetative stage and skipping the last irrigation at maturity stage.

Taha and Ouda (2016) indicated that application of deficit irrigation to wheat grown in sandy soil under sprinkler system and fertigation in 80% of irrigation time, where 11% saving in the applied water resulted in 2% yield losses. Whereas, fertigation in 60% of irrigation time resulted in saving the same amount of irrigation water with higher yield losses, namely 8%. The low percentage of yield losses under fertigation in 80% of irrigation time was resulted from increasing fertilizer use efficiency. Furthermore, Abdelraouf et al. (2013) indicated that application of 75% of wheat water requirements under sprinkler irrigation in sandy soil resulted in only 3% reduction in wheat yield as a result of applying 100% of NPK via fertigation pump. This technology resulted in reduction in fertilizer leaching, and improved plants growth and reduced yield losses.

Noreldin et al. (2015) tested the effect of reducing the applied irrigation water by 25 and 20% to wheat irrigated with either drip or sprinkler systems, respectively grown in sandy soil. They found that wheat yield was reduced by 20 and 18%, respectively. Because these yield losses were high under either system, they simulated the effect of reducing only 10% of the applied water under either system on wheat yield using CropSyst model (Stockle et al. 1994). Under these circumstances, yield losses became 3 and 4%, under drip and sprinkler systems respectively. Abdrabbo et al. (2013) indicated that saving 20% of the applied water to wheat in clay soil resulted in 8% yield losses under clay soil. Karrou et al. (2012) revealed that application of 78% of full irrigation of wheat grown in clay soil under surface irrigation resulted in 5% yield losses.

Simulation of deficit irrigation effects was also done. Ouda et al. (2015) simulated the effect of deducting 5% of full irrigation of wheat with fresh water

(Ec = 0.6 dS/m) and full irrigation of poor quality water (Ec = 6.3 dS/m) using CropSyst model and they found that yield losses were 5 and 6% under fresh and poor quality water, respectively. Ouda et al. (2010a) simulated the effect of reducing the applied irrigation water to wheat grown in clay soil under surface irrigation using Yield-Stress model (Ouda 2006). Their findings reported 3% yield losses under 20% saving in the applied irrigation water. Similarly, Ouda et al. (2007) simulated the effect of skipping the last irrigation applied for wheat in clay soil under surface irrigation. They indicated that water saving was 13% and yield losses was 2%. Ouda et al. (2008a) reported that simulation of the application of deficit irrigation, namely 20% reduction in full irrigation to wheat resulted in only 3% reduction in its yield. Furthermore, simulation of the effect of 30% in full irrigation to wheat resulted in 5% reduction in wheat yield.

3.8.1.2 Egyptian Clover

Khalil and Abouelenein (2012) reported that application of 70% of full irrigation to Egyptian clover grown in clay soil under surface irrigation resulted in 17% yield losses. Whereas, Abouelenein et al. (2010) showed that application of 70% of full irrigation to Egyptian clover resulted in 11% yield losses under surface irrigation in clay soil. Furthermore, simulation of the application of deficit irrigation to Egyptian clover grown in clay soil under surface system using Yield-Stress model (Ouda 2006), where 90% of full irrigation was applied resulted in 5% yield losses (Ouda et al. 2010b).

3.8.1.3 Sugar Beet

El-Darder et al. (2017) indicated that saving 23% of the applied water to sugar beet grown in sandy soil under sprinkler system resulted in 8% yield losses. Whereas, sugar beet yield losses were 7% and water saving was 22%, when sugar beet was irrigated with drip system. In sandy loam soil of Behira governorate of Egypt, Mehanna et al. (2017) studied the effect of application of deficit irrigation on sugar beet yield and they found that 33% saving in the applied irrigation water reduced yield by 18%. Eid and Ibrahim (2010) tested the effect of saving 17% of the applied irrigation water to sugar beet grown under surface irrigation in salt affected soil, where irrigation was done using fresh water and they found that percentage of yield reduction was 14%.

3.8.1.4 Other Winter Crops

- **Faba bean:** Sallam et al. (2014) indicated that application of deficit irrigation to faba bean grown in salt affected soil under surface irrigation, where 17% of the applied water was saved resulted in 12% yield losses. Ouda et al. (2010c) simulated the effect of application of 80% of full irrigation to faba bean grown in clay soil under surface irrigation and they found that this amount of water saving reduced yield by 5%.

- **Barley:** Ouda et al. (2007) indicated that omitting the last irrigation for barley at maturity stage reduced yield by 10%, whereas this percentage was reduced to 6% under spraying with $MgCO_3$ as an anti-transpirant compound during vegetative stage and omitting the last irrigation at maturity stage.
- **Onion:** Taha et al. (2019) indicated that saving 20% of the applied water to onion grown under sprinkler system in sandy soil reduced yield by 8%. Zayton (2007) studied the effect of skipping the last irrigation on the applied irrigation water and the yield of onion. He found that 20% of the applied irrigation water was saved and 15% the yield was lost. Ouda et al. (2010d) simulated the effect of applying 80% of full irrigation to onion grown in clay soil under surface system, where onion yield losses were 5%.

3.8.2 Effect of Deficit Irrigation on Summer Crops

3.8.2.1 Maize

Maize is another important crop in Egypt, where its consumption is higher than its production. Azab (2016) indicated that 15% yield losses for maize could be occurred under skipping the second irrigation (25 days after germination). Kubota et al. (2016) compared between the effect of conventional irrigation interval for maize grown in clay soil under surface irrigation (14 days) and prolonged irrigation interval on maize yield and they found that water saving was 8% with almost no yield losses under prolonged irrigation interval. Taha and Ouda (2016) indicated that application of deficit irrigation to maize grown in sandy soil under drip system and fertigation in 80% of irrigation time, where 14% saving in the applied water resulted in 12% yield losses. Whereas, fertigation in 60% of irrigation time resulted in saving the same amount of irrigation water with higher yield losses, namely 17%. The low percentage of yield losses under fertigation in 80% of irrigation time was resulted from increasing fertilizer use efficiency. El-Sherif and Ali (2015) indicated that the yield of maize grown in silty clay soil under surface irrigation was reduced by 14%, when irrigation water was reduced by 10%. Abd El-Halim (2015) compared between the applied water to maize cultivated on conventional furrows and maize cultivated on alternative furrow irrigation every 14 days. He found that using alternative furrow irrigation resulted in saving 7% of the applied irrigation water with only 2% yield losses.

Karrou et al. (2012) indicated that 30% saving in the applied irrigation to maize under surface irrigation in clay soil resulted in 8% yield losses. Abou Kheira (2009) reported that yield losses in maize cultivated in loamy clay soil using surface drip system was 4% under 11% water saving, whereas, 13% saving in the applied irrigation water under furrow irrigation using gated pipes resulted in 18% yield losses.

Tantawy et al. (2007) indicated that saving 20% of the applied water to maize grown in clay soil under surface irrigation resulted in 7% yield losses. Ouda et al. (2007) reported that applying deficit irrigation to maize, where 10% saving in the applied irrigation water resulted in 6% yield losses in clay soil under surface irrigation. Ouda et al. (2008b) simulated the effect of saving 20% of the applied irrigation water to maize grown under surface irrigation in clay soil. Their results indicated that 6% yield losses can occur. In another experiment, Ouda et al. (2006) simulated the effect of saving 20% of the applied water to maize grown in clay soil under surface irrigation using Yield-Stress model (Ouda 2006) and they found that maize yield was reduced by only 5%.

3.8.2.2 Soybean

Deficit irrigation effects on soybean were also studied. El-Sherif and Ali (2015) indicated that the soybean grown in silty clay soil under surface irrigation was reduced by 13%, when irrigation water was reduced by 10%. In a field experiment conducted in clay soil for soybean under surface irrigation, 10% saving in the applied irrigation water to it resulted in 3% yield reduction (Ouda et al. 2008c). Ouda et al. (2007) reported that applying deficit irrigation to soybean, where 10% saving in the applied irrigation water resulted in 8% yield losses in clay soil under surface irrigation. In a simulation study done by Ouda et al. (2010e) on the effect of deficit irrigation applied to soybean grown in clay soil under surface irrigation using Yield-Stress model (Ouda 2006), they indicated that saving 15% of the applied resulted in 5% reduction in the yield. Ouda et al. (2007) simulated the effect of deficit irrigation on soybean grown in silty clay soil under surface irrigation using Yield-Stress model (Ouda 2006). Their results indicated that saving 10% of the applied resulted in 4% reduction in the yield.

3.8.2.3 Other Summer Crops

- **Tomato:** Application of 80% of full irrigation to tomato grown in clay loam soil under subsurface drip system resulted in 15% yield losses (Abdelhady et al. 2017). Shalaby et al. (2014) indicated that saving 25% of the applied irrigation water to tomato grown under drip system in calcareous soil resulted in 9% yield losses. Additionally, Kamal and El-Shazly (2013) reported that 7% losses in tomato yield grown under drip system in calcareous soil occurred when 75% of full irrigation was applied.
- **Peanut:** Application of deficit irrigation to peanut grown under drip and sprinkler systems in sandy soil resulted in 20% saving in the applied water under both systems and 11 and 12% yield losses (El-Habbasha et al. 2015).
- **Sesame:** Elshamly et al. (2013) indicated that application of deficit irrigation to sesame grown in sandy soil under sprinkler system, where 14% of the applied water was saved, resulted in only 5% yield losses. Application of five irrigations

to sesame grown in clay soil under surface irrigation resulted in 26% saving in the applied irrigation water, compared to application of seven irrigations with only 6% yield losses (Tantawy et al. 2007).

3.8.3 Deficit Irrigation to Intercropping Systems

The effect of deficit irrigation under intercropping systems were studied for sunflower intercropped with peanut system under sprinkler system (El-Mehy et al. 2018) and under drip system (Ouda et al. 2018). Water saving was 16 and 15%, for sprinkler and drip systems, respectively. Yield losses for both sunflower and peanut were 4 and 3% under sprinkler and drip systems, respectively. Furthermore, saving 14% of the applied water to sunflower intercropped with soybean system under surface irrigation in clay soil resulted in 5% yield losses for both crops (Darwesh et al. 2016). Ouda et al. (2007) indicated that saving 6% of the applied irrigation water to soybean intercropped with maize, with 1:2 soybean to maize pattern cultivated in clay soil under surface irrigation resulted in losses by 13 and 5% for soybean and maize, respectively. Whereas, yield losses in sole planting of soybean and maize were 7 and 11% under the same percentage of saved water.

3.9 Conclusion

Egypt is blessed by suitable weather allows the cultivation of variety of crops. The Nile River is also a bless, where it is the main source of water for irrigation and consequently food production. Lots of valuable studies were conducted in Egypt to study the effect of water management on the final yield of crops. Other studies were done to test the effect of application of deficit irrigation on the yield of the crops and the amount of saved water. These studies revealed that there is high potential to save irrigation water with low yield losses. These studies also implied that water productivity could be increased under deficit irrigation. The saved irrigation water will permit the cultivation of new areas and increase food production.

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Chapter 4
Field Crops and Deficit Irrigation in Egypt

Samiha Ouda, Tahany Noreldin, and Abd El-Hafeez Zohry

Abstract In this chapter, we concerned about quantifying the effect of the application of deficit irrigation for Egyptian clover and sugar beet cultivated on raised beds to reduce the amount of applied water to raised beds to be lower than full irrigation. Data on the cultivated area and productivity of Egyptian clover and sugar beet were collected for both old and new lands on governorate level, as well as weather data in 2017 and water requirements were calculated. Five production alternatives were quantified on governorate level, namely traditional cultivation, raised beds cultivation, application of deficit irrigation, calculation of production without investing the saved water in adding new area, and calculation of production with investing the saved water in adding new area. In all alternatives, water productivity was calculated. The results showed that using the saved water from cultivation on raised beds and application of deficit irrigation to cultivate new areas with Egyptian clover resulted in 30% and 38% increase in its production, compared to its value under traditional cultivation. Furthermore, cultivation on raised beds and application of deficit irrigation without using the added area to cultivated new lands resulted in increasing total production by 13% and 8%, respectively. With respect to sugar beet, using the saved water from cultivation on raised beds and application of deficit irrigation to cultivate new areas with sugar beet resulted in 28% and 30% increase in its production, compared to its value under traditional cultivation. Whereas, cultivation on raised beds and application of deficit irrigation without using the added area to cultivated new lands resulted in increasing total production by 10% and 5%, respectively. In both crops, water productivity was the highest when deficit irrigation was applied and the saved irrigation water was used to cultivate new areas with the crop.

Keywords Egyptian clover · Sugar beet · Raised beds cultivation · Irrigation water saving · Water productivity

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4.1 Introduction

Water scarcity is particularly affecting food production and availably, which is the one of the main pillars of food security. Nowadays, Egypt suffers from food gaps in many crops. Production-consumption gaps exist for wheat (Ouda and Zohry 2017), maize (Zohry and Ouda 2017a), faba bean (Zohry and Ouda 2017b), and edible oil crops (Zohry and Ouda 2018). To narrow the gap between production and consumption of these crops, untraditional innovations need to be implemented.

The cultivated area in Egypt consists of two types according to soil characteristics and water resources: the old lands and the new lands (see Chap. 2 for more details). The old lands cover a total area of 2.38 million hectares, or about 68% of the total cultivated area. It located in the Nile Valley and Delta Regions and it has been cultivated a long time ago. It is characterized by having alluvial soils (clay to loamy). The Nile River is the main source for irrigation in the old lands. The new lands cover 1.01 million hectares and located mainly on both the east and west fringes of the Nile Delta, as well as scattered over various areas in the country. It is characterized by being sandy and calcareous soils. Thus, the total cultivated area in Egypt is amounted to 3.39 million hectares.

The cultivated area of winter crops occupied 3.25 million hectares. Egypt cultivates large number of crops, with variable cultivated area. Surface irrigation is the irrigation system prevailing in the old lands, which is the main user of irrigation water. The winter crops consume around 21.70 billion cubic meters (Ouda and Zohry 2018). The irrigation application efficiency of surface irrigation is between 50% and 60%, which endure large losses of this valuable resource to groundwater.

To attain win-win situation, namely facing water scarcity and increasing food security, changing traditional agricultural management practices and replacing it with practices could increase the production of unit land and water should be accomplished. Reduction of water losses to the groundwater under surface irrigation could be attained by conducting raised beds cultivation, instead of the traditional cultivation (cultivation in basins or on furrows).

In raised beds cultivation, water is sent through the ditches dug between the beds to provide water to plants, where water seep into raised beds through capillary action. It was documented, in previous research in Egypt, that raised beds cultivation for many crops can save 20–30% of the applied irrigation water (Abouelenein et al. 2009, 2010; Karrou et al. 2012; Khalil and Abouelenein 2012; Zohry et al. 2019). Furthermore, Ahmad et al. (2009) reported that raised beds cultivation increased water use efficiency, where 20–25% of irrigation water was saved. It also provided better opportunities to leach salts from the beds (Bakker et al. 2010). Hobbs et al. (2000) demonstrated that raised beds planting significantly contributed in improving water distribution and efficiency and reduced weed infestation, lodging and seed rate without sacrificing yield. Sing et al. (2010) found lower water consumption and higher wheat yield under raised beds planting than under conventional flat beds planting due to decrease in irrigation amount.

In addition to the role of raised beds cultivation in reducing the harmful effect of water scarcity under surface irrigation, it plays an important role in increasing land productivity, thus increasing food availability. It was also reported that cultivation on raised beds increased productivity by 15–22%, as a result of an increase in radiation used efficiency because crops are more exposed to solar radiation (Abouelenein et al. 2010; Khalil and Abouelenein 2012; Zohry et al. 2019). Furthermore, Majeed et al. (2015) indicated that raised beds planting of wheat, not only saved water but also improved fertilizer use efficiency and increase grain yield by 15%, compared to flat planting. Furthermore, it increase nitrogen use efficiency (Karrou et al. 2012; Majeed et al. 2015), thus increase productivity. Other studies on raised beds cultivation showed that it reduces seed mortality rates; and improves soil quality (Limon-Ortega et al. 2002), which led to enhanced root growth, and gave higher yield (Dey et al. 2015). Root length density was also longer in upper 45 cm in beds due to porous soil environment under raised beds cultivation (Dey et al. 2015). Raised beds cultivation significantly increased maize growth, microbial functional groups and enzyme activities compare to flat planting, thus it increasing availability of essential nutrients needed the crop by stimulating microbial activity (Zhang et al. 2012). Raised beds planting also created better soil physical environment throughout the crop growth period, which led to higher crop productivity (Aggarwal and Goswami 2003).

The other water saving strategy that can be used to face water scarcity is application of deficit irrigation instead of full irrigation to crops to increase its water use efficiency and increase the productivity of unit of irrigation water. Deficit irrigation is an irrigation practice characterized by application of irrigation water below the full required amounts for optimal growth and yield, aiming at improving the response of plants to a certain degree of water deficit in a positive manner, and improving crop's water use efficiency (Chai et al. 2016). When using deficit irrigation, the saved amount of irrigation water could be assigned to irrigate larger areas of crops, which will increase food availably, thus food security.

In the winter season, three field crops occupy the largest cultivated area in Egypt, namely wheat, clover, and sugar beet. Table 4.1 indicated that these three crops represent 64% of the total cultivated area of winter crops and consumes 15.6 BCM or 72% of the water assigned for winter crops.

In this chapter, we were concerned about quantifying the effect of the application of deficit irrigation Egyptian clover and sugar beet to reduce the amount of applied water, which will involve yield losses. To do this analysis, data on the cultivated area and productivity of Egyptian clover and sugar beet were collected for both old and new lands on governorate level from the Ministry of Agriculture and Land Reclamation in Egypt in 2017. Weather data for the winter season of 2016/17 were obtained from NASA Prediction of Worldwide Energy Resource website (https://power.larc.nasa.gov/data-access-viewer). On governorate level, water requirements for the selected

Table 4.1 The cultivated area of important field crops, its production and water requirements

Crop	Cultivated area (ha)	Production (ton)	Water requirements (m^3)
Wheat	1,220,912	8,414,466	7,989,241,305
Clover	625,041	44,909,464	5902,207,652
Sugar beet	220,133	10,822,754	1,671,149,930
Total	2,066,086		15,562,598,887

crops were calculated using BISm model (Snyder et al. 2004). Irrigation application efficiency assumed to be 60% in the old lands under surface irrigation and 75% and 85% under sprinkler and drip systems, respectively in the new lands.

For Egyptian clover and sugar beet, five production alternatives were quantified on governorate level as followed:

1. **Traditional cultivation**: The cultivated area and productivity per hectare of each crop in 2017 were multiplied to calculate total production. In addition, water requirements for each crop were calculated.
2. **Raised beds cultivation**: We assumed that cultivation on raised beds will increase productivity per hectare by 15%, and then the increase in the total production was calculated. We also assumed that 20% of the applied water under surface irrigation will be saved. The saved irrigation water will be used to irrigate new areas with each crop and this area will be added to the total cultivated area of the studied crops to increase its total production.
3. **Application of deficit irrigation**: The effect of application of deficit irrigation for both crops cultivated on raised beds. Because the amount of irrigation water resulted from cultivation on raised beds produced higher yield than the traditional cultivation, we applied deficit irrigation to raised beds and the losses in yield resulted from raised beds cultivation was calculated. The saved irrigation water will be used to irrigate new areas with each crop and this area will be added to the total cultivated area of the studied crops to increase its total production and compensate the loss in the productivity per hectare.
4. **Calculation of production without investing the saved water in adding new area**: Under cultivation on raised beds, we assumed that the saved water will be assigned to increase the cultivated area of another winter crop.
5. **Calculation of production without investing the saved water in adding new area:** Under application of deficit irrigation, we assumed that the saved water will be assigned to increase the cultivated area of another winter crop.

Water productivity values for each crop were calculated under these five production alternatives. Water productivity is a quantitative term used to define the relationship between crop produced and the amount of water involved in crop production (Igbadun et al. 2006). It is a good indicator to compare between the five productions alternatives, because it involves both crop production amount, and its applied irrigation water to produce this amount.

4.2 Egyptian Clover Production and Deficit Irrigation

Egyptian clover is one of the most important leguminous forages in the Mediterranean region and the Middle-East (De Santis et al. 2004). It contributes to soil fertility, improves soil physical characteristics (Graves et al. 1996) and its forage is superior to grasses in protein and mineral contents (Laghari et al. 2000). Egyptian clover is the major winter forage crop cultivated in the Nile Delta and Valley in both the old and the new lands. It occupies almost half of the cultivated area in the winter season.

It is considered as one of the most important leguminous forage crops in Egypt in the winter season, where it could be cultivated as early as in October and it could be harvested in May. Egyptian clover plays a very vital role in the sustainability of Egyptian agriculture. The crop can be mowed several times for forage and then ploughed to be use as green manure, which helps in increasing the organic matter content of the soil, thus improving soil physical, chemical and biological properties (El-Nahrawy 2011). Jabbar et al. (2011) indicated that residual soil fertility, residual soil nitrogen, and residual soil organic matter can be increased by cultivation of Egyptian clover. Furthermore, Nair (2015) reported that symbiotic relationships with soil bacterium are established when clover is cultivated and atmospheric nitrogen is fixed, adding significant amounts of nitrogen to the soil. Egyptian clover nourishes the soils, suppresses weeds and providing a disease break in cereal-dominated crop rotations existed in Egypt (El-Nahrawy 2011).

4.2.1 Effect of Water Stress on Egyptian Clover

Limitation of water supply is a major production constraint for this crop (Lazaridou and Koutroubas 2004). The impact of water stress on crop growth and productivity depends upon the intensity and duration of drought, growth stage, the genotype and physiology of the crop species. The effect of water stress on Egyptian clover was studied by Barzegar et al. (2016), where they stated that water stress resulted in lower leaf area, stem length and total dry mass. Iannucci et al. (2000) reported a significant reduction in total dry weight, plant height and proline content due to water stress treatments. They also reported that water stress influenced clover plant growth and its components. Furthermore plants subjected to periods of water stress during development stage have a lessened sensitivity to subsequent stress. Therefore, their ability to survive drought is mainly due to their capacity to avoid dehydration. Lazaridou and Koutroubas (2004) noted a 75% decrease in biomass; leaf area and transpiration rate was recorded as a result of water restriction. An average of 91-fold increase in proline levels in white clover leaves under water deficit was observed (Barker et al. 1993). Similar results have been found in subterranean clover by Socias and Medrano (1994). In a study done by Hussain et al. (2015) on the effect of water stress on Egyptian clover, they found significant effects of water restriction on yield, leaf gas exchange parameters, canopy temperature and osmotic adjustment. They also reported that most morpho-physiological traits had higher broad sense heritability than forage yield, both under full irrigation and water restriction conditions.

4.2.2 Effect of Deficit Irrigation on Egyptian Clover

Application of deficit irrigation to Egyptian clover was studied by Abouelenein et al. (2010), where they showed that application of 70% of full irrigation to Egyptian clover resulted in 11% yield losses under surface irrigation in clay soil. Furthermore, simulation of the application of 90% of full irrigation to Egyptian clover in clay soil under surface system using Yield-Stress model (Ouda 2006) was done. The results indicated that in 5% yield losses can be attained under this practice (Ouda et al. 2010).

4.2.3 Irrigation Water Savings Techniques for Egyptian Clover

4.2.3.1 Traditional Cultivation of Egyptian Clover

The traditional cultivation of Egyptian clover is cultivation in basins, where irrigation application efficiency is between 50% and 60%. The collected data on cultivated area and productivity of Egyptian clover in the old and new lands on governorate level are presented in Table 4.2. The calculated values of the required irrigation water was calculated and also presented in Table 4.2. Egypt was divided

Table 4.2 Cultivated areas of Egyptian clover in the old and new lands, its production and required irrigation water

	Old lands			New lands		
	Area (000 ha)	Production (000 ton)	WR (MCM)	Area (000 ha)	Production (000 ton)	WR (MCM)
Lower Egypt						
Alexandria	2.5	89.0	20.9	5.1	231.5	34.4
Behira	62.2	4504.8	541.3	28.6	2913.8	199.0
Gharbia	37.5	2850.1	374.0	0	0	0
Kafr El Sheikh	49.0	5460.0	426.4	0.8	63.1	5.3
Dakahlia	74.0	4032.5	673.9	2.2	97.5	15.8
Damietta	19.1	1430.6	181.2	1.2	53.9	9.1
Sharkia	55.5	4251.5	547.8	7.6	547.8	60.1
Ismailia	2.4	134.1	21.1	1.6	73.4	11.6
Port Said	0	0	0	5.6	267.4	38.7
Suez	1.4	79.3	13.1	0.1	5.3	0.6
Menoufia	42.8	3412.0	373.0	0	0	0
Qalyubia	15.6	1090.8	143.2	0	0	0
Cairo	0.2	11.1	2.2	0	0	0
Total	362.1	27,345.9	3318.2	52.7	4254.0	374.6
Middle Egypt						
Giza	15.7	1149.1	148.5	0.2	12.4	1.9
Bani Sweif	28.0	2388.2	273.8	1.5	82.3	11.7
Fayoum	44.6	1907.3	459.3	0	0	0
Minya	34.4	1806.4	364.8	1.8	85.2	15.0
Total	122.7	7251.0	1246.4	3.5	179.8	28.5

(continued)

Table 4.2 (continued)

	Old lands			New lands		
	Area (000 ha)	Production (000 ton)	WR (MCM)	Area (000 ha)	Production (000 ton)	WR (MCM)
Upper Egypt						
Assiut	20.7	1900.3	240.0	1.6	67.4	14.5
Sohag	29.6	2497.6	381.7	1.6	83.2	16.7
Qena	7.5	493.6	105.5	0.9	48.9	10.2
Luxor	2.7	103.8	37.7	0.4	14.2	4.9
Aswan	1.3	68.7	20.8	1.1	59.2	13.6
New Valley	0	0	0.0	7.6	501.4	75.9
Total	61.9	5064.1	785.6	13.3	774.3	135.9
Border governorates						
Marsa Matrouh	0	0	0	2.1	40.4	13.0
North Sinai	0	0	0	0.002	0.05	0.01
Total	0	0	0	2.1	40.5	13.0
Grand total	546.7	39,660.9	5350.3	71.5	5248.5	552.0

WR water requirements, *MCM* million cubic meter

in four regions, namely Lower Egypt (thirteen governorates), Middle Egypt (four governorates), Upper Egypt (six governorates) and boarder governorates (four governorates, only two of them cultivate Egyptian clover).

Table 4.2 indicated that the highest cultivated area of Egyptian clover in Lower Egypt existed in Dakhlia governorate, i.e. 74.0 thousand hectares in the old lands. In Middle and Upper Egypt, the highest cultivated area existed in Fayoum and Sohag governorates, namely 44.6 and 29.6 thousand hectares, respectively. In the new lands, the highest cultivated area existed in Behira governorate in Lower Egypt, i.e. 28.6 thousand hectares. Similarly, the highest cultivated area in Middle and Upper Egypt were found in Minia and New Valley governorates, namely 34.4 and 7.6 thousand hectares.

The total cultivated area of the old and new lands were 546.7 and 71.5 thousand hectares, respectively. These areas produced 39,660.9 and 5248.5 million ton of Egyptian clover in the old and new lands, respectively and consumed 5350.3 and 552.0 million cubic meters of irrigation water in the old and new lands, respectively (Table 4.2).

The total cultivated area of Egyptian clover was 618.2 thousand hectares, produced 44,909.5 million tons of Egyptian clover and consumed 5902.2 billion cubic meters of irrigation water. In Lower Egypt, the highest production of Egyptian clover was attained from Behira governorate (Table 4.3). The table also showed that in Middle and Upper Egypt, the highest production was attained from Beni Sweif and Sohage, respectively. According to the Central Agency for Public Mobilization and Statistics (2018), this amount of Egyptian clover national production is enough for local consumption.

4.2.3.2 Cultivation on Raised Beds

In this assessment, we assumed that cultivation of Egyptian clover on raised beds will increase its yield by 15% and save 20% of its water requirements in the old lands only (Abouelenein et al. 2010) and no irrigation water saving will practice in the new lands. Thus, the saved irrigation water could be used to cultivate more lands with Egyptian clover and increase the its total production without using any more irrigation water than its value under traditional cultivation.

The largest added area could be attained in Dakhlia, Fayoum and Sohage in Lower, Middle and Upper Egypt, respectively. The Table also showed that the saved amount of irrigation water under this practice could be invested in cultivating 136.7 thousand hectares, which increase the total cultivated area from 618.2 thousand hectares (Table 4.3) to 754.9 thousand hectares (Table 4.4), with 22% increase. Furthermore, increase the total production from 44,909.5 million tons (Table 4.3) to 58,317.9 million tons (Table 4.4), with 30% increase could be also obtained. The increase in Egyptian clover total production will result from the increase in productivity per hectare and increase in cultivated area.

Table 4.3 Total cultivated area of Egyptian clover, its production and required irrigation water

	Area (000 ha)	Production (000 ton)	Water requirements (BCM)
Lower Egypt			
Alexandria	7.6	320.5	55.3
Behira	90.8	7418.6	740.3
Gharbia	37.5	2850.1	374.0
Kafr El Sheikh	49.7	5523.1	431.8
Dakahlia	76.2	4130.0	689.7
Damietta	20.2	1484.6	190.3
Sharkia	63.1	4799.3	607.9
Ismailia	4.0	207.6	32.7
Port Said	5.6	267.4	38.7
Suez	1.5	84.7	13.6
Menoufia	42.8	3412.0	373.0
Qalyubia	15.6	1090.8	143.2
Cairo	0.2	11.1	2.2
Total	414.8	31,599.8	3692.8
Middle Egypt			
Giza	16.0	1161.4	150.4
Bani Sweif	29.5	2470.5	285.5
Fayoum	44.6	1907.3	459.3
Minya	36.1	1891.6	379.8
Total	126.2	7430.8	1275.0
Upper Egypt			
Assiut	22.3	1967.7	254.5
Sohag	31.2	2580.8	398.3

(continued)

Table 4.3 (continued)

	Area (000 ha)	Production (000 ton)	Water requirements (BCM)
Qena	8.4	542.5	115.7
Luxor	3.1	118.0	42.6
Aswan	2.4	127.9	34.4
New Valley	7.6	501.4	75.9
Total	75.1	5838.3	921.5
Bordered governorates			
Marsa Matrouh	2.1	40.4	13.0
North Sinai	0.002	0.05	0.01
Total	2.1	40.5	13.0
Grand total	618.2	44,909.5	5902.2

WR water requirements, *BCM* billion cubic meter

Table 4.4 Potential added cultivated area of Egyptian clover as a result of cultivation on raised beds, potential total cultivated area and its potential total production

	Added area (000 ha)	Total area (000 ha) (old + new + added)	Total production (000 ton)
Lower Egypt			
Alexandria	0.6	8.3	362.0
Behira	15.5	106.3	9679.9
Gharbia	9.4	46.9	3277.6
Kafr El Sheikh	12.2	62.0	7349.4
Dakahlia	18.5	94.7	5567.6
Damietta	4.8	25.0	1915.1
Sharkia	13.9	77.0	6435.7
Ismailia	0.6	4.6	254.3
Port Said	0	5.6	267.4
Suez	0.3	1.8	121.3
Menoufia	10.7	53.5	4694.8
Qalyubia	3.9	19.5	1534.5
Cairo	0.1	0.3	15.5
Total	90.5	505.3	41,475.0
Middle Egypt			
Giza	3.9	19.9	1529.4
Bani Sweif	7.0	36.5	3213.6
Fayoum	11.2	55.8	2193.4
Minya	8.6	44.7	2578.3
Total	30.7	156.9	9514.7
Upper Egypt			
Assiut	5.2	27.5	2475.2
Sohag	7.4	38.6	3336.2
Qena	1.9	10.3	717.4

(continued)

Table 4.4 (continued)

	Added area (000 ha)	Total area (000 ha) (old + new + added)	Total production (000 ton)
Luxor	0.7	3.8	155.3
Aswan	0.3	2.8	156.3
New Valley	0	7.6	501.4
Total	15.5	90.6	7341.8
Bordered governorates			
Marsa Matrouh	0	2.1	40.4
North Sinai	0	0.002	0.05
Total	0	2.1	40.4
Grand total	136.7	754.9	58,371.9

It worth noting that the total required irrigation water to attain the amount of production presented in the Table 4.4 is the value presented in Table 4.3 under traditional cultivation. Thus, with cultivation on raised beds more Egyptian clover could be obtained, as well as higher land and water productivity.

4.2.3.3 Application of Deficit Irrigation

Abouelenein et al. (2010) showed that application of 70% of full irrigation to Egyptian clover resulted in 11% yield losses under surface irrigation in clay soil. Similarly, Khalil and Abouelenein (2012) reported that application of 70% of full irrigation to Egyptian clover resulted in 17% yield losses.

Thus, to reduced yield losses under application of deficit irrigation, we assumed that application of 93% of full irrigation water under raised beds cultivation in the old lands will reduced Egyptian clover yield by 4%. Furthermore, we assumed that application of 95% of full irrigation in the new lands under sprinkler system will reduce yield by 5%.

Table 4.5 indicated that if we invest the saved irrigation water amounts in cultivating new lands, 51.0 thousand hectares can be added, which will increase the cultivated area to 805.9 thousand hectares, or by extra 7%, compared to the total cultivated area of Egyptian clover presented in Table 4.3 under traditional cultivation. Consequently, the total production of Egyptian clover could be increase to 61,933.8 million tons, or by 38%, compared to the total production of Egyptian clover under traditional cultivation.

4.2.3.4 Water Conservation and Egyptian Clover National Production

Another assumption was made, where the saved irrigation water from cultivation on raised beds and application of deficit irrigation could be invested in increasing the cultivated area of another crop to reduce its production-consumption gap.

Table 4.5 Potential added cultivated area of Egyptian clover as a result of application of deficit irrigation, total cultivated area and its total production

	Added area (000 ha)	Total area (000 ha) (old + new + added)	Total production (000 ton)
Lower Egypt			
Alexandria	0.5	8.7	374.4
Behira	6.9	113.2	9766.3
Gharbia	3.3	50.2	3892.1
Kafr El Sheikh	4.3	66.3	7875.1
Dakahlia	6.6	101.2	5900.7
Damietta	1.7	26.7	2085.9
Sharkia	5.2	82.2	6730.7
Ismailia	0.3	4.9	269.6
Port Said	0.3	5.9	280.8
Suez	0.1	1.9	122.6
Menoufia	3.7	57.3	4659.6
Qalyubia	1.4	20.8	1489.6
Cairo	0.02	0.3	15.2
Total	34.3	539.6	43,462.7
Middle Egypt			
Giza	1.4	21.3	1650.6
Bani Sweif	2.5	39.0	3482.5
Fayoum	3.9	59.7	2604.7
Minya	3.1	47.8	2701.9
Total	10.9	167.8	10,439.7
Upper Egypt			
Assiut	1.9	29.4	2743.8
Sohag	2.7	41.3	3631.4
Qena	0.7	11.0	760.7
Luxor	0.3	4.1	164.3
Aswan	0.2	2.9	162.4
New Valley	0	7.6	526.5
Total	5.7	96.3	7988.9
Bordered governorates			
Marsa Matrouh	0.1	2.2	42.5
North Sinai	0	0.002	0.05
Total	0.1	2.2	42.5
Grand total	51.0	805.9	61,933.8

Table 4.6 showed that under raised beds cultivation, 1070.1 billion cubic meters could be saved, or 18% of the applied irrigation water to Egyptian clover under traditional cultivation. In this case, no increase in the cultivated area will occur and the total production will increase to 50,858.6 million tons, or by 13%, compared to the total production of Egyptian clover under traditional cultivation.

Table 4.6 Saved irrigation water and total production of Egyptian clover as a result cultivation on raised beds and application of deficit irrigation without added area

	Raised beds cultivation		Deficit irrigation application	
	Saved water (MCM)	Total production (000 ton)	Saved water (MCM)	Total production (000 ton)
Lower Egypt				
Alexandria	4.2	333.8	3.2	319.5
Behira	108.3	8094.3	47.8	7718.8
Gharbia	74.8	3277.6	26.2	3113.7
Kafr El Sheikh	85.3	6342.1	30.1	6025.7
Dakahlia	134.8	4734.9	48.0	4499.1
Damietta	36.2	1699.1	13.1	1614.7
Sharkia	109.6	5437.0	41.4	5170.6
Ismailia	4.2	227.7	2.1	217.1
Port Said	0	267.4	1.9	256.7
Suez	2.6	96.6	0.9	91.8
Menoufia	74.6	3923.8	26.1	3727.7
Qalyubia	28.6	1254.4	10.0	1191.7
Cairo	0.4	12.8	0.2	12.1
Total	663.6	35,701.7	251.0	33959.2
Middle Egypt				
Giza	29.7	1333.8	10.5	1267.2
Bani Sweif	54.8	2828.7	19.8	2688.1
Fayoum	91.9	2193.4	32.2	2083.7
Minya	73.0	2162.6	26.3	2055.3
Total	249.3	8518.5	88.7	8094.3
Upper Egypt				
Assiut	48.0	2252.8	17.5	2140.8
Sohag	76.3	2955.4	27.6	2808.5
Qena	21.1	616.5	7.9	586.2
Luxor	7.5	133.6	2.9	127.1
Aswan	4.2	138.2	2.1	131.9
New Valley	0	501.4	3.8	481.3
Total	157.1	6597.9	61.8	6275.8
Bordered governorates				
Marsa Matrouh	0	40.4	0.6	38.8
North Sinai	0	0.049	0.002	0.047
Total	0	40.4	0.6	38.8
Grand total	1070.1	50,858.6	402.1	48,368.1

Under application of deficit irrigation, an extra 402.1 million cubic meters or 8% of the applied irrigation water to Egyptian clover presented in Table 4.3 could be saved. The total cultivated area in this case is the same as the cultivated area of Egyptian clover under traditional cultivation, but its total production was increased to 48,368.1 million tons, or by 5% compared to the production attained under traditional cultivation.

4.2.4 Water Productivity of Egyptian Clover Under the Production Alternatives

Water productivity values of Egyptian clover were calculated under the studied five production alternatives (Table 4.7). It worth noting that the total production of Egyptian clover under traditional cultivation, as well as under raised beds cultivation and deficit irrigation application with added new areas were produced using the same amount of applied irrigation water used in traditional cultivation of Egyptian clover.

The results in Table 4.7 showed that, in general, the traditional cultivation of Egyptian clover attained the lowest water productivity, namely 5.7 kg/ha. The highest average water productivity on the national level will be attain under raised beds cultivation and the saved water was used to cultivate new areas, as well as application of deficit irrigation and the saved water was not used to cultivate new areas, namely 7.4 kg/ha. Few exceptions existed, namely Alexandria, Behira, Port Said, New Valley, Marsa Matrouh and North Sinai governorates. In Alexandria governorate, low cultivated area in the old lands resulted in similar values of water productivity when raised beds cultivation was applied, either under taking into account added area or without taking it into account and resulted also in reduction in the value of water productivity under deficit irrigation and not using the saved water to cultivate new lands.

In Behira governorate, higher productivity per hectare in the new lands, compared to the its value in the new lands resulted in lower water productivity under not using the saved water to cultivate new lands in raised beds cultivation or application of deficit irrigation. Whereas, in Port Said, New Valley and Marsa Matrouh governorates, the cultivated area was only new lands and there is no cultivated area in the old lands, cultivation on raised beds was not implemented and deficit irrigation was applied. In North Sinai, the water productivity values were similar under all production alternatives because only new lands prevailing, and because groundwater is its irrigation source.

Furthermore, Table 4.7 also indicated that the highest water productivity in Lower Egypt was attained in Kafr El-Sheikh governorate, as a result of high productivity per hectare in the old lands.

Table 4.7 Water productivity (kg/ha) of Egyptian clover under traditional cultivation, raised beds cultivation and deficit irrigation application

	Traditional cultivation	Raised beds cultivation		Deficit irrigation application	
		With added area	Without added area	With added area	Without added area
Lower Egypt					
Alexandria	5.8	6.5	6.5	6.8	6.1
Behira	10.0	13.1	12.8	13.2	11.1
Gharbia	7.6	8.8	11.0	10.4	9.0
Kafr El Sheikh	12.8	17.0	18.3	18.2	15.0
Dakahlia	6.0	8.1	8.5	8.6	7.0
Damietta	7.8	10.1	11.0	11.0	9.1
Sharkia	7.9	10.6	10.9	11.1	9.1
Ismailia	6.3	7.8	8.0	8.2	7.1
Port Said	6.9	6.9	6.9	7.3	7.0
Suez	6.2	8.9	8.8	9.0	7.2
Menoufia	9.1	12.6	13.2	12.5	10.7
Qalyubia	7.6	10.7	10.9	10.4	8.9
Cairo	5.0	7.0	7.2	6.9	5.9
Average	7.6	9.8	10.3	10.3	8.7
Middle Egypt					
Giza	7.7	10.2	11.1	11.0	9.1
Bani Sweif	8.7	11.3	12.3	12.2	10.1
Fayoum	4.2	4.8	6.0	5.7	4.9
Minya	5.0	6.8	7.0	7.1	5.8
Average	6.4	8.2	9.1	9.0	7.5
Upper Egypt					
Assiut	7.7	9.7	10.9	10.8	9.0
Sohag	6.5	8.4	9.2	9.1	7.6
Qena	4.7	6.2	6.5	6.6	5.4
Luxor	2.8	3.6	3.8	3.9	3.2
Aswan	3.7	4.5	4.6	4.7	4.1
New Valley	6.6	6.6	6.6	6.9	6.7
Average	5.3	6.5	6.9	7.0	6.0
Border governorates					
Marsa Matrouh	3.1	3.1	3.1	3.3	3.1
North Sinai	3.6	3.6	3.6	3.6	3.6
Average	3.3	3.3	3.3	3.4	3.4
Overall average	5.7	7.0	7.4	7.4	6.4

4.3 Sugar Beet Production and Deficit Irrigation

Sugar beet is considered a relatively new crop in Egypt, where its experimental cultivation started in the late 1990s. It is considered the second source of sugar production in Egypt after sugarcane. The crop has the ability to grow in marginal soils that usually suffer from salinity and can tolerate poor quality of irrigation water. It can be grown in soils with varying texture from light sands to heavy clay under supply adequate amounts of plant nutrients, as well as water (Abdel-Mawly and Zanouny 2004). Wide expansion in the cultivated area of sugar beet is occurring on the behalf of legume crops. This situation is due to sugar beet high profitability, compared to other winter crops.

Sugar beet is a deep-rooted, salt-tolerant crop that can be used as part of a cyclic reuse program to reduce agricultural drainage water volume and to conserve high quality water (Kaffka et al. 1999). There is considerable evidence that crop yield and sugar production is directly related to the amount of radiation intercepted by sugar beet foliage between sowing and harvest: the greater the incident of radiation, the higher the yields that may be expected (Blackburn 1984). Therefore, its cultivation on raised beds resulted in higher yield and lower applied irrigation water values than the values obtained under furrow cultivation (Malik et al. 2018).

4.3.1 Effect of Water Stress on Sugar Beet

Water stress is the most limiting factor for sugar beet production. Esmaeili and Yasari (2011) concluded that the effect of water stress on root yield was significant. Taheri-Asghari et al. (2009) showed that water deficit stress had an adverse effect on leaf dry weight and root length but root diameter was not affected by drought stress. Baigy et al. (2012) reported that water deficit stress led to an increase of chlorophyll index in sugar beet. Furthermore, drought stress had a negative significant effect on roots dry weight, total dry weight, root yield, leaf temperature, leaf dry weight, crown dry weight, harvest index and root yield of investigated genotypes of sugar beet (Moosavi et al. 2017).

4.3.2 Effect of Deficit Irrigation on Sugar Beet

Deficit irrigation was practiced for sugar beet by several investigators in Egypt. El-Darder et al. (2017) indicated that 8% yield losses in sugar beet was obtained when 23% saving in the applied irrigation water in sandy soil under sprinkler system occurred. Whereas, sugar beet yield losses were 7% and water saving was 22% under drip system irrigation. Mehanna et al. (2017) found that 33% saving in the applied irrigation water reduced sugar beet yield by 18%. Eid and Ibrahim (2010) tested the effect of saving 17% of the applied irrigation water to sugar beet grown under surface irrigation in salt affected soil, where fresh water was used to irrigate it and they found that percentage of yield reduction was 14%.

4.3.3 Irrigation Water Savings Techniques for Sugar Beet

4.3.3.1 Traditional Cultivation of Sugar Beet

Table 4.8 presented the collected data of cultivated area and productivity of sugar beet in the old and new lands on governorate level, as well as the calculated values of the required irrigation water. The table indicated that the highest cultivated area of sugar beet in Lower Egypt existed in Kafr El-Sheik governorate, i.e. 53.2 thousand hectares in the old lands. This is due to the suitability of sugar beet to the prevailing salt affected soil in this governorate. In Middle Egypt, the highest cultivated area existed in Fayoum governorate, namely 12.8 thousand hectares in the old lands. In Upper Egypt, sugar beet was cultivated in only two governorates, Assuit and New Valley. In the new lands, the highest cultivated area existed in Sharkia governorate in Lower Egypt, i.e. 13.9 thousand hectares. Similarly, the highest cultivated area in Middle and Upper Egypt were found in Minia and New Valley governorates, namely 4.5 and 0.8 thousand hectares.

The total cultivated area of the old and new lands were 158.4 and 58.7 thousand hectares, respectively. These areas produced 8019.4 and 2803.4 million ton of sugar beet in the old and new lands, respectively and consumed 1351.0 and 350.8 million cubic meters of irrigation water in the old and new lands, respectively (Table 4.8).

Table 4.9 showed that highest cultivated area of sugar beet was obtained from Karf El Sheik in Lower Egypt and from Beni Sweif in Middle Egypt. Furthermore, Upper Egypt and the bordered governorates, Assuit and Marsa Matrouh had the largest cultivated areas, respectively. The table also showed that the total cultivated area of sugar beet was 217.0 thousand hectares, produced 10,822.8 million tons of sugar beet and consumed 1701.9 billion cubic meters of irrigation water. According to Central Agency for Public Mobilization and Statistics (2018), the national production of sugar beet in 2017 was enough for local consumption.

4.3.3.2 Cultivation on Raised Beds

Malik et al. (2018) indicated that sugar beet grown on raised beds consumed 80% of the applied water under furrow cultivation and the yield was increased by 17%. Thus, an assumption was made that cultivation of sugar beet on raised beds will increase its yield by 15% and save 20% of its water requirements in the old lands

Table 4.8 Cultivated areas of sugar beet in the old and new lands, its production and required irrigation water

	Old lands			New lands		
	Area (000 ha)	Production (000 ton)	WR (MCM)	Area (000 ha)	Production (000 ton)	WR (MCM)
Lower Egypt						
Alexandria	1.7	78.9	12.6	1.1	51.1	5.9
Behira	13.6	659.1	107.1	2.9	129.1	16.2
Gharbia	6.0	378.8	56.2	0	0	0
Kafr El Sheikh	53.2	2405.2	414.6	1.0	43.0	5.3
Dakahlia	25.5	1348.9	215.9	10.3	522.2	61.8
Damietta	1.8	94.7	14.6	0.2	9.7	1.1
Sharkia	19.1	982.9	172.1	13.9	664.1	88.8
Ismailia	0.2	13.8	2.0	3.4	162.5	19.6
Port Said	0	0	0	12.3	571.0	68.4
Suez	0	0	0	0.1	3.8	0.5
Menoufia	0.8	37.7	6.4	0	0	0
Qalyubia	0.1	6.8	1.2	0	0	0
Total	122.1	6006.8	1002.6	45.2	2156.4	267.5
Middle Egypt						
Giza	0.1	7.9	1.2	1.2	81.1	7.2
Bani Sweif	12.3	697.4	112.9	1.0	46.5	6.6
Fayoum	12.8	599.6	124.7	0	0	0
Minya	8.9	562.2	88.5	4.5	215.5	31.1
Total	34.3	1867.1	327.4	6.7	343.2	44.9
Upper Egypt						
Assiut	2.0	145.5	21.1	0.2	11.4	1.3
New Valley	0	0	0	0.8	37.2	6.4
Total	2.0	145.5	21.1	1.0	48.6	7.7
Bordered governorates						
Marsa Matrouh	0	0	0	5.8	255.2	30.7
Total	0	0	0	5.8	255.2	30.7
Grand total	158.4	8019.4	1351.0	58.7	2803.4	350.8

WR water requirements, *MCM* million cubic meter.

only and no irrigation water saving will practice in the new lands. Thus, the saved irrigation water was assumed to be used in cultivating more lands and increase the total production of sugar beet without using any more irrigation water than the value under traditional cultivation. Thus, Table 4.10 indicated that the saved amount of irrigation water could cultivate 44.9 thousand hectares, which increase the total cultivated area to 261.9 thousand hectares, with 21% increase, compared to the value under traditional cultivation. Furthermore, the total production was 13,881.3 million tons, with 28%, compared to the value under traditional cultivation.

Table 4.9 Total cultivated area of sugar beet, its production and required irrigation water

	Area (000 ha)	Production (000 ton)	Water requirements (BCM)
Lower Egypt			
Alexandria	2.8	130.0	18.5
Behira	16.5	788.2	123.3
Gharbia	6.0	378.8	56.2
Kafr El Sheikh	54.2	2448.2	419.9
Dakahlia	35.9	1871.2	277.6
Damietta	2.0	104.4	15.6
Sharkia	33.0	1647.0	260.9
Ismailia	3.6	176.2	21.6
Port Said	12.3	571.0	68.4
Suez	0.1	3.8	0.5
Menoufia	0.8	37.7	6.4
Qalyubia	0.1	6.8	1.2
Total	167.4	8163.2	1270.1
Middle Egypt			
Giza	1.4	89.0	8.4
Bani Sweif	13.3	743.9	119.5
Fayoum	12.8	599.6	124.7
Minya	13.4	777.7	119.6
Total	41.0	2210.3	372.3
Upper Egypt			
Assiut	2.1	156.9	22.3
New Valley	0.8	37.2	6.4
Total	2.9	194.1	28.7
Bordered governorates			
Marsa Matrouh	5.8	255.2	30.7
Total	5.8	255.2	30.7
Grand total	217.1	10,822.8	1701.9

MCM billion cubic meter

4.3.3.3 Application of Deficit Irrigation

Previous research done on the effect of deficit irrigation on sugar beet yield indicated that saving 27% of the applied irrigation water under surface irrigation resulted in 14% losses in its yield (Eid and Ibrahim 2010). Whereas, in sandy soil, Mehanna et al. (2017) and El-Darder et al. (2017) revealed that 23–33% saving in the applied water could reduce sugar beet yield 7–18%. Thus, we assumed that saving of 11% of the applied water in the old lands will result in 5% yield losses and saving of 7% of the applied water in the new lands will result in 6% yield losses.

Table 4.11 revealed that 36.7 thousand hectares can be added if we invest the saved irrigation water amounts from deficit irrigation application in cultivating new areas, which will increase the total cultivated area of sugar beet to 239.9 thousand

Table 4.10 Potential added area as a result of cultivation of sugar beet on raised beds, its total cultivated area and total production

	Added area (000 ha)	Total area (000 ha) (old + new + added)	Total production (000 ton)
Lower Egypt			
Alexandria	0.5	3.3	163.6
Behira	3.8	20.3	1057.9
Gharbia	1.7	7.7	435.6
Kafr El Sheikh	15.1	69.3	3485.1
Dakahlia	7.2	43.1	2438.6
Damietta	0.5	2.6	144.9
Sharkia	5.4	38.4	2051.8
Ismailia	0.1	3.7	181.6
Port Said	0	12.3	571.0
Suez	0	0.1	3.8
Menoufia	0.2	1.0	53.9
Qalyubia	0.04	0.2	9.7
Total	34.6	202.0	10,597.4
Middle Egypt			
Giza	0	1.4	92.9
Bani Sweif	3.5	16.8	1007.5
Fayoum	3.6	16.5	689.6
Minya	2.5	15.9	984.8
Total	9.7	50.7	2774.8
Upper Egypt			
Assiut	0.6	2.7	216.8
New Valley	0	0.8	37.2
Total	0.6	3.5	254.0
Bordered governorates			
Marsa Matrouh	0	5.8	255.2
Total	0	5.8	255.2
Grand total	44.9	261.9	13,881.3

hectares, or by extra 11%, compared to the value under traditional cultivation. Consequently, the total production of sugar beet could be increase to 14,110.0 million tons, or by 30%, compared to the value under traditional cultivation.

4.3.3.4 Water Conservation and Sugar Beet National Production

Table 4.12 showed that cultivation on raised beds and application of deficit irrigation to sugar beet resulted in saving in the applied irrigation water by 270.2 and 219.4 million cubic meters, respectively or 16% and 13% of the applied irrigation

Table 4.11 Potential add area to sugar beet, its total cultivated area and total production as a result of applying deficit irrigation

	Added area (000 ha)	Total area (000 ha) (old + new + added)	Total production (000 ton)
Lower Egypt			
Alexandria	0.3	2.5	159.7
Behira	3.0	20.5	1067.2
Gharbia	1.3	9.0	461.8
Kafr El Sheikh	11.3	79.6	3479.8
Dakahlia	6.0	38.7	2469.1
Damietta	0.4	2.8	145.2
Sharkia	4.8	29.3	2093.3
Ismailia	0.3	0.6	191.4
Port Said	0.7	0.7	605.2
Suez	0.0	0.0	4.0
Menoufia	0.2	1.2	45.9
Qalyubia	0	0.2	8.3
Total	28.3	185.0	10,731.2
Middle Egypt			
Giza	0.1	0.3	97.6
Bani Sweif	2.7	18.5	1017.6
Fayoum	2.7	19.2	731.0
Minya	2.1	13.6	1004.9
Total	7.6	51.6	2851.2
Upper Egypt			
Assiut	0.4	3.0	217.8
New Valley	0.05	0.05	39.4
Total	0.5	3.0	257.1
Bordered governorates			
Marsa Matrouh	0.3	0.3	270.5
Total	0.3	0.3	270.5
Grand total	36.7	239.9	14,110.0

water to sugar beet under traditional cultivation. These amounts of water will not use to cultivated new areas with sugar beet. Thus, the total cultivated area cultivation on raised beds and application of deficit irrigation will be the same as the current cultivated area, but its total production was increase to 11,949.3 and 11,396.3 million tons, respectively or by 10% and 5%, compared to the value of sugar beet under traditional cultivation.

Table 4.12 Saved irrigation water and total production of sugar beet as a result cultivation on raised beds and application of deficit irrigation

	Raised beds cultivation		Deficit irrigation application	
	Saved water (MCM)	Total production (000 ton)	Saved water (MCM)	Total production (000 ton)
Lower Egypt				
Alexandria	2.5	141.8	1.4	134.2
Behira	21.4	887.1	16.9	841.4
Gharbia	11.2	435.6	8.3	413.8
Kafr El Sheikh	82.9	2809.0	61.9	2668.1
Dakahlia	43.2	2073.5	35.8	1964.6
Damietta	2.9	118.7	2.2	112.6
Sharkia	34.4	1794.4	30.9	1698.0
Ismailia	0.4	178.3	1.5	167.7
Port Said	0	571.0	4.1	536.7
Suez	0	3.8	0.03	3.6
Menoufia	1.3	43.3	0.9	41.1
Qalyubia	0.2	7.8	0.2	7.4
Total	200.5	9064.2	164.1	8589.5
Middle Egypt				
Giza	0.2	90.2	0.6	84.9
Bani Sweif	22.6	848.5	17.2	805.6
Fayoum	24.9	689.6	18.5	655.1
Minya	17.7	862.0	15.0	816.8
Total	65.5	2490.3	51.3	2362.4
Upper Egypt				
Assiut	4.2	178.8	3.2	169.7
New Valley	0	0.0	0.4	34.93
Total	4.2	178.8	3.6	204.6
Bordered governorates				
Marsa Matrouh	0	37.2	0.4	239.9
Total	0	215.9	0.4	239.9
Grand total	270.2	11,949.3	219.4	11,396.3

MCM million cubic meter

4.3.4 Water Productivity of Sugar Beet Under the Studied Practices

Table 4.13 presented water productivity of sugar beet under the studied five production alternatives. It worth noting that the total production of sugar beet under traditional cultivation, as well as under raised beds cultivation and deficit irrigation application with added new areas were produced using the same amount of applied irrigation water under traditional cultivation.

Table 4.13 Water productivity (kg/ha) of sugar beet under traditional cultivation, raised beds cultivation and deficit irrigation application

	Traditional cultivation	Raised beds cultivation		Deficit irrigation application	
		With added area	Without added area	With added area	Without added area
Lower Egypt					
Alexandria	7.0	8.8	8.9	7.8	8.4
Behira	6.4	8.6	8.7	7.5	8.7
Gharbia	6.7	7.8	9.7	8.2	9.6
Kafr El Sheikh	5.8	8.3	8.3	7.1	8.3
Dakahlia	6.7	8.8	8.8	7.7	8.8
Damietta	6.7	9.3	9.3	8.0	9.3
Sharkia	6.3	7.9	7.9	7.0	7.9
Ismailia	8.2	8.4	8.4	7.9	8.4
Port Said	8.3	8.3	8.3	7.8	8.3
Suez	7.4	7.4	7.4	7.0	7.4
Menoufia	5.9	8.5	8.5	7.2	8.5
Qalyubia	5.6	7.9	8.0	6.8	7.9
Average	6.8	8.3	8.5	7.5	8.5
Middle Egypt					
Giza	10.6	11.0	11.0	10.2	10.9
Bani Sweif	6.2	8.4	8.8	7.5	8.7
Fayoum	4.8	5.5	6.9	5.9	6.9
Minya	6.5	8.2	8.5	7.4	8.5
Average	7.0	8.3	8.8	7.7	8.7
Upper Egypt					
Assiut	7.0	9.7	9.9	8.4	9.8
New Valley	5.8	5.8	5.8	5.4	5.7
Average	6.4	7.8	7.8	6.9	7.8
Border governorates					
Marsa Matrouh	8.3	8.3	8.3	7.8	8.3
Average	8.3	8.3	8.3	7.8	8.3
Overall average	5.1	6.1	6.3	5.5	6.2

Table 4.13 also showed that the traditional cultivation of sugar beet attained the lowest average national water productivity, namely 5.1 kg/ha. Raised beds cultivation and the saved water used to cultivate new areas to increase total production attained the highest water productivity for sugar beet.

Table 4.13 also indicated that the highest water productivity was attained in Giza governorate as a result of high productivity per hectare in the new lands. It can be also noticed that water productivity values in Marsa Matrouh were similar under all production alternatives, except under deficit irrigation with added area. This result is attributed to only new lands is cultivated this governorates, thus the cultivation on raised beds was not implemented.

4.4 Conclusion

Our results indicated that application of deficit irrigation to Egyptian clover and sugar beet grown on raised beds allowed saving large amounts of irrigation water. This amount could be used to increase the cultivated area of another crop has production-consumption gap. The results showed that cultivation on raised beds and application of deficit irrigation to Egyptian clover resulted in increasing its total production by 13% and 8%, respectively. With respect to sugar beet, cultivation on raised beds and application of deficit irrigation resulted in increasing its total production by 10% and 5%, respectively. In both crops, application of deficit irrigation on raised beds resulted in higher water productivity value than the value obtained under traditional cultivation.

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Chapter 5
Vegetable Crops and Deficit Irrigation in Egypt

Samiha Ouda, Tahany Noreldin, and Abd El-Hafeez Zohry

Abstract An assessment of the potential effects of applying deficit irrigation to onion and tomato grown on raised beds on its production was done. Data on the cultivated area and productivity of onion and tomato were collected for both old and new lands on governorate level, as well as weather data in 2017 and water requirements were calculated. Five production alternatives were quantified on governorate level, namely traditional cultivation, raised beds cultivation, application of deficit irrigation, calculation of production without investing the saved water in adding new area, and calculation of production with investing the saved water in adding new area. In all alternatives, water productivity was calculated. The results showed that using the saved water from cultivation on raised beds and application of deficit irrigation to cultivate new areas with onion resulted in 28 and 32% increase in its production, compared to its value under traditional cultivation. Furthermore, cultivation on raised beds and application of deficit irrigation without using the added area to cultivated new lands resulted in increasing total production by 11 and 6%, respectively. With respect to tomato, using the saved water from cultivation on raised beds and application of deficit irrigation to cultivate new areas with tomato resulted in 18 and 24% increase in its production, compared to its value under traditional cultivation. Whereas, cultivation on raised beds and application of deficit irrigation without using the added area to cultivated new lands resulted in increasing total production by 6 and 1%, respectively. In both crops, water productivity was the higher when deficit irrigation was applied and the saved irrigation water was used to cultivate new areas with the crop, compare to traditional cultivation.

Keywords Onion · Tomato · Raised beds cultivation · Irrigation water saving · Water productivity

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5.1 Introduction

Horticulture crops (vegetables and fruits) offers potentials to income generation and job opportunities in the rural areas. It provides the necessary food supplements to assure a balanced diet for a healthy population. In Egypt, the total cultivated areas of vegetable crops and fruit crops are about 240,110 and 697,646 hectares, respectively. Two vegetable crops occupy the largest cultivated area in the winter season, namely onion and tomato. These two crops represent 4% of the total cultivated area of winter crops and consumes 989.4 million cubic meters or 5% of the water assigned to winter crops (Table 5.1). Both onion and tomato productions are higher than its consumption, thus there is a surplus in its production as it stated by Central Agency for Public Mobilization and Statistics (2018).

Onion is an important vegetable crop in Egypt for local consumption, where its cultivated area ranked third after wheat and Egyptian clover. The crop is also one of the most important crops for exportation. The Egyptian onion varieties characterized by high quality due to its high nutritional value and pungency. It is grown mainly for its bulbs, which are stored to meet the increased demand for both local consumption and export (Taha et al. 2019). Tomato is also an important vegetable crop in Egypt. Fresh tomatoes and other processed tomatoes products make a significant contribution to human nutrition owing to the concentration and availability of several nutrients in these products and to their widespread consumption (Sibomana et al. 2013).

Agriculture is a largest consumer of water resources in Egypt, in which its sustainability has become a major concern. The adoption of irrigation water saving strategies and maintaining acceptable yields will probably contribute in preserving this valuable natural resource. Under surface irrigation, which is the prevailing system in Egypt, cultivation on raised beds is considered one of the strategies to save 20–30% of the applied irrigation water under surface irrigation to several crops (Abouelenein et al. 2009, 2010; Karrou et al. 2012; Khalil and Abouenein 2012; Zohry et al. 2019).

Raised beds cultivation allowed the irrigation water to seep inside it through capillary action, while it moves into the ditches dug between the beds. It was reported that both water and fertilizer use efficiency were increased under raised beds cultivation (Ahmad et al. 2009 and Majeed et al. 2015), it improved water distribution and efficiency, it reduced weed infestation, it reduced lodging and it reduced seed rate without sacrificing yield (Hobbs et al. 2000). Raised beds cultivation plays an important role in increasing food availability through increasing land productivity. It was also reported that cultivation on raised beds increased productivity by 15–20%, as a result of increasing in radiation used efficiency because crops are more exposed to solar radiation (Abouelenein et al. 2010). Other studies on raised beds cultivation

Table 5.1 The cultivated area of onion and tomato, its production and water requirements

Crop	Cultivated area (ha)	Production (ton)	Water requirements (m^3)
Onion	75,248	2776,771	626,866,776
Tomato	70,238	3,116,589	362,522,022
Total	145,486		989,388,798

showed that it improved soil quality (Limon-Ortega et al. 2002), which led to enhanced root growth (Dey et al. 2015), it increased microbial functional groups and enzyme activities and it increased availability of essential nutrients for crops by stimulating microbial activity (Zhang et al. 2012). Raised beds planting also created better soil physical environment throughout the crop growth period, which led to higher crop productivity (Aggarwal and Goswami 2003).

Another strategy to face water scarcity is the application of deficit irrigation. Deficit irrigation is a water saving strategy under which crops are exposed to a certain level of water stress either during a particular developmental stage or throughout the whole growing season (Pereira et al. 2002). Applying deficit irrigation for crops grown on raised beds will lower the amount of applied irrigation water and it will involve yield losses. The exception is that any yield reduction will be insignificant compared with the benefits that gained from the conservation of water (Pereira et al. 2002).

Thus, an assessment of the potential effects of applying deficit irrigation to onion and tomato grown on raised beds was done using data on its cultivated area and productivity on governorate level in both the old and new lands. (See Chap. 2 for more details on soil classification). This data was collected from the Ministry of Agriculture and Land Reclamation in Egypt in 2017. Weather data for the winter season of 2016/17 were obtained from NASA Prediction of Worldwide Energy Resource website (https://power.larc.nasa.gov/data-access-viewer). Water requirements for each of these two crops were calculated on governorate level using BISm model (Snyder et al. 2004). Irrigation application efficiency was assumed to be 60% in the old lands under surface irrigation and 85% under drip systems in the new lands.

For onion and winter tomato, five production alternatives were quantified on governorate level as followed:

1. **Traditional cultivation**: The cultivated area and productivity per hectare of each crop in 2017 were multiplied to calculate total production. In addition, water requirements for each crop were calculated.
2. **Raised beds cultivation**: We assumed that cultivation on raised beds will increase productivity per hectare by 15%, and then the increase in the total production was calculated. We also assumed that 20% of the applied water under surface irrigation will be saved. The saved irrigation water will be used to irrigate new areas with each crop and this area will be added to the total cultivated area of the studied crops to increase its total production.
3. **Application of deficit irrigation**: The effect of application of deficit irrigation for both crops cultivated on raised beds. Because the amount of irrigation water resulted from cultivation on raised beds produced higher yield than the traditional cultivation, we applied deficit irrigation to raised beds and the losses in yield resulted from raised beds cultivation was calculated. The saved irrigation water will be used to irrigate new areas with each crop and this area will be added to the total cultivated area of the studied crops to increase its total production and compensate the loss in the productivity per hectare.
4. **Calculation of production without investing the saved water in adding new area**: Under cultivation on raised beds, we assumed that the saved water will be assigned to increase the cultivated area of another winter crop.

5. **Calculation of production without investing the saved water in adding new area:** Under application of deficit irrigation, we assumed that the saved water will be assigned to increase the cultivated area of another winter crop.

Water productivity values for each crop were calculated under the five studied production alternatives. Water productivity is a quantitative term used to define the relationship between crop produced and the amount of water involved in crop production (Igbadun et al. 2006). In our assessment, we used crop water productivity to compare between the five studied production alternatives because both production amount and the applied irrigation water to produce this amount are included.

5.2 Onion Production and Deficit Irrigation

Onion plants have slow growth rate, shallow roots system and its above ground biomass is small. Drinkwater and Janes (1955) reported that because onion plants are a shallow-rooted, most of the roots were found in the top 0.18 m of soil and only a few roots were found deeper than 0.31 m, thus the maximum root penetration was found at 0.76 m. This trait limits the amount of soil water available to onion plants, especially when grown on coarse-textured soils. Therefore, sprinkler and drip irrigation systems are well suited for this crop (Al-Jamal et al. 2001).

5.2.1 Effect of Water Stress on Onion

Onion plants were found to be sensitive to water deficit during the whole growing season, rather than specific growth stage (Kadayifci et al. 2005). Patel and Rajput (2013) indicated that it is better to maintain moderate stress during the whole growing season, rather than creating a stress during non-critical growth stages. Pelter et al. (2004) indicated that the total onion yield was reduced as a result of imposed soil water stress at any growth stage, but the greatest effect was found at the 5-leaf and, 7-leaf stages, which reduced yield by 26% compared with the non-water stress control. Furthermore, the reproductive stage is the most critical stage for water stress because it strongly affect final yield (Patel and Rajput 2013).

5.2.2 Effect of Deficit Irrigation on Onion

Nagaz et al. (2012) reported that applying 60% of crop evapotranspiration caused significant decreases in fresh yield, dry matter, bulbs per hectare, and bulb weight of onion, compared to those under both full irrigation (100% ETc) and regulated deficit irrigation (80% ETc). Taha et al. (2019) indicated that saving 20% of the applied water to onion grown under sprinkler system in sandy soil reduced yield by 8%. Zayton (2007) studied the effect of skipping the last irrigation on the applied irrigation water and the yield of onion. He found that 20% of the applied irrigation water was saved and 15% the yield was lost. Ouda et al. (2010) simulated the effect of applying 80% of full irrigation to onion grown in clay soil under surface system, where onion yield losses were 5%.

5.2.3 Irrigation Water Savings Techniques for Onion

5.2.3.1 Traditional Cultivation of Onion

Under traditional cultivation of onion, Table 5.2 indicated that the highest cultivated area in the old lands in Lower Egypt existed in Gharbia governorate, i.e. 19.9 thousand hectares. In Middle and Upper Egypt, the highest cultivated area existed in Fayoum and Sohag governorates, namely 3.2 and 2.2 thousand hectares, respectively in the old lands. In the new lands, the highest cultivated area existed in Behira governorate in Lower Egypt, i.e. 5.2 thousand hectares. Similarly, the highest cultivated areas in Middle and Upper Egypt were found in Beni Sweif and Sohag gover-

Table 5.2 The old and new cultivated areas of onion, its production and required irrigation water

		Old lands			New lands	
	Area (000 ha)	Production (000 ton)	WR (MCM)	Area (000 ha)	Production (000 ton)	WR (MCM)
Lower Egypt						
Alexandria	0	0	0	0.02	0.4	0.1
Behira	4.4	174.3	33.5	5.2	197.1	29.7
Gharbia	19.9	789.5	177.7	0	0	0
Kafr El sheikh	0.7	25.1	5.4	0	0	0
Dakahlia	10.3	342.0	82.9	0	0	0
Damietta	0.7	21.7	5.4	0.1	2.1	0.4
Sharkia	5.2	171.6	45.6	0.3	10.2	2.0
Ismailia	0.1	2.1	0.6	0.1	2.7	0.6
Suez	0.2	5.1	1.3	0.1	4.0	0.8
Menoufia	0.4	13.4	3.1	0	0	0
Qalyubia	4.7	175.6	39.3	0	0	0
Total	46.6	1720.3	395.0	5.8	216.5	33.6
Middle Egypt						
Giza	0.5	12.2	4.0	0.1	1.2	0.3
Bani Sweif	2.6	81.9	22.6	3.1	100.2	20.5
Fayoum	3.2	114.2	29.5	1.4	50.3	9.7
Minya	0.9	34.9	8.8	1.0	38.4	7.3
Total	7.2	243.2	64.9	5.6	190.2	37.8

(continued)

Table 5.2 (continued)

		Old lands			New lands	
	Area (000 ha)	Production (000 ton)	WR (MCM)	Area (000 ha)	Production (000 ton)	WR (MCM)
Upper Egypt						
Assiut	0.7	27.1	6.9	0	0	0
Sohag	2.2	94.9	24.9	3.8	173.1	32.9
Qena	0.2	8.2	2.7	0.7	26.4	6.5
Luxor	0.2	6.2	2.3	0.1	2.3	0.7
Aswan	0.1	4.2	1.8	0.5	19.2	5.6
New Valley	0	0	0	1.1	40.6	9.3
Total	3.4	140.6	38.7	6.3	261.6	55.1
Bordered governorates						
Marsa Matrouh	0	0	0	0.3	4.3	1.8
Total	0	0	0	0.3	4.3	1.8
Grand total	57.2	2104.1	498.5	18.0	672.7	128.3

WR water requirements, *MCM* million cubic meter

norates, namely 3.1 and 3.8 thousand hectares. The total cultivated area of onion in the old and new lands were 57.2 and 18.0 thousand hectares, respectively. These areas produced 2104.1 and 672.7 million ton of onion in the old and new lands, respectively and consumed 4985.4 billion cubic meters and 128.3 million cubic meters of irrigation water in the old and new lands, respectively (Table 5.2).

Table 5.3 indicated that the total cultivated area of onion for both old and new lands in 2017 was 75.2 thousand hectares. These areas produced 2776.7 million tons of onion and consumed 626.8 million cubic meters of irrigation water. This amount of national onion production is enough for local consumption (Central Agency for Public Mobilization and Statistics 2018). Table 5.3 also showed that Gharbia, Beni Swief and Sohag governorate in Lower, Middle and Upper Egypt, respectively has the highest cultivated area of onion namely, 19.9, 5.7 and 6.0 thousand hectares, respectively.

5.2.3.2 Cultivation on Raised Beds

Kahlon (2017) indicated that raised beds cultivation for onion saved 33% of the applied irrigation water and increase yield by 14%. We assumed that cultivation of onion on raised beds will increase its yield by 15% and save 20% of its water requirements in the old lands only, no irrigation water saving will practice in the new lands. Furthermore, the saved irrigation water will be used to cultivate more lands and increase the total production of onion without using any more irrigation water than its value under traditional cultivation.

Table 5.4 showed that the saved amount of irrigation water under raised beds cultivation could be invested in cultivating 15.3 thousand hectares, which increase

Table 5.3 Total cultivated area of onion, its production and required irrigation water

	Area	Production	Water requirements
	(000 ha)	(000 ton)	(BCM)
Lower Egypt			
Alexandria	0.02	0.4	0.1
Behira	9.6	371.3	63.2
Gharbia	19.9	789.5	177.7
Kafr El Sheikh	0.7	25.1	5.4
Dakahlia	10.3	342.0	82.9
Damietta	0.8	23.8	5.8
Sharkia	5.5	181.8	47.7
Ismailia	0.2	4.8	1.3
Suez	0.3	9.0	2.1
Menoufia	0.4	13.4	3.1
Qalyubia	4.7	175.6	39.3
Total	52.4	1936.8	428.6
Middle Egypt			
Giza	0.6	13.4	4.3
Bani Sweif	5.7	182.1	43.0
Fayoum	4.6	164.6	39.2
Minya	2.0	73.3	16.1
Total	12.8	433.4	102.7
Upper Egypt			
Assiut	0.7	27.1	6.9
Sohag	6.0	268.0	57.8
Qena	0.9	34.6	9.2
Luxor	0.3	8.5	3.0
Aswan	0.7	23.4	7.5
New Valley	1.1	40.6	9.3
Total	9.6	402.2	93.7
Bordered governorates			
Marsa Matrouh	0.3	4.3	1.8
Total	0.3	4.3	1.8
Grand total	75.2	2776.7	626.8

BCM billion cubic meter

the total cultivated area to 90.5 thousand hectares, or 20% increase, compared to its value under traditional cultivation. Furthermore, an increase in the total production to 3544.7 million tons could occur, or 28% compared to its value under traditional cultivation. This increase in onion total production is resulted from increase in productivity per hectare and increase in the cultivated area under raised beds cultivation.

Table 5.4 Potential added cultivated area of onion as a result of cultivation on raised beds, total cultivated area and its total production

	Added area (000 ha)	Total area (000 ha) (Old+ new+ added)	Total production (000 ton)
Lower Egypt			
Alexandria	0	0	0.4
Behira	1.2	10.8	442.0
Gharbia	5.3	25.2	1109.0
Kafr El Sheikh	0.2	0.9	36.1
Dakahlia	2.7	13.0	393.3
Damietta	0.2	1.0	2.1
Sharkia	1.4	6.9	253.6
Ismailia	0	0.2	5.7
Suez	0	0.3	11.2
Menoufia	0.1	0.5	19.0
Qalyubia	1.3	6.0	244.0
Total	12.4	64.9	2547.1
Middle Egypt			
Giza	0.1	0.7	18.2
Bani Sweif	0.7	6.4	100.2
Fayoum	0.9	5.5	212.3
Minya	0.2	2.2	87.9
Total	1.9	14.8	418.6
Upper Egypt			
Assiut	0.2	0.9	39.3
Sohag	0.6	6.6	304.2
Qena	0.1	1.0	37.8
Luxor	0	0.3	11.2
Aswan	0	0.7	25.3
New Valley	0	1.1	40.6
Total	0.9	10.5	458.4
Bordered governorates			
Marsa Matrouh	0	0.3	4.3
Total	0	0.3	4.3
Grand total	15.3	90.5	3544.7

5.2.3.3 Application of Deficit Irrigation

Kandil et al. (2011) reported that application of 83% of full irrigation resulted in 10% yield losses in onion grown under surface irrigation. Whereas, Taha et al. (2019) indicated that saving 20% of the applied water to onion grown under sprinkler system in sandy soil reduced yield by 8%. Thus, we assumed that saving of 6 and 5% of the applied water to onion in the old and new lands, respectively will result in 5% yield losses in both regions.

Table 5.5 indicated that the amount of saved water as a result of deficit irrigation application will be 4.5 thousand hectares and the total cultivated area will be 94.8 million hectares, which will produce 3659.6 million tons of onion, with 31% increase.

Table 5.5 Potential added cultivated area of onion as a result of application of deficit irrigation, total cultivated area and its total production

	Added area (000 ha)	Total area (000 ha) (Old + new + added)	Total production (000 ton)
Lower Egypt			
Alexandria	0.001	0.02	0.4
Behira	0.5	11.33	458.6
Gharbia	1.3	26.51	1092.5
Kafr El Sheikh	0	0.96	34.7
Dakahlia	0.6	13.63	473.3
Damietta	0	1.01	33.6
Sharkia	0.3	7.23	259.1
Ismailia	0	0.22	5.9
Suez	0.02	0.34	11.5
Menoufia	0.03	0.54	18.5
Qalyubia	0.3	6.31	243.1
Total	3.2	68.1	2631.3
Middle Egypt			
Giza	0.03	0.73	18.9
Bani Sweif	0.3	6.73	223.8
Fayoum	0.3	5.73	218.2
Minya	0.1	2.33	90.9
Total	0.7	15.5	551.7
Upper Egypt			
Assiut	0.04	0.90	37.5
Sohag	0.3	6.90	319.2
Qena	0.05	1.02	39.6
Luxor	0.02	0.32	11.4
Aswan	0.04	0.75	26.2
New Valley	0.1	1.18	42.7
Total	0.5	11.1	476.7
Bordered governorates			
Marsa Matrouh	0.02	0.34	4.5
Total	0.02	0.09	0.02
Grand total	4.5	94.8	3659.6

5.2.3.4 Water Conservation and Onion National Production

Cultivation on raised beds and application of deficit irrigation to onion resulted in saving in the applied irrigation water by 99.7 and 30.1 million cubic meters, respectively, or 10 and 5% of the applied irrigation water to onion under traditional cultivation.

We assumed that these amounts of water will not use to cultivated new areas with onion, instead it will be used to irrigate new areas with other crops. Thus, the total cultivated area cultivation on raised beds and application of deficit irrigation will be the same as the cultivated area using traditional method, but its total production will be increase to 3092.3 and 2937.7 million tons, or by 11 and 6% (Table 5.6), compared to the production attained under traditional cultivation of onion.

5.2.4 Water Productivity of Onion Under the Studied Production Alternatives

Table 5.7 presented water productivity of onion under the studied five production alternatives. It worth noting that the total production of onion under traditional cultivation, as well as under raised beds cultivation and deficit irrigation application with added new areas will be produced using the same amount of applied irrigation water under traditional cultivation. The results in Table 5.7 showed that the traditional cultivation of onion will attain the lowest average water productivity on the national level, namely 3.6 kg/ha. The highest average national water productivity value will be attained under raised beds cultivation and the saved water will be used to cultivate new areas and application of deficit irrigation and the saved water will not be used to cultivate new areas, namely 4.4 kg/ha.

Table 5.7 also showed that, in Alexandria governorate, there was no difference between the values of water productivity when raised beds cultivation was applied, either under taking into account added area or without taking it into account. This result attributed to low cultivated area in the old lands, where raised beds cultivation is applied. Furthermore, the highest water productivity was found in Behira governorate as a result of high productivity per hectare in the old lands.

5.3 Winter Tomato Production and Deficit Irrigation

Winter tomato is very important vegetable crop in Egypt in term of local consumption and exportation. It constitutes an important source of potassium, vitamins E and C, and oleic acid (Ali and Ismail 2014). Tomato grows tap deep strong root systems, which facilitate the absorption of soil moisture from deeper layers. Furthermore, the roots of tomato leave the soil in a good mechanical condition for the following crop (Pressman et al. 1997).

Table 5.6 Saved irrigation water and total production of onion as a result cultivation on raised beds and application of deficit irrigation

	Raised beds cultivation		Deficit irrigation application	
	Saved water (MCM)	Total production (000 ton)	Saved water (MCM)	Total production (000 ton)
Lower Egypt				
Alexandria	0	0.4	0.004	0.4
Behira	6.7	397.5	3.1	377.6
Gharbia	35.5	907.9	8.4	862.5
Kafr El Sheikh	1.1	28.8	0.3	27.4
Dakahlia	16.6	393.3	3.9	373.6
Damietta	1.1	27.1	0.3	25.7
Sharkia	9.1	207.5	2.3	197.2
Ismailia	0.1	5.1	0.1	4.9
Suez	0.3	9.8	0.1	9.3
Menoufia	0.6	15.4	0.1	14.6
Qalyubia	7.9	202.0	1.9	191.9
Total	79.0	2194.9	20.4	2085.1
Middle Egypt				
Giza	0.8	15.2	0.2	14.5
Bani Sweif	4.5	194.4	2.1	184.6
Fayoum	5.9	181.7	1.9	172.6
Minya	1.8	78.6	0.8	74.6
Total	13.0	469.9	5.0	446.4
Upper Egypt				
Assiut	1.4	31.2	0.3	29.6
Sohag	5.0	282.2	2.8	268.1
Qena	0.5	35.9	0.5	34.1
Luxor	0.5	9.5	0.1	9.0
Aswan	0.4	24.0	0.4	22.8
New Valley	0	40.6	0.5	38.6
Total	7.7	423.3	4.6	402.1
Bordered governorates				
Marsa Matrouh	0	4.3	0.1	4.1
Total	0	4.3	0.1	4.1
Grand total	99.7	3092.3	30.1	2937.7

5.3.1 *Effect of Water Stress on Winter Tomato*

Water is the limiting factor in crops production and hence high yield. Thus, attempts should be made to obtain maximum yield with minimum water supply. Under water stress condition, tomato plants tend to grow a denser root system, compared to the root system grown under non-stress water condition (Nuruddin 2001). According to Shamsul et al. (2008), the water stress at earlier stage of growth (20 day stage) has

Table 5.7 Water productivity (kg/ha) of onion under traditional cultivation, raised beds cultivation and deficit irrigation application

	Traditional cultivation	Raised beds cultivation		Deficit irrigation application	
		With added area	Without added area	With added area	Without added area
Lower Egypt					
Alexandria	4.7	4.7	4.7	4.4	4.7
Behira	5.9	7.0	7.0	6.0	6.3
Gharbia	4.4	6.2	6.4	4.9	5.1
Kafr El Sheikh	4.6	6.6	6.6	5.0	5.3
Dakahlia	4.1	4.7	5.9	4.5	4.7
Damietta	4.1	5.7	5.7	4.4	4.7
Sharkia	3.8	5.3	5.4	4.1	4.3
Ismailia	3.8	4.5	4.5	3.8	4.0
Suez	4.3	5.3	5.3	4.4	4.7
Menoufia	4.3	6.1	6.2	5.9	4.9
Qalyubia	4.5	6.2	6.4	6.2	5.1
Average	4.4	5.7	5.8	4.9	4.9
Middle Egypt					
Giza	3.1	4.2	4.4	4.4	3.5
Bani Sweif	4.2	5.0	5.0	5.2	4.5
Fayoum	4.2	5.4	5.5	5.6	4.6
Minya	4.5	5.4	5.5	5.6	4.9
Average	4.0	5.0	5.1	5.2	4.4
Upper Egypt					
Assiut	3.9	5.7	5.6	5.4	4.5
Sohag	4.6	5.3	5.3	5.5	4.9
Qena	3.8	4.1	4.1	4.3	3.9
Luxor	2.8	3.7	3.7	3.8	3.1
Aswan	3.1	3.4	3.4	3.5	3.2
New Valley	4.4	4.4	4.4	4.6	4.4
Average	3.8	4.4	4.4	4.5	4.0
Border governorates					
Marsa Matrouh	2.4	2.4	2.4	2.5	2.4
Average	2.4	2.4	2.4	2.5	2.4
Overall average	3.6	4.4	4.4	4.3	3.9

more inhibitory effect compared to water stress in later stage (30 day stage). Tomato plants are very sensitive to water stress during and immediately after transplanting, at flowering and during fruit development (Nuruddin 2001). Decreases in chlorophyll content and electrolyte leakage were reported by Kirnak et al. (2001) under water stress, which resulted in reduced vegetative growth and fruit yield. Additionally, Nyabundi and Hsia (2009) reported that tomato plants subjected to different levels of water stress under field conditions had inhibited vegetative growth but enhanced fruit development.

The influence of water stress on tomato plants and fruit quality was investigated by Nahar and Gretzmacher (2002). They reported that yield and dry matter production of tomato were adversely affected under application of 40% of the field capacity. Furthermore, Nuruddin (2001) indicated that water stress throughout the growing season significantly reduced yield of tomato and fruit size, but plants stressed only during flowering showed fewer but bigger fruits than completely non-stressed plants. Under water stress conditions, Claussen (2005) found that proline content rise, as early as in 14 h after water stress. Pokluda et al. (2010) indicated that water stress reduced specific leaf area and leaf water content and increase leaf proline concentration in tomato. Reduction in leaf water potential content was also reported by Kirnak et al. (2001) as a result of soil moisture stress, which in turn may reduce transpiration. They also added that specific leaf area and leaf water content were good indicators of water stress in tomato, and proline content was a reliable parameter corresponding to the actual water stress of plants.

5.3.2 Effect of Deficit Irrigation on Winter Tomato

Shalaby et al. (2014) studied the effect of application of deficit irrigation to tomato grown under drip system in calcareous soil. They indicated that saving 25% of the applied irrigation water resulted in 9% yield losses. Furthermore, application of 80% of full irrigation to tomato grown in clay loam soil under subsurface drip system resulted in 15% yield losses (Abdelhady et al. 2017). Additionally, Kamal and El-Shazly (2013) reported that 7% losses in tomato yield grown under drip system in calcareous soil occurred when 75% of full irrigation was applied.

5.3.3 Irrigation Water Saving Techniques for Winter Tomato

5.3.3.1 Traditional Cultivation of Winter Tomato

Table 5.8 indicated that the highest cultivated area of winter tomato in Lower Egypt existed in Sharkia governorate, i.e. 9.0 thousand hectares in the old lands. In Middle, the highest cultivated area existed in Fayoum and Minia governorates, namely 1.6 thousand hectares, respectively. In Upper Egypt, the highest cultivated area existed in Sohag, namely 1.5 thousand hectares. In the new lands, the highest cultivated area existed in Behira governorate in Lower Egypt, i.e. 11.0 thousand hectares. Similarly, the highest cultivated area in Middle and Upper Egypt were found in both Beni Sweif and Sohag governorates, namely 3.2 thousand hectares.

The total cultivated area of winter tomato in the old and new lands were 28.3 and 42.1 thousand hectares, respectively. These areas produced 1338.2 and 1780.9

Table 5.8 The old and new cultivated areas of winter tomato, its production and required irrigation water

		Old lands			New lands	
	Area (000 ha)	Production (000 ton)	WR (MCM)	Area (000 ha)	Production (000 ton)	WR (MCM)
Lower Egypt						
Alexandria	1.1	54.2	6.1	0.6	26.6	2.3
Behira	2.1	70.1	11.8	11.0	440.1	45.4
Gharbia	0.1	1.5	0.4	0	0	0
Kafr El Sheikh	2.1	80.1	11.8	0	0.6	0.1
Dakahlia	0.2	5.5	1.1	1.2	28.4	4.8
Damietta	0.5	7.7	2.9	0	0	0
Sharkia	9.0	512.3	56.3	7.6	431.9	35.5
Ismailia	2.4	131.4	12.5	1.3	66.2	5.0
Port Said	0	0	0	0.3	4.2	1.2
Suez	0.5	15.4	2.7	0.2	11.2	1.0
Menoufia	0.04	1.6	0.2	0.2	10.0	0.8
Qalyubia	0.1	4.2	0.7	0	0	0
Cairo	0.01	0.2	0	0.01	0.3	0.04
Total	18.1	884.2	106.6	22.3	1019.4	96.1
Middle Egypt						
Giza	3.1	143.7	16.3	0.7	24.5	2.7
Bani Sweif	0.7	32.7	3.9	3.2	141.6	13.8
Fayoum	1.6	60.1	9.7	0.3	11.2	1.4
Minya	1.6	67.3	9.8	0.9	41.6	4.2
Total	6.9	303.8	39.7	5.1	218.8	22.1
Upper Egypt						
Assiut	1.0	36.3	6.7	1.2	46.4	6.5
Sohag	1.5	74.3	11.9	3.2	167.0	18.7
Qena	0.2	10.0	1.7	1.0	47.5	6.5
Luxor	0.5	29.1	4.8	2.0	93.8	13.2
Aswan	0.03	0.4	0.3	0.3	5.3	2.3
New Valley	0	0	0	0.1	2.5	0.7
Total	3.2	150.2	25.4	7.9	362.4	48.0
Bordered governorates						
Marsa Matrouh	0	0	0	4.7	128.4	18.3
North Sinai	0	0	0	2.0	50.8	8.3
South Sinai	0	0	0	0.05	1.0	0.2
Total	0	0	0	6.8	180.2	26.8
Grand total	28.3	1338.2	171.6	42.1	1780.9	192.8

WR water requirements, *MCM* million cubic meter million ton of winter tomato in the old and new lands, respectively and consumed 171.6 and 192.8 million cubic meters of irrigation water in the old and new lands, respectively (Table 5.8).

Table 5.9 indicated that the total cultivated area of winter tomato was 70.4 thousand hectares, produced 3.119.1 million tons of winter tomato and consumed 364.4 million cubic meters of irrigation water. This amount of national onion production is enough for local consumption (Central Agency for Public Mobilization and Statistics 2018).

5.3.3.2 Cultivation on Raised Beds

Similar to the previous studied crops, we assumed that cultivation of winter tomato on raised beds will increase its yield by 15% and save 20% of its water requirements in the old lands only. The saved irrigation water could be used to cultivate more lands and increase the total production of winter tomato without using any more irrigation water than the value used under the traditional cultivation of winter tomato. Table 5.10 indicated that the added cultivated area will be 7.5 thousand hectares, which increase the total cultivated area to 77.9 thousand hectares, with 11% increase, compare to the area cultivated with traditional method. Furthermore, the total production of winter tomato will increase to 3669.1 million tons, with 18% compared to its value under traditional cultivation.

5.3.3.3 Application of Deficit Irrigation

Shalaby et al. (2014) and Kamal and El-Shazly (2013) indicated that saving 25% of the applied irrigation water to tomato grown under drip system resulted in 7–9% yield losses. Based on these results, we assumed that 7 and 5% of the applied irrigation water to tomato could be saved in the old and new lands, respectively with yield losses 4 and 5%, respectively. Table 5.11 showed that 5.0 thousand hectares of winter tomato could be added.

Table 5.11 also showed that this added area could increase the total cultivated area to 82.9 thousand hectares, with 18% increase, compare to the area cultivated with traditional method. Thus, the total production of winter tomato will increase to 3873.0 million tons, with 24% compare to its value under traditional cultivation.

5.3.3.4 Water Conservation and Winter Tomato National Production

Cultivation on raised beds and application of deficit irrigation to tomato resulted in saving in the applied irrigation water by 34.3 and 22.7 million cubic meters, respectively, or 9 and 6% of the applied irrigation under traditional cultivation (Table 5.12).

Table 5.9 Total cultivated area of winter tomato, its production and required irrigation water

	Area	Production	Water requirements
	(000 ha)	(000 ton)	(MCM)
Lower Egypt			
Alexandria	1.7	80.9	8.5
Behira	13.1	510.3	57.2
Gharbia	0.1	1.5	0.4
Kafr El Sheikh	2.1	80.7	11.9
Dakahlia	1.4	33.8	5.9
Damietta	0.5	7.7	2.9
Sharkia	16.6	944.1	91.7
Ismailia	3.6	197.6	17.5
Port Said	0.3	4.2	1.18
Suez	0.7	26.6	3.7
Menoufia	0.2	11.6	1.0
Qalyubia	0.1	4.2	0.7
Cairo	0.02	0.5	0.1
Total	40.5	1903.6	202.6
Middle Egypt			
Giza	3.7	168.1	19.0
Bani Sweif	3.9	174.3	17.8
Fayoum	1.9	71.3	11.0
Minya	2.5	108.9	14.0
Total	12.0	522.6	61.7
Upper Egypt			
Assiut	2.2	82.8	13.2
Sohag	4.7	241.3	30.6
Qena	1.2	57.5	8.2
Luxor	2.6	122.9	18.0
Aswan	0.3	5.7	2.6
New Valley	0.1	2.5	0.7
Total	11.1	512.6	73.3
Bordered governorates			
Marsa Matrouh	4.7	128.4	18.3
North Sinai	2.0	50.8	8.3
South Sinai	0.05	1.0	0.2
Total	6.8	180.2	26.8
Grand total	70.4	3119.1	364.4

WR water requirements, *MCM* billion cubic meter

Table 5.10 Potential added cultivated area of winter tomato as a result of cultivation on raised beds, total cultivated area and its total production

	Added area	Total area (000 ha)	Total production
	(000 ha)	(Old+ new+ added)	(000 ton)
Lower Egypt			
Alexandria	0.3	1.9	103.0
Behira	0.6	13.7	543.7
Gharbia	0.02	0.1	1.7
Kafr El Sheikh	0.6	2.7	111.5
Dakahlia	0.1	1.5	36.0
Damietta	0.1	0.6	8.9
Sharkia	2.4	19.0	1158.0
Ismailia	0.6	4.2	250.6
Port Said	0	0.3	4.2
Suez	0.1	0.8	34.7
Menoufia	0.01	0.3	12.4
Qalyubia	0.03	0.2	6.6
Cairo	0.002	0.02	0.7
Total	4.8	45.3	2272.1
Middle Egypt			
Giza	0.8	4.5	219.6
Bani Sweif	0.2	4.1	187.2
Fayoum	0.4	2.3	96.2
Minya	0.4	2.9	138.4
Total	1.8	13.8	641.5
Upper Egypt			
Assiut	0.3	2.5	97.7
Sohag	0.4	5.1	273.8
Qena	0.1	1.2	61.5
Luxor	0.1	2.7	134.0
Aswan	0	0.4	5.9
New Valley	0	0.1	2.5
Total	0.9	12.0	575.4
Bordered governorates			
Marsa Matrouh	0	4.7	128.4
North Sinai	0	2.0	50.8
South Sinai	0	0.05	1.0
Total	0	6.8	180.2
Grand total	7.5	77.9	3669.1

Table 5.11 Potential added cultivated area of winter tomato as a result of application of deficit irrigation, total cultivated area and its total production

	Added area	Total area (000 ha)	Total production
	(000 ha)	(Old+new+added)	(000 ton)
Lower Egypt			
Alexandria	0.1	2.1	108.4
Behira	0.9	14.7	575.6
Gharbia	0	0.1	2.1
Kafr El Sheikh	0.2	2.8	118.1
Dakahlia	0.1	1.5	38.4
Damietta	0	0.7	10.8
Sharkia	1.2	20.3	1217.9
Ismailia	0.3	4.5	264.2
Port Said	0	0.3	4.2
Suez	0.1	0.9	35.1
Menoufia	0	0.3	13.1
Qalyubia	0	0.2	5.8
Cairo	0	0	0.6
Total	2.9	48.3	2394.3
Middle Egypt			
Giza	0.3	4.8	235.7
Bani Sweif	0.3	4.4	199.6
Fayoum	0.1	2.5	100.6
Minya	0.2	3.0	144.2
Total	0.9	14.7	680.1
Upper Egypt			
Assiut	0.2	2.6	103.2
Sohag	0.3	5.4	288.7
Qena	0.1	1.3	65.5
Luxor	0.2	2.9	143.0
Aswan	0	0.4	6.3
New Valley	0	0.1	2.7
Total	0.8	12.8	609.4
Bordered governorates	0.8		
Marsa Matrouh	0.3	5.1	137.4
North Sinai	0.0	2.0	50.8
South Sinai	0.0	0.0	1.0
Total	0.3	7.1	189.1
Grand total	5.0	82.9	3873.0

These water amounts will not use to cultivate new area with winter tomato. Thus, the total cultivated area under raised beds and application of deficit irrigation will be the same as the cultivated area using the traditional method, but its total production will be increased to 3319.8 and 3156.4 million tons (Table 5.12), or by 6 and 1%, compared to the production using the traditional method.

Table 5.12 Saved irrigation water and total production of winter tomato as a result cultivation on raised beds and application of deficit irrigation

	Raised beds cultivation		Deficit irrigation application	
	Saved water (MCM)	Total production (000 ton)	Saved water (MCM)	Total production (000 ton)
Lower Egypt				
Alexandria	1.2	89.0	0.5	84.5
Behira	2.4	520.8	3.9	494.7
Gharbia	0.1	1.7	0.02	1.6
Kafr El Sheikh	2.4	92.8	0.7	88.1
Dakahlia	0.2	34.7	0.4	32.9
Damietta	0.6	8.9	0.2	8.4
Sharkia	11.3	1021.0	5.7	969.9
Ismailia	2.5	217.3	1.1	206.4
Port Said	0	4.2	0	4.0
Suez	0.5	28.9	0.2	27.4
Menoufia	0	11.9	0.1	11.3
Qalyubia	0.1	4.8	0.04	4.5
Cairo	0.1	0.5	0.01	0.5
Total	21.3	2036.3	12.8	1934.5
Middle Egypt				
Giza	3.3	189.7	1.1	180.2
Bani Sweif	0.8	179.2	1.2	170.3
Fayoum	1.9	80.3	0.7	76.3
Minya	2.0	119.0	0.9	113.1
Total	7.9	568.2	3.8	539.8
Upper Egypt				
Assiut	1.3	88.2	0.8	83.8
Sohag	2.4	252.4	2.0	239.8
Qena	0.3	59.0	0.6	56.1
Luxor	1.0	127.2	1.2	120.9
Aswan	0.1	5.8	0.2	5.5
New Valley	0	2.5	0.1	2.4
Total	5.1	535.1	4.8	508.4
Border governorates				
Marsa Matrouh	0	128.4	1.3	122.0
North Sinai	0	50.8	0	50.8
South Sinai	0	1.0	0	1.0
Total	0	180.2	1.3	173.7
Grand total	34.3	3319.8	22.7	3156.4

MCM million cubic meter

5.3.4 Water Productivity of Winter Tomato Under the Studied Practices

Table 5.13 presented water productivity of winter tomato under the five studied production alternatives. The total production of winter tomato under traditional cultivation, as well as under raised beds cultivation and deficit irrigation application with added new areas will be produced using the same amount of applied irrigation water under traditional cultivation.

The results in Table 5.13 showed that the traditional cultivation attained the lowest value of winter tomato water productivity, namely 6.8 kg/ha. The highest water productivity values were attained under application of deficit irrigation and the saved water will be used to cultivate new areas to increase total production of winter tomato. In Gharbia, and Demietta governorates, low water productivity existed as a result of low cultivated area in the old lands. In Port Said and New Valley governorates, there was no difference between the values of water productivity under traditional cultivation, and when raised beds cultivation was applied, either under taking into account added area or without taking it into account. This result attributed to no cultivated area in the old lands. Furthermore, the highest water productivity in Lower Egypt on national level was attained in Menoufia governorate as a result of high productivity per hectare in the old lands.

It can be also noticed from the table that the values of water productivity in North Sinai and South Sinai are similar under the five production alternatives, either cultivation on raised beds or application of deficit irrigation. This is attributed to the soil of these two governorates are sandy and its source of irrigation is groundwater. Thus, these two water saving techniques were not applied.

5.4 Conclusion

Deficit irrigation application to onion and winter tomato grown on raised beds allowed saving large amounts of irrigation water. This amount could be used to increase the cultivated area of another crop has production-consumption gap. The results showed that cultivation on raised beds and application of deficit irrigation to onion resulted in increasing its total production by 11 and 6%, respectively. With respect to tomato, cultivation on raised beds and application of deficit irrigation resulted in increasing its total production by 6 and 1%, respectively. In both crops, application of deficit irrigation on raised beds resulted in higher water productivity value than the value obtained under traditional cultivation.

Table 5.13 Water productivity (kg/ha) of winter tomato under traditional cultivation, raised beds cultivation and deficit irrigation application

	Traditional cultivation	Raised beds cultivation		Deficit irrigation application	
		With added area	Without added area	With added area	Without added area
Lower Egypt					
Alexandria	9.5	12.1	12.3	12.8	10.4
Behira	8.9	9.5	9.5	10.1	8.8
Gharbia	3.8	4.4	5.5	5.4	4.5
Kafr El Sheikh	6.8	9.4	9.8	10.0	7.9
Dakahlia	5.7	6.1	6.1	6.5	5.6
Damietta	2.7	3.0	3.8	3.7	3.1
Sharkia	10.3	12.6	12.7	13.3	11.0
Ismailia	11.3	14.3	14.5	15.1	12.3
Port Said	3.5	3.5	3.5	3.5	3.4
Suez	7.2	9.4	9.2	9.5	7.8
Menoufia	11.6	12.4	12.3	13.1	11.4
Qalyubia	6.3	10.1	9.1	8.9	7.4
Cairo	5.5	7.3	6.6	6.8	5.7
Average	7.2	8.8	8.8	9.1	7.6
Middle Egypt					
Giza	8.9	11.6	12.1	12.4	10.0
Bani Sweif	9.8	10.5	10.6	11.2	9.7
Fayoum	6.5	8.7	8.8	9.1	7.3
Minya	7.8	9.9	9.9	10.3	8.4
Average	8.2	10.2	10.3	10.8	8.9
Upper Egypt					
Assiut	6.3	7.4	7.5	7.8	6.6
Sohag	7.9	8.9	8.9	9.4	8.0
Qena	7.0	7.5	7.5	8.0	6.9
Luxor	6.8	7.4	7.5	7.9	6.8
Aswan	2.2	2.3	2.3	2.4	2.1
New Valley	3.4	3.4	3.4	3.6	3.2
Average	5.6	6.2	6.2	6.5	5.6
Border governorates					
Marsa Matrouh	7.0	7.0	7.0	7.5	6.7
North Sinai	6.1	6.1	6.1	6.1	6.1
South Sinai	5.0	5.0	5.0	5.0	5.0
Average	6.0	6.0	6.0	6.2	5.9
Overall average	6.8	7.8	7.8	8.2	7.0

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Chapter 6
Wheat Insufficiency and Deficit Irrigation

Abd El-Hafeez Zohry and Samiha Ouda

Abstract In this chapter, we tested whether implementing different production alternatives will contribute in increasing wheat national production and increase its self-sufficiency ratio. Data on the cultivated area and productivity of wheat were collected for both old and new lands on governorate level, as well as weather data in 2017 and water requirements were calculated. Data on the cultivated area of winter tomato, sugar beet, cotton, fruit trees and sugarcane were collected. The population data was also collected. Five production alternatives were quantified on governorate level, namely traditional cultivation, raised beds cultivation, application of deficit irrigation, implementing intercropping systems with wheat and use the saved water from application of deficit irrigation to Egyptian clover, sugar beet, onion and tomato. Under all alternatives, self-sufficiency ratio and water productivity were calculated. The results showed that using the saved water from cultivation on raised beds and application of deficit irrigation to cultivate new areas with wheat resulted in 32 and 41% increase in its production, compared to its value under traditional cultivation and wheat self-sufficiency ratio was increased to 57 and 61%, respectively. Furthermore, application of deficit irrigation and implementing intercropping systems, as well as application of deficit irrigation, implementing intercropping systems and using the saved water from other crops to cultivate more wheat areas resulted in increasing total production by 61 and 100%, respectively compared to its value under traditional cultivation and that increased wheat self-sufficiency ratio to reach 70 and 85%, respectively. The highest water productivity values were found under application of deficit irrigation and implementing intercropping systems.

Keywords Raised beds cultivation · Application of deficit irrigation to raised beds · Wheat intercropping systems · Wheat self-sufficiency ratio

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6.1 Introduction

Globally, wheat is the most widely cultivated cereal crop, it is the largest contributor with nearly 30% of the world grain production and it contributes with 50% of the world grain trade (Sharma et al. 2015). Wheat is a very important crop in the diet of the Egyptian, where it is the main crop used in bread making. Egypt has the highest per capita consumption of wheat in the world. In 1960s, Egyptians consumed annually less than 110 kg per capita of wheat. In the 1980s, the wheat supply was enough to provide 175 kg per capita, compared to a world average of less than 60–75 kg per capita (Metz 1990). In 2012, Egyptians, on average, consume up to 200 kg of wheat per capita per year (Aegic 2015). As a result, Egypt is by far the largest importer of wheat globally. Wheat production-consumption is continuously increasing year after year as a result of population increase. Self-sufficiency of wheat declines from 51% in 2013 to 48% in 2016. This decline is a result of rise in wheat consumption by annual population increase, which approach 2.0 million/year (Mansour 2012).

The Egyptian wheat cultivars are suited to be grown throughout Egypt; in the old lands as well as in the new areas (See Chap. 2 for details on agricultural lands classification). The cultivated area of wheat is the highest among the winter crops, where it competes with Egyptian clover and most recently with sugar beet. Most of the wheat cultivated area lies in the Nile Delta with about 57% of the total area, and smaller areas in Middle and Upper Egypt with about 18 and 17%, respectively. In the old lands, wheat is cultivated in basins or on furrows under surface irrigation. Surface irrigation system has low water application efficiency, namely 50–60% led to many adverse consequences on the soils besides water loss to ground water. It also resulted in ineffective use of applied nitrogen owing to poor aeration, leaching and volatilization losses. Application of high amount of irrigation water results in greater crop lodging, lower water use efficiency, and crusting of the soil surface (Majeed et al. 2015).

On the other hand, these adverse consequences could be minimized by cultivation on raised beds. Irrigation water saving under raised beds cultivation was reported to be 15–30% (Abouelenin et al. 2009, 2011; Karrou et al. 2012; Khalil and Abouelenin 2012; Zohry et al. 2019). Crops cultivated on raised beds attain higher productivity by 15–20%, compared to the traditional cultivation in basins or on furrows (Ahmad et al. 2009; Hobbs et al. 2000; Abouelenin et al. 2009, 2010; Majeed et al. 2015). Improved water and fertilizer use efficiency was also reported under raised beds cultivation (Hobbs et al. 2000; Sing et al. 2010; Karrou et al. 2012; Majeed et al. 2015). Improved in soil quality (Limon-Ortega et al. 2002), enhanced root growth, (Dey et al. 2015), and increased microbial functional groups and enzyme activities, increased in availability of essential crop nutrients (Zhang et al. 2012) are other benefits could be obtained under raised beds cultivation. Thus, cultivation on raised beds could be used as a water saving strategy under surface irrigation in Egypt to face water scarcity, application of deficit irrigation instead of full irrigation to crops grown on raised beds can be used to increase the productivity of unit of irrigation water. Deficit irrigation is an irrigation practice characterized by application of irrigation water below the full required amounts for optimal growth and yield, aiming at improving the response of plants to the certain degree of water deficit in a positive manner, and improving crop's water use efficiency (Chai et al. 2016). The saved amount of irrigation water could be assigned to cultivate larger areas of a certain crop to compensate loss in productivity under deficit irrigation application.

Thus, in this chapter, we tested whether application of deficit irrigation to wheat grown on raised beds, use the saved irrigation water to cultivate new lands with wheat and use the saved water from application of deficit irrigation to Egyptian clover, sugar beet, onion and winter tomato will contribute in increasing wheat national production and increase its self-sufficiency.

Furthermore, in Chaps. 3 and 4, an amount of irrigation water could be saved as a result of application of deficit irrigation to raised beds cultivated four winter crops, namely Egyptian clover, sugar beet, onion and winter tomato. We assumed that these amounts of saved water can be invested in irrigating more areas cultivated with wheat to increase its national production and consequently increase wheat self-sufficiency ratio.

To do this analysis, data on cultivated area and productivity of wheat were collected for both old and new lands on governorate level from the Ministry of Agriculture and Land Reclamation in Egypt in 2017. Weather data for the winter season of 2016/17 were obtained from NASA Prediction of Worldwide Energy Resource website (https://power.larc.nasa.gov/data-access-viewer). Water requirements for wheat were calculated on governorate level using BISm model (Snyder et al. 2004). Irrigation application efficiency was assumed to be 60% in the old lands under the surface irrigation and 75% under sprinkler systems in the new lands. Five production alternatives were quantified as followed:

1. **Traditional cultivation**: the cultivated area of wheat and productivity per hectare in 2017 on governorate level in both the old and the new lands were multiplied to calculate total production. In addition, water requirements were calculated. Wheat consumption by the population was calculated as well as its production-consumption gap.
2. **Raised beds cultivation**: We assumed that cultivation on raised beds will increase productivity per hectare by 15%, and then the increase in the total production was calculated. We also assumed that 20% of the applied water under surface irrigation will be saved. The saved irrigation water will be used to irrigate new areas cultivated with wheat and this area will be added to the total cultivated area of wheat to increase its total production. Wheat production-consumption gap was calculated under this production alternative.
3. **Application of deficit irrigation**: The effect of application of deficit irrigation wheat cultivated on raised beds. Because the amount of irrigation water resulted from cultivation on raised beds produced higher yield than the traditional cultivation, we applied deficit irrigation to it and the losses in yield resulted from deficit irrigation application was calculated. The saved irrigation water was used to irrigate new areas with wheat and this area will be added to the total cultivated

area to increase its total production and compensate the loss in the productivity per hectare. Wheat production-consumption gap was calculated under this production alternative.

4. **Implementing intercropping systems for wheat**: the effect of five wheat intercropping systems on wheat total production was assessed. These intercropping systems are: wheat intercropping with tomato, cotton relay intercropped with wheat, wheat intercropping with sugar beet, wheat intercropped under fruit trees, and wheat intercropped with sugarcane. Wheat production resulted from intercropping systems was added to the production resulted from applying deficit irrigation on raised beds and its total production was calculated. Wheat production-consumption gap was calculated under this production alternative.
5. **Investment of the saved irrigation water:** the saved irrigation water resulted from cultivation on raised beds and application of deficit irrigation to Egyptian clover and sugar beet in Chap. 5 and resulted from onion and tomato in Chap. 6 was assumed to be used in cultivating new areas with wheat, then the total production was calculated. Wheat production resulted from intercropping systems was added to the production resulted from applying deficit irrigation and the production resulted from the saved water from the four crops. The total wheat production was calculated, as well as wheat production-consumption gap under this production alternative.

Igbadun et al. (2006) stated that Water productivity is a quantitative term used to define the relationship between crop produced and the amount of water involved in crop production. It is a good indicator to compare between the five productions alternatives, because it involves both crop production amount, and its applied irrigation water to produce this amount. Thus, water productivity was calculated under the above five production alternatives.

6.2 Wheat Production and Deficit Irrigation

Wheat is an annual C3 crop and it is the most widely grown cereal crop. Since the Green Revolution, wheat yields have increased in many regions of the world (Gewin 2010). To cope with the future demands for food, the yield of wheat and its yield potential under water-limited conditions needs to increase because farmland is increasingly being threatened by drought stress around the world (del Pozo et al. 2016).

6.2.1 Effect of Water Stress on Wheat

Under water-limited conditions, use of cultivars that have the ability to extract more water from the deeper soil profile to increase yield is a key strategy for wheat management (Thapa et al. 2017). Under water stress, plants close their stomata to prevent dehydration, which cause drastic reduction in transpiration rates (Taiz and Zeiger 2004), and abscisic acid increases by as much as 50-fold in leaves, which decreases leaf area due to lower-turgor-pressure cells, stomatal closure, the induction of senescence and ethylene production (Taiz and Zeiger 2013). A change in the osmotic potential, relative to the plasma membrane, can be a major cause of response to water stress at the molecular level (Bray 1993). Water stress also affects many important biochemical processes such as osmotic adjustment, antioxidant enzyme defense system, abscisic acid production, and lipid peroxidation (Sarto et al. 2016). A decrease in photosynthesis and increase in leaf senescence associated with drought stress during the grain filling period of wheat results in yield reduction (Zhang et al. 1998). The increase in Si in the plant can increase the efficiency of water use by some grasses (Sarto et al. 2017).

Rodrigues et al. (1998) highlighted three critical periods wherein the occurrence of drought most affects the wheat crop: floral initiation and inflorescence development, anthesis and fertilization, and grain formation. Dias (2008) indicated that the greatest reduction in wheat grains yield occur when plants suffer from water deficiency during 15 days before and 5 days after heading. Under severe stress, the dehydration in mesophyll cells inhibits photosynthesis and water use efficiency decreases as a result (Taiz and Zeiger 2004). Whereas, Kirigwi et al. (2004) indicated that the most sensitive growth stage to lack of water in wheat is the flag leaf stage, followed by the flowering stage. A reduction in water availability in plants leads to the reduction of cell solutes thus increasing the solute concentration. This causes the plasma membrane to become thicker, affecting the turgidity processes of cells, reducing the leaf area and causing stomatal closure. This results in a reduced rate of photosynthesis, influencing the plant development (Dias 2008). Decrease in water availability in wheat causes reduced growth by decreasing water potential, stomatal conductance, photosynthesis, and nitrogen assimilation. During the milk-grain stage, wheat is the least sensitive to water stress (Cunha et al. 2009).

6.2.2 *Effect of Deficit Irrigation*

Galavi and Moghaddam (2012) stated that wheat yield, harvest index, water use efficiency and evapotranspiration efficiency were negatively affected by deficit irrigation, compared to well-watered treatment. Malik and Ahmad (1993) indicated that deficit irrigation was found to reduce grain yield when applied at any physiological growth stage, but the extent of damage varied from stage to stage. Irrigation applied at the jointing and heading stages of winter wheat resulted in reasonable grain yield and water use efficiency besides increasing root length density due to the changes in the vertical distribution of root length density (Li et al. 2010).

Application of deficit irrigation to wheat grown in sandy soil was done and its effects were tested by Noreldin et al. (2015), where they reduced the applied irrigation water by 25 and 20% under drip and sprinkler systems, respectively. They found that wheat yield was reduced by 20 and 18%, respectively. Whereas, Abdelraouf et al. (2013) indicated that application of 75% of wheat water requirements under sprinkler irrigation in sandy soil resulted in only 3% reduction in wheat yield as a result of applying 100% of NPK via fertigation pump. This practice reduced the leaching of fertilizer, improved plants growth and reduce yield losses under deduction of 25% of the applied irrigation water. Similarly, Taha and Ouda (2016) indicated that application of deficit irrigation for wheat, where 11% saving in the applied water was practiced in sandy soil using sprinkler system and fertigation in 80% of irrigation time resulted in 2% yield losses only. The low percentage of yield losses under fertigation in 80% of irrigation time was resulted from increasing fertilizer use efficiency. In clay soil of Egypt, Abdrabbo et al. (2013) indicated that saving 20% of the applied water to wheat grown under drip irrigation resulted in 8% yield losses. Whereas, Karrou et al. (2012) revealed that application of 78% of full irrigation to wheat grown under surface irrigation resulted in 5% yield losses.

6.2.3 Irrigation Water Savings Techniques for Wheat

6.2.3.1 Traditional Cultivation of Wheat

Table 6.1 presented the collected data of cultivated area and productivity of wheat in the old and new lands on governorate level, as well as the calculated values of the required irrigation water.

The table indicated that the highest cultivated area of wheat in Lower Egypt existed in Behira governorate, i.e. 122.2 thousand hectares in the old lands. In Middle Egypt, the highest cultivated area existed in Minya governorate, namely 91.7 thousand hectares in the old lands. In Upper Egypt, the highest cultivated area was found in Assuit governorate, namely 80.5 thousand hectares. In the new lands, the highest cultivated area existed in Behira governorate in Lower Egypt, i.e. 54.1 thousand hectares. Similarly, the highest cultivated area in Middle and Upper Egypt were found in Minya and New Valley governorates, namely 4.5 and 63.5 thousand hectares. In the bordered governorates, Marsa Matrouh has the highest cultivated area of wheat, namely 3.9 thousand hectares. The total cultivated area of the old and new lands were 989.5 and 227.9 thousand hectares, respectively. These areas produced 6983.4 and 1431.1 million tons of wheat in the old and new lands, respectively and consumed 6733.8 and 1255.4 billion cubic of irrigation water in the old and new lands, respectively (Table 6.1).

Table 6.2 indicated that the highest total wheat cultivated area in Lower, Middle and Upper Egypt was found in Behira, Minya and Assuit governorates. The table also showed that total cultivated area of wheat was 1217.4 million hectares, produced 8414.5 million tons of wheat and consumed 7989.2 billion cubic meters of irrigation water.

Table 6.1 The old and new cultivated areas of wheat, its production and required irrigation water

	Old lands			New lands		
	Area (000 ha)	Production (000 ton)	WR (BCM)	Area (000 ha)	Production (000 ton)	WR (BCM)
Lower Egypt						
Alexandria	13.2	88.4	68.9	18.3	113.2	71.8
Behira	122.2	872.6	685.5	54.1	362.3	227.5
Gharbia	43.1	292.4	292.5	0	0	0
Kafr El Sheikh	84.9	556.2	471.6	1.0	6.5	4.3
Dakahlia	72.2	571.1	400.2	6.5	50.7	27.2
Damietta	8.2	55.3	46.7	0.5	2.9	2.0
Sharkia	139.1	971.4	920.1	9.9	60.7	49.1
Ismailia	8.6	56.0	51.3	5.7	36.9	25.7
Port Said	0	0	0.0	5.0	34.5	21.5
Suez	1.9	11.9	11.5	0.4	2.5	1.9
Menoufia	50.7	389.9	295.3	0	0	0
Qalyubia	20.9	147.9	130.9	0	0	0
Cairo	0	0	0	0	0	0
Total	564.9	4013.1	3374.5	101.5	670.2	431.0
Middle Egypt						
Giza	15.0	118.8	90.0	2.4	16.3	10.7
Bani Sweif	46.4	332.6	310.9	3.6	23.2	17.9
Fayoum	75.2	487.1	533.8	1.7	10.1	9.3
Minya	91.7	658.0	666.5	4.5	27.1	24.5
Total	228.3	1596.4	1601.2	12.2	76.6	62.4
Upper Egypt						
Assiut	80.5	583.9	642.4	7.4	45.5	44.1
Sohag	76.0	523.0	737.1	4.8	25.0	34.9
Qena	28.3	188.3	263.6	9.5	52.0	66.4
Luxor	6.6	44.1	64.9	6.5	35.7	47.9
Aswan	4.9	34.6	50.2	17.2	114.5	132.8
New Valley	0	0	0	63.5	385.6	412.1
Total	196.2	1373.9	1758.2	108.9	658.4	738.2
Bordered governorates						
Marsa Matrouh	0	0	0	3.9	22.6	16.7
North Sinai	0	0	0	1.0	1.2	4.0
South Sinai	0	0	0	0.5	2.0	3.1
Total	0	0	0	5.3	25.8	23.9
Grand total	989.5	6983.4	6733.8	227.9	1431.1	1255.4

WR water requirements, *BCM* Billion cubic meter

Table 6.2 Total cultivated area of wheat, its production and required irrigation water

	Area (000 ha)	Production (000 ton)	Water requirements (MCM)
Lower Egypt			
Alexandria	31.5	201.6	140.7
Behira	176.2	1234.9	912.9
Gharbia	43.1	292.4	292.5
Kafr El Sheikh	85.9	562.8	476.0
Dakahlia	78.7	621.9	427.3
Damietta	8.7	58.2	48.7
Sharkia	149.0	1032.0	969.2
Ismailia	14.3	92.8	77.1
Port Said	5.0	34.5	21.5
Suez	2.3	14.4	13.4
Menoufia	50.7	389.9	295.3
Qalyubia	20.9	147.9	130.9
Cairo	0	0	0
Total	666.4	4683.2	3805.4
Middle Egypt			
Giza	17.4	135.0	100.6
Bani Sweif	50.0	355.8	328.9
Fayoum	77.0	497.1	543.1
Minya	96.2	685.1	691.0
Total	240.5	1673.0	1663.6
Upper Egypt			
Assiut	87.8	629.4	686.5
Sohag	80.8	548.0	772.0
Qena	37.8	240.3	330.0
Luxor	13.1	79.8	112.8
Aswan	22.1	149.1	183.0
New Valley	63.5	385.6	412.1
Total	305.1	2032.4	2496.4
Bordered governorates			
Marsa Matrouh	3.9	22.6	16.7
North Sinai	1.0	1.2	4.0
South Sinai	0.5	2.0	3.1
Total	5.3	25.8	23.9
Grand total	1217.4	8414.5	7989.2

WR water requirements, *BCM* billion cubic meter

6.3 Population, Wheat Consumption and Wheat Production-Consumption Gap

Table 6.3 presented the Egyptian population in 2017, their consumption of wheat and the gap between production and consumption. The table revealed that, in Lower

Table 6.3 Egyptian population, wheat consumption and wheat production-consumption gap

	Population (000 inhabitants)	Consumption (000 ton)	Gap (000 ton)
Lower Egypt			
Alexandria	5179	1057	−855
Behira	6200	1265	−30
Gharbia	5019	1024	−731
Kafr El Sheikh	3377	689	−126
Dakahlia	6516	1329	−708
Damietta	1502	306	−248
Sharkia	7192	1467	−435
Ismailia	1309	267	−174
Port Said	751	153	−119
Suez	731	149	−135
Menoufia	4319	881	−491
Qalyubia	5648	1152	−1004
Cairo	9570	1952	−1952
Total	57,314	11,692	−7009
Middle Egypt			
Giza	8666	1768	−1633
Bani Sweif	3171	647	−291
Fayoum	3615	738	−240
Minya	5527	1127	−442
Total	20,980	4280	−2607
Upper Egypt			
Assiut	4407	899	−270
Sohag	4995	1019	−471
Qena	3182	649	−409
Luxor	1256	256	−176
Aswan	1481	302	−153
New Valley	242	49	**336**
Total	15,564	3175	−1143
Bordered governorates			
Marsa Matrouh	429	88	−65
North Sinai	452	92	−91
South Sinai	103	21	−19
Red Sea	361	74	−74
Total	1345	274	−249
Grand total	95,203	19,421	−11,007

Egypt, Cairo has the highest population, wheat consumption and wheat gap. Whereas, in Middle and Upper Egypt, Giza and Sohag have the highest population, wheat consumption and wheat gap, respectively. Table 6.3 also showed that in bordered governorate, North Sinai has the highest population, wheat consumption and wheat gap. Self-sufficiency ratio under this case was 43%.

It worth noting that Behira governorate has the lowest wheat gap and New Valley has surplus in wheat production. The total population was 95,203 million inhabitants, consumed 19,421 million tons of wheat, and wheat production-consumption gap was 11,007 million tons.

6.3.1 Cultivation on Raised Beds

It was documented in previous research in Egypt that raised beds cultivation for wheat can save 20–30% of the applied irrigation water and it can increase yield by 15–22% (Abouelenin et al. 2010; Karrou et al. 2012; Khalil and Abouelenin 2012; Zohry et al. 2019). We assumed that raised beds cultivation will save 20% of the applied irrigation water in the old lands and no water saving will occur in the new lands. In addition, wheat productivity will increase by 15% in the old lands only.

Table 6.4 indicated that 1346.8 billion cubic meters of water could be saved as a result of cultivation of wheat on raised beds. This amount of water could be used to cultivate 263.9 thousand hectares, when added to the total wheat area it will reach 1481.2 million hectares. These cultivated areas (old, new and added cultivated area) will produced 11,124.9 million tons of wheat and reduce wheat production-consumption gap to 8296.4 million ton, which could increase self-sufficiency ratio to 57%. Furthermore, it can be notice from the table that several governorates can attain self-sufficiency in addition to surplus in wheat production. These governorates were Behira and Kafr El-Sheik in Lower Egypt, in addition to New Valley in Upper Egypt.

6.3.2 Application of Deficit Irrigation

From previous research conducted in Egypt on application of deficit irrigation to wheat, we assumed that, in the old land, saving 10% of the applied water will result in 5% yield losses. Similarly, in the new lands, saving 5% of the applied water will result in 5% yield losses.

Table 6.5 indicated that 665.0 million cubic meters of water could be saved as a result of application of deficit irrigation to wheat cultivated on raised beds. This amount of water could be used to cultivate 134.1 thousand hectares, when added to the total wheat area it will reach 1615.4 million hectares. These cultivated areas (old, new and added cultivated area) will produced 11,894.4 million tons of wheat and reduce wheat production-consumption gap to 7526.9 million ton, in which self-

Table 6.4 Potential saved irrigation water, added area to wheat cultivated area as a result of cultivation on raised beds, total cultivated area and its total production

	Saved (MCM)	Added area (000 ha)	Total area (000 ha) (Old+ new+ added)	Total production (000 ton)	Gap (000)
Lower Egypt					
Alexandria	13.8	3.5	35.0	236.6	−820.0
Behira	137.1	32.6	208.8	1584.2	**319.4**
Gharbia	58.5	11.5	54.6	413.3	−610.5
Kafr El Sheikh	94.3	22.6	108.6	788.3	**99.5**
Dakahlia	80.0	19.2	98.0	856.9	−472.4
Damietta	9.3	2.2	10.9	80.3	−226.1
Sharkia	184.0	37.1	186.1	1404.9	−62.3
Ismailia	10.3	2.3	16.6	115.9	−151.2
Port Said	0	0	5.0	34.5	−118.7
Suez	2.3	0.5	2.7	19.2	−129.9
Menoufia	59.1	13.5	64.3	531.2	−349.9
Qalyubia	26.2	5.6	26.5	204.3	−947.8
Cairo	0	0	0	0	−1952.4
Total	674.9	150.7	817.1	6269.7	−5422.3
Middle Egypt					
Giza	18.0	4.0	21.4	180.3	−1587.6
Bani Sweif	62.2	12.4	62.3	486.2	−160.7
Fayoum	106.8	20.1	97.0	685.7	−51.9
Minya	133.3	24.4	120.6	931.1	−196.4
Total	320.2	60.9	301.3	2283.3	−1996.6
Upper Egypt					
Assiut	128.5	21.5	109.3	849.7	−49.4
Sohag	147.4	20.3	101.1	732.3	−286.8
Qena	52.7	7.5	45.3	309.9	−339.2
Luxor	13.0	1.8	14.9	96.1	−160.0
Aswan	10.0	1.3	23.4	163.0	−139.2
New Valley	0	0	63.5	385.6	**336.2**
Total	351.6	52.3	357.5	2536.5	−638.4
Bordered govern.					
Marsa Matrouh	0	0	3.9	33.9	−53.7
North Sinai	0	0	1.0	0.5	−91.7
South Sinai	0	0	0.5	1.1	−19.8
Red sea	0	0	0	0	−73.7
Total	0	0	5.3	35.4	−239.0
Grand total	1346.8	263.9	1481.2	11,124.9	−8296.4

BCM million cubic meter

Table 6.5 Potential saved irrigation water, added area to wheat cultivated area as deficit irrigation, total cultivated area and its total production

	Saved (MCM)	Added area (000 ha)	Total area (000 ha) (Old+ new+ added)	Total production (000 ton)	Gap (000)
Lower Egypt					
Alexandria	9.7	2.6	37.6	250.7	−805.8
Behira	71.7	17.9	226.7	1684.1	**419.2**
Gharbia	25.7	5.3	60.0	438.5	−585.3
Kafr El Sheikh	41.7	10.5	119.1	839.1	**150.3**
Dakahlia	36.6	9.3	107.2	909.4	−420.0
Damietta	4.2	1.0	11.9	85.6	−220.8
Sharkia	83.4	17.7	203.8	1507.9	**40.6**
Ismailia	5.8	1.4	18.0	122.6	−144.5
Port Said	1.1	0.3	5.3	36.2	−117.0
Suez	1.1	0.2	3.0	20.4	−128.7
Menoufia	26.0	6.3	70.5	576.4	−304.7
Qalyubia	11.5	2.6	29.1	219.9	−932.2
Cairo	0	0	0	0	−1952.4
Total	318.5	75.1	892.2	6690.9	−5001.1
Middle Egypt					
Giza	8.5	2.0	23.4	193.5	−1574.4
Bani Sweif	28.3	5.9	68.3	520.1	−126.9
Fayoum	47.4	9.4	106.4	735.4	−2.2
Minya	59.9	11.6	132.2	1003.8	−123.7
Total	144.0	28.8	330.2	2452.8	−1827.1
Upper Egypt					0.0
Assiut	58.7	10.3	119.6	914.2	15.1
Sohag	66.6	9.6	110.7	796.6	−222.4
Qena	26.5	4.0	49.3	333.4	−315.7
Luxor	8.1	1.2	16.1	102.8	−153.3
Aswan	11.1	1.5	24.9	172.0	−130.3
New Valley	20.6	3.3	66.8	404.9	**355.4**
Total	191.6	30.0	387.4	2723.8	−451.2
Bordered govern.					
Marsa Matrouh	0.8	0.2	4.1	23.7	−63.9
North Sinai	0	0	1.0	1.19	−91.0
South Sinai	0	0	0.5	2.0	−18.9
Red sea	0	0	0	0	−73.7
Total	0.8	0.2	5.5	26.9	−247.5
Grand total	655.0	134.1	1615.4	11,894.4	−7526.9

MCM million cubic meter

sufficiency ratio was increase to 61%. Table 6.5 also indicated that more governorates could attain self-sufficiency in addition to surplus in wheat production. These governorates are Behira, Kafr El-Sheik and Sharkia in Lower Egypt, in addition to New Valley in Upper Egypt.

6.3.3 Wheat Intercropping with Other Crops

Katyayan (2005) defined intercropping as a system of management of crops which involves growing two or more dissimilar crop species simultaneously in distinct row combination on the same piece of land. Intercropping offers a potential benefit over monoculture cultivation for yield increase through more effective use of resources, including water, nutrients, and solar energy (Nasri et al. 2014). This practice could be used as a way to improve soil fertility, increase land productivity and save on the applied irrigation water (Kamel et al. 2010), as well as increase water productivity as a result of using less water to irrigate two crops (Andersen 2005).

Furthermore, implementing intercropping systems can increase food availability and security (Ouma and Jeruto 2010). The most common reason for the adoption of intercropping systems technique is yield advantage, which is explained by the greater resource depletion by intercrops than monocultures (Hauggaard-Nielsen et al. 2006). The efficiency of the intercropping is directly depends on proper management of the factors of production, such as the spatial arrangement of crops and planting density, where it can reduce the competition for resources and increase the efficiency of the system (Porto et al. 2011). These factors, when properly managed, can bring ecological and economic benefits, as a result of increasing production when compared to monoculture (Batista et al. 2016).

The conventional ways of intensifying crop production are vertical and horizontal expansions, however intercropping offers two additional dimensions, time and space (Zohry and Ouda 2017). Francis (1986) stated that the intensification of land and resources use in space dimension is an important aspect of intercropping, where it enhance the efficient use of light as two or more species occupy the same land during a significant part of the growing season and have different pattern of foliage display. Furthermore, different rooting patterns can explore greater and different soil volume and depth (Francis 1986). These differences in foliage display and rooting patterns create the space dimension of intercropping (Dunn et al. 1999).

Assessment of the contribution of five intercropping systems of wheat on increasing its cultivated area and production was done. These five intercropping systems are wheat intercropping with winter tomato (Abd El-Zaher et al. 2013), cotton relay intercropped with wheat (Lamlom et al. 2018), wheat intercropping with sugar beet (Abou-Elela 2012), wheat intercropped under fruit trees, and wheat intercropped with sugarcane (Ahmed et al. 2013).

It worth noting that wheat production from the suggested systems use the applied water to the main crop in the intercropping system and did not use extra irrigation water.

6.3.3.1 Wheat Intercropped with Winter Tomato System

Intercropping wheat with winter tomato (Abd El-Zaher et al. 2013, Fig. 6.1) is implemented by cultivating tomato in the end of September on the top of the raised beds with 100% of its planting density. After 45 days, wheat seeds are sown in four rows on the top of the raised beds; where tomato plants will be locate between two wheat rows from each side of the raised beds. Wheat planting density under this system is 75% of its sole planting density. In this system, wheat plants use the applied amounts of water and fertilizer to tomato.

The growing season of winter tomato under monoculture cultivation is 3 months, where its life cycle ends by the end of December. However, when wheat intercropped with it, tomato plants continue to give fruits until the end of March as a result of the protection that wheat plants provide to tomato plants from low temperature in January and February (Abd El-Zaher et al. 2013).

Exposing tomato plants to low temperature reduce pollen production, shed, viability and tube growth (Fernandez-Munoz et al. 1995). Pressman et al. (1997) indicated that tomato grows tap deep strong root systems, which facilitate the absorption of soil moisture deeper than wheat root system. Furthermore, the roots of tomato leave the soil in a good mechanical condition and contain more fertilizing elements than most of other crops (Pressman et al. 1997). For that reason, wheat

Fig. 6.1 wheat intercropped with tomato

productivity increased under this system to be 80% of its sole planting, although 75% of its planting density was cultivated.

We assumed that 50% of the cultivated area with winter tomato will be assigned to be use in implementing wheat intercropping system with winter tomato. Table 6.6

Table 6.6 Tomato cultivated area, assigned area to wheat intercropped with tomato and wheat production

	Tomato cultivated area (000 ha)	Assigned area to wheat (000 ha)	Wheat production (000 ton)
Lower Egypt			
Alexandria	1.7	0.8	4.8
Behira	13.1	6.6	41.0
Gharbia	0.1	0.0	0.2
Kafr El Sheikh	2.1	1.1	6.1
Dakahlia	1.4	0.7	4.8
Damietta	0.5	0.3	1.5
Sharkia	16.6	8.3	50.7
Ismailia	3.6	1.8	10.3
Port Said	0.3	0.1	0.8
Suez	0.7	0.3	1.9
Menoufia	0.2	0.1	0.8
Qalyubia	0.1	0.1	0.4
Cairo	0.02	0.01	0.001
Total	40.5	20.2	123.4
Middle Egypt			
Giza	3.7	1.9	12.9
Bani Sweif	3.9	1.9	12.2
Fayoum	1.9	1.0	5.4
Minya	2.5	1.2	7.7
Total	12.0	6.0	38.2
Upper Egypt			
Assiut	2.2	1.1	7.0
Sohag	4.7	2.3	14.0
Qena	1.2	0.6	3.5
Luxor	2.6	1.3	7.5
Aswan	0.3	0.2	1.1
New Valley	0.1	0.1	0.3
Total	11.1	5.5	33.3
Bordered governorates			
Marsa Matrouh	4.7	2.4	7.6
North Sinai	2.0	1.0	0.6
South Sinai	0.05	0.02	0.07
Red Sea	0	0	0
Total	6.8	3.4	8.3
Grand total	70.4	35.2	203.1

indicated that tomato cultivated area was 70.4 thousand hectares and the assigned area to be use in the intercropping system with wheat was 35.2 thousand hectares. These areas produced 203.1 thousand tons of wheat seeds.

6.3.3.2 Cotton Relay Intercropped with Wheat

In Egypt, cotton, as an early summer crop, is cultivated in March to produce high yield. Egyptian clover is usually preceding cotton, cultivated as early as October and harvested in February before the cultivation of cotton. One way to increase the cultivated area of wheat is for wheat to replace Egyptian clover in the Egyptian clover-cotton system with wheat. Because wheat is cultivated in November and stays until April to be harvested, cotton can be relayed intercropped on it in March (Zohry 2005).

In this system, wheat is cultivated in November on the top of raised beds and in following March, cotton is cultivated on both edges of the raised beds. Thus, cotton shares 2 month of its life cycle with wheat before wheat harvest occur in April. The benefit of this system is to increase wheat cultivated area by the area assigned to be cultivated by cotton. Furthermore, planting density for wheat under this system is 80% of its recommended density and it attain 90% of its yield under sole planting (Lamlom et al. 2018).

In relay intercropping cotton on wheat system (Fig. 6.2), three main phases can be recognized: (1) wheat vegetative stage grown from November till April; (2) intercropping of wheat (reproductive stage) and cotton (seedling stage) from March till April, and (3) sole cotton (vegetative and reproductive stage) from April till September (Zohry 2005). The two component crops in the system interact directly

Fig. 6.2 Cotton relay intercropping with wheat

Table 6.7 Cotton cultivated area, assigned area to cotton relay intercropped with wheat and wheat production

	Cotton cultivated area (000 ha)	Assigned area to wheat (000 ha)	Wheat production (000 ton)
Lower Egypt			
Alexandria	0.29	0.26	1.7
Behira	6.11	5.50	38.6
Gharbia	2.12	1.91	12.7
Kafr El Sheikh	19.68	17.71	114.1
Dakahlia	8.16	7.34	57.1
Damietta	2.58	2.32	15.4
Sharkia	6.90	6.21	42.6
Ismailia	0.19	0.17	1.1
Port Said	0.14	0.13	0.7
Menoufia	0.41	0.37	2.8
Qalyubia	0.01	0.01	0.1
Total	46.6	41.9	286.9
Middle Egypt			
Bani Sweif	2.17	1.95	13.8
Fayoum	4.89	4.40	28.0
Minya	0.04	0.04	0.3
Total	7.1	6.4	42.1
Upper Egypt			
Assiut	1.07	0.97	6.9
Sohag	0.13	0.12	0.8
Total	1.2	1.1	7.7
Grand total	54.9	49.4	336.6

only during the second phase. Furthermore, Zhang et al. (2008) stated that the N-uptake of cotton was diminished during the intercropping phase, but recovered partially during later growth stages, with low effect on final cotton yield. They also stated that intercrops used more nitrogen per unit production than mono crops, which can reduce environmental risks of nitrogen leaching to groundwater.

In cotton relay intercropped with wheat system, we assumed that 90% of the total cultivated area of cotton will be assigned to this system. Table 6.7 showed that an increase of the cultivated area of wheat by 49.4 thousand hectares (90% of 54.9 thousand hectares of cotton cultivated area). This added area will contribute in increasing the wheat production by 336.6 thousand tons.

Fig. 6.3 Wheat intercropping with sugar beet

6.3.3.3 Wheat Intercropped with Sugar Beet System

Intercropping wheat with sugar beet system (Fig. 6.3) on raised beds was successfully implemented in Egypt. In this system, sugar beet is cultivated in October and wheat is intercropped on sugar beet after 45 days. Planting density of sugar beet is 100% and wheat planting density is 50%, which obtained the same yield of both crops as if both crops were planted solely. Wheat use the applied irrigation water to sugar beet and both crops are harvest in April (Abou-Elela 2012). The advantage of this system is to increase the cultivated area of wheat by the percentage of assigned area of sugar beet cultivated area.

We assumed that 25% of the cultivated area of sugar beet will be assigned to wheat intercropping system with sugar beet. Table 6.8 indicated that the cultivated area of sugar beet was 220.1 thousand hectares and the assigned area for wheat will be 55.0 thousand hectares. The table also showed that the assigned area can produce 211.0 thousand tons of wheat seeds.

6.3.3.4 Wheat Intercropped Under Fruit Trees

Egypt cultivates large varieties of fruit trees, where the total cultivated area with fruit trees is 695,292 thousand hectares. To make use of such large cultivated area, intercropping under fruit tree is done. Intercropping could be implemented under young evergreen fruit trees (1–3 years old) in the summer and winter seasons or under deciduous fruit trees in the winter. Intercropping wheat in rows between the

Table 6.8 Sugar beet cultivated area, assigned area to wheat intercropped with sugar beet and wheat production

	Sugar beet cultivated area (000 ha)	Assigned area to wheat (000 ha)	Wheat production (000 ton)
Lower Egypt			
Alexandria	2.8	0.7	2.6
Behira	16.5	4.1	16.1
Gharbia	6.0	1.5	5.6
Kafr El Sheikh	54.2	13.5	48.5
Dakahlia	35.9	9.0	38.8
Damietta	2.0	0.5	1.9
Sharkia	33.0	8.2	31.5
Ismailia	3.6	0.9	3.2
Port Said	12.3	3.1	16.0
Suez	0.1	0.04	0.1
Menoufia	0.8	0.2	0.8
Qalyubia	0.1	0.04	0.1
Total	167.4	41.8	165.1
Middle Egypt			
Giza	1.4	0.3	1.5
Bani Sweif	13.3	3.3	13.1
Fayoum	12.8	3.2	11.4
Minya	13.4	3.4	13.1
Total	41.0	10.2	39.1
Upper Egypt			
Assiut	2.1	0.5	2.1
New Valley	0.8	0.2	0.6
Total	2.9	0.7	2.7
Bordered governorates			
Marsa Matrouh	8.0	2.0	4.0
North Sinai	0.6	0.14	0.1
South Sinai	0.3	0.07	0.1
Total	8.9	2.2	4.2
Grand total	220.1	55.0	211.0

fruit trees give an extra economic incentive and also improve land productivity. This practice can be done by separation between fruit trees and wheat cultivated area to prevent the runoff of irrigation water to these trees (WOCAT 2016).

We assumed that 16% of the cultivated area by fruit trees will be used to intercropped wheat with 70% of its recommended planting density. Table 6.9 showed that 113.8 thousand hectares of the total fruit trees area could be assigned to be intercropped with wheat. This area will produce 838.2 thousand tons of wheat seeds.

Table 6.9 Fruit trees cultivated area, assigned area to wheat intercropped under Fruit trees and wheat production

	Fruit trees cultivated area (000 ha)	Assigned area to wheat (000 ha)	Wheat production (000 ton)
Lower Egypt			
Alexandria	4.7	0.8	5.5
Behira	282.3	45.2	352.5
Gharbia	11.1	1.8	13.2
Kafr El Sheikh	2.9	0.5	3.3
Dakahlia	5.7	0.9	7.9
Damietta	3.4	0.5	4.0
Sharkia	49.4	7.9	60.3
Ismailia	79.8	12.8	91.1
Port Said	0.1	0.02	0.2
Suez	11.0	1.8	12.4
Menoufia	29.9	4.8	40.1
Qalyubia	17.8	4.1	31.3
Total	498.3	80.9	621.9
Middle Egypt			
Giza	18.3	2.9	25.3
Bani Sweif	7.9	1.3	9.9
Fayoum	12.7	2.0	14.4
Minya	15.9	2.5	19.9
Total	54.8	8.8	69.5
Upper Egypt			
Assiut	14.2	2.3	18.0
Sohag	3.0	0.5	3.6
Qena	4.0	4.0	29.0
Luxor	5.1	0.01	37.3
Aswan	7.3	1.2	9.1
New Valley	9.5	1.5	8.8
Total	43.1	9.4	105.7
Bordered governorates			
Marsa Matrouh	47.8	7.6	30.6
North Sinai	33.6	5.4	4.2
South Sinai	10.1	1.6	6.2
Total	91.5	14.6	41.0
Grand total	687.8	113.8	838.2

6.3.3.5 Wheat Intercropped with Sugarcane

Ahmed et al. (2013) indicated that under wheat intercropped with fall sugarcane system, sugarcane is cultivated in September and wheat is cultivated in November on the top of the wide furrows in four rows. Wheat is harvested in April and sugarcane is continue its life cycle (Fig. 6.4).

Under wheat intercropped with fall sugarcane system, wheat is cultivated with 50% of its recommended planting density and produces 50% of its yield, compared to sole planting, with no reduction in sugarcane yield. We assumed that 10% of the fall sugarcane area will be assigned to be cultivated with the wheat intercropping system. Table 6.10 indicated that this intercropping system can produce 100.4 thousand tons of wheat seeds from the assigned area of the total area of fall sugarcane, namely 13.4 thousand hectares.

The total cultivated area with wheat as a result of implementing the suggested intercropping systems and its production are presented in Table 6.11 The results in

Fig. 6.4 Harvested wheat plants under intercropping it with sugarcane system

Table 6.10 Sugarcane cultivated area, assigned area to wheat intercropped with sugarcane and wheat production

	Sugarcane cultivated area (000 ha)	Assigned area to wheat (000 ha)	Wheat production (000 ton)
Minya	15.7	1.6	12.3
Assiut	0.4	0.04	0.4
Sohag	5.8	0.6	4.4
Qena	48.5	4.8	35.3
Luxor	27.8	2.8	20.2
Aswan	35.9	3.6	27.8
Total	134.2	13.4	100.4

Table 6.11 Total wheat cultivated area and its production under wheat intercropping systems, total wheat production under deficit system and intercropping systems and wheat production-consumption gap

	Wheat intercropping systems			
	Area (000 ha)	Production (000 ton)	Total wheat production (000 ton)	Gap (000 ton)
Lower Egypt				
Alexandria	2.5	14.6	265.4	−791.2
Behira	61.4	448.2	2132.3	**867.4**
Gharbia	5.2	31.7	470.2	−553.5
Kafr El Sheikh	32.8	172.0	1011.1	**322.2**
Dakahlia	17.9	108.6	1018.0	−311.4
Damietta	3.6	22.7	108.3	−198.1
Sharkia	30.7	185.2	1693.0	**225.8**
Ismailia	15.7	105.7	228.3	−38.8
Port Said	3.4	17.6	53.8	−99.4
Suez	2.1	14.4	34.8	−114.3
Menoufia	5.5	44.6	621.0	−260.1
Qalyubia	4.2	31.9	251.8	−900.3
Cairo	0	0	0	−1952.4
Total	184.9	1197.2	7888.1	−3803.9
Middle Egypt				
Giza	5.1	39.7	233.2	−1534.7
Bani Sweif	8.5	48.9	569.0	−77.9
Fayoum	10.6	59.2	794.6	**57.0**
Minya	8.7	53.3	1057.1	−70.4
Total	33.0	201.1	2653.9	−1626.0
Upper Egypt				
Assiut	4.9	34.3	948.5	**49.4**
Sohag	3.5	22.8	819.4	−199.6
Qena	9.4	67.8	401.1	−247.9
Luxor	4.1	65.0	167.8	−88.4
Aswan	4.9	37.9	209.9	−92.3
New Valley	1.8	9.7	414.6	**365.1**
Total	28.6	237.5	2961.3	−213.7
Border governorates				
Marsa Matrouh	12.0	42.2	65.9	−21.7
North Sinai	6.5	4.9	6.1	−86.1
South Sinai	1.7	6.4	8.4	−12.5
Red Sea	0	0	0	−73.7
Total	20.3	53.5	80.4	−194.0
Grand total	266.8	1689.3	13,583.7	−5837.6

the table indicated that wheat intercropping systems can add 266.8 thousand hectares of wheat, which produced 1689.3 million ton of wheat seeds. The total wheat production under application of deficit irrigation on raised beds and intercropping systems will reach 13,583.7 million tons, which will reduce wheat production-consumption gap to 5837.6 million tons, in which self-sufficiency ratio will increase to reach 70%.

Table 6.11 also indicated that more governorates can attain self-sufficiency in addition to surplus in wheat production. These governorates are Behira, Kafr El-Sheik and Sharkia in Lower Egypt, Fayoum in Middle Egypt, and Assuit and New Valley in Upper Egypt.

6.3.4 Saved Irrigation Water from Other Winter Crops and Wheat Self-Sufficiency

An amount of irrigation water was saved from cultivation on raised beds and application of deficit irrigation to Egyptian clover and sugar beet in Chap. 3 and to onion and winter tomato in Chap. 4. Because these four crops have surplus in their production, we assumed that these amounts of water could be used in cultivating more lands with wheat to increase its total production and reduce its production-consumption gap.

Table 6.12 indicated that the highest amount of saved irrigation water will be obtained from Egyptian clover as a result of its high cultivated area, namely 1472.2 billion cubic meters. The amount of irrigation water saved to sugar beet is ranked second, namely 491.1 million cubic meters. Whereas, lower amounts of irrigation water will be saved from onion and winter tomato, namely 129.8 and 57.1 million cubic meters, respectively. A total of 2150.1 billion cubic meters could be saved from these four crops.

6.4 Wheat Production-Consumption Gap Using Saved Water from Other Winter Crops

Table 6.13 showed that using the total saved water resulted from the four studied winter crops could result in cultivating 273.8 thousand hectares and produce 2861 million tons of wheat seeds. Under application of deficit irrigation to wheat on raised beds, wheat intercropping systems and the saved water resulted from the four studied winter crops, the total wheat production will reach 16,444 million tons, which will reduce the gap to reach 2977 million tons, in which self-sufficiency ratio will reach 85%.

Table 6.12 Saved amounts of irrigation water from raised beds cultivated and deficit irrigation application for Egyptian clover, sugar beet, onion and tomato

	Clover (MCM)	Sugar beet (MCM)	Onion (MCM)	Tomato (MCM)	Total (MCM)
Lower Egypt					
Alexandria	7.4	4.0	0	1.7	13.1
Behira	156.1	38.3	9.8	6.2	210.4
Gharbia	101.0	19.6	44.0	0.1	164.6
Kafr El Sheikh	115.4	144.8	1.3	3.0	264.6
Dakahlia	182.8	78.9	20.5	0.6	282.8
Damietta	49.4	5.1	1.4	0.8	56.6
Sharkia	150.9	65.3	11.4	17.0	244.6
Ismailia	6.3	1.9	0.2	3.6	11.9
Port Said	1.9	4.1	0.4	0.1	6.5
Suez	3.6	0.0	0.8	0.8	5.1
Menoufia	100.7	2.2	9.7	0.1	112.7
Qalyubia	38.7	0.4	0	0.2	39.3
Cairo	0.6	0	0	0	0.6
Total	914.6	364.7	99.4	34.2	1412.9
Middle Egypt					
Giza	40.2	0.9	1.0	4.4	46.4
Bani Sweif	74.5	39.7	6.6	2.0	122.8
Fayoum	124.0	43.5	7.8	2.6	177.9
Minya	99.2	32.7	2.6	2.8	137.3
Total	338.0	116.8	18.0	11.8	484.4
Upper Egypt					
Assiut	65.5	7.4	1.7	2.2	76.8
Sohag	103.9	0	7.8	4.4	116.1
Qena	29.0	0	1.0	0.9	30.9
Luxor	10.4	0	0.6	2.2	13.2
Aswan	6.3	0	0.7	0.2	7.3
New Valley	3.8	0.4	0.5	0.1	4.7
Total	218.9	7.8	12.3	9.9	248.9
Bordered governorates					
Marsa Matrouh	0.6	1.8	0.1	1.3	3.9
Total	0.6	1.8	0.1	1.3	3.9
Grand total	1472.2	491.1	129.8	57.1	2150.1

Table 6.13 Wheat added cultivated area and production using the saved amounts of irrigation water, total wheat production (from deficit irrigation, intercropping systems and the saved water) and wheat production-consumption gap

	Saved water from winter crops			
	Cultivated area (000 ha)	Production (000 ha)	Total wheat production (000 ton)	Gap (000 ton)
Lower Egypt				
Alexandria	1.9	20.6	286.0	−770.5
Behira	28.6	335.1	2467.4	**1202.6**
Gharbia	18.5	25.9	496.2	−527.6
Kafr El Sheikh	36.3	398.7	1409.7	**720.9**
Dakahlia	38.9	528.0	1546.0	**216.6**
Damietta	7.6	83.8	192.1	−114.3
Sharkia	28.2	301.9	1995.0	**527.7**
Ismailia	1.5	17.1	245.4	−21.7
Port Said	0.9	10.3	64.1	−89.1
Suez	0.6	6.9	41.7	−107.4
Menoufia	14.7	159.2	780.2	−100.9
Qalyubia	16.9	138.6	390.4	−761.7
Cairo	0	0	0	−1952.4
Total	194.5	2026.0	9914.1	−1777.9
Middle Egypt				
Giza	9.4	106.9	340.1	−1427.8
Bani Sweif	23.4	256.3	825.3	**178.4**
Fayoum	13.6	137.0	931.6	**194.1**
Minya	11.4	120.5	1177.7	**50.2**
Total	57.8	620.8	3274.7	−1005.2
Upper Egypt				
Assiut	5.4	58.4	1006.9	**107.8**
Sohag	9.5	88.1	907.5	−111.6
Qena	3.6	36.0	437.2	−211.9
Luxor	2.0	19.6	187.4	−68.8
Aswan	0.7	8.1	218.0	−84.2
New Valley	0.4	3.7	418.3	**368.8**
Total	21.6	213.9	3175.2	0.2
Border governorates				
Marsa Matrouh	0	0	65.9	−21.7
North Sinai	0	0	6.1	−86.1
South Sinai	0	0	8.4	−12.5
Red Sea	0	0	0	−73.7
Total	0	0	80.4	−194.0
Grand total	273.8	2861	16,444	−2977

Table 6.13 also showed that more governorates attain surplus in wheat production. These governorates are Behira, Kafr El-Sheik, Dakhlia and Sharkia in Lower Egypt, Beni sweif, Fayoum and Minya in Middle Egypt, and Assuit and New Valley in Upper Egypt.

6.5 Wheat Water Productivity Under the Studied Production Alternatives

Wheat water productivity under the five production alternatives are presented in Table 6.14. Under production alternative (1), namely wheat traditional cultivation, the lowest values of water productivity was attained. Cultivation on raised beds (production alternative 2) increased the values of water productivity as a result of producing more wheat seeds with the same amount of irrigation water applied under traditional cultivation. Similarly, the values of water productivity under application of deficit irrigation on raised beds (production alternative 3) was higher than its value under cultivation on raised beds, as a result of adding new area to the total cultivated area of wheat and using the same amount of irrigation water applied under traditional cultivation.

In production alternative (4), the amount of water use to irrigate wheat under traditional cultivation was used to produce wheat under application of deficit irrigation on raised beds. In addition, wheat produced from implementing its intercropping systems did not use any extra irrigation water because it used the water applied to the main crop in the intercropping systems. Therefore, water productivity of wheat was the highest under production alternative (4). Regarding production alternative (5), where wheat total production attained from application of deficit irrigation on raised beds, intercropping systems and using the saved water from the four winter crops to produce more wheat seeds, water productivity values were lower than its counterpart values under production alternative (4) because more water was involved in wheat production.

The results in Table 6.14 also indicated that the overall average of wheat water productivity values on all the studied governorates were 0.97, 1.21, 1.28, 1.97 and 1.85 kg/m^3 for production alternative 1, 2, 3, 4 and 5 respectively.

6.6 Conclusion

In this chapter, we quantified the effect of the interaction application of deficit irrigation to wheat grown on raised beds, implementing intercropping systems and using the saved water from application of deficit irrigation to Egyptian clover, sugar beet, onion and winter tomato to cultivate more areas with wheat. Our results showed wheat total production will be increased 100%, compared to its value under

Table 6.14 Water productivity (kg/ha) of wheat under suggested production alternatives

	Alternative (1)	Alternative (2)	Alternative (3)	Alternative (4)	Alternative (5)
Lower Egypt					
Alexandria	1.43	1.68	1.78	1.89	1.86
Behira	1.35	1.74	1.84	2.34	2.20
Gharbia	1.00	1.41	1.50	1.61	1.09
Kafr El Sheikh	1.18	1.66	1.76	2.12	1.90
Dakahlia	1.46	2.01	2.13	2.38	2.18
Damietta	1.20	1.65	1.76	2.23	1.82
Sharkia	1.06	1.45	1.56	1.75	1.64
Ismailia	1.20	1.50	1.59	2.96	2.76
Port Said	1.60	1.60	1.69	2.50	2.29
Suez	1.07	1.44	1.52	2.60	2.25
Menoufia	1.32	1.80	1.95	2.10	1.91
Qalyubia	1.13	1.56	1.68	1.92	2.29
Average	1.25	1.62	1.73	2.20	2.02
Middle Egypt					
Giza	1.34	1.79	1.92	2.32	2.31
Bani Sweif	1.08	1.48	1.58	1.73	1.83
Fayoum	0.92	1.26	1.35	1.46	1.29
Minya	0.99	1.35	1.45	1.53	1.42
Average	1.08	1.47	1.58	1.76	1.71
Upper Egypt					
Assiut	0.92	1.24	1.33	1.38	1.32
Sohag	0.71	0.95	1.03	1.06	1.02
Qena	0.73	0.94	1.01	1.22	1.21
Luxor	0.71	0.85	0.91	1.49	1.49
Aswan	0.81	0.89	0.94	1.15	1.15
New Valley	0.94	0.94	0.98	1.01	1.00
Average	0.80	0.97	1.03	1.22	1.20
Bordered governorates					
Marsa Matrouh	1.35	2.03	1.42	3.94	3.20
North Sinai	0.29	0.12	0.29	1.49	1.49
South Sinai	0.64	0.34	0.64	2.69	2.69
Average	0.76	0.76	0.78	2.71	2.46
Overall average	0.97	1.21	1.28	1.97	1.85

Production alternative (1) = conventional cultivation, Production alternative (2) = raised beds cultivation, Production alternative (3) = application of deficit irrigation on raised beds, Production alternative (4) = application of deficit irrigation on raised beds and intercropping systems, Production alternative (5) = application of deficit irrigation on raised beds, intercropping systems and using saved water traditional cultivation. This high percentage of increase in wheat production increased wheat self-sufficiency ratio to 85%, respectively. The highest water productivity values were found under application of deficit irrigation and implementing intercropping systems.

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Chapter 7
Climate Change Assessment in Egypt: A Review

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Abstract The objective of this chapter was to review all the previous climate change studies done in Egypt on water resources, crops production, evapotranspiration, seasonal crop coefficients, water consumptive use and water requirements of crops, cultivated soils and areas, suitability of growing area to be cultivated with a certain crop and food gaps in Egypt. Literature review was done for 67 research papers found on the internet to cover these items. Thus, adaptation strategies should be applied when possible to reduce the vulnerability associated with climate change.

Keywords Water resources · Crops production · Water requirements of crops · Cultivated soils and area · Suitability of growing area to be cultivated with a certain crop · Food gaps

7.1 Introduction

Egypt is particularly vulnerable to climate change, due to its geographical position and its dependence on climate-sensitive economic sectors, namely agriculture (FAO 2012). Sea level rise is expected to affect the living conditions of millions of people in the coastal zone of Egypt, which could exposed them to economic, social, and/or health risks (Leach et al. 2013). IPCC (2007) indicated that global climate models are probably the only way to investigate the non-linear interactions between the four major components of the climate system: atmosphere, biosphere, oceans and sea-ice. Furthermore, the study of climate variability and climate change has progressed

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over the last decade from the use of relatively simple global models, consisting of atmospheric models coupled to slab ocean models (IPCC 1990a, b), to more realistic global coupled ocean-atmosphere-land-ice models (IPCC 1999).

Uncertainty in future climate change presents a key challenge for water resources adaptation planning. Uncertainty in climate information form limitations in our ability to model the climate system and in our understanding of how future greenhouse gas emissions will change (Moss et al. 2010). Climate projections are based on a variety of scenarios, models and simulations procedures, which contain a number of embedded assumptions. Gagnon-Lebrun and Agrawala (2006) noted that the level of certainty associated with climate change and impact projections is a key in determining the extent to which such information can be used to formulate appropriate adaptation responses.

The objective of this chapter is to review all the previous climate change studies done in Egypt on water resources, crops production, evapotranspiration, seasonal crop coefficients, water consumptive use and water requirements of crops, cultivated soils and areas, suitability of growing area to be cultivated with a certain crop and food gaps in Egypt.

7.2 Climate Change and Water Resources

Egypt is enormously relays on the Nile River as a main source of water resources, which contributes with about 95% of Egypt's water budget. Other sources are precipitation and groundwater, which contribute with about 5% of the available supply. Hulme et al. (1995) indicated that temperature rise by 2 °C coupled with a 20% decrease in precipitation could reduce the flow of Nile by 88%. Whereas, a higher increase in temperature to 4 °C with the same reduction in precipitation could result in 98% decrease in Nile flows. Sayed (2004) indicated that the studies on the effect of climate change on the Nile flow clearly showed that the assessment is strongly dependent on the choice of the climate scenario and the underlying GCM model. For temperature, although the magnitude of the change varies, the direction of change is clear, where all models expected that a rise in the temperature. For rainfall, however, not only the magnitude varies substantially across the models, but even the signal of the change varies. The choice of the emission scenario also leads to different projection. In addition, other studies show that the Nile flow is extremely sensitive to climate, and especially rainfall changes due to the highly non-linear relationship between precipitation and runoff. The uncertainty about the increase or decrease in precipitation near the sources of the Nile, as well as variations in temperature could have a larger than expected effect on Nile flows because these two factors are also interrelated leads to moderate to extreme effects (Elsaeed 2012). In addition, Nour El-Din (2013) reported that there are some uncertainty about that the effect of future climate changes in East Africa, where roughly two-thirds of the general circulation models project an increase in precipitation on the Blue Nile; which contributes more than 75% of the Nile flows. Whereas, one-third expect reduced precipitation. However, it is virtually certain that the Nile Basin has become warmer and the warming is expected to continue.

Furthermore, Agrawala et al. (2004) indicated that vulnerability of Egypt's water resource and its dependence on the Nile is tied to trends in population growth, land use, and agriculture intensively concentrated along the Nile Valley and Delta. Alkitkat (2017) projected 32% increase in the Egyptian population by the year of 2030, compared to its value in 2014. Thus, it is likely that Nile water availability to be increasingly stressed as demand increases, due to growth in population and increases in temperature leading to greater evaporative losses.

It has also been suggested that Egypt's precipitation may decrease due to climate change, with an annual decline up to 5, 8 and 13% by 2030, 2050, and 2100, respectively (Barbi 2014). On the basis of rain fall deviations from the mean, four categories were developed by Kumar et al. (2009) to monitor and evaluate the rain fall patterns: ±10% deviation consider as normal, −10 to −60% deviation in the rain fall is consider as deficit, less than −60% deviation consider as scanty, and greater than 20% deviation consider as excess. Accordingly, Ouda et al. (2016a) the projected value of annual rainfall in eastern coast of Egypt in 2030 was the lowest than its counterpart values from 1997 to 2014, except for the amount of precipitation fall in 1999, which was lower (Figure 7.1a). Rainfall deviation in 2030 from the average of 18 years was −27%, which considered deficit. Similarly, in the western coast of Egypt, the projected annual rain fall value in 2030 will be the lowest compared to the recorded values from 1997 to 2014 (Figure 7.1b). Rainfall deviation in 2030 from the average of 18 years was −95%, which considered scantly.

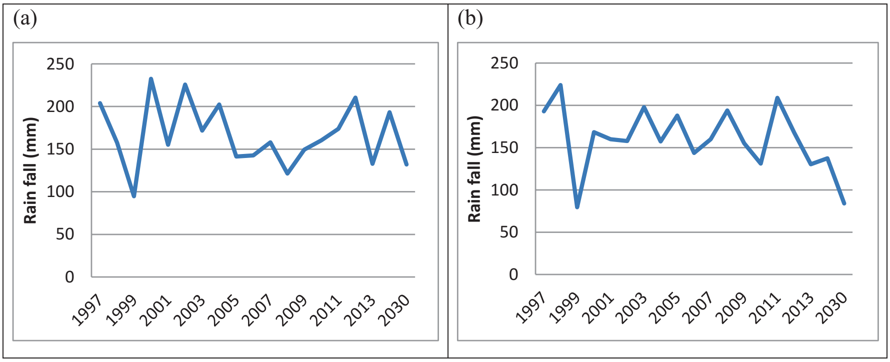

Fig. 7.1 Comparison between annual amounts of rain fall values from 1997 to 2014 and its projected value in 2030 in (**a**) North Sinai and (**b**) Marsa Matrouh. (Source: Ouda et al. 2016a)

7.3 Projection of Climate Change Impacts on Crops Production

7.3.1 *Using IPCC Report (1990)*

Global models of the climate system of the world are an important tool in climate research. Climate change impact on crops in Egypt started as early as in the 1990c, where the late Prof. Helmy Eid and others assessed its consequences on the production of the crops grown in clay soil under surface irrigation. In his early work, he used MAGICC/SCENGEN model to calculate the annual mean global surface air temperature and global-mean Sea-level implications of emissions scenarios for greenhouse gases. SCENGEN model was run using CSIRO-GCM model and climatic data were extracted using regression model for year 2000 and 2050. The results of this methodology indicated that the increase in annual temperature of Egypt will be 0.9–1.9 °C with an average of 1.4 °C, in addition to sea level rise averaged by 20 cm in the year 2050, compared to the current conditions (Eid et al. 1992).

Furthermore, climate change scenarios created by combining the daily climate data for each site with the output of three equilibrium General Circulation Models (GCMs): the Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Institute for Space Studies (GISS), and United Kingdom Meteorological Office (UKMO) models. Under these scenarios, projected precipitation changes are more uncertain, and solar radiation changes are projected to be small (El-Shaer et al. 1996).

To simulate the effect of climate change, DSSAT3 model (Jones et al. 2003) was used to project the yield of several crops on the national level in 2050, namely wheat, barely, maize, sorghum, rice and soybean under increased CO_2 concentration level. Table 7.1 summarized some of the work done in that era.

Table 7.1 Projected percentage of change (%) in the yield of several crops under climate change in 2050 using MAGICC/SCENGEN model

Crop	Change in yield (%)	References
Wheat	−23	Eid et al. (1993a)
	−19	Eid et al. (1994a)
	−19	Eid et al. (1997a)
Maize	−23	Eid et al. (1992)
	−19	Eid et al. (1997b)
Barley	−20	Eid et al. (1995)
Rice	−11	Eid et al. (1995)
	−11	Eid et al. (1996)
Soybean	−18	Eid and El-Sergany (1993)
	−28	Eid et al. (1994b)
	−26	Eid et al. (1996)
Cotton	+17	Eid et al. (1997c)

7.3.2 *Using IPCC Report (2001)*

Other researches depended on the Special Report on Emissions Scenarios (SRES) developed by the IPCC (2001) to generate climate change scenarios, namely A1, A2, B1 and B2. The SRES scenarios combined two sets of divergent tendencies; one set varies between strong economic values and strong environmental values, while the other set varies between increasing globalization and increasing regionalization. Table 7.2 presented some of these investigations.

In 2009, climate change effects on crops grown under different irrigation systems and different soils types in different sites in Egypt were implemented in field experiments to increase our knowledge on its contribution in reducing yield losses. The results of these experiments were used to calibrate CropsSyst model (Stockle et al. 1994) and simulate the effects of A2 and B2 on the yield of wheat, maize, cotton and barley without using CO_2 enrichment was done. Furthermore, early sowing, changing irrigation scheduling and using improved management practices were implemented in field experiments, and then the effect of climate change on these practices was simulated as followed:

In clay soil and surface irrigation, in 2030, Khalil et al. (2009) and Moneir (2012) indicated that wheat cultivar Sakha93 was superior in withstanding the stress of climate change, where its yield losses were the lowest, namely 33–36% and 31–35% for A2 and B2 climate change scenarios, respectively in both investigations. These two climate change scenarios were developed from HadCM3 climate change model. They also indicated that early sowing of wheat in the 1st week of November reduced yield losses by 3 and 4% for A2 and B2, respectively. Using the same climate change model, Ouda et al. (2009) indicated that maize hybrid TWC324 was found to be more tolerant to climate change stress, where its yield losses were 49 and 47% under A2 and B2, respectively. The best adaptation strategy was early sowing in the first week of May and applying irrigation in every 14 days, which reduced yield losses by 4 and 6% under A2 and B2, respectively. Furthermore, application of the second irrigation 21 days after sowing and then every 16 days until the end of the growing season was found to be the best adaptation study (Moneir 2012).

Similar assessment was done for barely, where two climate change scenarios (A2 and B2) resulted from CISRO climate change model were incorporated with

Table 7.2 Projected percentage of change (%) in the yield of several crops under climate change in 2050 using SRES scenarios

Crop	Change in yield (%)	References
Wheat	−18	Hassanein (2010)
Maize	−19	Hassanein (2010)
	−14	Hassanien and Medany (2007)
Rice	−11	Hassanein (2010)
Potato	−2	Medany and Hassanein 2006
	−11	Saleh (2007)
Tomato	−19	Abou-Shleel and Saleh (2011)

CropSyst model to study its effect on barley yield in the year of 2039. The results showed that barely yield will be reduced by 17 and 18% averaged over the six cultivars under A2 and B2 climate change scenarios, respectively. Moreover, changing irrigation schedule to applying irrigation every 23 days improved barley yield by an average of 2%. Giza2000 cv. was less affected by heat stress of climate change scenarios and had the least yield losses, and responded well to changing irrigation schedules. Changing irrigation schedule to barley by applying water every 23 days resulted in reduction of barley yield losses by an average of 2% for both scenarios (Ouda et al. 2010).

In silty clay soil and under sprinkler system, four wheat cultivars, i.e. Sakha94, Sakha93, Giza168 and Gemmiza9 were planted in three sowing dates: 9th of November, 24th of November and 8th of December under four irrigation treatments, i.e. irrigation with 0.6, 0.8, 1.0 and 1.2 ETc. The results indicated that Sakha93 planted in 24th of November under 1.2 ETc had the lowest yield losses, namely 39 and 34% under A2 and B2 climate change scenarios, respectively (Noreldin et al. 2012). In the above soil type and under drip system, four maize hybrids, i.e. SC10, SC128, TWC310 and TWC323 were sown under three sowing dates: on the 2nd of May, on the 13th of May and on 1st of June with 4 irrigation treatments, i.e. irrigation amount with 0.6, 0.8, 1.0 and 1.2 ETc in a field experiment. The effect of climate change was simulated using A2 and B2 climate change scenarios. The lowest yield losses were found for hybrid SC128 planted on 2nd week of May using 1.2 ETc, namely 28 and 25% under A2 and B2 climate change scenarios, respectively (Ouda et al. 2012a).

In salt affected soil and under surface irrigation, the effect of climate change on two crops was studied: wheat and cotton. In both experiments, three irrigation treatments were studied, i.e. farmer irrigation practice (characterized by large applied irrigation amount), required irrigation amount and irrigation amount applied for raised bed cultivation. With respect to cotton, yield losses under farmer practice were 28% under A2 climate change, and between 22% under B2 climate change scenario. Cotton yield losses were lower under required irrigation amount by 25 and 21% and under the irrigation amount applied for raised bed cultivation by 22 and 18% under A2 and B2 climate change scenarios (Ouda et al. 2013). Wheat yield losses under farmer irrigation practice were also high namely 47 and 44% under A2 and B2 climate change scenarios, respectively. Wheat yield losses were reduced by 5% when required irrigation amounts was applied, whereas the losses in wheat yield were further reduced by 7 and 9% under A2 and B2 climate change scenarios, respectively (Ouda et al. 2012b).

In sandy soil and under sprinkler irrigation, wheat was grown under two treatments: farmer traditional practice in applying chemicals through broadcasting fertilizers and use the sprayers to add herbicides to the plants, and chemigation, where chemicals are applied via the sprinkler system. Wheat yield losses under farmer practice were 32 and 27% under A2 and B2 climate change scenarios, respectively. Whereas, wheat yield losses under chemigation were 26 and 20% under A2 and B2 climate change scenarios, respectively (Ouda et al. 2010). In another experiments, the effect of using improved agricultural management practices on wheat yield was studied. Eight fertigation treatments (interaction between irrigation with 0.6, 0.8, 1.0 and 1.2 ETc and fertigation application in 60 and 80% of irrigation time), in addition to farmer irrigation were tested. The results showed that the highest yield reduction, i.e. 39 and 37% was obtained under A2 and B2 climate change scenarios, respectively for farmer irrigation. The lowest yield reduction was obtained under irrigation with 1.0 ETc and fertigation application in 80% of irrigation time, i.e. 27 and 24% under A2 and B2 climate change scenarios, respectively (Taha 2012). Similar experiment was applied for maize with the same treatments. The results showed that the highest yield reduction, i.e. 43 and 41% was obtained under A2 and B2 climate change scenarios, respectively for farmer irrigation. The lowest yield reduction was obtained under irrigation with 1.2 ETc and fertigation application in 80% of irrigation time, i.e. 38 and 35% under A2 and B2 climate change scenarios, respectively (Taha 2012).

7.3.3 Using IPCC Report (2013)

IPCC (2013) developed new global climate change models for new projection, mitigation and adaptation scenarios involving policy decisions and options for targeted climate change stabilization at different levels during the IPCC Fifth Assessment Report (AR5). Its findings were based on a new set of scenarios that replace SRES (Wayne 2013). The climate projections in the IPCC fifth assessment report were based on Coupled Model Inter-comparison Project Phase 5 (CMIP5). This presents an unprecedented level of information on which to base projections including the latest versions of climate models. It includes more complete representation of forcings to produce a new four Representative Concentration Pathways scenarios (RCPs) and more output available for analysis.

Sayad et al. (2015) compared between measured weather data and projected data (2006–2014) from four global climate models (BCC-CSM1-1, CCSM4, GFDL-ESM 2G and MIROC5), with four Representative Concentration Pathways scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) developed for four Egyptian governorates (Kafr El-Sheikh, El-Gharbia, El-Minya and Sohag) to determine the suitable RCPs climate change scenarios in 2030 at each governorate. Their results indicated that the RCP6.0 developed by CCSM4 model and RCP8.5 developed by BCC-CSM1-1 and MIROC5 models were acceptable for Kafr El-Sheikh governorate. Whereas, the suitable scenarios for El-Gharbia governorate was RCP6.0 developed by CCSM4 model and RCP8.5 developed by MIROC5 model. Nevertheless, in El-Minia governorate, the highest agreement between measured and projected values was found for RCP8.5 and RCP6.0 scenarios developed by CCSM4 model. With respect to Sohag, the most suitable scenario was RCP6.0 which is developed by CCSM4 model. Consequently, they recommended the use the RCP6.0 scenario developed by CCSM4 model as a suitable scenario for all selected governorates.

Using the results of the above investigation, Ouda (2017) calculated the increase in weather elements in 2030, compared to its values in 2040. Table 7.3 shows the

Table 7.3 The increase in the values of weather elements in 2030, compared with its values in 2014

	Solar radiation (MJ/m/day)	Temperature (°C)	Wind speed (m/s)
Alexandria	0.5	0.5	1.5
Behira	0.4	1.0	0.9
Gharbia	0.8	1.9	0.2
Kafr El Sheikh	0.9	1.2	0.6
Dakahlia	0.5	1.9	0.9
Damietta	0.7	1.1	0.8
Sharkia	0.9	0.7	0.7
Menoufia	0.9	2.0	0.8
Qalyubia	0.9	2.1	0.8
Giza	0.8	2.6	0.5
Bani Sweif	0.9	2.1	0.6
Fayoum	0.7	1.3	0.7
Minya	1.0	1.1	0.8
Assiut	1.0	1.7	1.3
Sohag	1.2	1.9	1.4
Qena	2.3	2.1	1.7
Aswan	3.3	2.2	1.3
New Valley	2.1	2.0	1.5
Average	1.1	1.6	0.9

Source: Ouda (2017)

increase in the values of weather elements in 2030 using RCP6.0 scenario developed by CCSM4 model, compared with its values in 2014. The table showed that it is expected that solar radiation will increase by 1.1 MJ/m/day, temperature will increase by 1.1 °C and wind Speed will increase by 0.9 m/s in 2030.

Furthermore, Morsy (2015) simulated the effect of climate change on wheat and maize yield using under climate change using RCP6.0 scenario developed by CCSM4 model in 2030 and he projected 10–12% wheat yield losses and 13–15% maize yield losses.

7.4 Climate Change and Evapotranspiration

Climate change is likely to have significant impacts on the hydrological cycle, and it will be intensified with more evaporation and variable precipitation will be unequally distributed around the globe (IPCC 2001).

The IPCC Forth Assessment Report (IPCC 2007) synthesized current scientific understanding of global warming and projected future climate change using the most comprehensive set of well-established global climate models. The report identified three climate change scenarios: B1, A2 and A1B, where the global tempera-

Table 7.4 Percentage of increase in ETo under A1b climate change scenario in 2020, 2030 and 2040

Governorate	ETo in 2020	ETo in 2030	ETo in 2040
Nile Delta			
Alexandria	1	3	4
Demiatte	1	2	2
Kafr El-Sheik	2	2	2
El-Dakahlia	1	1	2
El-Behira	1	2	2
El-Gharbia	7	10	19
El-Monofia	5	10	19
El-Sharkia	7	14	17
El-Kalubia	7	11	19
Middle Egypt			
Giza	8	15	16
Fayoum	8	12	16
Beni Sweif	10	13	18
El-Minia	10	15	19
Upper Egypt			
Assuit	11	12	17
Sohag	12	10	18
Qena	11	14	19
Aswan	12	14	19
Average	7	9	13

Source: Ouda et al. (2016b)

ture is expected to rise by 1.8, 2.4 and 2.8 °C, respectively by the end of twenty-first century. These scenarios are also known as AR4 climate change scenarios.

A1B climate change scenario was used to calculate annual evapotranspiration (ETo) values in 2020, 2030 and 2040. ETo values under A1B climate change scenario were calculated for each month in each governorate and annual average values were calculated and compared to ETo values under current climate. The results indicated that the projected annual values of ETo is expected to increase by 7, 9 and 13% under 2020, 2030 and 2040, respectively (Table 7.4) (Ouda et al. 2016b).

Scientific understandings of phenomena are often tested via predictions that are compared against observations. Thus, one way to reduce uncertainty of climate change models is comparison between measured weather data and data from climate scenarios of these models and develops ensemble climate scenarios to improve the assessment of the effect of climate change. Ouda et al. (2016c) compared between measured weather data (2010–2013) and projected data from three global climate models (CSIRO-Mk3.5, ECHAM5 and CNRMCM3), with three climate change scenarios (A1B, A2 and B1) for El-Behira governorate (North Nile Delta) to find out the highest goodness of fit between each measured weather elements and its projected values for the three scenarios developed by the three models. They found out that the projected solar radiation obtained from ECHAM5 model, maximum

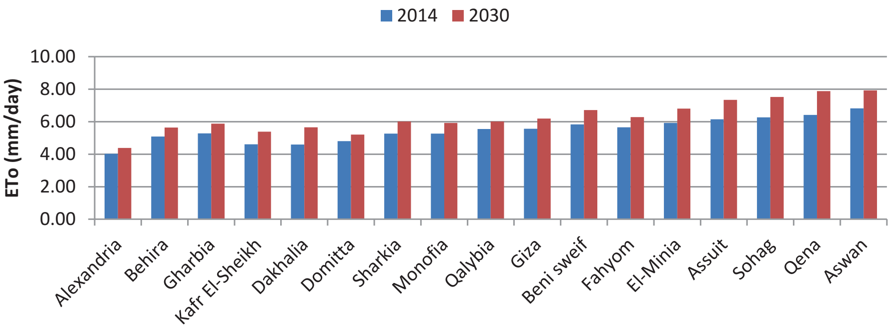

Fig. 7.2 Comparison between ETo values in 2014 and the projected ETo values in 2030. (Source: Ouda 2017)

temperature obtained from CSIRO-Mk3.5 and minimum temperature obtained from CNRM-CM3 had the highest closeness to the measured data. Thus, an ensemble model (ECCM) was developed and composed of solar radiation obtained from ECHAM5 model, maximum temperature obtained from CSIRO-Mk3.5 model and minimum temperature obtained from CNRM-CM3 model for A1B, A2 and B1 climate scenarios. The results also showed that ETc values for wheat and maize using the three climate change scenarios resulted from ECCM model in 2010 were more close to the values calculated from the measured weather values in the same year.

A comparison was made between ETo values in 2014 and the projected ETo values in 2030 using the RCP6.0 scenario developed by CCSM4 as the most suitable scenario for Egypt (Sayad et al. 2015) and it presented in Fig. 7.2. The figure showed that low differences in the values of ETo existed in North Egypt governorates and it gradually increased to be the highest in south Egypt governorates.

7.5 Effect of Climate Change on Seasonal Crop Coefficients

A comparison between crop coefficinets (Kc) values of several field crops in 2016 obtained from Ouda (2019a) and the projected Kc values in 2030 obtained from Ouda (2019b) is presented in Fig. 7.3. The figure showed that the values of Kc_{ini} were lower in 2030, compared to its counterpart values in 2016, except for faba bean. The values of Kc_{med} were higher in 2030, compared to its counterpart values in 2016 and the values of Kc_{end} were higher or similar in 2030, compared to its counterpart values in 2016.

Furthermore, a comparison between the Kc values of several fruit crops in 2016 (Ouda 2019a) and its values in 2030. Figure 7.4 showed that there were no differences in the value of Kc in its three growth stages in 2030, compared to its counterpart values in 2016. This could be attributed to that fact that fruit trees established ground cover all year long, could make it less responsive to the weather of winter and summer seasons.

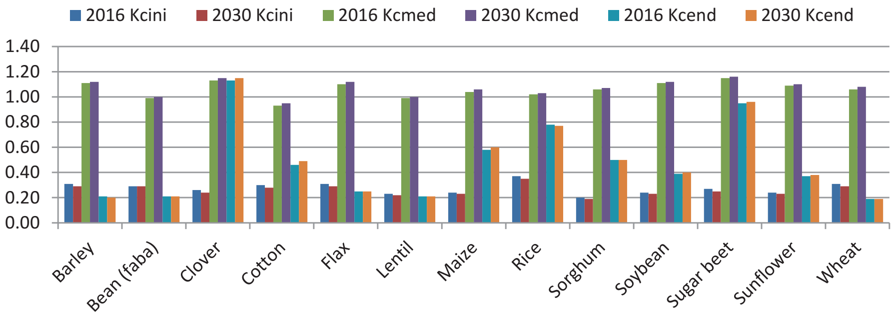

Fig. 7.3 Comparison between Kc values in 2016 and 2030 for several field crops in Egypt. (Source: Ouda 2019b)

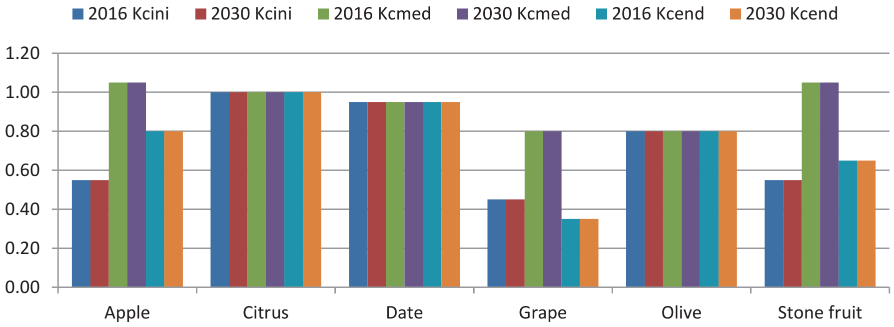

Fig. 7.4 Comparison between Kc values in 2016 and 2030 for several fruit crops in Egypt. (Source: Ouda 2019b)

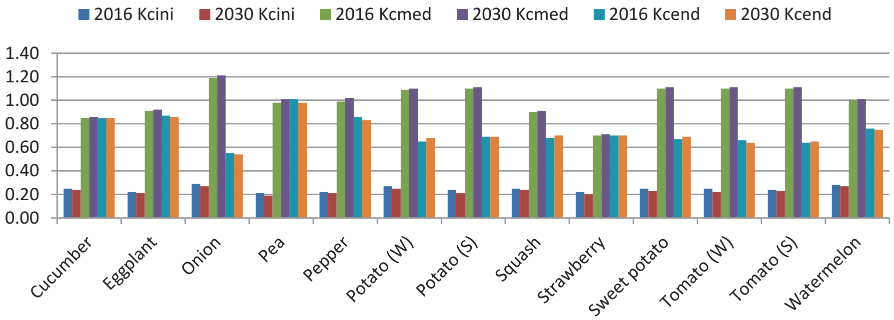

Fig. 7.5 Comparison between Kc values in 2016 and 2030 for several vegetable crops in Egypt. (Source: Ouda 2019b)

The values of Kc for the studied vegetable crops in 2016 (Ouda 2019a), were compared to its counterpart values in 2030 (Ouda 2019b) in Fig. 7.5. The figure showes that the values of Kc_{ini} were lower in 2030, compared to its counterpart values in 2016. The values of Kc_{med} were higher in 2030 and Kc_{end} values were lower in 2030, compared to its counterpart values in 2016, except for potato, squach, and sweet potato. The projected increase in the Kc values, especially in the middle of the growing season, where maximum growth existed, will cause increases in irrigation amounts required to satisfy the needs of these crops.

7.6 Effect of Climate Change on Water Consumptive Use/Water Requirements of Crops

MAGICC/SCENGEN model was used to calculate the annual mean global surface air temperature and global-mean Sea-level implications of emissions scenarios for greenhouse gases. SCENGEN model was run using CSIRO-GCM model and climatic data were extracted using regression model for year 2000 and 2050. Eid et al. (1992) indicated that climate change could increase crops water demand for summer and winter crops by 16 and 2%, respectively in the year 2050.

Water requirements for several crops were projected and percentages of increase in its values, compared to its current values are presented in Table 7.5.

Using climate change scenarios of the IPCC third assessment report (TAR) published in 2001, Attaher et al. (2006) calculated national irrigation water demand in 2050 and 2010. Their results indicated that A1 and A2 climate change scenarios will result in the highest increase in national irrigation water demand, compared to B1 and B2 climate change scenarios. Table 7.6 showed the percentage of increase in national irrigation water demand in 2050 and 2010.

Ouda et al. (2009) indicated that maize water consumptive use will increase by 11% under both A2 and B2 climate change scenarios. Furthermore, water requirements for barley will increase by 4 and 5% for the above mentioned climate change scenarios (Ouda et al. 2010).

A comparison was done between the water consumptive use (ETc) of different crops in 2016 presented by Ouda (2019a) and its counterpart values presented by

Table 7.5 Projected percentage of increase in the water requirements of several crops under climate change in 2050 using MAGICC/SCENGEN model

Crop	Percentage of increase (%)	References
Wheat	+3	Eid et al. (1993a, b)
	Not changed	Eid et al. (1994a, b)
	+1	Eid et al. (1997a)
Maize	+8	Eid et al. (1992)
Barley	+1	Eid et al. (1995)
Rice	+16	Eid et al. (1995)
Soybean	+3	Eid and El-Sergany (1993)
	+1	Eid et al. (1994a, b)

Table 7.6 Percentage of increase in national irrigation water demand in 2050 and 2010

Climate change scenario	2050[a]	2100[a]
A1	8	16
A2	7	11
B1	6	7
B2	7	9
Average	7	11

[a]calculated by the authors from Attaher et al. (2006)

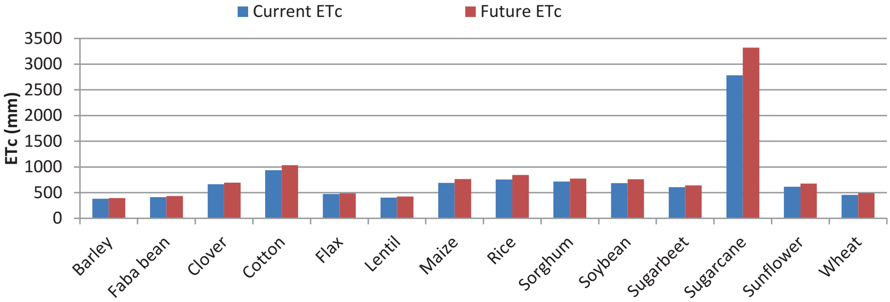

Fig. 7.6 comparison between water consumptive use of different crop in 2016 and 2030. (Source: Ouda 2019b).

Ouda (2019b) in 2030 in Fig. 7.6. A noticeable increase in water consumptive use values in 2030 is shown in the figure under climate change for the studied crops.

7.7 Climate Change and Cultivated Lands

Egypt, as a Mediterranean agricultural area, its soil is characterized by low soil organic carbon contents often degraded and highly vulnerable to environmental changes. Climate change is expected to have a large impact upon these areas (IPCC 2007). The evaluation of climate change impacts on soil organic carbon stocks can be done using carbon models and climate change scenarios (Karmakar et al. 2016).

7.7.1 Effect of Climate Change on the Soils of Egypt

Only one study was done on the effect of climate change on the soil of Egypt. For an example, Muñoz-Rojas et al. (2017) applied the CarboSOIL model and global climate models to predict the effects climate changes on soil organic carbon contents in 2030, 2050 and 2100 at standard soil depths (0–25, 25–50 and 50–75 cm) in Northern Egypt under different land use types. Overall decreases of soil organic carbon contents in the topsoil soil layer and increases in the subsoil layers are expected in the short, medium and long term. However, intensity of these changes will depend on the land use type and the results suggested that agricultural land uses relying on irrigation will be particularly vulnerable to losses of soil organic carbon stocks.

7.7.2 *Effect of Climate Change on Cultivated Area*

The effect of climate change on the cultivated area of Egypt has been studied. Fawaz and Soliman (2016) calculated the loss in the total cultivated area of Egypt in 2030 to be 8%, compared to the current cultivated area. Furthermore, Ouda and Zohry (2018) calculated the loss of the cultivated area of several winter and summer crops, as affected by the increase in water requirements of these cultivated crops and the expected water deficiency in the future in Egypt (Table 7.7). Their results indicated that the highest loss in the cultivated area of winter crops will occur for onion, namely 13% compared to its counterpart value in 2015. Whereas, for the summer

Table 7.7 The cultivated area of different winter and summer crops in 2015, the projected cultivated area in 2030 and percentage of reduction in the cultivated area

	Total cultivated area in 2015 (ha)	Total cultivated area in 2030 (ha)	Percentage of reduction (%)
Winter crops			
Wheat	1,354,844	1,260,005	7
Faba bean	34,418	32,353	6
Clover	624,741	568,514	9
Onion	148,173	128,910	13
Tomato	70,173	64,559	8
Potato	102,285	96,148	6
Sugar beet	231,193	212,697	8
Average			8
Summer crops			
Cotton	100,349	84,665	16
Rice	506,249	445,499	12
Maize	938,329	760,046	19
Soybean	14,130	11,728	17
Sunflower	6585	5465	17
Potato	53,110	43,989	17
Tomato	89,825	71,860	20
Sugarcane	134,656	111,765	17
Fruit trees	524,763	455,565	13
Average			16

Source: Ouda and Zohry (2018)

crops, the highest losses in the cultivated area will occur for tomato, namely 20% compared to its counterpart value in 2015. The overall losses in the national level will reach 8 and 16% compared to its counterpart value in 2015 in the winter and summer crops, respectively.

7.7.3 Effect of Climate Change on the Suitability of Cultivated Area to a Certain Crop

Under climate change, the expected rise in the temperature could limit suitability of a certain area to grow a certain crop, in which very low productivity per hectare will result. Thus, under these circumstances, it will be uneconomical to cultivate that crop in this area. Mahmoud et al. (2016) stated that the cutoff temperature (a temperature value under which plant growth ceases) for rice is 35 °C. They compared between the expected maximum temperature under climate change in 2040 and the cutoff temperature in the cultivated zone of rice in the Nile Delta of Egypt in eight governorates. A summary of their results presented in Table 7.8.

During the growing season of rice in 2040, no yield losses will occur in Alexandria and Demiatte, where both located on the Mediterranean Sea and maximum temperature will not rise above 35 °C. At Kafr El-Sheikh and El-Dakahlia, a rise above 35 °C will occur for few days. Maximum temperature will rise above 40 °C for few days, at El-Behira and El-Gharbia. Governorates south of the above governorates will experience more heat stress as a result of rise in maximum temperature above 40 °C for more days. Thus, the above results implied that climate change risk on rice production will increase in 2040, as a result of heat stress, which will affect physiological process in the growing plants and results in losses in rice productivity and might also result in reduction in the cultivated zone by stopping its cultivation in Sharkia and Kalubia governorates.

Similar study was done for sugarcane by Taha et al. (2016), where they assessed the suitability of south Egypt governorates for sugarcane cultivation in 2040. Cutoff

Table 7.8 Rise above cutoff temperature during rice growing season under climate change in 2040

Governorate	Early season	Middle season	Late season
Alexandria	Below 35 °C	Below 35 °C	Below 35 °C
Demiatte	Below 35 °C	Below 35 °C	Below 35 °C
Kafr El-Sheikh	Few days above 35 °C	Few days above 35 °C	Below 35 °C
El-Dakahlia	Few days above 35 °C	Few days above 35 °C	Below 35 °C
El-Behira	Few days above 40 °C	Few days above 40 °C	Few days above 40 °C
El-Gharbia	Few days above 40 °C	Few days above 40 °C	Few days above 40 °C
El-Sharkia	More days above 40 °C	More days above 40 °C	More days above 40 °C
El-Kalubia	More days above 40 °C	More days above 40 °C	More days above 40 °C

Summarized by the authors from Mahmoud et al. (2016)

Table 7.9 Rise above cutoff temperature during fall sugarcane growing season under climate change in 2040

Governorate	Higher than 38 °C	Reach 44 °C	Higher than 45 °C
Minya	May–September	–	–
Sohag	May–September	–	–
Qena	–	May–September	–
Aswan	–	–.	May–October

Summarized by the authors from Taha et al. (2016)

temperature for sugarcane is above 38 °C, growth seizes (Bonnett et al. 2006). Their results indicated that in Minya and Sohag, a rise in temperature above 38 °C is expected to occur between May and September. In Qena and Aswan governorates, the rise in temperature will reach 44 °C and it will be higher than 45 °C, respectively in 2040 (Table 7.9). These findings implied that sugarcane productivity will be reduced in 2040 in this region as a result of heat stress and it will be still suitable to grow sugarcane.

7.8 Effect of Climate Change on Food Gaps

7.8.1 Wheat Production-Consumption Gap

As a result of reduction in the cultivated area of wheat under climate change, it is expected that wheat production will be reduced under the traditional cultivation and wheat self-sufficiency will reach 37% in 2030, compared to 47% in 2015. Furthermore, implementing the improved management package will increase wheat self-sufficiency to 61%, compared to 82% in 2015 (Table 7.10) (Ouda and Zohry 2017).

7.8.2 Maize Production-Consumption Gap

Table 7.11 showed that maize production is expected to be reduced under the traditional cultivation and its self-sufficiency will reach 42% in 2030, compared to 53% in 2015. Furthermore, implementing the improved management package will increase its self-sufficiency to 69%, compared to 86% in 2015 (Zohry and Ouda 2017a).

7.8.3 Faba Bean Production-Consumption Gap

Similarly, Table 7.12 indicated that faba bean self-sufficiency will be reduced in 2030 under climate change and will reach 18% under traditional cultivation, compared to 21% in 2015. Whereas, faba bean self-sufficiency will increase to reach

Table 7.10 Projected self-sufficiency of wheat in 2030 under traditional cultivation and under using improved management package

	Self-sufficiency under traditional cultivation (%)[a]	Self-sufficiency under improved management (%)[a]
Lower Egypt	40	66
Middle Egypt	32	53
Upper Egypt	37	55
Average	37	61

[a] Calculated by the authors from Ouda and Zohry (2017)

Table 7.11 Projected self-sufficiency of maize in 2030 under traditional cultivation and under using improved management package

	Self-sufficiency under traditional cultivation (%)[a]	Self-sufficiency under improved management (%)[a]
Lower Egypt	38	63
Middle Egypt	54	90
Upper Egypt	39	61
Average	42	69

[a] Calculated by the authors from Zohry and Ouda (2017a)

Table 7.12 Projected self-sufficiency of faba bean in 2030 under traditional cultivation and under using improved management package

	Self-sufficiency under traditional cultivation (%)[a]	Self-sufficiency under improved management (%)[a]
Lower Egypt	27	87
Middle Egypt	2	33
Upper Egypt	8	79
Average	18	74

[a] Calculated by the authors from Zohry and Ouda (2017b)

74% under implementing the improved management practices in 2030. However, in 2015 and under implementing the improved management practices, faba bean could attain surplus production (Zohry and Ouda 2017b).

7.8.4 *Edible Oil Crops Production-Consumption Gap*

Under climate change in 2030, Zohry and Ouda (2018a) indicated that the total cultivated area of cotton, sunflower, soybean, maize and flax could be increased through implementing intercropping systems and cultivation of three-crop sequences, compared to its value under traditional cultivation. However, it will be lower than the cultivated area attained under intensive cropping, compared to its value in 2015. The cultivated area of these five crops will increase to 1,836,714 ha, which represent an increase by 89% of the total cultivated area, compared to the cultivated area in 2015.

7.8.5 *Summer Forage Crops Production-Consumption Gap*

In 2030, the total potential cultivated area of summer forage a result of fahl clover cultivation and intercropping cowpea with other summer crops in 2030 is expected to be reduced from 1,382,301 ha to 1,251,567 ha, compared to the value of these two crops under traditional cultivation in 2015, This reduction represents 9% less than its counterpart value attained in 2015 under intensive cropping for these two crops (Zohry and Ouda 2018b).

7.9 Conclusion

Reviewing 67 research papers previously published on the effect of climate change on natural resources related to crops production revealed that Egypt will be vulnerable to climate change as a result of its dependence on the Nile River as the main water resources. Furthermore, the Egyptian population is expected to increase to reach 125 million inhabitants in the future. The expected population increase will put more pressure on water and lands resources to produce more food to provide to the growing population. Thus, adaptation strategies should be applied when possible to reduce the vulnerability associated with climate change.

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Chapter 8
Climate Change and Wheat Self-Sufficiency

Samiha Ouda and Abd El-Hafeez Zohry

Abstract In this chapter, we assessed the effect of climate change on wheat cultivated area and total production under five production alternatives, namely traditional cultivation, raised beds cultivation, application of deficit irrigation to wheat grown on raised beds, implementing wheat intercropping systems and use the saved irrigation water from other winter crops to cultivate new lands with wheat. Our aim was to produce more wheat seeds to increase its self-sufficiency. To assess the effect of climate change on evapotranspiration, climate change scenario RCP6.0 resulted from MIROC5 model in 2030 was used in this analysis. Water requirements for wheat were calculated on governorate level and the reductions in the cultivated area were calculated. Wheat self-sufficiency ratios under the five production alternatives were calculated, as well as water productivity values. The results showed that traditional cultivation resulted in 36% self-sufficiency ratio. Cultivation on raised beds and application of deficit irrigation increased wheat self-sufficiency ratio to 47 and 50%, respectively as a result of increase in its production by 32 and 41%, compared to its value under traditional cultivation. Furthermore, application of deficit irrigation and implementing intercropping systems, as well as application of deficit irrigation, implementing intercropping systems and using the saved water from other crops to cultivate more wheat areas resulted in increasing total production by 57 and 68%, respectively compared to its value under traditional cultivation and that increased wheat self-sufficiency ratio to reach 57 and 59%, respectively. The highest water productivity values were found under application of deficit irrigation, implementing intercropping systems and use of saved water from two winter crops to increase the cultivated area of wheat.

Keywords RCP6.0 resulted from MIROC5 model · Raised beds · Deficit irrigation · Wheat intercropping systems

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8.1 Introduction

Global warming are the major and important environmental issues that are affecting the world and are expected to be more severe in coming decades (Lashkari et al. 2011). According to the IPCC report published in (2007), greenhouse gases emission might induce many changes in the global climate system during the twenty-first century. These changes are expected to be greater than those observed during the twentieth century (IPCC 2013). Global warming phenomenon appears as a widespread rising of surface air temperatures, alteration of precipitation patterns and global hydrologic cycle that increased the frequency of severe weather events such as drought spells and floods leading to low water availability (Mo et al. 2009) Global climate models predicted 1–6 °C increase in the mean ambient temperature in the end of twenty-first century (De Costa 2011). Such increase may have a significant negative influence on agricultural productivity (Bates et al. 2008), in addition to drought, salinity, waterlogging, and mineral toxicity stresses (Teixeira et al. 2013). Hence, these changes will have a dramatic effect on agricultural systems especially in temperate countries, where the water shortage and high temperatures are the main limiting factors for the crop production (Rinaldi 2009).

Temperature warming will accelerate crop development, alter the phenological time duration, and increase maintenance respiration (Mo et al. 2009). Eyshi Rezaei et al. (2018) indicated that changing crop phenology is considered an important bio-indicator of climate change, with the recent warming trend causing advancement in crop phenology. Increased air temperature and altered precipitation pattern will considerably affect crop phenological stages and stomatal conductance, causing variation of yield and water use efficiency (Mo et al. 2009). On the other hand, alteration of precipitation will affect water availability and irrigation requirements for crops, so that crop yield will be severely affected or even crop failure could occur (Asseng et al. 2013). Thus, global climate change adversely impacts crop production and imposes a wide range of constraints on agricultural systems especially in water-limited environments (Paymard et al. 2018). It including increasing atmosphere carbon dioxide concentration, warming temperature, changing surface solar radiation, and variable precipitation is expected to have a significant effect on crop development and production (Knox et al. 2016). It is estimated that up to one fifth of the global population could suffer severe shortages of fresh water (Schiermeier 2014) or quality water in the future (Girones et al. 2010).

Climate change is expected to have large effects on global wheat production. Liu et al. (2016) indicated that for every 1 °C increase in temperature, global wheat yields are predicted to decline by 4.1–6.4%. Furthermore, Liu and Yang (2010) stated that 2–5 °C increase in temperature in China could have more effects on wheat yield than the rise in CO_2 concentration, although it is mainly a negative impact. Parry et al. (2004) also reported a reduction of rain fed and irrigated wheat yield by 10–40 and 5–20%, respectively. Wheat grown in warmer regions is likely to experience greater yield losses than that grown in cooler regions, though there is also general agreement that high latitude spring wheat production will benefit from a warmer climate through an extension of the growing period (Sommer et al. 2013).

In this chapter, we assessed the effect of climate change on wheat cultivated area and total production under five production alternatives, namely traditional cultivation, raised beds cultivation, application of deficit irrigation to wheat grown on raised beds, implementing intercropping systems for wheat and use the saved irrigation water from other winter crops to cultivate new lands with wheat. Our aim was to produce more wheat seeds to increase its national production and to reduce its production-consumption gap.

8.2 Effect of Heat Stress on Wheat

Heat stress is expressed as the rise in air temperature beyond a threshold level for a period sufficient to cause injury or irremediable damage in plants in general (Teixeira et al. 2013). In wheat, heat stress affects various plant processes leading to morphophysiological alterations in plants, hindering the development processes and eventually resulting into great yield loss (Grant et al. 2011). The primary effect of heat stress is the impediment of seed germination and poor stand establishment in wheat (Hossain et al. 2013) and it negatively affects plant meristems (Kosova et al. 2011). Almeselmani et al. (2009) observed that high temperature (35/25 °C) imposed after tillering showed a significant reduction in water potential in wheat and reduces plant growth by promoting leaf senescence and abscission (Kosova et al. 2011). Heat stress in wheat during anthesis causes reduction in pollen tube development, and increases of pollen mortality (Oshino et al. 2011). Plants exposed to temperatures above >24 °C during reproductive stage significantly reduced grain yield and yield reduction continued with increasing duration of exposure to high temperature (Prasad and Djanaguiraman 2014). It reduces the number of grains leading to lower harvest index in wheat (Lukac et al. 2011). Increase in temperature of 1–2 °C reduces seed mass by accelerating seed growth rate and by shortening grain-filling periods in wheat (Nahar et al. 2010). Heat stress speeds up the rate of seed filling by reducing the duration of this stage and therefore the yield potential (Kaushal et al. 2016). Other damages were observed under heat stress, namely it decreases metabolic activities (Farooq et al. 2011), and production of oxidative reactive species (Wang et al. 2011).

8.3 Effect of Climate Change on Wheat

It was reported by Valizadeh et al. (2014) that a rise in temperature under climate change condition has had negative impacts on the grain filling period causing reduction in the growing season, reduction in harvest index and yield losses in comparison to the current situation. Asseng et al. (2014) tested 30 wheat crop simulation models where mean temperatures in the growing season ranged from 15 to 32 °C with artificial heating. Their results indicated that rise in temperature decreased grain yield in the majority of wheat growing locations. Average yields for the periods between 1981 and 2010 decreased; ranging between 1% and 28% across 30 sites under increase in temperature by 2 °C. Furthermore, yield losses rose to between 6% and 55% for a temperature of 4 °C. They also predicted that global wheat production will fall by 6% for each 1 °C of further temperature increase. Eyshi Rezaei and Bannayan (2012) studied rain fed wheat yield using the HadCM3 climate change model under the A2 scenario and using DSSAT crop simulation model. They reported a yield reduction by 50% in the 2040–2069 periods. In another simulation study in Mexico, Hernandez-Ochoa et al. (2018) projected a general decline in wheat yields by the 2050s. They also stated that despite the growth-stimulating effect of elevated CO_2 concentrations, consistent yield declines were simulated across most of the main wheat growing regions of Mexico due to the projected increase in temperature. They added that national wheat production of Mexico is projected to decline between 6.9% for RCP4.5 and 7.9% for RCP8.5 climate change scenarios.

Using A2 and B2 climate change scenarios developed from HadCM3 model, Khalil et al. (2009) and Moneir, (2012) found that for wheat planted in clay soil and surface irrigation, yield losses will occur namely 33–36% and 31–35%, respectively in both investigations. Whereas, for wheat grown in silty clay soil and under sprinkler system, yield losses were 39% and 34% under A2 and B2 climate change scenarios, respectively (Noreldin et al. 2012). In salt affected soil and under surface irrigation, wheat yield losses under farmer irrigation practice were high, namely 47% and 44% under A2 and B2 climate change scenarios, respectively (Ouda et al. 2012). Similarly, for farmer irrigation practice in sandy soil and under sprinkler irrigation, yield losses were 32% and 27% under A2 and B2 climate change scenarios, respectively (Ouda et al. 2010).

8.4 Climate Change Assessment

8.4.1 Projection of Wheat Water Requirements in 2030

To assess the effect of climate change on ETo, climate change scenario RCP6.0 resulted from MIROC5 model in 2030 was used in this analysis. It is available from the following web site: http://www.ccafs.cgiar.org/marksimgcm#.Ujh1gjGfMY. The MIROC5 model is one of the CMIP5 General Circulation Models developed by Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology. The model has a horizontal resolution of 1.40° × 1.40°.

RCP6.0 climate change scenario is one of the four RCPs scenarios produced by MIROC5 model to represent a larger set of mitigation scenarios and have different targets in terms of radiative forcing in 2100. The scenario is a stabilization scenario, in which total radiative forcing is stabilized shortly after 2100, without overshoot, by the application of a range of technologies and strategies for reducing greenhouse gas emissions (Fujino et al. 2006, Hijioka et al. 2008).

The BISm model (Snyder et al. 2004) was used to calculate the values of ETo using the data resulted RCP6.0 climate change scenario produced by MIROC5 model. The BISm model calculates ETo using Penman-Monteith equation (Allen et al. 1998). Penman-Monteith equation is widely recommended because of its detailed theoretical base and its accommodation of small time periods (Shahidian et al. 2012). Wheat Kc values for each growing stage was calculated using planting and harvest dates of wheat in 2030.

Under climate change in 2030 and as a result of the rise in air temperature, it is expected that planting date will be earlier by 5–7 days. Morsy (2015) simulated the effect of early planting for wheat under climate change in 2030 and found that early planting resulted in reduction of wheat yield losses. Furthermore, it is also expected that season length of wheat will be reduced under climate change. Khalil et al. (2009) reported that wheat season length was reduced by 5 days in 2030, as a result of acceleration in its growing season. According to the previous results, we assumed that, in 2030, planting date of wheat will be 5 days earlier and season length will be 151 days instead of 155 days under current weather. Table 8.1 presented projected planting and harvest dates of wheat, season length, date of Kc stages, and Kc value in 2030 in Lower, Middle and Upper Egypt.

ETo values was multiplied by wheat Kc values and water consumptive use of wheat was calculated in 2030. Comparison between water consumptive use values for wheat on governorate level in 2017 and the projected the water consumptive use values are presented in Fig. 8.1.

Finally, water requirements for wheat was calculated using BISm (Snyder et al. 2004) in the old lands under the surface irrigation with 60% irrigation application efficiency and 75% irrigation application efficiency under sprinkler systems in the new lands.

Table 8.1 Projected planting and harvest dates of wheat, season length, date of Kc stages, and Kc value in 2030

Wheat information			
Begin and end season	Planting date:10-Nov	Harvest date: 9-Apr	Season length: 151 days
Date of Kc stages			
Lower Egypt	Kc_{ini}: 10-Dec	Kc_{mid}: 16-Jan	Kc_{end}: 9-Apr
Middle Egypt	Kc_{ini}: 9-Dec	Kc_{mid}: 15-Jan	Kc_{end}: 9-Apr
Upper Egypt	Kc_{ini}: 9-Dec	Kc_{mid}: 15-Jan	Kc_{end}: 9-Apr
Values of Kc			
Lower Egypt	Kc_{ini}: 0.28	Kc_{mid}: 1.08	Kc_{end}: 0.18
Middle Egypt	Kc_{ini}: 0.26	Kc_{mid}: 1.08	Kc_{end}: 0.16
Upper Egypt	Kc_{ini}: 0.24	Kc_{mid}: 1.08	Kc_{end}: 0.16

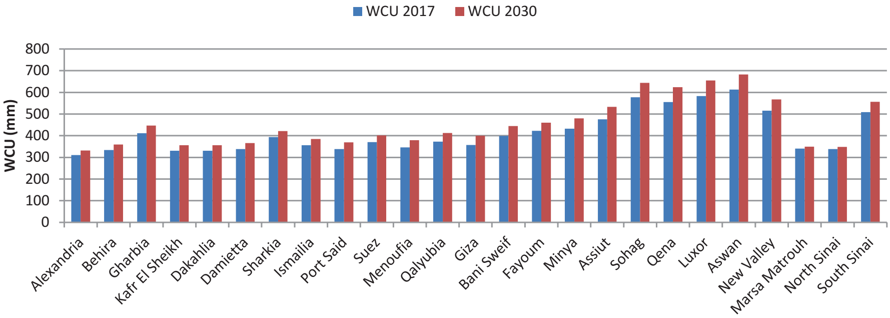

Fig. 8.1 Comparison between water consumptive use (WCU) values for wheat on governorate level in 2017 and the projected the water consumptive use values

8.4.2 Projection of Wheat Cultivated Area and Total Production

The cultivated area and productivity of wheat in 2017 were collected for both old and new lands on governorate level from the Ministry of Agriculture and Land Reclamation in Egypt and used as a base for comparison (see Chap. 6 for full details). We calculated the potential cultivated area of wheat, which is negatively affected by increasing wheat water requirements as a result fixed amount of irrigation assigned to agriculture. We assumed that wheat breeding programs will be able to produce cultivars tolerant to water and heat stresses that climate change will cause. Thus, wheat productivity will be the same as its recorded value in 2017 on governorate level. As we stated earlier wheat production-consumpation gap was assessed using five production alternatives as followed:

1. **Traditional cultivation**: the cultivated area of wheat in 2030 on governorate level in both the old and the new lands were calculated by dividing total water requirements on governorate level by wheat water requirements per hectare. Then, it was multiply by its productivity per hectare to calculate total production. Wheat consumption by the population was calculated as well as the production-consumption gap.
2. **Raised beds cultivation**: We assumed that cultivation on raised beds will increase productivity per hectare by 15%, and then the increase in the total production was calculated. We also assumed that 20% of the applied water under surface irrigation will be saved. The saved irrigation water will be used to irrigate new areas cultivated with wheat and this area will be added to the total cultivated area of wheat to increase its total production. Wheat production-consumption gap was calculated under this production alternative.
3. **Application of deficit irrigation**: The effect of application of deficit irrigation wheat cultivated on raised beds was calculated, taking into account previous research done in this matter. Because the amount of irrigation water resulted from cultivation on raised beds produced higher yield than the traditional

cultivation, we applied deficit irrigation to it and the losses in yield resulted from raised beds cultivation was calculated. The saved irrigation water will be used to irrigate new areas with wheat and this area will be added to wheat total cultivated area to increase its total production and compensate the loss in the productivity per hectare. Wheat production-consumption gap was calculated under this production alternative.

4. **Implementing intercropping systems for wheat**: the effect of five wheat intercropping systems was assessed on wheat total production, where wheat was the secondary crop in the intercropping system. These intercropping systems are: wheat intercropping with tomato, cotton relay intercropped with wheat, wheat intercropping with sugar beet, wheat intercropped under fruit trees, and wheat intercropped with sugarcane. Reduction in the cultivated area of the main crops in these intercropping systems was calculated using similar approach to the one done for wheat. Wheat production resulted from intercropping systems was added to wheat production resulted from applying deficit irrigation on raised beds and its total production was calculated. Wheat production-consumption gap was calculated under this production alternative.
5. **Investment of the saved irrigation water:** in Chap. 6, the saved irrigation water resulted from cultivation on raised beds and application of deficit irrigation to Egyptian clover and sugar beet in Chap. 4 and resulted from onion and winter tomato in Chap. 5 was assumed to be used in cultivating new area of wheat. Under climate change we assessed the possibility of saving an amount of water to be use in adding new areas to wheat. Wheat production resulted from intercropping systems was added to the production resulted from applying deficit irrigation and the production resulted from the saved water from these four crops. The total wheat production was calculated, as well as wheat production-consumption gap under this production alternative.

Water productivity was calculated under these five production alternatives. Water productivity is a quantitative term used to define the relationship between crop produced and the amount of water involved in crop production (Igbadun et al. 2006). It is a good indicator to compare between the five productions alternatives, because it involves both crop production amount, and its applied irrigation water to produce this amount.

8.4.3 Production Alternatives for Wheat Under Climate Change

8.4.3.1 Traditional Cultivation of Wheat

The values of projected wheat water consumptive use and consequently its water requirement on governorate levels was used to calculated the wheat cultivated area using the amount assigned irrigation water to irrigate wheat in 2017 presented in

Chap. 6. This assumption is due to the limitation of water resources in Egypt and there is no chance to increase it in the future. Table 8.2 presented projected wheat cultivated area and its production in 2030 in the old lands. The table showed that, in Lower Egypt, the percentage of reduction in the cultivated area of wheat and its production was between 6% and 10%, with average of 7% and 6%, respectively. In Middle Egypt, the percentage of reduction in the cultivated area and production was between 8% and 11%, with an average of 10%. Whereas, the percentage of reduction in the cultivated area of wheat and its production in Upper Egypt was between 8% and 11%, with average of 7% and 6%, respectively. In Middle Egypt, the

Table 8.2 Projected cultivated areas of wheat and its production in the old lands in 2030 and percentage of reduction in the cultivated area and production

	Wheat cultivated area (000 ha)	Percentage of reduction (%)	Production (000 ton)	Percentage of reduction (%)
Lower Egypt				
Alexandria	12.3	6	82.8	6
Behira	113.7	7	811.8	7
Gharbia	38.9	10	264.0	10
Kafr El Sheikh	79.0	7	517.3	7
Dakahlia	66.9	7	529.4	7
Damietta	7.6	7	51.1	8
Sharkia	129.9	7	907.0	7
Ismailia	7.9	8	51.8	8
Suez	1.7	10	11.0	8
Menoufia	46.4	9	356.4	9
Qalyubia	18.9	10	133.5	10
Total/ average	523.2	7	3728.4	6
Middle Egypt				
Giza	13.4	11	106.0	11
Bani Sweif	41.6	11	298.4	10
Fayoum	69.1	8	447.8	8
Minya	82.6	10	593.3	10
Total/ average	206.8	10	1445.4	10
Upper Egypt				
Assiut	71.7	11	520.7	11
Sohag	68.1	10	468.8	10
Qena	25.1	11	167.5	11
Luxor	5.9	11	39.3	11
Aswan	4.4	11	31.0	10
Total/ average	175.3	10	1227.26	10
Grand total	905.3	8	6388.62	8

percentage of reduction in the cultivated area and production was between 10% and 11%, with an average of 10%. The table also showed that the total cultivated area of wheat in the old lands will be reduced to 905.3 thousand hectares and its production will be reduced to 6388.6 million tons of wheat seeds with 8% reduction in both area and production, compared to the their values in 2017.

With respect to the new lands, the total cultivated area will be reduced by 8% to reach 208.7 thousand hectares and its production will be 1311.0 million tons, with 7% reduction, compared to 2017. In Lower Egypt, the percentage of reduction in the cultivated area of wheat and its production was between 6% and 9%, with average of 7%. In Middle Egypt, the percentage of reduction in the cultivated area and production was between 8% and 11%, with an average of 10%. Whereas, the percentage of reduction in the cultivated area of wheat and its production in Upper Egypt was between 8% and 11%, with average of 7% and 6%, respectively. In Upper Egypt, the percentage of reduction in the cultivated area and production was between 9% and 11%, with an average of 11% and 10%, respectively. Furthermore, 3–11% reduction in the cultivated area of wheat in the boarder governorates and its cultivated area will be reduced by 3–8% under climate change, with an average of 8 and 7% respectively (Table 8.3).

Similar trend was observed for wheat total cultivated area and total production, where the lowest percentage of reduction will be found in Lower Egypt and the highest percentage of reduction will be found in Upper Egypt. The total cultivated area will be reduced to be 1114.0 million hectares and it will produce 7700.1 million tons of wheat seeds, with percentage of reduction equal to 9% and 7% respectively (Table 8.4).

Population, Wheat Consumption and Wheat Production-Consumption Gap

Table 8.5 presented the projected Egyptian population in 2030, which it was obtained from a report published by the Academy of Science and Technology in Egypt in 2016. The consumption of wheat by the population is also presented. The table revealed that, in Lower, Middle, and Upper Egypt, and boarder governorates, population will be increase by 30, 29, 37 and 62%, respectively, compared to its values in 2017.

Table 8.5 also showed that the total population will reach 125,871 million inhabitants, with 32% increase compare to its value in 2017. Accordingly, wheat consumption will be increase by 12, 10, 17 and 39% in Lower, Middle, and Upper Egypt, and boarder governorates, with 13% increase compare to its value in 2017. Thus, wheat consumed will reach 22,027 million tons, and wheat production-consumption gap was 14,212 million tons. The ratio of wheat self-sufficiency in 2017 was 36%. Furthermore, it can be notice from the table only New Valley governorate in Upper Egypt will attain self-sufficiency in addition to surplus in wheat production as a result of lower wheat consumption, compared to its wheat production.

Table 8.3 Projected cultivated areas of wheat and its production in the new lands in 2030 and percentage of reduction in the cultivated area and production

	Area (000 ha)	Percentage of reduction (%)	Production (000 ton)	Percentage of reduction (%)
Lower Egypt				
Alexandria	17.2	6	106.0	6
Behira	50.3	7	337.1	7
Kafr El Sheikh	1.0	7	6.1	7
Dakahlia	6.1	7	47.0	7
Damietta	0.4	8	2.7	8
Sharkia	9.2	7	56.6	7
Ismailia	5.3	7	34.1	7
Port Said	4.6	8	31.5	9
Suez	0.4	8	2.3	8
Total	94.4	7	623.4	7
Middle Egypt				
Giza	2.1	10	14.5	11
Bani Sweif	3.2	11	20.8	10
Fayoum	1.6	8	9.2	8
Minya	4.1	9	24.4	10
Total/average	11.0	10	69.0	10
Upper Egypt				
Assiut	6.6	11	40.6	11
Sohag	4.3	10	22.4	11
Qena	8.4	11	46.3	10
Luxor	5.8	11	31.8	11
Aswan	15.4	10	102.7	10
New Valley	57.6	9	349.7	9
Total/average	98.1	11	593.5	10
Border governorates				
Marsa Matrouh	3.8	3	22.0	3
North Sinai	0.9	8	1.1	4
South Sinai	0.4	11	1.8	8
Total/average	5.0	7	25.0	5
Grand total	208.7	8	1311.0	7

8.4.3.2 Cultivation on Raised Beds

According to previous research in Egypt on wheat cultivation on raised beds (Abouelenin et al. 2010; Karrou et al. 2012; Khalil and Abouelenin 2012; Zohry et al. 2019), we assumed that raised beds cultivation will save 20% of the applied irrigation water in the old lands and no water saving will occur in the new lands. In addition, wheat productivity will increase by 15% in the old lands only.

Table 8.4 Projected total cultivated areas of wheat and its production in the old and new lands in 2030 and percentage of reduction in the cultivated area and production

	Area (000 ha)	Percentage of reduction (%)	Production (000 ton)	Percentage of reduction (%)
Lower Egypt				
Alexandria	29.5	6	188.7	6
Behira	163.9	7	1148.8	7
Gharbia	38.9	10	264.0	10
Kafr El Sheikh	79.9	7	523.4	7
Dakahlia	73.0	7	576.4	7
Damietta	8.0	8	53.8	8
Sharkia	139.1	7	963.7	7
Ismailia	13.2	7	85.9	7
Port Said	4.6	8	31.5	9
Suez	2.1	10	13.3	8
Menoufia	46.4	9	356.4	9
Qalyubia	18.9	10	133.5	10
Total/average	617.6	7	4339.4	7
Middle Egypt				
Giza	15.5	11	120.5	11
Bani Sweif	44.8	10	319.2	10
Fayoum	70.8	8	457.0	8
Minya	86.7	10	617.7	10
Total/average	217.8	10	1514.4	10
Upper Egypt				
Assiut	78.3	11	561.3	11
Sohag	72.4	10	491.2	10
Qena	33.6	11	213.8	11
Luxor	11.7	11	71.1	11
Aswan	19.8	10	133.7	10
New Valley	57.6	9	349.7	9
Total/average	273.4	10	1820.8	10
Border governorates				
Marsa Matrouh	3.8	3	22.5	0.5
North Sinai	0.9	8	1.2	3
South Sinai	0.4	11	1.9	4
Total/average	5.2	7	25.6	3
Grand total	1114.0	9	7700.1	7

Table 8.5 Projected Egyptian population and its percentage of increase compared to 2017, wheat consumption and its percentage of increase compared to 2017 and wheat production-consumption gap under traditional cultivation in 2030

	Population[a] (000 inhabitants)	Percentage of increase (%)	Consumption (000 ton)	Percentage of increase (%)	Gap (000 ton)
Lower Egypt					
Alexandria	6188	19	1083	2	−894
Behira	8625	39	1509	19	−360
Gharbia	6980	39	1222	19	−945
Kafr El Sheikh	4720	40	826	20	−303
Dakahlia	8756	34	1532	15	−956
Damietta	1946	30	341	11	−287
Sharkia	9648	34	1688	15	−725
Ismailia	1744	33	305	14	−219
Port Said	860	15	151	2	−119
Suez	808	11	141	5	−128
Menoufia	5805	34	1016	15	−659
Qalyubia	7602	35	1330	15	−1197
Cairo	11,994	25	2099	8	−2099
Total	75,675	30	13,243	12	−8891
Middle Egypt					
Giza	10,833	25	1896	7	−1772
Bani Sweif	4119	30	721	11	−394
Fayoum	4564	26	799	8	−342
Minya	7406	34	1296	15	−665
Total	26,923	29	4712	10	−3174
Upper Egypt					
Assiut	6140	39	1075	20	−490
Sohag	6621	33	1159	14	−643
Qena	4423	39	774	19	−549
Luxor	1660	32	291	13	−216
Aswan	2074	40	363	20	−222
New Valley	332	37	58	19	**302**
Total	21,250	37	3719	17	−1818
Bordered governorates					
Marsa Matrouh	665	55	116	32	−94
North Sinai	651	44	114	24	−113
South Sinai	222	115	39	85	−37
Red Sea	485	34	85	15	−85
Total	2022	62	354	39	−328
Grand total	125,871	32	22,027	13	−14,212

[a] Academy of Scientific Research and Technology (2016)

Table 8.6 indicated that the saved irrigation water as a result of cultivation of wheat on raised beds could be used to cultivate other area with wheat and added to the total area. The added area will be 241.4 thousand hectares, and the total wheat area it will reach 1355.4 million hectares, with 8% reduction compared to its added area and cultivated area in 2017.

Table 8.6 Projected added area and total area of wheat under raised beds cultivation in 2030 and percentages of reduction (PR) compared to its values in 2017

	Added area (000 ha)	PR (%)	Total area (000 ton) (old + new + added)	PR (%)
Lower Egypt				
Alexandria	3.3	6	32.8	6
Behira	30.3	7	194.2	7
Gharbia	10.4	10	49.3	10
Kafr El Sheikh	21.1	7	101.0	7
Dakahlia	17.8	7	90.8	7
Damietta	2.0	8	10.0	8
Sharkia	34.6	7	173.7	7
Ismailia	2.1	8	15.4	7
Port Said	0	0	4.6	8
Suez	0.5	9	2.5	6
Menoufia	12.4	8	58.7	9
Qalyubia	5.0	10	23.9	10
Total/average	139.5	7	757.1	7
Middle Egypt				
Giza	3.6	11	19.1	11
Bani Sweif	11.1	10	55.9	10
Fayoum	18.4	8	89.2	8
Minya	22.0	10	108.7	10
Total/average	55.1	9	272.9	10
Upper Egypt				
Assiut	19.1	11	97.4	11
Sohag	18.2	11	90.6	10
Qena	6.7	11	40.3	11
Luxor	1.6	13	13.3	11
Aswan	1.2	10	21.0	10
New Valley	0	0	57.6	9
Total/average	46.7	9	320.2	10
Border governorates				
Marsa Matrouh	0	0	3.8	3
North Sinai	0	0	0.9	8
South Sinai	0	0	0.4	11
Total/average	0	0	5.2	5
Grand total	241.4	8	1355.4	8

Table 8.7 presented the projected total wheat production resulted from the old, new and added lands in 2030 under raised beds cultivation and percentage of reduction in the total production, compared to its values in 2017. The table showed that the total production could reach 10,171.5 million tons of wheat seeds, with 8% reduction compared to its value in 2017.

Table 8.7 Projected total wheat production in 2030 under raised beds cultivation, percentage of reduction (PR), compared to its values in 2017, and wheat production-consumption gap in 2030

	Production (000 ha)	PR in production (%)	Gap (000)
Lower Egypt			
Alexandria	221.5	6	−861.4
Behira	1473.8	7	−35.6
Gharbia	373.2	10	−830.9
Kafr El sheikh	733.1	7	−92.9
Dakahlia	794.3	7	−737.9
Damietta	74.2	8	−266.4
Sharkia	1311.8	7	−376.5
Ismailia	107.3	7	−197.9
Port Said	31.5	9	−119.0
Suez	17.8	8	−123.6
Menoufia	485.5	9	−530.3
Qalyubia	184.4	10	−1145.9
Cairo	0	0	−2099.0
Total/average	5808.5	7	−7417.2
Middle Egypt			
Giza	160.8	11	−1730.8
Bani Sweif	436.2	10	−274.6
Fayoum	630.4	8	−168.4
Minya	839.5	10	−438.7
Total/average	2066.9	9	−2612.6
Upper Egypt			
Assiut	757.7	11	−285.8
Sohag	656.3	10	−470.2
Qena	275.7	11	−483.9
Luxor	85.6	11	−200.2
Aswan	146.1	10	−209.4
New Valley	349.7	9	302.4
Total/average	2271.1	10	−1347.2
Border governorates			
Marsa Matrouh	22.0	3	−93.9
North Sinai	1.1	4	−112.7
South Sinai	1.8	8	−36.9
Red Sea	0	0	−84.8
Total/average	25.0	4	−328.4
Grand total	10,171.5	8	−11,705.4

The table also showed that the production-consumption gap in 2030 will reach 11,705.4 million tons, with 16% reduction compared to its values under traditional cultivation in 2030. In this case, wheat self-sufficiency ratio will increase to 47%.

Furthermore, New Valley governorate in Upper Egypt will continue to attain self-sufficiency in addition to surplus in wheat production (Table 8.7).

8.4.3.3 Application of Deficit Irrigation

From previous research conducted in Egypt on application of deficit irrigation to wheat, we assumed that, in the old land, saving 10% of the applied water will result in 5% yield losses. Similarly, in the new lands, saving 5% of the applied water will result in 5% yield losses. Table 8.8 indicated that the amount of saved water under deficit irrigation could be used to cultivate 122.7 thousand hectares, when added to the total wheat area it will reach 1478.1 million hectares, with 8% reduction, compared to its value in 2017.

Table 8.9 indicated that the total wheat cultivated area will produced 11,883.7 million tons of wheat, with 8% reduction compared to its values in 2017. Furthermore, wheat production-consumption gap will be reduced to 10,982.2 million ton. Wheat self-sufficiency ratio could reach 50% under deficit irrigation application. It could be noticed from the table that Behira governorate attained self-sufficiency and surplus of wheat, in addition to New Valley governorates.

8.4.3.4 Wheat Intercropping with Other Crops

In over populated countries, implementing intercropping system offers potential benefits over monoculture cultivation. It increase yield through more effective use of resources, including water, nutrients, solar energy (Nasri et al. 2014). Implementing intercropping systems can increase food availability and security (Ouma and Jeruto 2010). Katyayan (2005) defined intercropping as a system of management of crops which involves growing of two or more dissimilar crop species simultaneously in distinct row combination on the same piece of land. This practice could be used as a way to improve soil fertility, increase land productivity and save on the applied irrigation water (Kamel et al. 2010), as well as increase water productivity as a result of using less water to irrigate two crops (Andersen 2005). Furthermore, The efficiency of the intercropping is directly depends on proper management of the factors of production, such as the spatial arrangement of crops and planting density, where it can reduce the competition for resources and increase the efficiency of the system (Porto et al. 2011).

The contribution of five intercropping systems of wheat on increasing its cultivated area and production in 2030 under climate change was assessed. These five intercropping systems are wheat intercropping with winter tomato (Abd El-Zaher et al. 2013), cotton relay intercropped with wheat (Lamlom et al. 2018), wheat intercropping with sugar beet (Abou-Elela 2012), wheat intercropped under fruit trees,

Table 8.8 Projected added area and total area of wheat under deficit irrigation application in 2030 and percentages of reduction (PR) compared to its values in 2017

	Added area (000 ha)	PR in added area (%)	Total area (000 ton) (old + new + added)	PR in total area (%)
Lower Egypt				
Alexandria	2.4	7	35.2	6
Behira	16.7	7	210.9	7
Gharbia	4.8	9	54.1	10
Kafr El Sheikh	9.8	7	110.8	7
Dakahlia	8.6	8	99.4	7
Damietta	1.0	4	11.0	8
Sharkia	16.5	7	190.3	7
Ismailia	1.3	10	16.6	8
Port Said	0.2	19	4.9	8
Suez	0.23	8	2.8	8
Menoufia	5.7	9	64.5	9
Qalyubia	2.3	10	26.3	10
Total/average	69.6	8	826.7	7
Middle Egypt				
Giza	1.8	12	20.8	11
Bani Sweif	5.3	10	61.2	10
Fayoum	8.6	8	97.8	8
Minya	10.4	10	119.2	10
Total/average	26.1	10	299.1	10
Upper Egypt				
Assiut	9.2	11	106.6	11
Sohag	8.6	10	99.2	10
Qena	3.6	11	43.8	11
Luxor	1.0	14	14.3	11
Aswan	1.4	10	22.3	10
New Valley	3.0	8	60.6	9
Total/average	26.8	11	347.0	10
Border governorates				
Marsa Matrouh	0.2	5	4.0	3
North Sinai	0	0	0.9	7
South Sinai	0	0	0.4	11
Total/average	0.2	3	5.4	6
Grand value	122.7	8	1478.1	8

Table 8.9 Projected total wheat production in 2030 under deficit irrigation application, percentage of reduction (PR), compared to its values in 2017, production-consumption gap in 2030 and percentage of reduction

	Production (000 ha)	PR in production (%)	Gap (000)
Lower Egypt			
Alexandria	234.8	6	−848.2
Behira	1566.7	7	**57.3**
Gharbia	395.9	10	−807.0
Kafr El Sheikh	780.4	7	−45.7
Dakahlia	842.9	7	−689.3
Damietta	79.1	8	−261.4
Sharkia	1408.0	7	−280.4
Ismailia	113.5	7	−191.7
Port Said	33.1	9	−117.4
Suez	18.9	8	−122.5
Menoufia	526.9	9	−488.9
Qalyubia	198.5	10	−1131.7
Cairo	0	0	−2099.0
Total/average	6198.6	7	−7026.0
Middle Egypt			
Giza	172.6	11	−1718.7
Bani Sweif	466.5	10	−243.6
Fayoum	676.1	8	−122.7
Minya	905.1	10	−371.8
Total/average	2220.3	10	−2456.8
Upper Egypt			
Assiut	815.2	11	−225.9
Sohag	714.0	10	−409.8
Qena	296.6	11	−461.9
Luxor	91.5	11	−194.0
Aswan	154.1	10	−200.9
New Valley	367.2	9	**320.5**
Total/average	2438.6	10	−1172.1
Border governorates			
Marsa Matrouh	23.1	3	−92.9
North Sinai	1.15	3	−112.7
South Sinai	1.8	8	−36.9
Red Sea	0	0	−84.8
Total/average	26.1	3	−327.3
Grand total	10,883.7	8	−10,982.2

and wheat intercropped with sugarcane (Ahmed et al. 2013). Detailed description of these intercropping systems is provided in Chap. 6.

Wheat Intercropped with Tomato System

There are many advantages of intercropping wheat with tomato. Abd El-Zaher et al. (2013) indicated that monoculture cultivation of winter tomato resulted in termination of its growing season by the end of December. However, when wheat intercropped with it, tomato plants continue to give fruits until the end of March as a result of the protection that wheat plants provide to tomato plants from low temperature in January and February.

In this system, we assumed that 50% of the cultivated area with tomato will be assigned to be use in implementing wheat intercropping system with tomato. Table 8.10 indicated that winter tomato cultivated area will be reduced from 70.4 thousand hectares in 2017 to 65.0 thousand hectares in 2030 and the assigned area to be use in the intercropping system with wheat will be from 35.2 thousand hectares. These areas will produce 187.2 thousand tons of wheat seeds, with 7% reduction compared to its value in 2017.

Cotton Relay Intercropped with Wheat

Zohry (2005) indicated that, in Egypt, cotton is an early summer crop cultivated in March to produce high yield. Egyptian clover is usually preceding cotton, cultivated as early as in October and harvested in February before the cultivation of cotton. Relay intercropping cotton on wheat allows cultivation of cotton in is suitable planting date and in the same time add an area to cultivate wheat and increase its cultivated area.

In cotton relay intercropped with wheat system, we assumed that 90% of the total cultivated area of cotton will be assigned to this system. Table 8.11 showed that the cultivated area by wheat will be reduced from 49.4 thousand hectares to 41.5 thousand hectares. Wheat production will be reduced by 12% from 336.0 thousand tons in 2017 to 282.2 thousand tons in 2030.

Wheat Intercropped with Sugar Beet System

In this system, we assumed that 25% of the cultivated area of sugar beet will be assigned to wheat intercropping system with sugar beet (Abou El-Elela 2012). Table 8.12 indicated that the cultivated area of sugar beet will be reduced from 220.1 thousand hectares to 202.5 thousand hectares and the assigned area to wheat will be reduced from 55.0 thousand hectares to 50.6 thousand hectares in 2030. The table also showed that the assigned area to wheat will produce 195.4 thousand tons of wheat seeds in 2030, compared to 211.0 thousand tons in 2017 with 7% reduction.

Table 8.10 Potential cultivated area of winter tomato, assigned area to wheat intercropped with winter tomato, wheat production and percentage of reduction in wheat production compared to its value in 2017

	Tomato area (000 ha)	Assigned area to wheat (000 ha)	Wheat production (000 ton)	PR in production (%)
Lower Egypt				
Alexandria	1.5	0.8	4.5	8
Behira	12.1	6.0	37.7	8
Gharbia	0.1	0.0	0.2	8
Kafr El Sheikh	1.9	1.0	5.6	8
Dakahlia	1.3	0.6	4.5	7
Damietta	0.5	0.2	1.4	7
Sharkia	15.5	7.7	47.2	7
Ismailia	3.4	1.7	9.6	7
Port Said	0.3	0.1	0.7	7
Suez	0.6	0.3	1.8	7
Menoufia	0.2	0.1	0.8	8
Qalyubia	0.1	0.1	0.3	8
Cairo	0.02	0.01	0.001	7
Total	37.5	18.7	114.2	7
Middle Egypt				
Giza	3.4	1.7	11.9	8
Bani Sweif	3.6	1.8	11.2	8
Fayoum	1.7	0.9	4.9	9
Minya	2.2	1.1	7.0	9
Total	11.0	5.5	35.0	8
Upper Egypt				
Assiut	2.0	1.0	6.4	9
Sohag	4.2	2.1	12.6	10
Qena	1.1	0.5	3.2	8
Luxor	2.3	1.2	6.8	9
Aswan	0.3	0.2	1.0	10
New Valley	0.1	0.1	0.3	10
Total	10.1	5.0	30.2	9
Bordered governorates				
Marsa Matrouh	4.5	2.2	7.2	5
North Sinai	1.9	1.0	0.6	5
South Sinai	0.04	0.02	0.07	8
Total	6.5	3.2	7.9	5
Grand total	65.0	32.5	187.2	7

Table 8.11 Potential cultivated area of cotton, assigned area to wheat intercropping system, wheat production and percentage of reduction in wheat production compared to its value in 2017

	Cotton area (000 ha)	Assigned area to wheat (000 ha)	Wheat production (000 ton)	PR in production (%)
Lower Egypt				
Alexandria	0.24	0.22	1.4	16
Behira	5.1	4.6	32.4	16
Gharbia	1.8	1.6	10.7	15
Kafr El Sheikh	16.5	14.9	95.8	16
Dakahlia	6.9	6.2	48.0	14
Damietta	2.2	2.0	12.9	16
Sharkia	5.8	5.2	35.8	16
Ismailia	0.2	0.1	0.9	17
Port Said	0.1	0.1	0.6	14
Menoufia	0.3	0.3	2.3	17
Qalyubia	0.009	0.008	0.1	20
Total	39.1	35.2	240.4	16
Middle Egypt				
Bani Sweif	1.8	1.6	11.6	16
Fayoum	4.1	3.7	23.5	16
Minya	0.04	0.03	0.2	23
Total	6.0	5.4	35.3	14
Upper Egypt				
Assiut	0.9	0.8	5.8	16
Sohag	0.1	0.1	0.7	17
Total	1.0	0.9	6.5	5
Grand total	46.1	41.5	282.2	12

Wheat Intercropped Under Fruit Trees

We assumed that 16% of the cultivated area by fruit trees will be used to intercropped wheat with 70% of its recommended planting density. Table 8.13 showed that 99.0 thousand hectares of the total fruit trees area (609.3 thousand hectares) could be assigned to be intercropped with wheat. This area will produce 729.2 thousand tons of wheat seeds in 2030, which is lower than wheat production in 2017 by 11%.

Wheat Intercropped with Sugarcane

Under wheat intercropped with fall sugarcane system (Ahmed et al. 2013), we assumed that 10% of the fall sugarcane area will be assigned to be cultivated with the wheat intercropping system. Table 8.14 indicated that, under this system, the total production of wheat from the assigned area will be reduced from 100.4 thousand tons in 2017 to 83.3 thousand tons, with 19% reduction.

Table 8.12 Potential cultivated area of sugar beet, assigned area to wheat intercropped with sugar beet, wheat production and percentage of reduction in wheat production compared to its value in 2017

	Sugar beet area (000 ha)	Assigned area to wheat (000 ha)	Wheat production (000 ton)	PR in production (%)
Lower Egypt				
Alexandria	2.6	0.7	2.4	8
Behira	15.2	3.8	14.8	7
Gharbia	5.5	1.4	5.1	8
Kafr El Sheikh	49.9	12.5	44.6	7
Dakahlia	33.0	8.3	35.7	8
Damietta	1.9	0.5	1.7	8
Sharkia	30.3	7.6	28.9	8
Ismailia	3.3	0.8	3.0	9
Port Said	11.3	2.8	16.0	7
Suez	0.1	0.02	0.1	8
Menoufia	0.7	0.2	0.8	8
Qalyubia	0.1	0.03	0.1	7
Total	154.0	38.5	153.1	7
Middle Egypt				
Giza	1.3	0.3	1.4	9
Bani Sweif	12.3	3.1	12.0	8
Fayoum	11.8	3.0	10.4	7
Minya	12.3	3.1	12.1	8
Total	37.7	9.4	35.9	8
Upper Egypt				
Assiut	2.0	0.5	1.9	8
New Valley	0.7	0.2	0.5	7
Total	2.7	0.7	2.5	8
Bordered governorates				
Marsa Matrouh	7.4	1.8	3.7	8
North Sinai	0.5	0.13	0.1	7
South Sinai	0.2	0.06	0.1	8
Total	8.2	2.0	3.9	6
Grand total	202.5	50.6	195.4	7

The total cultivated area with wheat as a result of implementing the suggested intercropping systems and its production are presented in Table 8.15. Wheat intercropping systems can add 234.7 thousand hectares, which produced 1477.9 million tons of wheat seeds. The total wheat production under application of deficit irrigation on raised beds and intercropping systems will reach 12,361.6 million tons, which will reduce wheat production-consumption gap to 9504.5 million tons. Wheat self-sufficiency ration will be increase to 57%.

Table 8.13 Potential fruit trees cultivated area, assigned area to wheat intercropped under Fruit trees, wheat production and percentage of reduction in wheat production compared to its value in 2017

	Fruit trees area (000 ha)	Assigned area to wheat (000 ha)	Wheat production (000 ton)	PR in production (%)
Lower Egypt				
Alexandria	4.1	0.7	4.8	13
Behira	245.6	39.3	306.7	11
Gharbia	9.7	1.5	11.5	13
Kafr El Sheikh	2.5	0.4	2.9	13
Dakahlia	5.0	0.8	6.9	13
Damietta	3.0	0.5	3.5	12
Sharkia	43.0	6.9	52.5	13
Ismailia	69.5	11.1	79.3	13
Port Said	0.1	0.02	0.1	11
Suez	9.6	1.5	10.8	13
Menoufia	26.0	4.2	34.9	12
Qalyubia	17.8	3.5	27.2	13
Total/average	443.3	70.4	541.0	12
Middle Egypt				
Giza	15.9	2.5	22.0	13
Bani Sweif	6.9	1.1	8.6	11
Fayoum	11.1	1.8	12.5	12
Minya	13.8	2.2	17.3	13
Total/average	47.7	7.6	60.5	12
Upper Egypt				
Assiut	12.3	2.0	15.6	13
Sohag	2.6	0.4	3.1	13
Qena	4.0	3.5	25.3	11
Luxor	5.1	0.01	32.4	12
Aswan	6.4	1.0	7.9	13
New Valley	8.3	1.3	7.7	12
Total/average	38.7	8.2	92.0	12
Bordered governorates				
Marsa Matrouh	41.6	6.7	26.6	12
North Sinai	29.2	4.7	3.7	13
South Sinai	8.8	1.4	5.4	11
Total/average	79.6	12.7	35.7	9
Grand total/ average	609.3	99.0	729.2	11

Table 8.14 Potential sugarcane cultivated area, assigned area to wheat intercropped with sugarcane, wheat production and percentage of reduction in wheat production compared to its value in 2017

	Sugarcane area (000 ha)	Assigned area to wheat (000 ha)	Wheat production (000 ton)	PR in production (%)
Minya	13.0	1.3	10.2	17
Assiut	0.4	0.04	0.3	26
Sohag	4.9	0.5	3.6	17
Qena	40.2	4.0	29.3	17
Luxor	23.1	2.3	16.8	17
Aswan	29.8	3.0	23.1	17
Total	111.4	11.1	83.3	19

The table also indicated that more governorates can attain self-sufficiency in addition to surplus in wheat production, namely Behira, and Kafr El-Sheik governorates in Lower Egypt, in addition to New Valley governorate in Upper Egypt.

8.4.4 Saved Irrigation Water from Other Winter Crops and Wheat Production

In Chaps. 3 and 4, application of deficit irrigation on raised beds to Egyptian clover and sugar beet, as well as onion and tomato resulted in saving large amounts of irrigation water. Because these four crops have surplus in their production in 2017, we assumed that these amounts of water could be used in cultivating more lands with wheat to increase its total production and reduce its production-consumption gap (Chap. 6). However, in 2030, the rise in water requirements of cultivated crops will reduce its cultivated area and consequently its production. Taking into consideration population increased from 95,203 million inhabitants in 2017 to 125,871 million inhabitants, or by 32% in 2030, it may affect the sufficiency of these four crops and change their situation from surplus to insufficient production.

Thus, we assumed that the total production of these four crops is directly related to the total population in 2030 and it will increase with the same percentage as population increase, namely 32%. Furthermore, we calculated the increase in the required water of these four crops and calculated its cultivated area and production in 2030. Then, we assessed the effect of raised beds cultivation and application of deficit irrigation to these four crops and saved water will be use to cultivate more areas with wheat to increase its total production. In addition, four these four crops, we assessed the effect of application of deficit irrigation and used the saved water from new lands to add new area and to the saved irrigation water from old lands will be assigned to wheat cultivation.

Table 8.15 Projected total wheat cultivated area and production under application of deficit irrigation on raised beds and implementing intercropping systems for wheat in 2030

	Intercropping systems			
	Area (000 ha)	Production (000 ton)	Production (deficit + intercropping) (000 ton)	Gap (000 ton)
Lower Egypt				
Alexandria	2.3	13.1	247.8	−835.1
Behira	53.8	391.6	1958.3	**449.0**
Gharbia	4.6	27.5	423.4	−779.5
Kafr El Sheikh	28.7	148.9	929.3	**103.2**
Dakahlia	15.9	95.0	938.0	−594.3
Damietta	3.1	19.5	98.6	−242.0
Sharkia	27.4	164.4	1572.4	−116.5
Ismailia	13.8	92.7	206.2	−99.1
Port Said	3.1	17.4	50.5	−100.0
Suez	1.9	12.6	31.5	−109.9
Menoufia	4.8	38.8	565.6	−450.2
Qalyubia	3.6	27.8	226.3	−1104.0
Cairo	0	0	0	−2098.9
Total	162.9	1049.4	7248.0	−5977.3
Middle Egypt				
Giza	4.6	35.3	207.9	−1683.5
Bani Sweif	7.6	43.4	510.0	−200.2
Fayoum	9.3	51.5	727.5	−71.2
Minya	7.7	46.8	951.9	−324.9
Total	29.2	177.0	2397.3	−2279.7
Upper Egypt				
Assiut	4.3	30.0	845.2	−195.8
Sohag	3.1	20.1	734.1	−389.4
Qena	8.0	57.7	354.3	−404.2
Luxor	3.5	56.0	147.5	−137.9
Aswan	4.2	31.9	186.0	−169.0
New Valley	1.6	8.5	375.7	**328.9**
Total	24.7	204.2	2642.9	−967.4
Border governorates				
Marsa Matrouh	10.7	37.5	60.6	−55.6
North Sinai	5.8	4.3	5.5	−108.4
South Sinai	1.5	5.6	7.4	−31.3
Red Sea	0	0	0	−84.8
Total	18.0	47.4	73.5	−280.1
Grand total	234.7	1477.9	12,361.6	−9504.5

1. **Egyptian clover**

Table 8.16 indicated that traditional cultivation of Egyptian clover will produce only 41,201.3 million tons in 2030. Meanwhile, the total production of Egyptian

Table 8.16 Potential Egyptian clover production (000 tons) in 2030 under traditional cultivation, raised beds, application of deficit irrigation with added area, application of deficit irrigation and added area from new lands and the saved water (MCM)

			Deficit irrigation with		
	Traditional cultivation	Raised beds cultivation	Added area	Added area from new lands	Saved water
Lower Egypt					
Alexandria	294.0	332.1	343.5	323.9	1.5
Behira	6806.1	8880.7	8959.9	8317.1	37.9
Gharbia	2614.8	3007.0	3570.8	3570.8	26.2
Kafr El Sheikh	5067.1	6742.5	7224.9	6898.6	29.8
Dakahlia	3789.0	5107.9	5413.5	5141.6	47.2
Damietta	1362.0	1756.9	1913.7	1841.9	12.7
Sharkia	4403.0	5904.3	6174.9	5829.1	38.3
Ismailia	190.4	233.3	247.3	235.4	1.5
Port Said	245.4	245.4	257.6	245.4	0
Suez	77.7	111.3	112.5	104.3	0.9
Menoufia	3130.3	4307.1	4274.8	4274.8	26.1
Qalyubia	1000.7	1407.8	1366.6	1366.6	10.0
Cairo	10.2	14.2	13.9	13.9	0.2
Total	28,990.7	38,050.5	39,874.1	38,163.4	232.3
Middle Egypt					
Giza	1065.5	1403.1	1514.3	1451.0	10.4
Bani Sweif	2266.5	2948.3	3195.0	3067.6	19.2
Fayoum	1749.8	2012.3	2389.6	2389.6	32.2
Minya	1735.4	2365.4	2478.8	2341.4	25.5
Total	6817.3	8729.1	9577.7	9249.5	87.2
Upper Egypt					
Assiut	1805.3	2270.9	2517.2	2442.7	16.8
Sohag	2367.7	3060.7	3331.6	3205.5	26.7
Qena	497.7	658.1	697.9	663.2	7.4
Luxor	108.3	142.5	150.7	143.1	2.6
Aswan	117.4	143.4	148.9	140.4	1.5
New Valley	460.0	460.0	483.0	460.0	0
Total	5356.3	6735.6	7329.3	7054.9	55.0
Border governorates					
Marsa Matrouh	37.1	37.1	39.0	37.1	0
Total	37.1	37.1	39.0	37.1	0
Grand total	41,201.3	53,552.3	56,820.0	54,505.0	374.5

clover should be 54,385.8 million tons to meet the demand for it in 2030 (production multiplied by percentage of increase in the population, namely 32%). The production under traditional cultivation will only attain 76% self-sufficiency ratio. Furthermore, under raised beds cultivation and using the saved water to cultivate new areas, the total production of Egyptian clover will reach 53,552.3 million tons, with 98% self-sufficiency. Application of deficit irrigation and used the saved to added new area to the cultivated area of Egyptian clover water from new lands only to cultivate new areas with Egyptian clover will produce 56,820.0 million tons, with 104% self-sufficiency ratio. Furthermore, application of deficit irrigation and used the saved water from new lands to add new areas and the saved irrigation water from old lands will be assigned to wheat cultivation resulted in 54,505.0 million tons Egyptian clover, with 100% self-sufficiency. In this case, the amount of saved water will be 374.5 million cubic meters.

2. **Sugar beet**

We assumed that the demand for sugar beet will increase by the same percentage of population increase, namely 32% in 2030 over the production resulted from traditional cultivation to reach 13,277.8 million tons of sugar beet. Table 8.17 showed that application of deficit irrigation to all the area cultivated under raised beds and using the saved water from deficit irrigation to add new area will produce 13,064.8 million tons of sugar beet, which will attain 99% self-sufficiency. Furthermore, application of deficit irrigation and used the saved water from new lands only to add new area will result in lower total production, namely 11,648.5, with 88% self-sufficiency. In this case, we cannot save any irrigation water from sugar beet cultivation in 2030.

3. **Onion**

Similar procedure was done for onion, where traditional cultivation can only produce 2457.3 million tons in of onion 2030 and the demand for it is expected to increase by 32%, thus it will be 3243.6 million tons and the self-sufficiency ratio will be 76%. Cultivation of onion on raised beds will increase the production to 3136.9 million tons with 97% self-sufficiency ratio. Application of deficit irrigation to the old and new lands and used the saved water to cultivate new lands with onion will increase the total production to 3242.6 million tons and attain self-sufficiency. Furthermore, Application of deficit irrigation to the old and new lands and used the saved water from new lands only to cultivate new areas with onion will produce 3172.0 million tons of onion attain 98% self-sufficiency. Thus, the saved irrigation water from the old lands will be 23.7 million cubic could be assign to cultivate wheat (Table 8.18).

4. **Tomato**

With respect to tomato (Table 8.19), its total production in 2030 will be 2888.0 million tons. In the meantime, the demand for it will be increase by 32% also to reach 3809.2 million tons. Cultivation on raised beds and application of deficit irrigation and used all the saved water to add new areas will increase tomato production

Table 8.17 Potential sugar beet total production (000 tons) in 2030 under traditional cultivation, raised beds, application of deficit irrigation with added area, application of deficit irrigation and added area from new lands only

			Deficit irrigation and	
	Traditional cultivation	Raised beds cultivation	All added area	Added area from new lands
Lower Egypt				
Alexandria	120.3	151.5	147.9	136.3
Behira	729.8	979.5	988.1	863.6
Gharbia	350.7	403.3	427.6	427.6
Kafr El Sheikh	2266.9	3226.9	3222.0	2755.0
Dakahlia	1732.6	2257.9	2286.2	2006.3
Damietta	96.7	134.1	134.5	115.9
Sharkia	1525.0	1899.8	1938.3	1724.4
Ismailia	163.2	168.1	177.3	166.0
Port Said	528.7	528.7	560.4	528.7
Suez	3.5	3.5	3.7	3.5
Menoufia	34.9	49.9	42.5	42.5
Qalyubia	6.3	9.0	7.7	7.7
Total	7558.5	9812.4	9936.3	8777.5
Middle Egypt				
Giza	82.4	86.0	90.4	84.1
Bani Sweif	688.8	932.9	942.2	830.3
Fayoum	555.2	638.5	676.9	676.9
Minya	720.1	911.8	930.5	834.2
Total	2046.6	2569.2	2640.0	2425.4
Upper Egypt				
Assiut	145.3	200.7	201.6	174.8
New Valley	34.4	34.4	36.5	34.4
Total	179.7	235.2	238.1	209.2
Bordered governorates				
Marsa Matrouh	236.3	236.3	250.4	236.3
Total	236.3	236.3	250.4	236.3
Grand total	10,021.1	12,853.1	13,064.8	11,648.5

to reach 3397.3 and 3586.1 million tons, respectively. Self-sufficiency percentage for tomato will be 78, 81 and 94% under traditional cultivation, cultivation on raised beds and application of deficit irrigation, respectively. Thus, no water could be saved from tomato cultivation to be used in wheat cultivation.

Table 8.18 Potential total production of onion (000 tons) in 2030 under traditional and raised beds cultivation, under application of deficit irrigation, application of deficit irrigation and used the saved water from new lands to add new area and the saved irrigation amounts (MCM)

	Traditional cultivation	Beds cultivation	Deficit irrigation with added area	Deficit irrigation with added area from new lands	Saved water
Lower Egypt					
Alexandria	0.4	0.4	0.4	0.4	0
Behira	328.6	391.1	405.9	387.8	1.6
Gharbia	698.7	981.4	966.8	966.8	8.4
Kafr El Sheikh	22.2	32.0	30.7	30.7	0.3
Dakahlia	302.7	348.1	418.8	418.8	3.9
Damietta	21.1	29.1	29.8	28.4	0.3
Sharkia	160.9	224.4	229.3	219.2	2.2
Ismailia	4.3	5.0	5.2	5.0	0
Suez	8.0	9.9	10.2	9.7	0.1
Menoufia	11.8	16.8	16.4	16.4	0.1
Qalyubia	155.4	215.9	215.1	215.1	1.9
Total	1714.0	2254.1	2328.6	2298.3	18.7
Middle Egypt					
Giza	11.9	16.1	16.7	16.0	0.2
Bani Sweif	161.1	191.6	198.0	188.9	1.1
Fayoum	145.6	187.9	193.1	184.4	1.4
Minya	64.9	77.7	80.4	76.8	0.4
Total	383.5	473.3	488.2	466.1	3.1
Upper Egypt					
Assiut	24.0	34.8	33.2	33.2	0.3
Sohag	237.1	269.2	282.5	269.4	1.2
Qena	30.6	33.4	35.1	33.4	0.1
Luxor	7.5	9.9	10.1	9.6	0.1
Aswan	20.7	22.4	23.2	22.1	0.1
New Valley	36.0	36.0	37.8	36.0	0
Total	355.9	405.7	421.8	403.7	1.8
Bordered governorates					
Marsa Matrouh	3.8	3.8	4.0	3.8	0
Total	3.8	3.8	4.0	3.8	0
Grand total	2457.3	3136.9	3242.6	3172.0	23.7

Table 8.19 Potential tomato total production (000 tons) in 2030 under traditional cultivation, raised beds cultivation, and application of deficit irrigation

	Traditional cultivation	Raised beds cultivation	Deficit irrigation to all area
Lower Egypt			
Alexandria	74.9	95.4	100.3
Behira	472.5	503.4	533.0
Gharbia	1.4	1.6	1.9
Kafr El Sheikh	74.8	103.3	109.4
Dakahlia	31.3	33.3	35.5
Damietta	7.2	8.2	10.0
Sharkia	874.2	1072.2	1127.7
Ismailia	182.9	232.1	244.6
Port Said	3.9	3.9	3.9
Suez	24.6	32.1	32.5
Menoufia	10.8	11.5	12.2
Qalyubia	3.9	6.2	5.4
Cairo	0.5	0.6	0.6
Total	1762.6	2103.8	2217.0
Middle Egypt			
Giza	155.7	203.4	218.2
Bani Sweif	161.4	173.3	184.8
Fayoum	66.0	89.1	93.2
Minya	100.8	128.2	133.5
Total	483.9	593.9	629.7
Upper Egypt			
Assiut	76.6	90.5	95.6
Sohag	223.4	253.5	267.4
Qena	53.2	56.9	60.7
Luxor	113.8	124.1	132.4
Aswan	5.3	5.5	5.8
New Valley	2.3	2.3	2.5
Total	474.7	532.8	564.3
Bordered governorates			
Marsa Matrouh	118.9	118.9	127.2
North Sinai	47.1	47.1	47.1
South Sinai	0.9	0.9	0.9
Total	166.8	166.8	175.1
Grand total	2888.0	3397.3	3586.1

8.5 Wheat Production-Consumption Gap Using Saved Water from Other Winter Crops

Table 8.20 showed that using the total saved water resulted from Egyptian clover and onion could result in cultivating 175.3 thousand hectares of wheat and will produce 469.0 thousand tons of wheat seeds. The saved water from application of deficit irrigation to wheat, wheat intercropping systems, and the saved water resulted from the two crops; the total wheat production will reach 12,831.7 million tons, which will reduce the gap to reach 9065.7 million tons. In this case, wheat self-sufficiency ratio could reach 59%.

Table 8.20 also showed that more governorates could attain surplus in wheat production. These governorates are Behira, and Kafr El-Sheik, in Lower Egypt, and New Valley in Upper Egypt.

8.6 Wheat Water Productivity Under the Studied Production Alternatives

Wheat water productivity under the five production alternatives are presented in Table 8.19. Under production alternative (1), namely wheat traditional cultivation, the lowest values of water productivity was attained. Cultivation on raised beds (production alternative 2) increased the values of water productivity as a result of producing more wheat seeds with the same amount of irrigation water applied under traditional cultivation. Similarly, the values of water productivity under application of deficit irrigation on raised beds (production alternative 3) were higher than its value under cultivation on raised beds as a result of producing more wheat seeds with the same amount of water applied under traditional cultivation.

In production alternative (4), the amount of water irrigated wheat under traditional cultivation was used to produce wheat under application of deficit irrigation on raised beds, in addition to wheat produced from implementing its intercropping systems (wheat did not use any extra irrigation water because it used the water applied to the main crop in the intercropping system). Therefore, water productivity of wheat was the highest under production alternative (4). Regarding production alternative (5), where wheat total production attained from application of deficit irrigation on raised beds, intercropping systems and using the saved water from the two winter crops to produce more wheat seeds, water productivity values were lower than its counterpart values under production alternative (4) because more water was involved in wheat production.

The results in Table 8.21 also indicated that the average of wheat water productivity values on over all the studied governorates will be 0.91, 1.13, 1.20, 1.81 and 1.92 kg/m^3 for production alternative 1, 2, 3, 4 and 5 respectively.

Table 8.20 Potential wheat added cultivated area and production using the saved amounts of irrigation water, total wheat production (from deficit irrigation, intercropping systems and the saved water) and wheat production-consumption gap

	Added area (000 ha)	Production (000 ton)	Total production (000 ton)	Gap (000 ton)
Lower Egypt				
Alexandria	0.8	2.0	249.8	−833.1
Behira	17.5	48.7	2007.1	**495.8**
Gharbia	15.8	44.1	467.6	−746.2
Kafr El Sheikh	14.5	37.9	967.2	**140.8**
Dakahlia	23.5	75.9	1013.9	−524.2
Damietta	6.5	17.1	115.7	−225.2
Sharkia	18.3	46.7	1619.1	−72.3
Ismailia	0.7	1.8	208.1	−97.3
Port Said	0	0	50.5	−100.0
Suez	0.5	1.2	32.7	−108.8
Menoufia	11.9	30.9	596.5	−419.5
Qalyubia	5.5	14.2	240.5	−1092.0
Cairo	0.1	0.2	0.2	−2098.7
Total	115.5	320.8	7568.8	−5680.8
Middle Egypt				
Giza	4.6	13.1	221.0	−1670.6
Bani Sweif	8.3	22.5	532.5	−178.9
Fayoum	14.6	35.1	762.6	−37.6
Minya	10.7	26.9	978.8	−298.4
Total	38.2	97.5	2494.8	−2185.5
Upper Egypt				
Assiut	6.7	17.2	862.4	−179.0
Sohag	10.6	23.1	757.2	−367.2
Qena	2.8	6.3	360.6	−398.0
Luxor	1.0	2.7	150.3	−135.3
Aswan	0.5	1.3	187.4	−167.8
New Valley	0	0	375.7	**328.9**
Total	21.6	50.7	2693.6	−918.3
Border governorates				
Marsa Matrouh	0	0	60.6	−55.6
North Sinai	0	0	5.5	−108.4
South Sinai	0	0	7.4	−31.3
Red Sea	0	0	0	−84.8
Total	0	0	73.5	−280.1
Grand total	175.3	469	12,831	−9065.7

Table 8.21 Water productivity (kg/ha) of wheat under suggested production alternatives

	Alternative[a]	Alternative[b]	Alternative[c]	Alternative[d]	Alternative[e]
Lower Egypt					
Alexandria	1.34	1.57	1.67	1.76	1.79
Behira	1.26	1.61	1.72	2.15	2.29
Gharbia	0.94	1.34	1.42	1.51	1.78
Kafr El Sheikh	1.10	1.54	1.64	1.95	2.17
Dakahlia	1.35	1.86	1.97	2.19	2.65
Damietta	1.11	1.52	1.63	2.03	3.21
Sharkia	0.99	1.35	1.45	1.62	1.74
Ismailia	1.12	1.39	1.47	2.67	2.75
Port Said	1.47	1.47	1.54	2.35	2.35
Suez	0.99	1.33	1.41	2.35	2.61
Menoufia	1.21	1.64	1.78	1.92	2.22
Qalyubia	1.02	1.41	1.52	1.73	1.97
Cairo	0	0	0	0	1.54
Average	1.16	1.50	1.60	2.02	2.24
Middle Egypt					
Giza	1.23	1.64	1.76	2.11	2.49
Bani Sweif	0.99	1.36	1.45	1.58	1.75
Fayoum	0.84	1.16	1.24	1.34	1.49
Minya	0.91	1.24	1.34	1.41	1.50
Average	0.99	1.35	1.45	1.61	1.81
Upper Egypt					
Assiut	0.85	1.15	1.24	1.28	1.34
Sohag	0.67	0.89	0.97	1.00	1.06
Qena	0.68	0.88	0.95	1.12	1.17
Luxor	0.66	0.80	0.86	1.35	1.41
Aswan	0.77	0.84	0.88	1.06	1.07
New Valley	0.87	0.87	0.92	0.94	0.94
Average	0.75	0.91	0.97	1.12	1.16
Bordered governorates					
Marsa Matrouh	1.35	1.35	1.41	3.64	3.64
North Sinai	0.29	0.29	0.29	1.36	1.36
South Sinai	0.61	0.61	0.61	2.40	2.40
Average	0.75	0.75	0.77	2.47	2.47
Overall average	0.91	1.13	1.20	1.81	1.92

Production alternative
[a]conventional cultivation, Production alternative
[b]raised beds cultivation, Production alternative
[c]application of deficit irrigation on raised beds, Production alternative
[d]application of deficit irrigation on raised beds and intercropping systems, Production alternative
[e]application of deficit irrigation on raised beds, intercropping systems and using saved water.

8.7 Conclusion

Climate change is expected to have deteriorated effected on wheat production in 2030. Under traditional cultivation, wheat self-sufficiency ratio is expected to be reduced compared to its value in 2017, namely 35%. To increase wheat self-sufficiency ratio, several production alternatives were assessed. Application of deficit irrigation for wheat grown on raised beds in 2030 could raise wheat self-sufficiency ratio to 50%. Furthermore, application of deficit irrigation and implementing intercropping systems, as well as application of deficit irrigation, implementing intercropping systems and using the saved water from other crops to cultivate more wheat areas could result in increasing total production by 57 and 68%, respectively compared to its value under traditional cultivation and that increased wheat self-sufficiency ratio to reach 57 and 59%, respectively. The highest water productivity values were found under application of deficit irrigation, implementing intercropping systems and use of saved water from two winter crops to increase the cultivated area of wheat. It is recommended that these production alternatives to be implemented to increase wheat production and its self-sufficiency ratio.

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