Earth and Environmental Sciences Library

Shakir Ali
Asaad Mater Armanuos *Editors*

Groundwater in Arid and Semi-Arid Areas

Monitoring, Assessment, Modelling, and Management

Springer

Earth and Environmental Sciences Library

Earth and Environmental Sciences Library (EESL) is a multidisciplinary book series focusing on innovative approaches and solid reviews to strengthen the role of the Earth and Environmental Sciences communities, while also providing sound guidance for stakeholders, decision-makers, policymakers, international organizations, and NGOs.

Topics of interest include oceanography, the marine environment, atmospheric sciences, hydrology and soil sciences, geophysics and geology, agriculture, environmental pollution, remote sensing, climate change, water resources, and natural resources management. In pursuit of these topics, the Earth Sciences and Environmental Sciences communities are invited to share their knowledge and expertise in the form of edited books, monographs, and conference proceedings.

Shakir Ali · Asaad Mater Armanuos
Editors

Groundwater in Arid and Semi-Arid Areas

Monitoring, Assessment, Modelling, and Management

Springer

Editors
Shakir Ali
Department of Geology
University of Delhi
Delhi, India

Asaad Mater Armanuos
Irrigation and Hydraulics Engineering
Tanta University
Tanta, Egypt

ISSN 2730-6674 ISSN 2730-6682 (electronic)
Earth and Environmental Sciences Library
ISBN 978-3-031-43347-4 ISBN 978-3-031-43348-1 (eBook)
https://doi.org/10.1007/978-3-031-43348-1

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Paper in this product is recyclable.

Preface

The editors bring this book due to huge demand of groundwater in areas like arid and semi-arid regions where rainfall is less and temperature is very high, even though, a detailed book on the groundwater in arid and semi-arid regions is inadequate. The book reveals that the major drivers in the arid and semi-arid regions on the groundwater are rapid population growth, climate change, and urbanization.

In arid and semi-arid areas, groundwater is no doubt an important resource to meet the various demands of human being. However, the area receives scanty rainfall and very high evaporation rate. Thus, the judicious management of the groundwater in the area is pivotal. This book is a collective effort from various potential authors worldwide and contributed good chapters on various issues such as groundwater modelling, monitoring and management (MMM). The chapters will be highly helpful to manage the groundwater in arid and semi-arid areas where water is deficient and demand of water is high.

This book contains 14 chapters focussing mainly arid and semi-arid regions on groundwater. It is divided broadly into four themes, namely, An Introduction in two chapters, Groundwater Monitoring and Assessment in four chapters, Groundwater Modelling in three chapters, and Groundwater Management in five chapters.

All authors highlighted knowledge gaps, importance of the study and the management options and various challenges. More specifically, chapters from Afghanistan and Iraq are important as very less is known about groundwater from these countries. This book also highlighted few critical regions like Koyna Closed Basin in Türkiye where groundwater shows significant decline in last decades due to uncontrolled extraction of groundwater and will be water scarce shortly if not properly managed.

The North African regions are always in shortage of water due to warm climatic condition and scanty rainfall. In these areas, groundwater is one of the important sources of water supply in these regions. Therefore, this book contains four chapters on the groundwater of North African regions.

One chapter investigated the entire Nile Delta and reviewed all aspects of groundwater management. Nile Delta is an important water potential region in Egypt; however, the authors highlighted that huge abstraction of groundwater and mismanagement leads to significant decline of water level.

A detailed chapter on India investigates about the problem of groundwater quality and various challenges associated with groundwater management. One chapter delineates how urbanization is potentially deteriorating the groundwater quality and reducing recharge area which in turn leads to flooding.

Major groundwater pollutants in India like fluoride is extensively investigated in a chapter into the Indo-Gangetic plain (semi-arid) where huge population of India segregated and extensively use groundwater for drinking without any prior filtration. One chapter on identification of potential of river bank filtration were investigated in Egypt. The authors shows how river bank can be used as a cheaper option of filtration of water for the sustainable water supply.

Few chapters deal with the recently developed advanced methods like Irrigation Water Quality Index (IWQI), including numerical groundwater flow modelling and machine learning to manage the groundwater particularly in arid and semi-arid regions.

All authors of this book are highly experts with very good academic and professional background. All authors with their vast knowledge covered many aspects to highlight the existing situation, knowledge gaps and the challenges for the groundwater MMM in the arid and semi-arid regions. We both editors worked hard to further improve the quality of each chapter and re-revised many times. The book concluded that the science-based policy intervention of water management should be adopted over traditional methods to combat the shortage of water particularly in the arid and semi-arid regions.

Furthermore, we feel that more books on the groundwater in arid and semi-arid regions should be developed to understand the further aspects of water resource in arid and semi-arid in more detail. We also hope that this book is first book covered extensively on the groundwater in the region and hopefully we will make every effort in bringing more books on this topic in the future.

Also, both editors thank the book series editor (Prof. Abdelazim Negm) for his critical constructive review of the manuscript and invaluable advice throughout all stages of the manuscript preparation.

Delhi, India — Dr. Shakir Ali
Tanta, Egypt — Dr. Asaad Mater Armanuos
June 2023

Contents

Introduction

Introduction to "Groundwater in Arid and Semi-Arid Areas"

Shakir Ali and Asaad M. Armanuos

Abstract Arid and semi-arid areas covers nearly one-third of the global land. Groundwater in these regions is an important source for drinking and irrigation. Therefore, the book "Groundwater in Arid and Semi-Arid Areas" cover topics like groundwater quality management and challenges, groundwater vulnerability to pollution, impacts of urbanization on groundwater, evaluation of groundwater quality using muticriteria analysis, groundwater management, groundwater modelling using machine learning, groundwater contaminant transport, and application of river bank infiltration. The chapters on groundwater in book of arid and semi-arid areas are imperative for a deeper understanding of resources to formulate various policies to conserve the groundwater. Thus, various newly advanced topics are covered in this book and would be significant for related stakeholders, and policy makers. The aim of this chapter is to introduce readers about the significant findings discussed in each chapters of the entire book.

Keywords Groundwater management · Groundwater modelling · Machine learning · Groundwater quality · Riverbank infiltration

1 Background

Groundwater is one of the precious resources used to fulfill humans demand. There is no doubt that life is not possible without water. However, groundwater management and groundwater quality in arid and semi-arid areas is crucial to fulfill water requirements for irrigation, drinking, and industrial needs. Groundwater evaluation, groundwater vulnerability, and groundwater modelling are important for achieving

S. Ali (✉)
Department of Geology, University of Delhi, Delhi 110007, India
e-mail: shakiriitb@gmail.com

A. M. Armanuos
Irrigation and Hydraulics Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt
e-mail: asaad.matter@f-eng.tanta.edu.eg

S. Ali and A. M. Armanuos (eds.), *Groundwater in Arid and Semi-Arid Areas*, Earth and Environmental Sciences Library, https://doi.org/10.1007/978-3-031-43348-1_1

sustainable management of groundwater resources in these regions. In this book, groundwater is extensively discussed in terms of modelling, evaluation, vulnerability, and management, including challenges and sum up by recommendations. This book highlighted that the rapid population growth, urbanization and significant climate change are major drivers potentially responsible for the deterioration of groundwater in arid and semi-arid areas.

Scientists and researchers worldwide having their long research backgrounds put their great efforts for about one year to produce this amazing book for all the readers who are interested in groundwater, particularly in arid and semi-arid regions. The book mainly covers groundwater Monitoring, Modelling and Management (MMM). The book contains 13 different chapters from globally including Afghanistan and Iraq where research on groundwater is limited. All chapters are finished with extensive conclusions/recommendations.

In this introductory chapter, a brief summary is presented for each chapter. For sure, interested readers should consult the chapters for further details.

1.1 Themes of the Book

The book intends to address in more detail the following three main themes:

1. Groundwater Monitoring and Assessment,
2. Groundwater Modelling, and
3. Groundwater Management.

2 Chapters' Summaries

In the following subsection, brief descriptions of the 14 chapters of the book are presented.

The introduction section consists of this chapter and the chapter titled "**Groundwater in Arid and Semi-Arid Regions of India: A Review on the Quality, Management and Challenges**". The authors investigate and summarize in detail the arid and semi-arid regions of Indian groundwater quality, management and various challenges associated with groundwater management. The authors highlighted major contaminants such as nitrate, fluoride, arsenic and potential toxic elements which are significant pollutants found in the groundwater of India [2, 3]. The authors highlighted that the inadequate steps from the concerned governing authorities are insufficient to combat the issue. Further, the lack of groundwater monitoring and quality data are major hindrances in groundwater management. All groundwater pollutants are found to be greater than the safe limit prescribed by World Health Organisation (WHO) in many regions. The major challenges are highlighted in the chapter for the management of groundwater in arid and semi-arid areas of India.

2.1 Groundwater Monitoring and Assessment

The Groundwater Monitoring and Assessment is presented in four chapters. The chapter titled "**Vulnerability to Pollution of Karstic Aquifers in the Tafna River Basin and Risk Mitigation Strategies**, **(NW Algeria)**" presents the vulnerability to pollution in karstic aquifers in Tafna River basin of NW Algeria.

The Tafna basin falls in semi-arid areas and the groundwater occurs in karst aquifers are significant for the socio-economic development of the region. However, the water is subjected to contamination from various anthropogenic means due to rapid population growth. The authors highlighted that the use of groundwater models for sustainable management of limited groundwater in the area is pivotal. Therefore, it is vital to protect this groundwater resource from any form of contamination. The chapter recommended that numerous actions should be undertaken by the competent authorities to mitigate this risk of pollution. The authors emphasis that large-scale mapping of areas vulnerable to pollution is needed in karstic environments.

In the chapter titled "**Effect of Urbanization on Water Resources: Challenges and Prospects**," the authors discussed the effects of urbanization on water resources. The authors highlight, how urbanization has resulted in the over-extraction of groundwater, flooding and degradation of groundwater quality. The authors discussed few examples of cities where urbanization has potentially deteriorated the water resources, particularly in arid and semi-arid regions [7, 14]. The study mainly highlights the importance of sustainable water management to protect and conserve water resources in urban areas. Furthermore, the migration of the population to urban areas should be checked by providing various facilities to rural areas. Finally, cities should implement green infrastructure measures to reduce flooding and waterlogging. Through these measures, cities can manage their water resources more effectively and conserve water resources, particularly in urban areas of arid and semi-arid regions.

In the chapter titled "**Understanding the Challenges: Sustainable Usage of Groundwater Resources in Türkiye**", the sustainable use of groundwater in Turkiye (previously Turkey) is evaluated. Most of the Turkiye area falls in the semi-arid zones and currently experiencing water stress and likely to be out of water in the near future particularly in Konya Closed Basin. Konya Closed Basin is highly affected region where groundwater level shows rapid decline due to heavy groundwater extraction through thousands of unlicensed installed wells. The large amount of groundwater in Turkiye is used for irrigation. In addition, the sustainable management of groundwater consumption has become more difficult and challenging due to climate change, rapid population growth, urbanization, pollution of water resources, over-exploitation, and seawater intrusion [6]. Thus, immediate possible measures for sustainable management options to preserve groundwater in the country is need of the hour.

The last chapter in this section is titled "**Application of Geospatial Multicriteria Decision Analysis in the Evaluation of Groundwater Quality for Irrigation in the Northern sector of Gabes region (SE Tunisia)**". In this chapter, the Gabes region falls in the semi-arid region of SE Tunisia is studied and the authors found that groundwater is highly polluted [8]. The geospatial multicriteria decision is applied to evaluate the groundwater quality for irrigation in Gabes region. The groundwater quality for irrigation through Irrigation Water Quality Index (IWQI) is evaluated. An attempt is made to provide groundwater management focusing primarily on the sustainability of irrigation in the North Gabes (Tunisia) phreatic aquifer to provide baseline information on the groundwater suitability for agricultural purposes. The analytical physicochemical data and the associated hazards to soil characteristics and crop yield are evaluated and then processed with the hybrid GIS-Multi-Criteria Decision Analysis (MCDA) techniques and by the hierarchical clustering technique (HCA). Therefore, the chapter will be highly useful for agricultural planners and decision-makers to take proactive actions to preserve groundwater resources in the region.

2.2 Groundwater Modelling

This part is presented in three chapters. The first one is titled "**Creation of Rational Groundwater Management Schemes in the Chu Valley of the Kyrgyz Republic Based on Groundwater Modelling**". The Chu valley of Kyrgyz Republic through groundwater modelling for the groundwater management is evaluated. Numerical groundwater flow modelling (MODFLOW) is used to address additional water intake in the Chu Valley. Quantitative criteria for evaluating the considered scenarios are proposed. Management variants are considered based on groundwater modelling. Rational schemes are developed for the sustainable development of water resources in the Chu Valley [13]. The chapter also highlights the issues of minimizing the impact of management actions in transboundary aquifers.

The next chapter is titled "**Applications of Machine Learning Models for Solving Complex Groundwater Modelling, Monitoring and Management Problems**". In this chapter, machine learning model application is used for co-solving complex groundwater modelling, monitoring and management problems globally especially in arid and semi-arid areas [12]. The author's emphasis on using machine learning models over traditional numerical models for replicating complex groundwater system for making effective future predictions, monitoring and groundwater resources management and challenges. The input–output datasets for the construction of prediction models are generated using a 3D groundwater numerical simulation model. FEMWATER, a finite element-based groundwater flow and transport modelling package is used to construct 3D groundwater numerical simulation models for different aquifer systems. An accurately designed, executed, and implemented groundwater management methodologies based on the two approaches may ultimately prove complementary.

The last chapter in this section is titled "**New Trends in Groundwater Contaminant Transport Modelling**". It presents the results of the evaluation of groundwater transport modelling based on new trends. The author observed that numerical modelling is gaining importance for diagnosing, managing and predicting groundwater behavior. In the chapter, a simplified systematic picture of the current status of groundwater contamination is provided. Also, it documents various literatures to systematically study the available theoretical and experimental work on groundwater contaminant transport modelling [10]. The authors highlight that the application of data mining in forecasting and predicting the behavioral attempt of contaminated plumes is an important scientific way of understanding the pollution in the groundwater.

2.3 Groundwater Management

This part is presented in four chapters. The first chapter is titled "**Groundwater Environment and Management in Kabul, Afghanistan**". Groundwater management in Kabul basin of Afghanistan is investigated in this chapter. The lack of coordination between the relevant organizations, a shortage of monitoring data, and the absence of an appropriate management framework are the main problems in managing groundwater resources in the Kabul basin. The management of groundwater in the Kabul Plain requires good co-ordination and centralization of governing authorities. The state of the groundwater as well as numerous management concerns is illustrated. The major challenges in groundwater resource management are the lack of coordination among concerned organizations, unavailability of monitoring data, and lack of proper management framework [15].

The second chapter in this section is titled "**Groundwater in the Nile Delta Aquifer, Egypt: Assessment, Modelling and Management with Climate Change in the Core**". The authors present fundamental information on groundwater in the Nile Delta aquifer, Egypt: and its assessment, modelling and management. The previous literatures on groundwater vulnerability studies, groundwater modelling, seawater intrusion modelling, and groundwater management studies in the Nile Delta aquifer, is summarized and extensively analyzed [4]. The findings of recently related published articles are presented and knowledge gaps are highlighted. The possible future management of groundwater resources in the Nile Delta, including freshwater protection, and risk management are investigated. The chapter will broaden the understanding of groundwater vulnerability for decision-makers to manage groundwater resources and assess risks effectively. Moreover, it presents a comprehensive overview of groundwater flow and contaminant transport through aquifers, aiding in assessment and groundwater resources management. The chapter is highly useful for future resource management for groundwater in the Nile Delta.

In the chapter titled "**Groundwater Contamination by Fluoride and Mitigation Measures for Sustainable Management of Groundwater in the Indo-Gangetic Plains of India**", the fluoride contamination and the groundwater management challenges in the Indo-Gangetic Plain of India is evaluated. The large region of Indo-Gangetic plains falls in the semi-arid areas [9]. Fluoride (F^-) in the groundwater in the region is a major pollution found throughout the plain. The geological deposits with significant input from anthropogenic activities, predominantly contribute significant amount of fluoride in the groundwater of the Indo-Gangetic Plains. The chapter highlighted that the researchers should investigate the fluoride pollution behavior in groundwater of the Indo-Gangetic Plains. The authors emphasis that the chapter will be highly useful in investigating fluoride contamination in groundwater of the Indo-Gangetic Plains, to conserve resources and reduce pollution burden. The authors highlighted that the proper monitoring of groundwater and implementation of updated policies should be timely formulated by the governing state and central agencies.

The next chapter is titled "**Groundwater Quality in Shallow Aquifers of the Sedimentary Plain in Iraq: A Potential Concern for Drinking and Irrigation**". The chapter focuses on the groundwater in shallow aquifers of sedimentary rocks. The authors presented that groundwater is largely unsuitable for drinking and irrigation. Further, the construction of huge dams has substantially reduced the water in rivers, reducing the recharge to the groundwater [11]. The major drivers affecting groundwater quantity and quality in the study area are high evaporation rate, low rainfall and rapid population growth. It is expected that the outcomes of this chapter could be helpful to governing authorities in planning any management schemes in Iraq.

The last chapter in the book and in this section is titled "**Investigating and Improving Natural Treatment Processes by Riverbank Filtration in Egypt**". The potential of river bank filtration in Egypt is investigated in this Chapter. The authors proved that the contaminated surface water can be filtered through the river sediments at a cheaper and sustainable way and a highly effective technique in the developing world. Riverbank filtration is a green water filtration method that uses natural materials of the Earth as a filter [1, 5]. Riverbank filtration intimate's immense potential in heavily stressed and polluted areas as a pre-treatment phase for drinking water production. The authors highlighted that Riverbank filtration is a viable and cost-effective technique of resource recovery.

Acknowledgements The editors who wrote this chapter want to acknowledged all the authors of this book who contributed chapters and are highly thankful for their efforts during the different phases of the book. We both editors thank the entire team of Springer for their support in bringing this book.

References

1. Abd-Elaty I, Kuriqi A, Ganayem HM, Ahmed A, Saleh OK, Garrote L (2023) Assessment of riverbank filtration performance for climatic change and a growing population. Front Environ Sci 11:1136313. https://doi.org/10.3389/fenvs.2023.1136313
2. Ali S, Thakur SK, Sarkar A, Shekhar S (2016) Worldwide contamination of water by fluoride. Environ Chem Lett 14:291–315. https://doi.org/10.1007/s10311-016-0563-5
3. Ali S, Shekhar S, Chandrasekhar T, Yadav AK, Arora NK, Kashyap CA, Bhattacharya P, Rai SP, Pande P, Chandrasekharam D (2021) Influence of the water–sediment interaction on the

major ions chemistry and fluoride pollution in groundwater of the older alluvial plains of Delhi, India. J Earth Syst Sci 130(2):98. https://doi.org/10.1007/s12040-021-01585-3

4. Armanuos AM, Eldin Ibrahim MG, Negm A, Takemura J, Yoshimura C, Mahmod WE (2022) Investigation of seawater intrusion in the Nile delta aquifer, Egypt. J Eng Res 6(1):10–28
5. Armanuos AM, Negm A (2018) Integrated groundwater modeling for simulation of saltwater intrusion in the Nile delta aquifer, Egypt. Groundw Nile Delta 489–544. https://doi.org/10.1007/698_2017_184
6. Arslan H (2013) Application of multivariate statistical techniques in the assessment of groundwater quality in seawater intrusion area in Bafra plain, Türkiye. Environ Monit Assess 185(3):2439–2452. https://doi.org/10.1007/s10661-012-2722-x
7. Baba A, Yazdani H (2017) Effect of urbanization on groundwater resources of İzmir city. https://www.hidropolitikakademi.org/uploads/wp/2019/02/Effect-of-Urbanization-on-Groundwater-Resources-of-Izmir-City.pdf
8. Ben Brahim F, Boughariou E, Bouri S (2021) Multicriteria-analysis of deep groundwater quality using WQI and fuzzy logic tool in GIS: a case study of Kebilli region, SW Tunisia. J Afr Earth Sc 180:104224. https://doi.org/10.1016/j.jafrearsci.2021.104224
9. Divya, Sulaiman MA, Zafar MM, Kumari A (2023) Assesing the fluoride toxicity, and the source contributors to the major ionic constituents in the groundwater aquifer of middle Ganga river basin, Rohtas. India. Int J Energy Water Resour. https://doi.org/10.1007/s42108-023-00245-0
10. Hagagg K, Abdallah HR, Sadek M (2023) Numerical modeling constrained by environmental isotopes for sustainable development of partially renewable aquifers in desert area. Carbonates Evaporites 38:30. https://doi.org/10.1007/s13146-023-00850-4
11. Ismail AH, Shareef MA, Alatar FM (2019) Hydrochemistry of groundwater and its suitability for drinking and irrigation in Baghdad, Iraq. Environ Process 6:543–560. https://doi.org/10.1007/s40710-019-00374-x
12. Lal A, Datta B (2019) Multi-objective groundwater management strategy under uncertainties for sustainable control of saltwater intrusion: solution for an island country in the South Pacific. J Environ Manage 234:115–130. https://doi.org/10.1016/j.jenvman.2018.12.054
13. Litvak RG, Nemaltseva EI (2022) Development of rational groundwater management schemes for the central part of the Chui valley for sustainable irrigation under climate change conditions based on ground water modeling. Report KNIIIR. Bishkek, p 85
14. Zaryab A, Nassery HR, Alijani F (2022) The effects of urbanization on the groundwater system of the Kabul shallow aquifers, Afghanistan. Hydrogeol J 30(2):429–443. https://doi.org/10.1007/s10040-021-02445-6
15. Zaryab A, Nassery HR, Alijani F (2021) Identifying sources of groundwater salinity and major hydrogeochemical processes in the lower Kabul Basin aquifer, Afghanistan. Environ Sci Process Impacts 23:1589–1599. https://doi.org/10.1039/D1EM00262G

Groundwater in Arid and Semi-arid Regions of India: A Review on the Quality, Management and Challenges

Faheem Ahamad, Sandeep Kumar Tyagi, Mahavir Singh, and Arun Kumar Sharma

Abstract Groundwater and water supplied from the surface water are important sources for drinking in arid and semi-arid areas such as India. In India, arid and semi-arid regions cover approximately 15.8% and 37% respectively, which is roughly half of the total geographical area (about 3,287,263 km^2). Groundwater in these regions is scarce; therefore, along with quantity, groundwater quality is a major concern in arid and semi-arid areas of India. Therefore, in the present work, groundwater quality was documented for arid and semi-arid regions of India and observed that groundwater in many regions is unsuitable for drinking. This review revealed that pollutants like nitrate, fluoride, arsenic, lead, toxic metals, etc. are higher than the safe limit as per WHO guidelines. It was found that supply of sufficient healthy water and continuous monitoring are the two major challenges in these regions. Besides this, lack of sustainable management practices was found in all the Indian states except Bihar where fluoride removal centre (FRC) and arsenic removal unit (ARU) have been installed. However, their continuous surveillance is challenging. This chapter highlights various pollutants in the groundwater, along with management and major challenges for providing safe water in arid and semi-arid regions.

Keywords India · Arid and semi-arid areas · Fluoride pollution · Nitrate · Groundwater quality in India

F. Ahamad (✉)
Department of Environmental Science, Keral Verma Subharti College of Science (KVSCOS), Swami Vivekanand Subharti University, Meerut 250005, UP, India
e-mail: faheem.ahamad170390@gmail.com

S. K. Tyagi
IIMT University, O Pocket Ganga Nagar, Meerut 250001, UP, India

M. Singh
Keral Verma Subharti College of Science (KVSCOS), Swami Vivekanand Subharti University, Meerut 250005, UP, India

A. K. Sharma
Enviro Analytical Laboratories LLP, Haridwar 249407, Uttarakhand, India

S. Ali and A. M. Armanuos (eds.), *Groundwater in Arid and Semi-Arid Areas*, Earth and Environmental Sciences Library, https://doi.org/10.1007/978-3-031-43348-1_2

1 Introduction

Among the seventeen sustainable development goals (SDG) designed by United Nations (UN), goal 6 is specifically designed for water which focuses on quantity and management practices and ensures the availability of safe water for the masses. Further, target 3 of goal 7 of the millennium development goals (MDG) focused to reduce the number of people unable to access safe and clean drinking water at its half [73, 77]. Clean water is a fundamental regulating factor for the financial growth and enhancement of the quality of life [87, 167]. Globally, approximately 2.1 billion people still lack safe water and about 844 million people lack even a basic water supply [42, 212]. If the same pace continues, then by 2030 approximately 1.6 billion people will lack access to clean water supply (SDG report 2022). The major causes of water pollution are unsystematic and unplanned dumping of sewage, solid waste and industrial waste that adversely affects the health of living beings [74].

In India, 4/5th of the domestic water needs and more than half of the agricultural need is fulfilled by groundwater [99, 215]. As per WHO reports, about 36% of the urban and 65% of the rural population of India don't have access to safe drinking water. Over-exploitation of groundwater, insertion of solid and liquid effluent, agricultural runoff, dissolution of rock materials, and disturbance in various physico-chemical reactions are the main causes of groundwater and surface water pollution [5, 25, 26, 41, 137, 150, 159]. Climate and topography of the area, soil and rock formation, depth and nature of aquifers, seepage, amount of rainfall, amount and nature of recharging water, and water–rock interactions are some of the important factors that control the groundwater quality of a particular area [10, 32, 62, 115, 116, 136, 159, 170]. Many health issues or diseases such as water born (Cholera, typhoid, bacillary, trachoma), water-related (Malaria, yellow fever, dengue), water-washed (Trachoma, dysentery), water-based (intestinal helminthiasis, jaundice, Schistosomiasis) are directly linked with drinking contaminated groundwater [201]. Nearly 30% (about 1 billion people) of the global population consumes unfit water [140]. Fluoride, nitrate, boron, arsenic, and many other water pollutants are responsible for health risks to about 66 million people in India [25, 134, 175]. Lakshminarayanan and Jayalakshmy [113] reported that Diarrhoea is responsible for 13% of all deaths/ year in children under 5 years old and it is the third most important trigger of childhood mortality in India.

Numerous studies are available discussing the groundwater quality of arid and semi-arid areas of India, however the studies are limited to particular region of a particular state. Therefore, in the chapter, an attempt has been made to document the groundwater quality of all the Indian states falling in the arid and semi-arid region. The chapter highlighted the management practices and the major challenges in providing safe water to these regions with recommendations.

2 Arid and Semi-arid Areas of India

The word "arid" originates from the Greek word "arere" which means to be dry. Generally, the term "arid" denotes an area with insufficient rainfall, higher insolation, greater evaporation rate, and scanty vegetation. The United Nations Environment Programme (UNEP), classifies the climate into three categories based on the aridity index (AI). The aridity index is defined as the ratio of precipitation to potential evapotranspiration [172].

In India, an arid and semi-arid region covers roughly 15.8% (31,900 million km^2) and 37% (970,530 km^2) respectively, which is near to the half of the total geographical area (3,287,263 km^2). In India, the hot arid part is mainly situated between 24° to 29° N latitude, and 70° to 76°E longitude. This region falls in seven states: Andhra Pradesh (7%), Rajasthan (61%), Karnataka (3%), Haryana and Punjab (9%), Gujarat (19.6%), and Maharashtra (0.4%) (Fig. 1).

The arid parts of Haryana, Punjab, Gujarat, and western Rajasthan are collectively known as the Great Indian Desert or the Thar Desert covering an area of 89.6% of the total hot arid zone of India. This region is also known as the principal hot arid zone of India while the arid parts of Karnataka, Andhra Pradesh, and Maharashtra are known as the peninsular hot arid zone [172]. Apart from this, an area of about 78,300 km^2 located in Jammu and Kashmir is known as cold desert. Semi-arid areas are the zones where evaporation exceeds the precipitation but the ratio of the both is lower as compared to desert. This can also define as intermediate climate between desert and humid climate. The semi-arid zone is distributed in the states of Andhra Pradesh, Bihar, Delhi, Gujarat, Haryana, Karnataka, Madhya Pradesh, Maharashtra, Punjab, Rajasthan, Telangana, Tamil Nadu, and Uttar Pradesh. This type of climate support short duration and thorny or scrubby vegetation usually grasses and shrubs.

Groundwater is one of the important source used for drinking and irrigation in arid and semi-arid areas of developed and developing nations such as India [114, 162, 186]. Along with quantity, the quality of groundwater is a major concern in arid and semi-arid areas of India. Therefore, in the present chapter, an attempt has been made to document the groundwater quality of arid and semi-arid regions of India along with management practices and challenges.

3 Materials and Methods

For this study, a thorough search was performed in various research platforms such as Google Scholar, Research Gate, Science Direct, etc. to collect the related studies using different keywords. Then a careful reading of all the research articles was performed and suitable articles were separated. We used the following criteria for the selection of suitable articles:

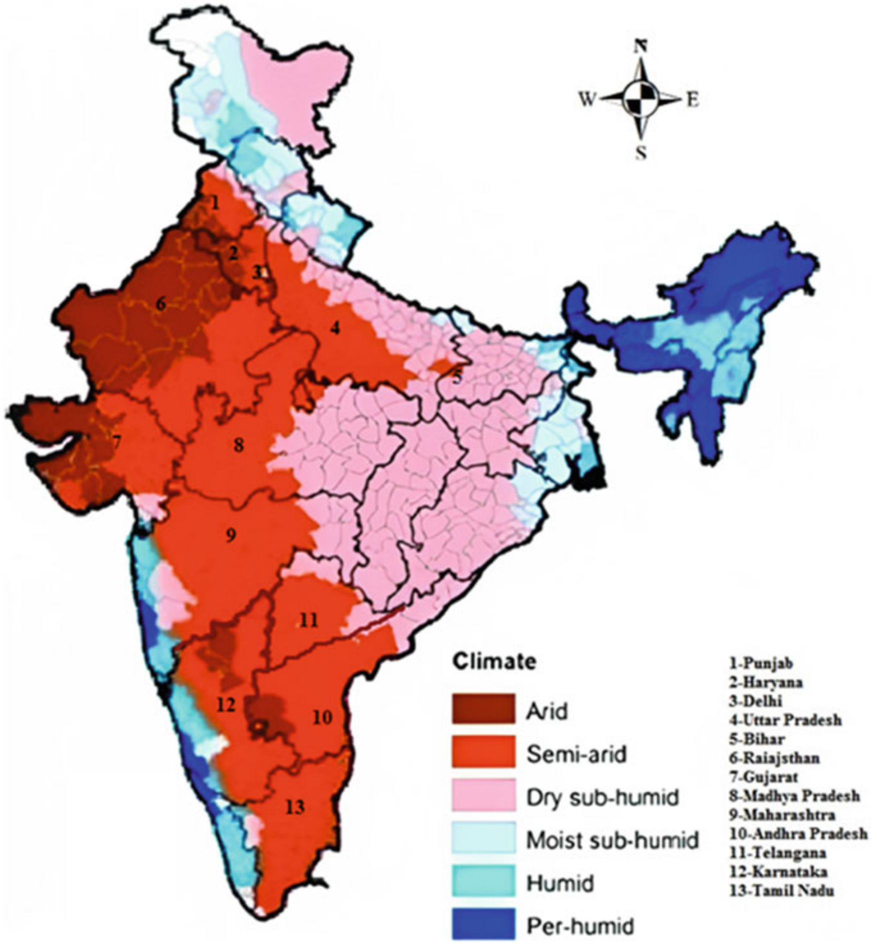


Fig. 1 Arid and semi-arid regions in India. (*Source* https://www.biologydiscussion.com/ecology/arid-zone/indian-arid-zone-with-diagram/34415, [188, 200])

a. **Studies Related to Groundwater Quality of Arid and Semi-arid Areas**

   After careful reading of all the articles, the articles related to groundwater quality of arid and semi-arid states were separated and arranged state wise.

b. **Recent Studies (from 2015 onwards)**

   In this present review article, all the articles discussing the groundwater quality of the selected states and published after 2015 were included.

c. **Studies Focusing on Challenges and Management Practices of Groundwater in Arid and Semi-arid Areas**

Then another search was performed for the articles focusing on challenges and management practices of groundwater in arid and semi-arid areas.

Due to rapid population growth, expansion of agriculture and economic development in India, water demand has increased (largest extractor of groundwater) to a tremendous level, which puts huge pressure on the groundwater resource to an unbalanced level [144, 145, 180]. The availability of per capita average annual fresh water has reduced 64.81% from 1951 to 2001 and it is estimated to reduce to 74.09% till 2025 and 77.97% till 2050 [99]. Therefore, there is a need to monitor groundwater quantity and quality at regular intervals to cope with water scarcity.

Due to different geological, topographical and climatic conditions in India, groundwater availability and consumption pattern varies from region to region. The susceptibility of groundwater quality and quantity reduction was found to be higher in the country's arid and semi-arid areas (India) due to low precipitation and high evaporation [144, 145, 163]. Agriculture is one of the main occupations in almost all the arid and semi-arid states except few. Groundwater extraction for irrigation makes the problem of water scarcity more complex. The summary of groundwater quality of all the districts of arid and semi-arid states of the country (India) is presented in Table 2.

4 Water Quality in Different Arid and Semi-arid States of India

4.1 Water Quality in Andhra Pradesh

Andhra Pradesh is situated in southern part of India (Table 1; Fig. 1). It has the 2nd longest coastline in India after Gujarat. The geographical area is dominated by hills having unconsolidated silty mineral rich soil.

Upland with or without forest cover is the dominant type of LULC (Land Use Land Cover) of the state. In most of the districts of Andhra Pradesh, values of EC (1190–5560 μS/cm), TDS (1210–3010 mg/L), chloride (266–322 mg/L), sulphate (224–738 mg/L), nitrate (84–589 mg/L), and fluoride (4.7–5.8 mg/L) were found above the limit of BIS (Bureau of Indian Standards) and WHO (World Health Organization) in the groundwater (Table 2). Maximum values of sulphate and nitrate were observed in Cuddapah basin. In the Anantapur district most of the water samples shows salinity hazard, chloride hazard, and magnesium hazard [186]. In the Kadapa district (formerly known as Cuddapah), the mean values of fluoride were found above the limit in 35% of the samples may be due to geogenic sources while an excess of nitrate in 45% of the samples may be due to anthropogenic causes [215]. In the Chittoor district, groundwater chemistry is controlled by the rock-water interface and silicate weathering [62]. Water quality was found to be poor to unsuitable for drinking as per the water quality indices [62, 136, 159, 186, 190, 193, 215].

Table 1 Arid and semi-arid regions of the country [156, 172, 180]

SN	States	Arid areas	Semi-arid areas	Latitude and longitude	Temperature (°C)	Rainfall (mm)
1	Punjab	Arid areas (27,350 km^2)	Semi-arid areas (58,650 km^2)	29″30′N to 32″32′N and 73″55′E to 76″50′E	11–44.6	120–679
2	Haryana			27°39′ to 30°35′N and 74°28′ to 77°36′E	6.4–40.2	603–617
3	Delhi	–	Semi-arid areas (1483 km^2)	28°24´17´´N to 28°53´00´´N and 77°50´24´´E to 77°20´37´´E	2–46	774–779
4	Uttar Pradesh	–	Semi-arid areas (64,230 km^2)	23°52′ to 31°28′N and 77°3′ to 84°39′E	0–50	650–1000
5	Bihar	–	Semi-arid areas (44,800 km^2)	24°20′N to 27°31′N and 83°20′E to 88°18′E	7.9–40.5	1186–1326
6	Rajasthan	Arid areas (196,150 km^2)	Semi-arid areas (121,020 km^2)	24°31′ to 30°12′N and 69°15′ to 76°42′E	0–50	313–675
7	Gujarat	Arid areas (62,180 km^2)	Semi-arid areas (90,520 km^2)	20°01′ to 24°07′N and 68°04′ to 74°04′E	15–45	300–2100
8	Madhya Pradesh	–	Semi-arid areas (59,470 km^2)	21.6°N to 26.30°N and 74°9′E to 82°48′E	15–45	1017–1338
9	Maharashtra	Arid areas (1290 km^2)	Semi-arid areas (189,580 km^2)	5°35′N to 22°02′N and 72°36′ to 80°54′E	18–32	882–1034
10	Andhra Pradesh	Arid areas (21,550 km^2)	Semi-arid areas (138,670 km^2)	12°41′ to 19.07°N and 77° to 84°40′E	12–41	558–1151
11	Telangana			15° 46′ to 19° 47′N and 77° 16′ to 81° 43′E	22–32	721–906

(continued)

Table 1 (continued)

SN	States	Arid areas	Semi-arid areas	Latitude and longitude	Temperature (°C)	Rainfall (mm)
12	Karnataka	Arid areas (8570 km^2)	Semi-arid areas (139,360 km^2)	11.5° to 18.5°N and 74° to 78.5°E	20–34	731–1126
13	Tamil Nadu	–	Semi-arid areas (95,250 km^2)	8° 5′ to 13° 35′N and 76° 15′ to 80° 20′E	29–32	317–1890

4.2 Water Quality in Bihar

Bihar is situated in eastern part of India (Table 1; Fig. 1). Upland with or without forest cover is the state's dominant type of LULC. In most of the districts of Bihar, values of EC (1963 µS/cm), arsenic (0.168–0.397 mg/L), iron (1.2 mg/L), manganese (1.2 mg/L), and fluoride (5.1 mg/L) were found above the limit of BIS and WHO in the groundwater (Table 2). Gupta et al. [70] and Kumar et al. [100] observed that the concentration of arsenic and fluoride was found beyond the permissible limit of BIS standard in more than 50% of the samples collected from Begusarai, Buxar, Katihar, Khagaria, Munger, Samastipur, and Saran districts of Bihar. The most affected district was Saran (77%) and the least affected was Begusarai (56%). In the Saran district, water quality was found impacted with higher values of salinity and faecal coliform [100]. The higher concentration of arsenic in Bhojpur district may be due to arseniferrous aquifers, first reported in 2002 [46]. As per the Public Health Engineering Department (PHED) report, 50 ppb of arsenic was observed in 13 districts and more than 1.5 mg/L fluoride in 11 districts. Different health implications (dental fluorosis, hyperkeratosis, cancer) to residents living in the state were also reported. As per the water quality indices, the quality of water was found unacceptable for the drinking purposes [39, 46, 70, 100, 118, 161, 187].

4.3 Water Quality in Delhi

Delhi, India's capital, is one of India's metro cities (Table 1; Fig. 1). Due to rapid urbanization, huge change was observed in the LULC of the state. The area covered by green plants, wastelands and water bodies have decreased while built-up area increased up to 35% [104]. The nature of aquifer varied from unconfined to confined [43]. Values of EC (2052–10,870 µS/cm), TDS (2382–5875 mg/L), chloride (667–4685 mg/L), sulphate (447–1220 mg/L), nitrate (129–1500 mg/L), fluoride (1.57–17 mg/L), iron (2.4–30 mg/L), arsenic (0.107–0.200 mg/L), chromium (7.85–13.06 mg/L), copper (4.2 mg/L), manganese (3 mg/L), and zinc (10.36 mg/L)

Table 2 Water quality in different districts of arid and semi-arid states of India

State	District	No of samples	Parameters above the BIS value	References
Andhra Pradesh	Ananatpur	36	EC (5560 μS/cm), TDS (3010 mg/L),	[186]
	Ananatpur	50	Cl (300 mg/L), SO_4^{2-} (240 mg/L), NO_3^- (88 mg/L), F (5.7 mg/L)	[159]
	Nellore	30	EC (1190 μS/cm), Cl (306 mg/L)	[136]
	Cuddapah basin	50	EC (2920 μS/cm),TDS (1987 mg/L), NO_3^- (589 mg/L), Cl (322 mg/L), F (4.7 mg/L), SO_4^{2-} (224 mg/L)	[215]
	Chittoor	31	EC (2340 μS/cm), TDS (1210 mg/L), SO_4^{2-} (738 mg/L), Cl (266 mg/L)	[62]
	Visakhapatnam	30	EC (2100 μS/cm), TDS (1365 mg/L), Cl (290 mg/L), NO_3^- (84 mg/L)	[190]
	Prakasam	505	EC (4400 μS/cm), TDS (2640 mg/L), SO_4^{2-} (300 mg/L), NO_3^- (180 mg/L), F (5.8 mg/L), Cr (1.170 mg/L), As (40.952 mg/L), Cd (0.160 mg/L), Hg (0.168 mg/L), Cr (2.099 mg/L), Sr (26.250 mg/L)	[94, 193]
	Guntur	20	TDS (2190 mg/L), Cl (665 mg/L), NO_3^- (78 mg/L), F (12.9 mg/L)	[191]
	Godavari	164	EC (8234 μS/cm), TDS (5517 mg/L), Cl (2654 mg/L), SO_4^{2-} (384 mg/L), NO_3^- (126 mg/L)	[112]

(continued)

Table 2 (continued)

State	District	No of samples	Parameters above the BIS value	References
Bihar	KhapTola, West Champaran	140	As (0.397 mg/L)	[39]
	Saran	128	As (0.244 mg/L)	[100]
	Bhojpur	218	Fe (1.2 mg/L), Pb (0.04 mg/L), NO_3^- (159 mg/L), As (168 µg/L), Mn (1.2 mg/L)	[118]
	Nawada	124	F (8.56 mg/L)	[125, 161]
	Munger	195	F (12.0 mg/L)	[111]
	Samastipur	23	As (0.135 mg/L)	[103]
Delhi	Older Alluvial Plains	22	F (3.15 mg/L)	[23]
	Different parts of Delhi		EC (8980 µS/cm), TDS (5875 mg/L), Cl (2610 mg/L), SO_4^{2-} (1220 mg/L), NO_3^- (1500 mg/L), F (17 mg/L), Fe (30 mg/L), As (107 ppb), Cr (7.85 mg/L)	[45, 106, 166, 183]
	Yamuna flood plain (YFP)	11	EC (4660 µS/cm), Cl (1215 mg/L), SO_4^{2-} (447 mg/L), F (1.57 mg/L), NO_3^- (129 mg/L)	[28]
	South West Delhi	110	EC (2052 µS/cm), TDS (5645 mg/L), Salinity (11,046), Cl (4585 mg/L)	[3, 158]
	Eastern border of the Delhi	8	As (200 ppb), Cr (13.06 mg/L), Cu (4.2 mg/L)	[2]
	Central and southeast districts of Delhi	20	TDS (3103 mg/L), Cl (1168 mg/L), SO_4^{2-} (553 mg/L), F (2.9 mg/L)	[40]
	Different parts of Delhi	258	F (8.13 mg/L), NO_3^- (284 mg/L)	[160]

(continued)

Table 2 (continued)

State	District	No of samples	Parameters above the BIS value	References
	Municipal solid waste disposal site, Ghazipur	20	TDS (2382 mg/L), Cl (991 mg/L), F (1.66 mg/L), SO_4^{2-} (631 mg/L), Fe (2.4 mg/L)	[109]
	Municipal solid waste disposal site, Bhalswa	60	EC (10,870 µS/cm), TDS (5437 mg/L), Cl (667 mg/L), Zn (10.36 mg/L), Fe (4.47 mg/L), Mn (3 mg/L)	[17]
Gujarat	Amba Danger area	104	EC (2170 µS/cm), TDS (804 mg/L), F (3.35 mg/L), NO_3^- (129 mg/L)	[175]
	Mehsana	74	EC (6006 µS/cm), TDS (3185 mg/L), F (12 mg/L), NO_3^- (191 mg/L), Cl (1472 mg/L), SO_4^{2-} (374 mg/L)	[120]
	Anand	66	EC (8230 µS/cm), NO_3^- (120 mg/L), Cl (4875 mg/L), SO_4^{2-} (234 mg/L)	[105]
	Kachchh	26	EC (15,900 µS/cm), TDS (9850 mg/L), Cl (2662 mg/L), F (2.05 mg/L), NO_3^- (129 mg/L), SO_4^{2-} (230 mg/L)	[126]
	Surat	57	EC (3971 µS/cm), TDS (3360 mg/L), Cl (250 mg/L), F (4.17 mg/L)	[146]
	Central Gujarat	45	EC (1780 µS/cm), TDS (1140 mg/L), Cl (855 mg/L)	[144, 145]
	Vadodara and Panchmahal	60	EC (30,736 µS/cm), TDS (15,368 mg/L), Cl (8203 mg/L), Fe (19.52 mg/L)	[177]

(continued)

Table 2 (continued)

State	District	No of samples	Parameters above the BIS value	References
	Navsari	03	EC (1840 µS/cm), TDS (1190 mg/L), Cl (530 mg/L), F (8.4 mg/L), Salinity (957 mg/L)	[169]
Haryana	Bhiwani	275	TDS (6300 mg/L), Cl (1978 mg/L), F (86.0 mg/L), SO_4^{2-} (1222 mg/L)	[65]
	Bhiwani	10	EC (8500 µS/cm), NO_3^- (246 mg/L), F (18.5 mg/L), Cl (678 mg/L)	[24]
	Mewat	60	EC (10,181 µS/cm), TDS (12,000 mg/L), Cl (5233 mg/L), SO_4^{2-} (887 mg/L)	[98, 206]
	Jhajjar	20	EC (5640 µS/cm), TDS (3920 mg/L), F (3.8 mg/L), Cl (2439 mg/L)	[72]
	Sonipat	60	TDS (3776 mg/L), F (2.7 mg/L), Cl (1335 mg/L), NO_3^- (565 mg/L), SO_4^{2-} (2129 mg/L)	[52, 192]
	Panipat	74	TDS (1842 mg/L), F (6.9 mg/L), Cl (690 mg/L), NO_3^- (69 mg/L), SO_4^{2-} (1559 mg/L)	[52, 84]
	Hisar	68	Uranium (0.274 mg/L)	[58]
	Southern Haryana	64	EC (14,625 µS/cm), TDS (3920 mg/L), F (13.8 mg/L), Cl (4924 mg/L), SO_4^{2-} (4023 mg/L), NO_3^- (690 mg/L)	[110]

(continued)

Table 2 (continued)

State	District	No of samples	Parameters above the BIS value	References
Karnataka	Mysore	30	EC (3070 µS/cm), TDS (1789 mg/L), Cl (459 mg/L)	[14]
	Gulbarga	32	EC (1479 µS/cm), TDS (824 mg/L), F (1.97 mg/L), Cl (374 mg/L), NO_3^- (90 mg/L)	[129]
	Koppal and Ballery	17	Mn (9.1 mg/L), Ni (20.6 mg/L)	[37]
	Yadgir	367	EC (15,560 µS/cm), Cl (5083 mg/L), SO_4^{2-} (695 mg/L), NO_3^- (590 mg/L), Pb (0.049 mg/L), Uranium (0.302 mg/L)	[121]
	Udupi district	212	TDS (900 mg/L), F (2.35 mg/L), Fe (4.5 mg/L), Cl (361 mg/L)	[22, 54]
	Bagalkot District		F (>1.5 mg/L), NO_3^- (>45 mg/L)	[55]
Madhya Pradesh	Sidhi	39	EC (1351 µS/cm), TDS (796 mg/L), F (3.5 mg/L)	[135]
	Rewa	30	EC (3186 µS/cm), TDS (2106 mg/L), F (2.8 mg/L), Cl (572 mg/L), SO_4^{2-} (624 mg/L), NO_3^- (105 mg/L)	[198]
	Singrauli	48	As (0. 209 mg/L), Hg (0.033 mg/L), Pb (0.317 mg/L), Cd (0.108 mg/L)	[36]
	Singrauli	60	EC (1148 µS/cm), F (1.75 mg/L), SO_4^{2-} (735 mg/L), NO_3^- (97 mg/L)	[204]

(continued)

Table 2 (continued)

State	District	No of samples	Parameters above the BIS value	References
Punjab	Rupnagar	14	EC (1295 μS/cm), NO_3^- (79 mg/L), Fe (1.92 mg/L), Mn (1.16 mg/L)	[48, 181]
	Chandigarh Region	140	EC (1550 μS/cm), TDS (679 mg/L)	[139]
	Bhatinda	58	EC (4014 μS/cm), TDS (2811 mg/L), F (4.4 mg/L), Cl (1278 mg/L), SO_4^{2-} (784 mg/L), NO_3^- (390 mg/L)	[97, 173]
	Jalandhar	41	EC (1058 μS/cm), TDS (677 mg/L), NO_3^- (318 mg/L), F (2 mg/L)	[182]
	Malwa region	76	TDS (1952 mg/L), NO_3^- (198 mg/L), F (5 mg/L), Cl (334 mg/L)	[1, 16]
	Malwa region	24	EC (7007 μS/cm), TDS (4480 mg/L), NO_3^- (318 mg/L), F (3.74 mg/L), Cl (808 mg/L), SO_4^{2-} (692 mg/L), Fe (5.41 mg/L), As (0.0233 mg/L)	[85]
	Mansa	59	EC (7600 μS/cm), TDS (3800 mg/L), NO_3^- (195 mg/L), F (2.7 mg/L), Cl (1363 mg/L), SO_4^{2-} (1636 mg/L), Hg (0.070 mg/L), As (1.260 mg/L), U (0.104 mg/L)	[174]

(continued)

Table 2 (continued)

State	District	No of samples	Parameters above the BIS value	References
Uttar Pradesh	Mathura	276	EC (14,400 µS/cm), TDS (17,110 mg/L), F (1.4 mg/L), Cl (3905 mg/L), NO_3^- (149 mg/L), SO_4^{2-} (2238 mg/L), Cd (3.6 mg/L), Pb (5.9 mg/L), Ni (4.7 mg/L), Fe (3.7 mg/L), Cr (3.8 mg/L)	[19–21]
	Ramganga Sub basin	45	EC (1866 µS/cm), TDS (2000 mg/L), Cl (1150 mg/L), Fe (14.5 mg/L), F (85 mg/L), NO_3^- (886 mg/L), SO_4^{2-} (600 mg/L)	[89, 151, 199]
	Agra	288	EC (2483 µS/cm), TDS (1766 mg/L), F (2.5 mg/L), Cl (982 mg/L)	[33, 93, 213]
	Mainpuri	37	EC (998 µS/cm), TDS (1384 mg/L), NO_3^- (56 mg/L), F (1.9 mg/L)	[90]
	Agra-Firozabad industrial belt		SO_4^{2-} (514 mg/L), NO_3^- (67 mg/L), F (2 mg/L),	[91]
	Kanpur	97	EC (3830 µS/cm), TDS (2835 mg/L), NO_3^- (84 mg/L), F (3.2 mg/L), SO_4^{2-} (345 mg/L), Cl (905 mg/L)	[71, 104]
Rajasthan	Ajmer	16	Cu (1.62 mg/L), F (3.2 mg/L), Cd (0.13 mg/L), Salinity (685 mg/L), As (0.05 mg/L)	[69]

(continued)

Table 2 (continued)

State	District	No of samples	Parameters above the BIS value	References
	Jhunjhunu	42	EC (11,000 μS/cm), TDS (7040 mg/L), SO_4^{2-} (449 mg/L), F (5.7 mg/L), NO_3^- (520 mg/L),Cl (986 mg/L)	[76, 92, 194, 195]
	Bikaner	123	EC (10,090 μS/cm), TDS (6667 mg/L), Fe (3.66 mg/L), F (10.41 mg/L), NO_3^- (1126 mg/L), SO_4^{2-} (2534 mg/L), Cl (2087 mg/L)	[35, 101, 102]
	Dausa	134	EC (6300 μS/cm), TDS (3826 mg/L), Cl (1574 mg/L), SO_4^{2-} (754 mg/L), NO_3^- (162 mg/L), F (4.8 mg/L)	[147, 197]
	Jaipur	157	EC (5000 μS/cm), TDS (2906 mg/L), Cl (1212 mg/L), SO_4^{2-} (279 mg/L), NO_3^- (76 mg/L), F (2.6 mg/L)	[63, 148]
	SriGanganagar	300	EC (8050 μS/cm), TDS (2770 mg/L), Cl (1249 mg/L), F (5.75 mg/L)	[47]
	Jodhpur	710	TDS (1728 mg/L), Cl (675 mg/L)	[185]
Maharashtra	Ahmednagar	57	EC (2987 μS/cm), TDS (1916 mg/L), SO_4^{2-} (369 mg/L), Cl (367 mg/L), NO_3^- (108 mg/L)	[171]

(continued)

Table 2 (continued)

State	District	No of samples	Parameters above the BIS value	References
	Yavatmal	72	EC (8140 μS/cm), TDS (4139 mg/L), SO_4^{2-} (925 mg/L), Cl (1136 mg/L), NO_3^- (803 mg/L), F (1.9 mg/L)	[123]
	Solapur	55	EC (11,400 μS/cm), SO_4^{2-} (240 mg/L), Cl (2073 mg/L), NO_3^- (97 mg/L)	[132]
	Pune	68	B (12.4 mg/L)	[78]
	Akola	35	EC (5432 μS/cm), TDS (3265 mg/L), Cl (1384 mg/L)	[61]
	Nagpur	18	EC (5010 μS/cm), TDS (2564 mg/L), SO_4^{2-} (427 mg/L), Cl (332 mg/L)	[203]
	Nanded	50	EC (64,400 μS/cm), TDS (41,216 mg/L), Cl (1043 mg/L)	[210]
	Yavatmal	206	EC (2785 μS/cm), TDS (1518 mg/L), Cl (665 mg/L), SO_4^{2-} (338 mg/L), NO_3^- (305 mg/L), F (12.7 mg/L)	[141]
Tamil Nadu	Yadgir	40	EC (2475 μS/cm), TDS (1962 mg/L), Cl (565 mg/L), SO_4^{2-} (390 mg/L), NO_3^- (78 mg/L), F (1.7 mg/L)	[154]
	Coimbatore	154	EC (3430 μS/cm), TDS (2401 mg/L), Cl (664 mg/L), SO_4^{2-} (452 mg/L), F (3.3 mg/L), NO_3^- (415 mg/L)	[82, 83, 143]

(continued)

Table 2 (continued)

State	District	No of samples	Parameters above the BIS value	References
	Villupuram	48	EC (4080 μS/cm), TDS (1573 mg/L), Cl (412 mg/L), NO_3^- (64 mg/L), F (3.6 mg/L)	[53]
	Dindigul and Karur	112	EC (5810 μS/cm), TDS (4067 mg/L), Cl (912 mg/L), SO_4^{2-} (960 mg/L), NO_3^- (90 mg/L), F (3.58 mg/L)	[79, 142]
	Salem	59	EC (3800 μS/cm), TDS (2310 mg/L), Cl (710 mg/L), SO_4^{2-} (288 mg/L), NO_3^- (60 mg/L), F (1.7 mg/L)	[31]
Telangana	Medak	245	EC (3850 μS/cm), TDS (2464 mg/L), Cl (973 mg/L), F (7.1 mg/L), SO_4^{2-} (280 mg/L), NO_3^- (348 mg/L)	[6, 11]
	Nalgonda	82	EC (5900 μS/cm), TDS (2640 mg/L), Cl (808 mg/L), F (7.50 mg/L), SO_4^{2-} (403 mg/L), NO_3^- (719 mg/L)	[9, 189]
	Adilabad	34	EC (2118 μS/cm), TDS (1355 mg/L), Cl (1010 mg/L), F (4.3 mg/L), SO_4^{2-} (600 mg/L), NO_3^- (130 mg/L)	[4]
	Central part of Telangana	105	EC (2390 μS/cm), TDS (1529 mg/L), Cl (320 mg/L), F (3.5 mg/L), SO_4^{2-} (425 mg/L), NO_3^- (212 mg/L)	[8, 13]

(continued)

Table 2 (continued)

State	District	No of samples	Parameters above the BIS value	References
	Nirmal	34	EC (2118 µS/cm), TDS (1355 mg/L), Cl (320 mg/L), F (4.33 mg/L), SO_4^{2-} (375 mg/L), NO_3^- (80 mg/L)	[7]
	Medchal	56	EC (2664 µS/cm), TDS (1705 mg/L), Cl (410 mg/L), F (3.2 mg/L), NO_3^- (396 mg/L)	[60, 68]
	Kamareddy	160	EC (3170 µS/cm), TDS (2029 mg/L), Cl (1207 mg/L), F (7.4 mg/L), SO_4^{2-} (328 mg/L), NO_3^- (440 mg/L)	[12]

were found above the limit of BIS and WHO in the groundwater (Table 2). Salinity (11,046 mg/L) was reported in south Delhi by Rawat et al. [158] and Acharya et al. [3]. Arsenic was found highest (200 ppb) in Patparganj Industrial area [2]. Water quality was found poor to unfit for drinking purpose at almost all the locations as per the water quality indices [2, 3, 17, 27, 28, 40, 45, 109, 158, 160, 166, 206].

4.4 Water Quality in Gujarat

Gujarat is located along the western coast of India (Table 1; Fig. 1). Based on topography, Gujarat is divided into 3 main parts: the peninsular area (dominated by hilly tract), the Kutch area (dominated by barren and rocky land) and mainland. The LULC study suggests the increase in urban built-up and aquaculture area and depreciation in mudflats due to speedy urbanization [127]. In most of the districts of Gujarat, values of EC (1780–15,900 µS/cm), TDS (804–9850 mg/L), chloride (250–4875 mg/L), sulphate (230–374 mg/L), nitrate (120–191 mg/L), and fluoride (2.05–12 mg/L) were found above the limit of BIS and WHO in the groundwater (Table 2). The highest values of EC and TDS were found in the Kachchh area due to rock-water interaction, land use pattern, ion exchange, excess of evaporation, and dissolution or precipitation of ions. Area's declining water table, seawater intrusion and salinization are the other two major problems [126]. The geology of Mehsana district is dominated by granite, calc-schist, and biotite-gneiss rocks which may be the reason behind the elevated values of physicochemical parameters [120]. Kumar et al. [105] studied the decadal changes in the groundwater quality of the Anand district of Gujarat and observed that the values of most of the water quality parameters (EC, TDS, fluoride, chloride) increased due to change in climate and land use pattern. Fluoride was found in higher concentration in the Surat district may be due to the dissolution and weathering of fluoride rich minerals [146]. Vadodara district of central Gujarat and Bharuch, Tapi districts of south Gujarat were significantly affected. Vansda and Ahwa were irregularly affected by landscape and minor industrialization. Khambhat region is found highly affected by salinity due to saltwater intrusion from the Arabian Sea [144, 145]. Water quality was not fit for drinking purpose in almost all the districts as per the water quality indices except South and Central districts of Gujarat where the water quality varied from good to moderate for all three seasons [105, 120, 126, 144–146, 169, 175].

4.5 Water Quality in Haryana

Haryana is located in Northern part of the country (Table 1; Fig. 1). Based on topography, Haryana is divided into 4 main parts viz. Yamuna-Ghaggar, Lower Shivalik Hills, Bagar tract and Aravali Range's. LULC study witnessed the decreasing vegetation cover in the area while built-up area and salinity shows the increasing trends [107]. In most of the districts of Haryana, values of EC (5640–14,625 μS/cm), TDS (3920–12,000 mg/L), chloride (678–5233 mg/L), sulphate (887–4023 mg/L), nitrate (69–690 mg/L), and fluoride (3.8–80 mg/L) were found above the limit of BIS and WHO in the groundwater (Table 2). The value of fluoride observed in Bhiwani district (86 mg/L in Motipura village) was the highest ever recorded in Haryana state. In the Rohtak and Jhajjar districts of Haryana, percolation from the canal water irrigated fields is the main cause of groundwater recharge which raised the level of the groundwater table (approximately 13.7 cm/year) continuously. Farmers in the study area use canal water mostly for irrigation due to the high quantity of salts in the groundwater. The increasing water table level is not good for agricultural production [178]. In the Mewat district, salinity of the water was observed high in all the seasons due to sodium, calcium, and chloride chemistry [98]. As per the USSL (United States Salinity Laboratory) classification, 85% of the samples shows high salinity hazard making the water unsuitable for irrigation in the southern part of Haryana [110]. Water quality was not fit for drinking purpose in almost all the districts as per the water quality indices [65, 72, 84, 98, 110, 178, 192].

4.6 Water Quality in Karnataka

Karnataka is located in southwestern part of the India (Table 1; Fig. 1). The state is divided into three different geographical zones viz., the coastal region (Karavali and Tulu Nadu), the hilly Malenadu region (Western Ghats) and the Bayaluseeme region (plains of the Deccan Plateau). LULC study witnessed the decreasing forest cover in the state while increase in built-up area [165, 168]. Karnataka ranked second in terms of drought (18 out of 30 districts) events after Rajasthan. Values of EC (1479–15,560 μS/cm), TDS (824–1789 mg/L), chloride (374–5083 mg/L), sulphate (695 mg/L), nitrate (90–590 mg/L), and fluoride (1.97 mg/L) were found above the limit of BIS and WHO in most of the districts of Karnataka (Table 2). The geochemistry of groundwater of Gulbarga district is controlled by water–rock interaction [129]. In 25% of the samples of Yadgir district uranium is found beyond the permissible limit of WHO [211]. Water quality was ranged from good to unfit for drinking category in almost all the districts as per the water quality indices [14, 37, 121, 129].

4.7 Water Quality in Madhya Pradesh

Madhya Pradesh is located in central part of India (Table 1; Fig. 1). Geographically the state is divided into 7 regions viz., Eastern Plateau, Plateau of Malwa, Plateau of Central India, Plateau of Bundelkhand, Plateau of Rewa and Panna, Narmada-Sone Valley, and Satpura and Maikal Region (https://dolr.gov.in/sites/default/files/Madhya%20Pradesh_SPSP.pdf). LULC witnessed the agricultural land and forest land in arid and semi-arid region [179, 181]. Values of EC (1148–3186 μS/cm), TDS (796–2106 mg/L), chloride (572 mg/L), sulphate (624–735 mg/L), nitrate (97–105 mg/L), and fluoride (1.75–3.8 mg/L) were found above the limit of BIS and WHO in most of the districts of Madhya Pradesh (Table 2). [119] studied the vulnerability risk of groundwater in the Hoshangabad district and classify the area into three zones i.e. low-risk zone (38.28%), medium-risk zone (34.32%) and high-risk zone (27.39%). In the Singrauli district, values of arsenic (12–209 ppb), mercury (5–33 ppb), lead (5–317 ppb), and cadmium (3–108 ppb) were found above the limit of most of the agencies (BIS, WHO, EPA) except at few locations. The increased value may be due to burning of coal [36]. The results of the heavy metal evaluation index (HEI), heavy metal pollution index (HPI), and contamination index (CI) pointed out high metal pollution in both ground and surface water. A decrease in water bodies and agricultural land and an increase in mining sites and fly ash dumping yards were also found using LULC change in a study carried out by [36] in the Singrauli district. The water is medium to highly susceptible to pollution as per the findings of Tiwari et al. [198] using the DRASTIC model. Water quality was ranged from good to moderately polluted category in almost all the districts as per the water quality indices [36, 119, 135, 198, 204].

4.8 Water Quality in Maharashtra

Maharashtra is located in the western part of India (Table 1; Fig. 1). Topographically the state is divided into plateaus, valleys, plains, hills, and coastal low land. LULC studies show the increase in agriculture land upto 98% due to the conversion of wasteland and fallow land into agricultural land. Reduction in forest canopy also observed due to increase in agriculture land (https://wotr-website-publications.s3.ap-south-1.amazonaws.com/LULC_2_Mar_2020.pdf). Values of EC (2785–11,400 μS/cm), TDS (1518–4139 mg/L), chloride (332–2073 mg/L), sulphate (240–905 mg/L), nitrate (97–803 mg/L), and fluoride (1.9–12.7 mg/L) were found above the limit of BIS and WHO in different parts of the state. In the Solapur district, values of physicochemical parameters were found above the limit in and around the industrial area while at distant places values of some parameters were below the limit. The elevated values may be due to the dumping of solid and liquid effluent in the Chincholi industrial area [132]. In Pune district boron (0.10–12.45 ppm) was found above the limit, possibly due to combined geogenic and anthropogenic effects. Water quality in the area is moderately to highly polluted as per the water quality indices [61, 78, 123, 132, 171, 203] except Sindhudurg, Satara and Nanded district, where water quality was in excellent category [64, 75, 210].

4.9 Water Quality in Punjab

Punjab is located in north-west part of India (Table 1; Fig. 1). Topographically, Punjab is divided into two regions: sub-Shivalik area and Ghaggar river basin. LULC studies show the shift from agriculture, bare soil and forest to urban area. An increase in temperature was also witnessed in the direction of LULC change [117]. In most of the districts of Punjab, values of EC (1098–7600 μS/cm), TDS (677–4480 mg/L), chloride (334–1363 mg/L), sulphate (692–1636 mg/L), nitrate (79–390 mg/L), and fluoride (2–5 mg/L) were found above the limit of BIS and WHO. Values of iron (5.41 mg/L), arsenic (0.023–1.26 mg/L), mercury (0.07 mg/L), and uranium (0.104 mg/L) were also reported above the limit of BIS in some parts of Punjab (Table 2). In the Rupnagar district, water quality was observed badly affected by an anthropogenic factor as well as weathering and leaching activity [48]. In Bhatinda district, water quality was found to be saline in nature due to the presence of an excess of salts [173]. In the Jalandhar district, water quality was found in the category of poor to unfit for drinking in southwestern and central parts based on water quality index (WQI) and Revelle index values. Salinity issues were also observed in the area. The originating source of most of the cations is geogenic while anions are anthropogenic [182]. In the Malwa region, a continuous decrease in groundwater level (GWL) was observed from 1997 to 2018 in a study carried out by Sahoo et al. [164]. In this area, GWL was declining 40 cm/year, on an average in more than 30% of the tube wells whereas a rise was also observed in 20% of the tube wells. The problem of water logging was also observed in some places [164]. In most parts of Punjab, nitrate and fluoride are the two major contaminants reported in almost all the groundwater samples. Water quality was ranged from very poor to unsuitable for drinking category in almost all the districts as per the water quality indices [48, 85, 97, 164, 173, 174, 182].

4.10 Water Quality in Rajasthan

Rajasthan is located in the north-western part of India (Table 1; Fig. 1). Geographically, the state is divided into Thar Desert and Aravalli range. LULC studies show the increase in agriculture land due to the construction of Indira Gandhi Canal (IGC) [95]. In most of the districts of Rajasthan, values of EC (5000–11,000 μS/cm), TDS (1728–7040 mg/L), chloride (648–2087 mg/L), sulphate (254–2534 mg/L), nitrate (76–1126 mg/L), and fluoride (2.6–10.41 mg/L) were found above the limit of BIS and WHO in the groundwater (Table 2). Heavy metal such as copper (1.62 mg/L), cadmium (0.13 mg/L), and arsenic (0.05 mg/L) were also observed above the limit of BIS. The highest value of chloride, sulphate, nitrate, and fluoride were observed in the Bikaner region [35, 101, 102]. Higher salinity was observed throughout the Rajasthan may be due to higher evaporation and lower precipitation. In the Ajmer district of Rajasthan, groundwater recharging was observed very slow, and the water quality was in the worst condition and extremely vulnerable to pollution [69]. Water quality was ranged from very poor to unsuitable for drinking category in almost all the districts as per the water quality indices [35, 47, 69, 76, 92, 101, 102, 147, 148, 185].

4.11 Water Quality in Tamil Nadu

Tamil Nadu is located in the southern-most part of India (Table 1; Fig. 1). The state is prone to droughts due to high dependency on monsoon rainfall. Topographically the state is divided into hills, ghats and coastal lands. LULC study witnessed the increase in agricultural area and forest cover due to watershed and irrigation management practices in the state and increase in built-up area in rural and urban areas [66, 153, 205]. In different districts, values of EC (2475–5810 μS/cm), TDS (1573–4067 mg/L), chloride (565–912 mg/L), sulphate (288–960 mg/L), nitrate (60–90 mg/L), and fluoride (1.7–3.6 mg/L) were found above the limit of BIS and WHO in the groundwater (Table 2). In the Yadgir district, Nitrogen Pollution Index (NPI) value revealed that about 40% of the sampling sites are moderately polluted while 17.5% are significantly polluted may be due to rock-water interaction and other anthropogenic factors [154]. In the Coimbatore district, the average value of fluoride was found below the permissible at most places while above the limit at some places. In a study performed by [131] in the Kanchipuram district, the authors observed the uneven distribution of groundwater due to the recharging of the groundwater table. The water quality indices divulged that water quality in the state fall in the poor to the unsuitable category for drinking purposes [31, 53, 82, 154]. In the Dindigul and Karur districts, water quality in the area falls under the excellent to good category and the geochemical chemistry of the area is controlled by rock-water interaction [79, 142].

4.12 Water Quality in Telangana

Telangana is located in the south-central stretch of India (Table 1; Fig. 1). Topographically, the state is divided into hills, mountain ranges, and dense forests. LULC study witnessed the increase in agricultural area and decrease in forest cover due to deforestation for agriculture, timber harvesting and cattle grazing. Aneesha Satya et al. [30] predicts the decrease in agricultural land and increase in barren land in future. Values of EC (2118–5900 μS/cm), TDS (1355–2640 mg/L), chloride (320–1207 mg/L), sulphate (280–600 mg/L), nitrate (80–719 mg/L), and fluoride (3.5–7.4 mg/L) were found above the limit of BIS and WHO in different districts (Table 2). Water quality throughout Telangana was found to be heavily affected by fluoride and nitrate. More than 50% of the samples collected from each district show the higher values of fluoride and nitrate. The water quality indices divulged that water quality in the state fall in the poor to the unsuitable category for drinking purposes [6, 7, 9, 157] except Adilabad district and central part of Telangana [4, 8, 189].

4.13 Water Quality in Uttar Pradesh

Uttar Pradesh is located in northern part of India (Table 1; Fig. 1). The geology of the state is of hard rock strata type. Topographically the state is divided into plateaus, plains, hills, and valleys. As per LULC, the state land is divided into agricultural land, barren or wasteland, built-up area, forest land and wetlands (https://bhuvan-app1.nrsc.gov.in). Values of EC (998–14,400 μS/cm), TDS (1384–17,110 mg/L), chloride (905–3905 mg/L), sulphate (345–2238 mg/L), nitrate (56–886 mg/L), fluoride (1.4–85 mg/L), and iron (3.7–14.5 mg/L) were found above the limit of BIS and WHO in most of the districts of Uttar Pradesh (Table 2). The highest value of nitrate, fluoride and iron was observed in Ramganga basin, while the highest value of EC, TDS, chloride and sulphate were observed in Mathura region. Heavy metal such as cadmium (3.6 mg/L), lead (5.9 mg/L), nickel (4.7 mg/L), and chromium (3.8 mg/L) were also observed above the limit of BIS. In the Ramganga basin, the water quality of most of the districts (J.P. Nagar, Pilibhit, Shahjahanpur, Hardoi, Bijnor, Moradabad, and Bareilly) deteriorated due to iron, nitrate, salinity, and fluoride [151]. In the arid and semi-arid region of Uttar Pradesh water level is declining at a rate of 0.17 m per year in monsoon and 0.19 m per year in post-monsoon [18]. The water quality in the Aligarh district was found impacted due to fly ash disposal as almost all the physicochemical parameters were found above the permissible level [89]. Water quality was ranged from very poor to unsuitable for drinking category in almost all the districts as per the water quality indices [18, 20, 71, 88, 90, 91, 93, 104, 151, 206, 213].

5 Health Effects

Exposure of air, water, soil, noise, and thermal pollution threaten the health of living beings, especially humans. Health Risk Index (HRI) integrates the exposure of various water pollutants on human health in various ways [78, 175]. United States Environmental Protection Agency (USEPA) recommended the following four steps for the calculation of HRI [196]:

1. **Hazard identification**: Determination of particular pollutant causing adverse toxicological impacts on human health.
2. **Dose–response assessment**: Determination of the dose of pollutants beyond which the pollutant pose threat to the health of human beings.
3. **Exposure assessment**: Determination of exposure factors such as pathways of exposure (ingestion and dermal contact), body parameters (body weight, age), exposure frequency and duration etc. [202].
4. **Risk characterization**: Risk due to exposure of various toxic elements is characterized into carcinogenic and non-carcinogenic risks.

Groundwater quality of arid and semi-arid areas was found to be highly affected with nitrate, fluoride, chloride, and sulphate. In some areas boron (Tamil Nadu), radon (Punjab) and other heavy metals were also reported by various researchers. Children's are more prone to the non- carcinogenic health risk (NCR) due to lower body weight as compared to male and female as per the values of health risk index (HRI) of groundwater ingestion and dermal contact in Andhra Pradesh [7, 112, 130], Bihar [103, 111, 118, 125], Delhi [2, 17, 28], Gujarat [56, 120, 124, 175, 177], Haryana [52, 58, 84, 192], Karnataka [38], Madhya Pradesh [26, 67], Punjab [1, 16, 48, 59, 174, 208], Uttar Pradesh [29, 90, 152, 176, 206, 213], Rajasthan [57, 76, 81, 92, 147, 194, 195], Maharashtra [78, 122, 123, 133, 171], Tamil Nadu [22, 82, 143, 154], and Telangana [6–8, 60, 68, 96, 138].

Dental, skeletal and crippling fluorosis and mottled enamel due to fluoride contaminated water consumption were commonly found in Andhra Pradesh as evidence to non-carcinogenic risk (NCR) [191]. Carcinogenic health risk (CR) due to consumption of heavy metals and strontium (Sr) rich water consumption were also reported in Prakasam district by Khandare et al. [94]. Both NCR and CR were reported in Tungabhadra basin of Karnataka due to consumption of heavy metals contaminated water [38]. The radon in groundwater of Barnala district of Punjab was found below the prescribed limit and therefore health risk was not reported [155]. CR was also reported in southern Punjab due to consumption of arsenic and chromium contaminated water [102, 128, 208]. Both NCR and CR was observed in and around the

Industrial area of Virudhunagar, Tamil Nadu, India [149] and in the cathchment area of river Shanmughanadhi of district Dindigul [209] and river Palar [207].

6 Management

Due to the scarcity of water in arid and semi-arid areas, groundwater management becomes more essential than any other area. In this era of urbanization and industrialization, the management of groundwater resources becomes an urgent task throughout the world for the long-term survival of the human race on this planet earth. Here are some strategies that can be followed for the management of groundwater resource:

1. **Integrated watershed management**: There is a need for harmony between water, soil, and nutrients for a sustainable environment in arid and semi-arid areas to protect underground and surface water resources.
2. **Using the remote sensing technique**: By applying remote sensing (RS), land-use patterns or thematic maps can be prepared which helps in locating the water structure, forest area, plain area, and populated areas easily. Protecting identified water bodies from exploitation and maintaining the forest area near these water bodies help in the groundwater recharge which will enhance the area's water table. Using the thematic map, planning of watershed and check dam construction, rainwater harvesting, and soil conservation schemes can be planned easily which will reduce the capital of water management plan to a great extent. By using a Geographic information system (GIS), identification and quantification of the groundwater can be performed for effective management of groundwater and planning the groundwater recharging sites [15, 131, 188, 214].
3. **Construction of reservoir**: Reservoir construction increases the infiltration or recharge of groundwater. The construction of reservoir at the appropriate place is necessary to store the water of rivers and surface runoff. A thematic map of that particular area will help in the selection of an appropriate place for the construction of reservoir. Felicitous and consistent maintenance of these reservoirs (such as silt cleaning, and construction of a check dam in the route of inlet streams) is necessary for effective working.
4. **Construction of wastewater treatment plants**: In India we have the facility to treat only 30% (either domestic or industrial) of the wastewater generated per day and the rest of the wastewater is discharged on open ground and in freshwater resources (pond, lake rives) [50, 51]. In this way, we are creating two major problems; water scarcity (due to the extraction of a large amount of groundwater) and water pollution. Therefore, to resolve both problems, treatment of wastewater is necessary. After the launching of Namami Gange Programme (NGP), the capacity extension and construction of the effluent treatment plants (ETP), sewage treatment plants (STP) and common effluent treatment plants

(CETP) has been increased. In NGP, 160 wastewater treatment plants have been sanctioned. Among them, some are completed and rests are in under the progress.

5. **Construction of groundwater recharge pond**: Groundwater recharge ponds should be prepared after careful consideration of the geology of the area. As per the report of the Central Ground Water Board [44], the groundwater extraction rate in India is about 245 km^3 per year. To enhance groundwater recharge via minor irrigation systems or managed aquifer recharge (MAR) check dams are used throughout the world [49]. Groundwater recharge is affected by geologic formation, slope, precipitation, LULC, soil type, and drainage characteristics [34]. Implementation of MAR along the degraded wells can reduce the number of salts in the groundwater [121].
6. **Applying the rain water harvesting (RWH) scheme**: RS and GIS are the major and handy tools for the easy characterization of rainwater harvesting (RWH) structures. These two technologies help in the derivation of RWH potential zone maps which provide useful insights to planners, water managers, policymakers, and water resource engineers [184]. Tamil Nadu is the first state in India to make RWH compulsory in every new building. RWH improves groundwater infiltration, water table, water quality, and water yields.
7. **By reducing the groundwater consumption**: Maximum groundwater is used in agriculture followed by industries. There is a need to regulate the drilling of wells in agriculture-intensive areas as well as in industrial clusters. Although many such schemes exist for the industrial sector but we found no such scheme for agricultural areas. By developing a licensing scheme for bore well drilling, we can check groundwater abstraction.
8. **By increasing the Research and Development (R&D)**: By increasing the R&D in wastewater treatment, we will be able to find new technology and resolve the issues of existing treatment plants. In every part of India, there is a huge potential for R&D, but motivation is needed by increasing the employability chances in R&D.
9. **By the involvement of NABL accredited Laboratories**: Our country has a huge chain of NABL (National Accreditation Board for Testing and Calibration Laboratories) accredited laboratories. These laboratories will become assets for the government in the monitoring of surface as well as groundwater quality throughout the country. By making it mandatory for NABL-accredited laboratories as part of social corporate responsibility (CSR) to regularly monitor the ground and surface water quality of the concerned districts and submit the data to the government. For this, a memorandum of understanding (MOU) should be signed between the governments, NABL-accredited laboratories, and companies working in that particular area.

7 Challenges

1. **Monitoring challenges**: India is a huge country with more than a billion of population. In order to protect the water resource of the country from pollution, there is a need for proper monitoring of all the resources. Even in this twenty-first century, we are unable to map all the perennial and non-perennial rivers, ponds, lakes, and streams. First of all, proper mapping of all the water resources with the help of Remote Sensing and Geographic Information System (RS-GIS) and ground survey should be prepared and then the monitoring plan should be launched in each state whether it is arid or semi-arid simultaneously. During the literature survey, we don't find any guidelines for the selection of sampling sites for groundwater monitoring. In absence of proper guidelines, monitoring groundwater quality is a big challenge and a time-consuming task.
2. **Authentic data**: As we have no guidelines for the selection of sampling sites for groundwater quality monitoring, there is doubt about the data obtained. Each person selects the sampling sites at their convenience. During the review, we observed a large variation in the water quality parameters reported by different authors at the same time in the same area. In that case, authentic prediction of water quality is a big challenge. Besides this, we observed a lack of studies assessing the complete water quality parameters.
3. **Treatment challenges**: In Bihar, water quality is mostly affected by arsenic, fluoride, and iron (http://phedbihar.gov.in/WaterQuality.aspx). For the treatment of fluoride, a fluoride removal centre (FRC) and for arsenic, an arsenic removal unit (ARU) was established. But most of the units were reported as non-functional by various researchers [108]. Lack of maintenance (backwashing and sludge removal from filter unit) resulted in filter blockage and lack of awareness are the other problems observed from the literature study. Therefore, regular inspection of all the treatment facilities available in the country is needed. RWH was made mandatory for all new buildings in Tamil Nadu for groundwater management. Except Bihar and Tamil Nadu, such treatment facilities were not found in any other state.

8 Conclusion

The present review was carried out to assess the groundwater quality, management practices, and challenges in arid and semi-arid parts of India. It was concluded that groundwater was polluted due to the presence of recalcitration toxic organic, inorganic and microbiological contaminants in the arid and semi-arid areas of India. The concentration of the various parameters was found beyond the desirable and permissible limit of the BIS standard which may cause the number of harmful effects on the human health. In almost all the arid and semi-arid states, none of the groundwater management practices was found which shows the neutrality of government as well as the public towards the environment and health issues except in Bihar, where the government installed fluoride removal centre (FRC) for fluoride removal and arsenic removal unit (ARU) for arsenic removal and in Tamil Nadu, where RWH was made mandatory for all the new buildings. However, the central government focused on wastewater treatment and sanctioned the 160 STPs in different parts of the country under the Namami Gange Programme.

9 Recommendations

On the basis of present study following are the recommendations:-

1. Groundwater resources assessment and management for drinking purose is very essential globally especially in arid and semi-arid areas. When it comes the developing nations such as India, this essential task becomes the need of the present hour. Therefore, there is a need to increase the awareness among the public and government regarding environmental issues so that we can be able to protect this precious life commodity.
2. It is also recommended that to establish the dynamic and GIS based database of all the essential statistics and data related to ground water resources in arid and semi arid regions of India.
3. In all the arid and semi-arid areas rain water harvesting (RWH) for large buildings should be made mandatory.
4. Regular monitoring plan should be prepared for groundwater management practices installed by the government such as fluoride removal centre (FRC) and arsenic removal centre (ARU).
5. A study of depth based spatio-temporal variations in groundwater quality is also recommended in all the arid and semi-arid areas of the country.

Acknowledgements The corresponding author would like to thanks to Dr. Varun Tyagi for his continuous support in map preparation. We also acknowledge our thanks to the editors for their support during the preparation of this manuscript.

Abbreviation

EC	Electrical Conductivity
TDS	Total Dissolved Solids
TH	Total Hardness
Ca^{2+}	Calcium
Mg^{2+}	Magnesium
TA	Total Alkalinity
$SO_4{}^{2-}$	Sulpahte
$NO_3{}^{-}$	Nitrate

Cl	Chloride
F	Fluoride
Na	Sodium
K	Potassium
As	Arsenic
WQI	Water Quality Index
Fe	Iron
Zn	Zinc
Mn	Manganese
HCO_3^-	Bicarbonate
Hg	Mercury
Pb	Lead
Cd	Cadmium
LULC	Land use land cover
Cr	Chromium
Cu	Copper
HRI	Health Risk Index
mg/L	Miligram per litre

References

1. Ahada CP, Suthar S (2018) Groundwater nitrate contamination and associated human health risk assessment in southern districts of Punjab, India. Environ Sci Pollut Res 25:25336–25347. https://doi.org/10.1007/s11356-018-2581-2
2. Alsubih M, El Morabet R, Khan RA, Khan NA, ul Haq Khan M, Ahmed S, Qadir A, Changani F (2021) Occurrence and health risk assessment of arsenic and heavy metals in groundwater of three industrial areas in Delhi, India. Environ Sci Pollut Res 28:63017–63031. https://doi.org/10.1007/s11356-021-15062-3
3. Acharya S, Sharma SK, Khandegar V (2018) Assessment of groundwater quality by water quality indices for irrigation and drinking in South West Delhi, India. Data Brief 18:2019–2028. https://doi.org/10.1016/j.dib.2018.04.120
4. Adimalla N, Venkatayogi S (2018) Geochemical characterization and evaluation of groundwater suitability for domestic and agricultural utility in semi-arid region of Basara, Telangana State, South India. Appl Water Sci 8(1):1–14. https://doi.org/10.1007/s13201-018-0682-1
5. Adimalla N, Venkatayogi SJEES (2017) Mechanism of fluoride enrichment in groundwater of hard rock aquifers in Medak, Telangana State, South India. Environ Earth Sci 76(1):1–10. https://doi.org/10.1007/s12665-016-6362-2
6. Adimalla N, Wu J (2019) Groundwater quality and associated health risks in a semi-arid region of south India: implication to sustainable groundwater management. Hum Ecol Risk Assess Int J 25(1–2):191–216. https://doi.org/10.1080/10807039.2018.1546550
7. Adimalla N, Li P, Qian H (2018) Evaluation of groundwater contamination for fluoride and nitrate in semi-arid region of Nirmal Province, South India: a special emphasis on human health risk assessment (HHRA). Hum Ecol Risk Assess Int J 25(5):1107–1124. https://doi.org/10.1080/10807039.2018.1460579
8. Adimalla N, Li P, Venkatayogi S (2018) Hydrogeochemical evaluation of groundwater quality for drinking and irrigation purposes and integrated interpretation with water quality index studies. Environ Process 5(2):363–383. https://doi.org/10.1007/s40710-018-0297-4

9. Adimalla N, Manne R, Zhang Y, Xu P, Qian H (2022) Evaluation of groundwater quality and its suitability for drinking purposes in semi-arid region of Southern India: an application of GIS. Geocarto Int, 1–12. https://doi.org/10.1080/10106049.2022.2040603
10. Adimalla N, Qian H, Li P (2020) Entropy water quality index and probabilistic health risk assessment from geochemistry of groundwaters in hard rock terrain of Nanganur County, South India. Geochemistry 80(4):125544. https://doi.org/10.1016/j.chemer.2019.125544
11. Adimalla N (2019) Groundwater quality for drinking and irrigation purposes and potential health risks assessment: a case study from semi-arid region of South India. Expo Health 11:109–123. https://doi.org/10.1007/s12403-018-0288-8
12. Adimalla N (2020) Controlling factors and mechanism of groundwater quality variation in semiarid region of South India: an approach of water quality index (WQI) and health risk assessment (HRA). Environ Geochem Health 42(6):1725–1752. https://doi.org/10.1007/s10653-019-00374-8
13. Adimalla N, Li P (2019) Occurrence, health risks, and geochemical mechanisms of fluoride and nitrate in groundwater of the rock-dominant semi-arid region, Telangana State, India. Hum Ecol Risk Assess Int J 25(1–2):81–103. https://doi.org/10.1080/10807039.2018.1480353
14. Afshan N, Nagaraju D, Bhanuprakash HM, Deep PG (2022) Seasonal analysis of groundwater samples to identify water quality index and comparative statistical analysis of HunsurTaluk, Mysuru, Karnataka, India. SN Appl Sci 4(8):1–15. https://doi.org/10.1007/s42452-022-05102-z
15. Ahamad F, Bhutiani R, Ruhela M (2022) Environmental quality monitoring using environmental quality indices (EQI), geographic information system (GIS), and remote sensing: a review. GIScience Sustain Manag Water Resour, 331. (Chapter number-18, pp 331–348, ISBN ebook: 9781003284512). https://doi.org/10.1201/9781003284512-21
16. Ahada CP, Suthar S (2018) Assessing groundwater hydrochemistry of Malwa Punjab, India. Arab J Geosci 11:1–15. https://doi.org/10.1007/s12517-017-3355-8
17. Ahamad A, Raju NJ, Madhav S, Gossel W, Wycisk P (2019) Impact of non-engineered Bhalswa landfill on groundwater from Quaternary alluvium in Yamuna flood plain and potential human health risk, New Delhi, India. Quatern Int 507:352–369. https://doi.org/10.1016/j.quaint.2018.06.011
18. Ahmad S, Abdullah M, Rehman A (2021) Temporal and spatial trends of groundwater depth level in Ganga-Yamuna Doab, central Ganga basin, India. J Indian Geophys Union 25(3):79–89
19. Ahmad S, Umar R, Arshad I (2019) Groundwater quality appraisal and its hydrogeochemical characterization—Mathura City, Western Uttar Pradesh. J Geol Soc India 94(6):611–623. https://doi.org/10.1007/s12594-019-1368-5
20. Ahmed S, Khurshid S, Qureshi F, Hussain A, Bhattacharya A (2019) Heavy metals and geo-accumulation index development for groundwater of Mathura city, Uttar Pradesh. Desalin Water Treat 138:291–300. https://doi.org/10.5004/dwt.2019.23322
21. Ahmed S, Khurshid S, Madan R, Amarah BAA, Naushad M (2020) Water quality assessment of shallow aquifer based on Canadian Council of Ministers of the environment index and its impact on irrigation of Mathura District, Uttar Pradesh. J King Saud Univ-Sci 32(1):1218–1225. https://doi.org/10.1016/j.jksus.2019.11.019
22. Akshitha V, Balakrishna K, Udayashankar HN (2022) Evaluation of groundwater quality using GIS techniques in part of Udupi district, Karnataka, Southern India. In: Innovative trends in hydrological and environmental systems: select proceedings of ITHES 2021. Singapore: Springer Nature Singapore, pp 385–396. https://doi.org/10.1007/978-981-19-0304-5_28
23. Ali S, Khan SU, Gupta SK, Sinha A, Gupta MK, Abbasnia A, Mohammadi AA (2021) Health risk assessment due to fluoride exposure from groundwater in rural areas of Agra, India: Monte Carlo simulation. Int J Environ Sci Technol 18(11):3665–3676. https://doi.org/10.1007/s13762-020-03084-2
24. Ali S, Shekhar S, Bhattacharya P, Verma G, Chandrasekhar T, Chandrashekhar AK (2018) Elevated fluoride in groundwater of Siwani Block, Western Haryana, India: a potential concern for sustainable water supplies for drinking and irrigation. Groundw Sustain Dev 7:410–420. https://doi.org/10.1016/j.gsd.2018.05.008

25. Ali S, Thakur SK, Sarkar A, Shekhar S (2016) Worldwide contamination of water by fluoride. Environ Chem Lett 14:291–315. https://doi.org/10.1007/s10311-016-0563-5
26. Ali S, Fakhri Y, Golbini M, Thakur SK, Alinejad A, Parseh I, Shekhar S, Bhattacharya P (2019) Concentration of fluoride in groundwater of India: a systematic review, meta-analysis and risk assessment. Groundw Sustain Dev 9:100224. https://doi.org/10.1016/j.gsd.2019.100224
27. Ali S, Shekhar S, Chandrasekhar T, Yadav AK, Arora NK, Kashyap CA, Bhattacharya P, Rai SP, Pande P, Chandrasekharam D (2021) Influence of the water–sediment interaction on the major ions chemistry and fluoride pollution in groundwater of the Older Alluvial Plains of Delhi, India. J Earth Syst Sci 130(2):98. https://doi.org/10.1007/s12040-021-01585-3
28. Ali S, Shekhar S, Chandrasekhar T (2022) Non-carcinogenic health risk assessment of fluoride in groundwater of the River Yamuna flood plain, Delhi, India. In: Computers in earth and environmental sciences. Elsevier, pp 455–466. https://doi.org/10.1016/B978-0-323-89861-4.00046-4
29. Ali S, Kumari M, Gupta SK, Sinha A, Mishra BK (2017) Investigation and mapping of fluoride-endemic areas and associated health risk—a case study of Agra, Uttar Pradesh, India. Hum Ecol Risk Assess Int J 23(3):590–604. https://doi.org/10.1080/10807039.2016.1255139
30. Aneesha Satya B, Shashi M, Deva P (2020) Future land use land cover scenario simulation using open source GIS for the city of Warangal, Telangana, India. Appl Geomat 12:281–290. https://doi.org/10.1007/s12518-020-00298-4
31. Arulbalaji P, Gurugnanam B (2017) Groundwater quality assessment using geospatial and statistical tools in Salem District, Tamil Nadu, India. Appl Water Sci 7:2737–2751. https://doi.org/10.1007/s13201-016-0501-5
32. Balaji E, Veeraswamy G, Prasad M (2018) Assessing groundwater hydrochemistry of Atmakur, SPSR Nellore district, Andhra Pradesh, India. Fresenius Environ Bull 27(11):7897–7905
33. Bano N (2017) Assessment of physicochemical characteristics of groundwater quality used for drinking water supply of Firozabad City, India using index method. J Appl Sci Environ Manag 21(4):729–731. https://doi.org/10.4314/jasem.v21i4.13
34. Bhagwat TN, Hegde VS, Shetty A (2018) Application of remote sensing and GIS for identification of potential ground water recharge sites in Semi-arid regions of Hard-rock terrain, in north Karnataka, South India. Sustain Water Resour Manag 4(4):1063–1076. https://doi.org/10.1007/s40899-018-0244-6
35. Bhakar P, Singh AP (2019) Groundwater quality assessment in a hyper-arid region of Rajasthan, India. Nat Resour Res 28(2):505–522. https://doi.org/10.1007/s11053-018-9405-4
36. Bhardwaj S, Soni R, Gupta SK, Shukla DP (2020) Mercury, arsenic, lead and cadmium in waters of the Singrauli coal mining and power plants industrial zone, Central East India. Environ Monit Assess 192(4):1–20. https://doi.org/10.1007/s10661-020-8225-2
37. Bhat NA, Ghosh P, Ahmed W, Naaz F, Priyadashinee A (2019) Hydrochemical characteristics and quality assessment of stream water in parts of Gadag, Koppal and Ballery districts of Karnataka, India. J Geol Soc India 94(6):635–640. https://doi.org/10.1007/s12594-019-1370-y
38. Bhat NA, Ghosh P, Ahmed W, Naaz F, Darshinee AP (2022) Heavy metal contamination in soils and stream water in Tungabhadra basin, Karnataka: environmental and health risk assessment. Int J Environ Sci Technol, 1–14. https://doi.org/10.1007/s13762-022-04040-y
39. Bhatia S, Balamurugan G, Baranwal A (2014) High arsenic contamination in drinking water hand-pumps in KhapTola, West Champaran, Bihar, India. Front Environ Sci 2:49. https://doi.org/10.3389/fenvs.2014.00049
40. Bidhuri S, Khan MMA (2020) Assessment of ground water quality of central and southeast districts of NCT of Delhi. J Geol Soc India 95:95–103. https://doi.org/10.1007/s12594-020-1390-7
41. Bojago, E, Tyagi, I, Ahamad, F, Chandniha SK (2023) GIS based spatial-temporal distribution of water quality parameters and heavy metals in drinking water: ecological and health modelling. Phys Chem Earth, Parts A/B/C, 103399. https://doi.org/10.1016/j.pce.2023.103399

42. Carrard N, Foster T, Willetts J (2019) Groundwater as a source of drinking water in southeast Asia and the Pacific: a multi-country review of current reliance and resource concerns. Water 11(8):1605. https://doi.org/10.3390/w11081605
43. CGWB (2009) District brochure of Ghaziabad district, U.P. groundwater central ground water board. http://www.cgwb.gov.in/District_Profile/UP/Ghaziabad.pdf
44. CGWB (2019) Dynamic ground water resources of India, 2017, government of India, Ministry of Jal Shakti, central ground water board. http://cgwb.gov.in/GW-Assessment/GWRA-2017-National-Compilation.pdf
45. CGWB (2012) Groundwater quality of NCT Delhi, report. Central ground water board, report, ministry of water resources, government of India
46. Chakraborti D, Mukherjee SC, Pati S, Sengupta MK, Rahman MM, Chowdhury UK, Lodh D, Chanda CR, Chakraborti AK, Basu GK (2003) Arsenic groundwater contamination in Middle Ganga Plain, Bihar, India: a future danger? Environ Health Perspect 111(9):1194–1201. https://doi.org/10.1289/ehp.5966
47. Chaudhary V, Satheeshkumar S (2018) Assessment of groundwater quality for drinking and irrigation purposes in arid areas of Rajasthan, India. Appl Water Sci 8(8):1–17. https://doi.org/10.1007/s13201-018-0865-9
48. Chaudhry AK, Sachdeva P (2020) Groundwater quality and non-carcinogenic health risk assessment of nitrate in the semi-arid region of Punjab, India. J Water Health 18(6):1073–1083. https://doi.org/10.2166/wh.2020.121
49. Chinnasamy P, Maske AB, Honap V, Chaudhary S, Agoramoorthy G (May 2021) Sustainable development of water resources in marginalised semi-arid regions of India: case study of Dahod in Gujarat, India. In: Natural resources forum, vol. 45, no 2. Blackwell Publishing Ltd., Oxford, UK, pp. 105–119. https://doi.org/10.1111/1477-8947.12217
50. CPCB (1999) Status of water supply and wastewater collection treatment & disposal in class I cities-1999, Control of urban pollution series: CUPS/44/1999-2000
51. CPCB (2005) Parivesh sewage pollution–news letter. Central pollution control board, ministry of environment and forests, govt. of India, PariveshBhawan, East Arjun Nagar, Delhi 110 032. http://cpcbenvis.nic.in/newsletter/sewagepollution/contentsewagepoll0205.html
52. Daulta R, Singh B, Kataria N, Garg VK (2018) Assessment of uranium concentration in the drinking water and associated health risks in Eastern Haryana, India. Hum Ecol Risk Assess Int J 24(4):1115–1126. https://doi.org/10.1080/10807039.2017.1406305
53. Deepa S, Venkateswaran S (2018) Appraisal of groundwater quality in upper Manimuktha sub basin, Vellarriver, Tamil Nadu, India by using Water Quality Index (WQI) and multivariate statistical techniques. Model Earth Syst Environ 4(3):1165–1180. https://doi.org/10.1007/s40808-018-0468-3
54. Deepika BV, Ramakrishnaiah CR, Naganna SR (2020) Spatial variability of ground water quality: a case study of Udupi district, Karnataka State, India. J Earth Syst Sci 129:1–20. https://doi.org/10.1007/s12040-020-01471-4
55. Dhaduti M, Hunashyal A, Sujay K (2022) An assessment of groundwater quality of Ilkal Taluk, Bagalkot district, Karnataka, India using GIS and CCME WQI. In: Recent advances in civil engineering: select proceedings of CTCS 2021. Springer Nature Singapore, Singapore, pp 601–615. https://doi.org/10.1007/978-981-19-1862-9_38
56. Dhiman SD (2021) Multivariate analysis and human health risk assessment of groundwater in Amreli district of Gujarat state, India. In: Mathematical modeling, computational intelligence techniques and renewable energy: proceedings of the second international conference, MMCITRE 2021. Springer Singapore, Singapore, pp 313–319. https://doi.org/10.1007/978-981-16-5952-2_27
57. Duggal V, Sharma S, Mehra R (2020) Risk assessment of radon in drinking water in Khetri Copper Belt of Rajasthan, India. Chemosphere 239:124782. https://doi.org/10.1016/j.chemosphere.2019.124782
58. Duggal V, Sharma S, Singh A (2021) Risk assessment of uranium in drinking water in Hisar district of Haryana, India. Water Supply 21(1):249–261. https://doi.org/10.2166/ws.2020.313

59. Duggal V, Sharma S (2022) Fluoride contamination in drinking water and associated health risk assessment in the Malwa Belt of Punjab, India. Environ Adv 8:100242. https://doi.org/10.1016/j.envadv.2022.100242
60. Duvva LK, Panga KK, Dhakate R, Himabindu V (2022) Health risk assessment of nitrate and fluoride toxicity in groundwater contamination in the semi-arid area of Medchal, South India. Appl Water Sci 12(1):11. https://doi.org/10.1007/s13201-021-01557-4
61. Elbeltagi A, Pande CB, Kouadri S, Islam ARM (2022) Applications of various data-driven models for the prediction of groundwater quality index in the Akot basin, Maharashtra, India. Environ Sci Pollut Res 29(12):17591–17605. https://doi.org/10.1007/s11356-021-17064-7
62. Etikala B, Golla V, Adimalla N, Marapatla S (2019) Factors controlling groundwater chemistry of Renigunta area, Chittoor District, Andhra Pradesh, South India: a multivariate statistical approach. HydroResearch 1:57–62. https://doi.org/10.1016/j.hydres.2019.06.002
63. Frommen T, Groeschke M, Nölscher M, Koeniger P, Schneider M (2021) Anthropogenic and geogenic influences on peri-urban aquifers in semi-arid regions: insights from a case study in northeast Jaipur, Rajasthan, India. Hydrogeol J 29(3):1261–1278. https://doi.org/10.1007/s10040-021-02301-7
64. Gaikwad SK, Kadam AK, Ramgir RR, Kashikar AS, Wagh VM, Kandekar AM, Gaikwad SP, Madale RB, Pawar NJ, Kamble KD (2020) Assessment of the groundwater geochemistry from a part of west coast of India using statistical methods and water quality index. HydroResearch 3:48–60. https://doi.org/10.1016/j.hydres.2020.04.001
65. Garg VK, Suthar S, Singh S, Sheoran A, Jain S (2009) Drinking water quality in villages of southwestern Haryana, India: assessing human health risks associated with hydrochemistry. Environ Geol 58(6):1329–1340. https://doi.org/10.1007/s00254-008-1636-y
66. Ghorai D, Roy S, Paul AK (2017) Land use/land cover assessment of Tamil Nadu coast, India using remote sensing and GIS techniques. J Remote Sens GIS 8(2):25–37
67. Godfrey S, Labhasetwar P, Wate S, Pimpalkar S (2011) How safe are the global water coverage figures? Case study from Madhya Pradesh, India. Environ Monit Assess 176:561–574. https://doi.org/10.1007/s10661-010-1604-3
68. Gugulothu S, Subba Rao N, Das R, Duvva LK, Dhakate R (2022) Judging the sources of inferior groundwater quality and health risk problems through intake of groundwater nitrate and fluoride from a rural part of Telangana, India. Environ Sci Pollut Res 29(32):49070–49091. https://doi.org/10.1007/s11356-022-18967-9
69. Gupta PK, Sharma D (2019) Assessment of hydrological and hydrochemical vulnerability of groundwater in semi-arid region of Rajasthan, India. Sustain Water Resour Manag 5(2):847–861. https://doi.org/10.1007/s40899-018-0260-6
70. Gupta RN, Chand G, Kumar A, Kumar T, Vimal BK, Sah SB, Saha T (2016) Assessment of arsenic contamination in water: a case study of surveyed Districts of Bihar, India. Ecol Environ Conserv 22(3):153–159
71. Gupta R, Jindal T, Khan AS, Srivastava P, Kanaujia A (2019) Assessment of ground water quality and its suitability for drinking in industrial area Jajmau, Kanpur, India. Plant Arch 19(1):1569–1571. http://phedbihar.gov.in/WaterQuality.aspx
72. Gupta R, Misra AK (2018) Groundwater quality analysis of quaternary aquifers in Jhajjar District, Haryana, India: focus on groundwater fluoride and health implications. Alex Eng J 57(1):375–381. https://doi.org/10.1016/j.aej.2016.08.031
73. Hutchings P, Parker A, Jeffrey P (2016) The political risks of technological determinism in rural water supply: a case study from Bihar, India. J Rural Stud 45:252–259. https://doi.org/10.1016/j.jrurstud.2016.03.016
74. Inyinbor Adejumoke A, Adebesin Babatunde O, Oluyori Abimbola P, Adelani Akande Tabitha A, Dada Adewumi O, Oreofe Toyin A (2018) Water pollution: effects, prevention, and climatic impact. Water Chall Urban World 33:33–47. https://doi.org/10.5772/intechopen.72018
75. Jadhav SD, Jadhav MS (2021) Evaluation of ground water quality with special reference to sulphate concentration of rural area near Karad City, (Satara) Maharashtra. EM Int Ecol Environ Conserv 27:S174–S177

76. Jandu A, Malik A, Dhull SB (2021) Fluoride and nitrate in groundwater of rural habitations of semiarid region of northern Rajasthan, India: a hydrogeochemical, multivariate statistical, and human health risk assessment perspective. Environ Geochem Health 43(10):3997–4026. https://doi.org/10.1007/s10653-021-00882-6
77. Joint Monitoring Programme for Water Supply and Sanitation WHO/UNICEF (2012) Progress on sanitation and drinking-water: 2012 update. World Health Organization, Geneva
78. Kadam A, Wagh V, Umrikar B, Sankhua R (2020) An implication of boron and fluoride contamination and its exposure risk in groundwater resources in semi-arid region, Western India. Environ Dev Sustain 22(7):7033–7056. https://doi.org/10.1007/s10668-019-00527-w
79. Kalaivanan K, Gurugnanam B, Pourghasemi HR, Suresh M, Kumaravel S (2018) Spatial assessment of groundwater quality using water quality index and hydrochemical indices in the Kodavanar sub-basin, Tamil Nadu, India. Sustain Water Resour Manag 4(3):627–641. https://doi.org/10.1007/s40899-017-0148-x
80. Kalsi RS (2007) Status, distribution and management of Galliformes in arid and semi-arid zones of India. Galliformes of India, pp 101–104
81. Kar S, Gupta R (2023) Fluoride toxicity in Rajasthan, India: human health risk assessment, low-cost water filter preparation, and contaminant remediation. Water Conserv Sci Eng 8(1):3. https://doi.org/10.1007/s41101-023-00175-2
82. Karunanidhi D, Aravinthasamy P, Subramani T, Muthusankar G (2021) Revealing drinking water quality issues and possible health risks based on water quality index (WQI) method in the Shanmuganadhi River basin of South India. Environ Geochem Health 43(2):931–948. https://doi.org/10.1007/s10653-020-00613-3
83. Karunanidhi D, Aravinthasamy P, Deepali M, Subramani T, Roy PD (2020) The effects of geochemical processes on groundwater chemistry and the health risks associated with fluoride intake in a semi-arid region of South India. RSC Adv 10(8):4840–4859. https://doi.org/10.1039/c9ra10332e
84. Kaur L, Rishi MS, Siddiqui AU (2020) Deterministic and probabilistic health risk assessment techniques to evaluate non-carcinogenic human health risk (NHHR) due to fluoride and nitrate in groundwater of Panipat, Haryana, India. Environ Pollut 259:113711. https://doi.org/10.1016/j.envpol.2019.113711
85. Kaur T, Bhardwaj R, Arora S (2017) Assessment of groundwater quality for drinking and irrigation purposes using hydrochemical studies in Malwa region, southwestern part of Punjab, India. Appl Water Sci 7:3301–3316. https://doi.org/10.1007/s13201-016-0476-2
86. Kaushik N (2018) Impact of climate change on water resources in arid and semi-arid region of Rajasthan. J Water Land Use Manag 16(2):53–62
87. Khadija D, Hicham A, Rida A, Hicham E, Nordine N, Najlaa F (2021) Surface water quality assessment in the semi-arid area by a combination of heavy metal pollution indices and statistical approaches for sustainable management. Environ Chall 5:100230. https://doi.org/10.1016/j.envc.2021.100230
88. Khan A, Govil H, Taloor AK, Kumar G (2020) Identification of artificial groundwater recharge sites in parts of Yamuna River basin India based on remote sensing and geographical information system. Groundw Sustain Dev 11:100415. https://doi.org/10.1016/j.gsd.2020.100415
89. Khan I, Umar R (2019) Environmental risk assessment of coal fly ash on soil and groundwater quality, Aligarh, India. Groundw Sustain Dev 8:346–357. https://doi.org/10.1016/j.gsd.2018.12.002
90. Khan I, Umar R, Izhar S (2022) Hydrogeochemical and health risk assessment in and around a Ramsar-designated wetland, the Ganges River Basin, India: implications for natural and human interactions. Environ Monit Assess 194(7):1–24. https://doi.org/10.1007/s10661-022-10154-0
91. Khan MA, Khan N, Ahmad A, Kumar R, Singh A, Chaurasia D, Neogi S, Kumar V, Bhargava PC (2023) Potential health risk assessment, spatio-temporal hydrochemistry and groundwater quality of Yamuna river basin, Northern India. Chemosphere 311:136880. https://doi.org/10.1016/j.chemosphere.2022.136880

92. Khan N, Malik A, Nehra K (2021) Groundwater hydro-geochemistry, quality, microbiology and human health risk assessment in semi-arid area of Rajasthan, India: a chemometric approach. Environ Monit Assess 193(4):1–36. https://doi.org/10.1007/s10661-021-08979-2
93. Khan SU, Noor A, Farooqi IH (2015) GIS application for groundwater management and quality mapping in rural areas of district Agra, India. Int J Water Res Arid Env 4(1):89–96
94. Khandare AL, Validandi V, Rajendran A, Singh TG, Thingnganing L, Kurella S, Nagaraju R, Dheeravath S, Vaddi N, Kommu S, Maddela Y (2020) Health risk assessment of heavy metals and strontium in groundwater used for drinking and cooking in 58 villages of Prakasam district, Andhra Pradesh, India. Environ Geochem Health 42:3675–3701. https://doi.org/10.1007/s10653-020-00596-1
95. Kharol SK, Kaskaoutis DG, Badarinath KVS, Sharma AR, Singh RP (2013) Influence of land use/land cover (LULC) changes on atmospheric dynamics over the arid region of Rajasthan state, India. J Arid Environ 88:90–101. https://doi.org/10.1016/j.jaridenv.2012.09.006
96. Kom KP, Gurugnanam B, Bairavi S, Chidambaram S (2023) Sources and geochemistry of high fluoride groundwater in hard rock aquifer of the semi-arid region. A special focus on human health risk assessment. Total Environ Res Themes, 100026. https://doi.org/10.1016/j.totert.2023.100026
97. Krishan G, Rao MS, Kumar CP, Semwal P (2013) Identifying salinization using isotopes and ion chemistry in semi-arid region of Punjab, India. J Geol Geosci 2(4):1–6. https://doi.org/10.4172/2329-6755.1000129
98. Krishan G, Sejwal P, Bhagwat A, Prasad G, Yadav BK, Kumar CP, Kansal ML, Singh S, Sudarsan N, Bradley A, Muste M (2021) Role of ion chemistry and hydro-geochemical processes in aquifer salinization—a case study from a semi-arid region of Haryana, India. Water 13(5):617. https://doi.org/10.3390/w13050617
99. Kumar R, Singh RD, Sharma KD (2005) Water resources of India. Curr Sci, 794–811. https://doi.org/10.3390/w11040724, https://www.jstor.org/stable/24111024
100. Kumar A, Kumar R, Rahman M, Ali M, Kumar R, Nupur N, Gaurav A, Raj V, Anand G, Niraj PK, Ghosh AK (2021) Assessment of arsenic exposure in the population of Sabalpur village of Saran district of Bihar with mitigation approach. Environ Sci Pollut Res 28(32):43923–43934. https://doi.org/10.1007/s11356-021-13521-5
101. Kumar J, Biswas B, Verghese S (2021) Assessment of groundwater quality for drinking and irrigation purpose using geospatial and statistical techniques in a semi-arid region of Rajasthan, India. J Geol Soc India 97(4):416–427. https://doi.org/10.1007/s12594-021-1699-x
102. Kumar R, Mittal S, Sahoo PK, Sahoo SK (2021) Source apportionment, chemometric pattern recognition and health risk assessment of groundwater from southwestern Punjab, India. Environ Geochem Health 43:733–755. https://doi.org/10.1007/s10653-020-00518-1
103. Kumar M, Rahman MM, Ramanathan AL, Naidu R (2016) Arsenic and other elements in drinking water and dietary components from the middle Gangetic plain of Bihar, India: health risk index. Sci Total Environ 539:125–134. https://doi.org/10.1016/j.scitotenv.2015.08.039
104. Kumar N, Kumar D, Kumar S, Shukla V, Shukla P, Raj B (2018) Spatio-temporal variations in hydro-geochemistry of groundwater at rural, urban and industrial areas of Kanpur, India. Environ Sustain 1(2):197–208. https://doi.org/10.1007/s42398-018-0019-x
105. Kumar P, Dasgupta R, Johnson BA, Saraswat C, Basu M, Kefi M, Mishra BK (2019) Effect of land use changes on water quality in an ephemeral coastal plain: Khambhat City, Gujarat, India. Water 11(4):724
106. Kumar S, Sarkar A, Ali S, Shekhar S (2018) Groundwater system of national capital region Delhi, India. In: Mukherjee A (eds) Groundwater of South Asia. Springer hydrogeology. Springer, Singapore, pp 131–152. ISBN: 978-981-10-3888-4. https://doi.org/10.1007/978-981-10-3889-1_9
107. Kumar S, Singh R (2021) Geospatial applications in land use/land cover change detection for sustainable regional development: the case of central Haryana, India. Geomat Environ Eng 15(3):81–98. https://doi.org/10.7494/geom.2021.15.3.81

108. Kumari A, Maurya NS (2018) Evaluation of treatment technologies for arsenic-free drinking water supply, disposal of backwash water and exhausted media in Bihar, India. In: Water quality management. Springer, Singapore, pp 15–25. https://doi.org/10.1007/978-981-10-5795-32
109. Kumari P, Gupta NC, Kaur A, Singh K (2019) Application of principal component analysis and correlation for assessing groundwater contamination in and around municipal solid waste landfill of Ghazipur, Delhi. J Geol Soc India 94:595–604. https://doi.org/10.1007/s12594-019-1366-7
110. Kumari M, Rai SC (2020) Hydrogeochemical evaluation of groundwater quality for drinking and irrigation purposes using water quality index in semi-arid region of India. J Geol Soc India 95:159–168. https://doi.org/10.1007/s12594-020-1405-4
111. Kumari P, Misra AK (2023) Potential health risk assessment and distribution of fluoride in groundwater of Munger, Bihar India: a case study. Hum Ecol Risk Assess Int J, 1–20. https://doi.org/10.1080/10807039.2023.2178879
112. Kuppan C, Sangadi P (2021) Hydro-geochemical evaluation and health risk assessment of groundwater in coastal regions: a case study of eastern Andhra Pradesh, South India. Arab J Geosci 14:1–18. https://doi.org/10.1007/s12517-021-07467-8
113. Lakshminarayanan S, Jayalakshmy R (2015) Diarrheal diseases among children in India: current scenario and future perspectives. J Nat Sci Biol Med 6(1):24. https://doi.org/10.4103/0976-9668.149073
114. Li P, Qian H (2018) Water resources research to support a sustainable China. Int J Water Resour Dev 34(3):327–336. https://doi.org/10.1080/07900627.2018.1452723
115. Li P, He S, He X, Tian R (2018) Seasonal hydrochemical characterization and groundwater quality delineation based on matter element extension analysis in a paper wastewater irrigation area, northwest China. Expo Health 10(4):241–258. https://doi.org/10.1007/s12403-017-0258-6
116. Li P, Zhang Y, Yang N, Jing L, Yu P (2016) Major ion chemistry and quality assessment of groundwater in and around a mountainous tourist town of China. Expo Health 8(2):239–252. https://doi.org/10.1007/s12403-016-0198-6
117. Majumder A, Kingra PK, Setia R, Singh SP, Pateriya B (2020) Influence of land use/land cover changes on surface temperature and its effect on crop yield in different agro-climatic regions of Indian Punjab. Geocarto Int 35(6):663–686. https://doi.org/10.1080/10106049.2018.1520927
118. Maity S, Biswas R, Sarkar A (2020) Comparative valuation of groundwater quality parameters in Bhojpur, Bihar for arsenic risk assessment. Chemosphere 259:127398. https://doi.org/10.1016/j.chemosphere.2020.127398
119. Malik MS, Shukla JP (2019) Assessment of groundwater vulnerability risk in shallow aquifers of Kandaihimmat Watershed, Hoshangabad, Madhya Pradesh. J Geol Soc India 93(2):199–206. https://doi.org/10.1007/s12594-019-1152-6
120. Mandal R, Das A, Sudheer AK, Kumar S, Verma S, Gaddam M, Deshpande RD (2021) Sources, controls, and probabilistic health risk assessment of fluoride contamination in groundwater from a semi-arid region in Gujarat, Western India: an isotope–hydrogeochemical perspective. Environ Geochem Health 43(10):4043–4059. https://doi.org/10.1007/s10653-021-00894-2
121. Manoj S, Thirumurugan M, Elango L (2017) An integrated approach for assessment of groundwater quality in and around uranium mineralized zone, Gogi region, Karnataka, India. Arab J Geosci 10(24):1–17. https://doi.org/10.1007/s12517-017-3321-5
122. Mawari G, Kumar N, Sarkar S, Frank AL, Daga MK, Singh MM, Joshi TK, Singh I (2022) Human health risk assessment due to heavy metals in ground and surface water and association of diseases with drinking water sources: a study from Maharashtra, India. Environ Health Insights 16:11786302221146020. https://doi.org/10.1177/11786302221146020
123. Marghade D, Malpe DB, SubbaRao N (2021) Applications of geochemical and multivariate statistical approaches for the evaluation of groundwater quality and human health risks in a semi-arid region of eastern Maharashtra, India. Environ Geochem Health 43(2):683–703. https://doi.org/10.1007/s10653-019-00478-1

124. Masood N, Farooqi A, Zafar MI (2019) Health risk assessment of arsenic and other potentially toxic elements in drinking water from an industrial zone of Gujrat, Pakistan: a case study. Environ Monit Assess 191:1–15. https://doi.org/10.1007/s12665-020-08972-x
125. Mridha D, Priyadarshni P, Bhaskar K, Gaurav A, De A, Das A, Joardar M, Chowdhury NR, Roychowdhury T (2021) Fluoride exposure and its potential health risk assessment in drinking water and staple food in the population from fluoride endemic regions of Bihar, India. Groundw Sustain Dev 13:100558. https://doi.org/10.1016/j.gsd.2021.100558
126. Maurya P, Kumari R, Mukherjee S (2019) Hydrochemistry in integration with stable isotopes (δ18O and δD) to assess seawater intrusion in coastal aquifers of Kachchh district, Gujarat, India. J Geochem Explor 196:42–56. https://doi.org/10.1016/j.gexplo.2018.09.013
127. Misra A, Balaji R (2015) Decadal changes in the land use/land cover and shoreline along the coastal districts of southern Gujarat, India. Environ Monit Assess 187:1–13. https://doi.org/10.1007/s10661-015-4684-2
128. Mittal S, Sahoo PK, Sahoo SK, Kumar R, Tiwari RP (2021) Hydrochemical characteristics and human health risk assessment of groundwater in the Shivalik region of Sutlej basin, Punjab, India. Arab J Geosci 14(10):847. https://doi.org/10.1007/s12517-021-07043-0
129. Mohammed-Aslam MA, Rizvi SS (2020) Hydrogeochemicalcharacterisation and appraisal of groundwater suitability for domestic and irrigational purposes in a semi-arid region, Karnataka state, India. Appl Water Sci 10(12):1–37. https://doi.org/10.1007/s13201-020-01320-1
130. Molagamudi SR, Uravakonda S, Badapalli PK, Golla VS (2022) Evaluation of groundwater chemistry and its impact on drinking, irrigation, and human health hazard risk assessment (HHRA) in Pincha river basin, semi-arid region of Andhra Pradesh, India. Int J Energy Water Resour, 1–7. https://doi.org/10.1007/s42108-021-00170-0
131. Mookiah M, Jha SK, Biswas A (2021) Assessment of groundwater mass balance and zone budget in the semi-arid region: a case study of Palar sub-basin, Tamil Nadu, India. J Earth Syst Sci 130(4):1–18. https://doi.org/10.1007/s12040-021-01691-2
132. Mukate S, Panaskar D, Wagh V, Muley A, Jangam C, Pawar R (2018) Impact of anthropogenic inputs on water quality in Chincholi industrial area of Solapur, Maharashtra, India. Groundw Sustain Dev 7:359–371. https://doi.org/10.1016/j.gsd.2017.11.001
133. Mukate S, Bhoominathan S, Solanky V (2022) Assessment of human health risk arising due to fluoride and nitrate in groundwater: a case study of Bhokardan tehsil of Maharashtra. Hum Ecol Risk Assess Int J 28(5–6):594–620. https://doi.org/10.1080/10807039.2022.2081837
134. Mukherjee I, Singh UK (2018) Groundwater fluoride contamination, probable release, and containment mechanisms: a review on Indian context. Environ Geochem Health 40(6):2259–2301. https://doi.org/10.1007/s10653-018-0096-x
135. Naaz A, Kumar B, Narayan C, Shukla K (2015) Assessment of fluoride pollution in groundwater of arid and semi-arid regions of tonalite–trondjhemite series in central India. Water Qual Expo Health 7(4):545–556. https://doi.org/10.1007/s12403-015-0171-9
136. Nagaraju A, Sreedhar Y, Thejaswi A, Sayadi MH (2017) Water quality analysis of the Rapur area, Andhra Pradesh, South India using multivariate techniques. Appl Water Sci 7(6):2767–2777. https://doi.org/10.1007/s13201-016-0504-2
137. Narsimha A, Sudarshan V (2017) Contamination of fluoride in groundwater and its effect on human health: a case study in hard rock aquifers of Siddipet, Telangana State, India. Appl Water Sci 7(5):2501–2512. https://doi.org/10.1007/s13201-016-0441-0
138. Narsimha A, Rajitha S (2018) Spatial distribution and seasonal variation in fluoride enrichment in groundwater and its associated human health risk assessment in Telangana State, South India. Hum Ecol Risk Assess Int J 24(8):2119–2132. https://doi.org/10.1016/j.chemer.2019.125548
139. Negi P, Mor S, Ravindra K (2020) Impact of landfill leachate on the groundwater quality in three cities of North India and health risk assessment. Environ Dev Sustain 22:1455–1474. https://doi.org/10.1007/s10668-018-0257-1
140. Onda K, LoBuglio J, Bartram J (2012) Global access to safe water: accounting for water quality and the resulting impact on MDG progress. Int J Environ Res Public Health 9(3):880–894. https://doi.org/10.3390/ijerph9030880

141. Pandith M, Malpe DB, Rao AD, Rao PN (2016) Aquifer wise seasonal variations and spatial distribution of major ions with focus on fluoride contamination-Pandharkawada block, Yavatmal district, Maharashtra, India. Environ Monit Assess 188:1–20. https://doi.org/10.1007/s10661-015-5027-z
142. Panneerselvam B, Muniraj K, Pande C, Ravichandran N (2021) Prediction and evaluation of groundwater characteristics using the radial basic model in Semi-arid region, India. Int J Environ Anal Chem, 1–17. https://doi.org/10.1080/03067319.2021.1873316
143. Pazhuparambil Jayarajan SK, Kuriachan L (2021) Exposure and health risk assessment of nitrate contamination in groundwater in Coimbatore and Tirupur districts in Tamil Nadu, South India. Environ Sci Pollut Res 28(8):10248–10261. https://doi.org/10.1007/s11356-020-11552-y
144. Patel MP, Gami B, Patel A, Patel P, Patel B (2020) Climatic and anthropogenic impact on groundwater quality of agriculture dominated areas of southern and central Gujarat, India. Groundw Sustain Dev 10:100306. https://doi.org/10.1016/j.gsd.2019.100306
145. Patel PM, Saha D, Shah T (2020) Sustainability of groundwater through community-driven distributed recharge: an analysis of arguments for water scarce regions of semi-arid India. J Hydrol Reg Stud 29:100680. https://doi.org/10.1016/j.ejrh.2020.100680
146. Prajapati M, Jariwala N, Agnihotri P (2017) Spatial distribution of groundwater quality with special emphasis on fluoride of MandviTaluka, Surat, Gujarat, India. Appl Water Sci 7(8):4735–4742. https://doi.org/10.1007/s13201-017-0636-z
147. Rahman A, Mondal NC, Tiwari KK (2021) Anthropogenic nitrate in groundwater and its health risks in the view of background concentration in a semi-arid area of Rajasthan, India. Sci Rep 11(1):1–13. https://doi.org/10.1038/s41598-021-88600-1
148. Rahman A, Tiwari KK, Mondal NC (2020) Hydrochemical characterization for groundwater suitability in a semi-arid area in Sanganer Block, Jaipur District, Rajasthan. J Geol Soc India 96(4):399–409. https://doi.org/10.1007/s12594-020-1569-y
149. Raja V, Lakshmi RV, Sekar CP, Chidambaram S, Neelakantan MA (2021) Health risk assessment of heavy metals in groundwater of industrial township Virudhunagar, Tamil Nadu, India. Arch Environ Contam Toxicol 80:144–163. https://doi.org/10.1007/s00244-020-00795-y
150. Rajasekhar M, SudarsanaRaju G, Bramaiah C, Deepthi P, Amaravathi Y, SiddiRaju R (2018) Delineation of groundwater potential zones of semi-arid region of YSR Kadapa District, Andhra Pradesh, India using RS, GIS and analytic hierarchy process. Remote Sens Land 2(2):76–86. https://doi.org/10.21523/gcj1.18020201
151. Rajmohan N, Amarasinghe U (2016) Groundwater quality issues and management in Ramganga Sub-Basin. Environ Earth Sci 75(12):1–14. https://doi.org/10.1007/s12665-016-5833-9
152. Raju NJ, Dey S, Gossel W, Wycisk P (2012) Fluoride hazard and assessment of groundwater quality in the semi-arid Upper Panda River basin, Sonbhadra district, Uttar Pradesh, India. Hydrol Sci J 57(7):1433–1452. https://doi.org/10.1080/02626667.2012.715748
153. Rajkumar R, Kumaran MM, Prasath RM, Senthilshanmugavelayutham SP (Dec 2020) Agro-climatic zonation for Tamil Nadu using GIS and AHP techniques. In: IOP conference series: materials science and engineering, vol 1006, no 1. IOP Publishing, p 012015. https://doi.org/10.1088/1757-899X/1006/1/012015
154. Ramalingam S, Panneerselvam B, Kaliappan SP (2022) Effect of high nitrate contamination of groundwater on human health and water quality index in semi-arid region, South India. Arab J Geosci 15(3):1–14. https://doi.org/10.1007/s12517-022-09553-x
155. Rani S, Kansal S, Singla AK, Mehra R (2021) Radiological risk assessment to the public due to the presence of radon in water of Barnala district, Punjab, India. Environ Geochem Health 43(12):5011–5024. https://doi.org/10.1007/s10653-021-01012-y
156. Rao AK, Wani SP, Singh KK, Ahmed MI, Srinivas K, Bairagi SD, Ramadevi O (2013) Increased arid and semi-arid areas in India with associated shifts during 1971–2004. J Agrometeorol 15(1):11–18
157. Rao NS, Sunitha B, Rambabu R, Rao PV, Rao PS, Spandana BD, Sravanthi M, Marghade D (2018) Quality and degree of pollution of groundwater, using PIG from a rural part of Telangana State, India. Appl Water Sci 8(8):1–13. https://doi.org/10.1007/s13201-018-0864-x

158. Rawat KS, Tripathi VK, Singh SK (2018) Groundwater quality evaluation using numerical indices: a case study (Delhi, India). Sustain Water Resour Manag 4:875–885. https://doi.org/10.1007/s40899-017-0181-9
159. Reddy BM, Sunitha V, Prasad M, Reddy YS, Reddy MR (2019) Evaluation of groundwater suitability for domestic and agricultural utility in semi-arid region of Anantapur, Andhra Pradesh State, South India. Groundw Sustain Dev 9:100262. https://doi.org/10.1016/j.gsd.2019.100262
160. Roy SS, Rahman A, Ahmed S, Ahmad IA (2020) Alarming groundwater depletion in the Delhi Metropolitan Region: a long-term assessment. Environ Monit Assess 192:1–14. https://doi.org/10.1007/s10661-020-08585-8
161. Ruhela M, Singh VK, Ahamad F (2021) Assessment of groundwater quality of two selected villages of Nawada district of Bihar using water quality index. Environ Conserv J 22(3):387–394. https://doi.org/10.36953/ECJ.2021.22344
162. Saha D, Shekhar S, Ali S, Vittala SS, Raju NJ (2016) Recent hydrogeological research in India. In: Proceedings of the Indian national science academy, vol 82, no 3, pp 787–803. https://doi.org/10.16943/ptinsa/2016/48485
163. Saha D, Marwaha S, Mukherjee A (2017) Groundwater resources and sustainable management issues in India. In: Saha D, Marawaha S, Mukherjee A (eds) Clean and sustainable groundwater in India. Springer, Singapore, pp 4551–4556. https://doi.org/10.1007/978-981-10-4552-3_1
164. Sahoo S, Swain S, Goswami A, Sharma R, Pateriya B (2021) Assessment of trends and multi-decadal changes in groundwater level in parts of the Malwa region, Punjab, India. Groundw Sustain Dev 14:100644. https://doi.org/10.1016/j.gsd.2021.100644
165. Santhosh LG, Shilpa DN (2023) Assessment of LULC change dynamics and its relationship with LST and spectral indices in a rural area of Bengaluru district, Karnataka India. Remote Sens Appl Soc Environ 29:100886. https://doi.org/10.1016/j.rsase.2022.100886
166. Sarkar A, Ali S, Kumar S, Shekhar S, Rao SVN (2016) Groundwater environment in Delhi, India. Groundwater environment in Asian Cities: concepts, methods and case studies. https://doi.org/10.1016/B978-0-12-803166-7.00005-2
167. Şener Ş, Şener E, Davraz A (2017) Evaluation of water quality using water quality index (WQI) method and GIS in Aksu River (SW-Turkey). Sci Total Environ 584:131–144. https://doi.org/10.1016/j.scitotenv.2017.01.102
168. Setturu B, Ramachandra TV (2021) Modeling landscape dynamics of policy interventions in Karnataka State, India. J Geovisualization Spat Anal 5(2):22. https://doi.org/10.1007/s41651-021-00091-w
169. Shah M, Sircar A, Varsada R, Vaishnani S, Savaliya U, Faldu M, Vaidya D, Bhattacharya P (2019) Assessment of geothermal water quality for industrial and irrigation purposes in the Unai geothermal field, Gujarat, India. Groundw Sustain Dev 8:59–68. https://doi.org/10.1016/j.gsd.2018.08.006
170. Shah T (2010) Taming the anarchy: groundwater governance in South Asia. Routledge. https://doi.org/10.4324/9781936331598
171. Shaikh H, Gaikwad H, Kadam A, Umrikar B (2020) Hydrogeochemical characterization of groundwater from semiarid region of western India for drinking and agricultural purposes with special reference to water quality index and potential health risks assessment. Appl Water Sci 10(9):1–16. https://doi.org/10.1007/s13201-020-01287-z
172. Sharma AK, Tewari JC (2009) Arid zone forestry with special reference to Indian hot arid zone. Forests and forests plants. Eolss Publishers Company, UK, pp 90–130. http://eolss.net/Sample-Chapters/C10/E5-03-02-05.pdf
173. Sharma DA, Rishi MS, Keesari T (2017) Evaluation of groundwater quality and suitability for irrigation and drinking purposes in southwest Punjab, India using hydrochemical approach. Appl Water Sci 7:3137–3150. https://doi.org/10.1007/s13201-016-0456-6
174. Sharma T, Litoria PK, Bajwa BS, Kaur I (2021) Appraisal of groundwater quality and associated risks in Mansa district (Punjab, India). Environ Monit Assess 193:1–21. https://doi.org/10.1007/s10661-021-08892-8

175. Shirke KD, Kadam AK, Pawar NJ (2020) Temporal variations in hydro-geochemistry and potential health risk assessment of groundwater from lithological diversity of semi-arid region, Western Gujarat, India. Appl Water Sci 10(6):1–20. https://doi.org/10.1007/s13201-020-01235-x
176. Shukla S, Saxena A (2020) Groundwater quality and associated human health risk assessment in parts of Raebareli district, Uttar Pradesh, India. Groundw Sustain Dev 10:100366. https://doi.org/10.1016/j.gsd.2020.100366
177. Siddha S, Sahu P (2020) Assessment of groundwater quality and associated human health risk of Central Gujarat, India. CLEAN–Soil Air Water 48(12):2000056. https://doi.org/10.1002/clen.202000056
178. Singh A, Krause P, Panda SN, Flugel WA (2010) Rising water table: a threat to sustainable agriculture in an irrigated semi-arid region of Haryana, India. Agric Water Manag 97(10):1443–1451. https://doi.org/10.1016/j.agwat.2010.04.010
179. Singh P, Thakur JK, Kumar S, Singh UC (2011) Assessment of land use/land cover using Geospatial Techniques in a semi-arid region of Madhya Pradesh, India. Geospatial Tech Manag Environ Resour, 152–163. https://doi.org/10.1007/978-94-007-1858-6_10
180. Singh O, Turkiya S (2013) A survey of household domestic water consumption patterns in rural semi-arid village, India. GeoJournal 78:777–790. https://doi.org/10.1007/s10708-012-9465-7
181. Singh CK, Shashtri S, Mukherjee S, Kumari R, Avatar R, Singh A, Singh RP (2011) Application of GWQI to assess effect of land use change on groundwater quality in lower Shiwaliks of Punjab: remote sensing and GIS based approach. Water Resour Manage 25:1881–1898. https://doi.org/10.1007/s11269-011-9779-0
182. Singh G, Rishi MS, Herojeet R, Kaur L, Sharma K (2020) Evaluation of groundwater quality and human health risks from fluoride and nitrate in semi-arid region of northern India. Environ Geochem Health 42(7):1833–1862. https://doi.org/10.1007/s10653-019-00449-6
183. Singh CK, Kumar A, Shashtri S, Kumar A, Kumar P, Mallick J (2017) Multivariate statistical analysis and geochemical modeling for geochemical assessment of groundwater of Delhi, India. J Geochem Explor 175:59–71. https://doi.org/10.1016/j.gexplo.2017.01.001
184. Singhai A, Das S, Kadam AK, Shukla JP, Bundela DS, Kalashetty M (2019) GIS-based multi-criteria approach for identification of rainwater harvesting zones in upper Betwa sub-basin of Madhya Pradesh, India. Environ Dev Sustain 21(2):777–797. https://doi.org/10.1007/s10668-017-0060-4
185. Sinha KK, Gupta MK, Banerjee MK, Meraj G, Singh SK, Kanga S, Farooq M, Kumar P, Sahu N (2022) Neural network-based modeling of water quality in Jodhpur, India. Hydrology 9(5):92. https://doi.org/10.3390/hydrology9050092
186. Sreedevi PD, Sreekanth PD, Ahmed S, Reddy DV (2019) Evaluation of groundwater quality for irrigation in a semi-arid region of South India. Sustain Water Resour Manag 5(3):1043–1056. https://doi.org/10.1007/s40899-018-0279-8
187. Srikanth R (2013) Access, monitoring and intervention challenges in the provision of safe drinking water in rural Bihar, India. J Water SanitIon Hyg Dev 3(1):61–69. https://doi.org/10.2166/washdev.2013.033
188. Srinivasarao C, Subha Lakshmi C, Sumanta Kundu S, Ranjith Kumar G, Manasa R, Rakesh S (2020) Integrated nutrient management strategies for rainfed agro-ecosystems of India. Indian J Fertil 16(4):344–361
189. SubbaRao N, Dinakar A, Surya Rao P, Rao PN, Madhnure P, Prasad KM, Sudarshan G (2016) Geochemical processes controlling fluoride-bearing groundwater in the granitic aquifer of a semi-arid region. J Geol Soc India 88(3):350–356. https://doi.org/10.1007/s12594-016-0497-3
190. SubbaRao N, Srihari C, DeepthiSpandana B, Sravanthi M, Kamalesh T, Abraham Jayadeep V (2019) Comprehensive understanding of groundwater quality and hydrogeochemistry for the sustainable development of suburban area of Visakhapatnam, Andhra Pradesh, India. Hum Ecol Risk Assess Int J 25(1–2):52–80. https://doi.org/10.1080/10807039.2019.1571403

191. Subba Rao N, Ravindra B, Wu J (2020) Geochemical and health risk evaluation of fluoride rich groundwater in Sattenapalle Region, Guntur district, Andhra Pradesh, India. Hum Ecol Risk Assess Int J 26(9):2316–2348. https://doi.org/10.1080/10807039.2020.1741338
192. Shukla S, Khan R, Varshney SK, Ganguly R, Amiri V, Hussain CM, Selvam S, Senapathi V, Ravindran B, Karuppannan S, Bhattachara P, Dotaniya ML (2022) Appraisal of groundwater chemistry, its suitability for crop productivity in Sonipat district and human health risk evaluation. Hum Ecol Risk Assess Int J, 1–22. https://doi.org/10.1080/10807039.2022.2137779
193. Sudarshan V, Narsimha A, Das SVG (2018) Geochemical behavior of fluoride-rich groundwater in Markapur, Andhra Pradesh, South India. Data Brief 18:87–95. https://doi.org/10.1016/j.dib.2018.02.084
194. Tanwer N, Deswal M, Khyalia P, Laura JS, Khosla B (2023) Assessment of groundwater potability and health risk due to fluoride and nitrate in groundwater of Churu District of Rajasthan, India. Environ Geochem Health, 1–23. https://doi.org/10.1007/s10653-023-01485-z
195. Tanwer N, Deswal M, Khyalia P, Laura JS, Khosla B (2023) Fluoride and nitrate in groundwater: a comprehensive analysis of health risk and potability of groundwater of Jhunjhunu district of Rajasthan, India. Environ Monit Assess 195(2):267
196. Tian M, Li W, Ruan M, Wei J, Ma W (2019) Water quality pollutants and health risk assessment for four different drinking water sources. In: E3S web of conferences, vol 78. EDP Sciences, p 03004. https://doi.org/10.1051/e3sconf/20197803004
197. Tiwari KK, Krishan G, Prasad G, Mondal NC, Bhardwaj V (2020) Evaluation of fluoride contamination in groundwater in a semi-arid region, Dausa District, Rajasthan, India. Groundw Sustain Dev 11:100465. https://doi.org/10.1016/j.gsd.2020.100465
198. Tiwari RN (2011) Assessment of groundwater quality and pollution potential of Jawa block Rewa district, Madhya Pradesh, India. Proc Int Acad Ecol Environ Sci 1(3–4):202
199. Tiwari SK, Bartarya SK, Rai SK, Gupta AK, Asthana AKL (2016) Isotopic and geochemical studies of groundwater from the Ramganga basin and the middle Ganga Plains: implication for pollution and metal contamination. Environ Earth Sci 75:1–15. https://doi.org/10.1007/s12665-016-5971-0
200. UNEP (1992) World atlas of desertification
201. USEPA (2002) Child-specific exposure factors handbook. Interim report. National Center for Environmental Assessment, Office of Research and Development, Washington DC. NCEA-W, 853
202. USEPA (1992) Guidelines for exposure assessment. Fed Reg 57(104):22888–22938
203. Varade AM, Yenkie RO, Shende RR, Golekar RB, Wagh VM, Khandare HW (2018) Assessment of water quality for the groundwater resources of urbanized part of the Nagpur District, Maharashtra (India). Am J Water Resour 6(3):89–111. https://doi.org/10.12691/ajwr-6-3-1
204. Varshney R, Modi P, Sonkar AK, Singh P, Jamal A (2022) Assessment of surface water quality in and around Singrauli coalfield, India and its remediation: an integrated approach of GIS, water quality index, multivariate statistics and phytoremediation. Arab J Geosci 15(18):1–20. https://doi.org/10.1007/s12517-022-10806-y
205. Vasanthavigar M, Srinivasamoorthy K, Rajiv Ganthi R, Vijayaraghavan K, Sarma VS (2012) Characterisation and quality assessment of groundwater with a special emphasis on irrigation utility: Thirumanimuttar sub-basin, Tamil Nadu, India. Arab J Geosci 5(2):245–258. https://doi.org/10.1007/s12517-010-0190-6
206. Verma G, Sood S, Sharma P, Ali S (2021) Salinity and corrosion potential of groundwater in Mewat district of Haryana, India. In: Spatial modeling and assessment of environmental contaminants: risk assessment and remediation, pp 277–288. https://doi.org/10.1007/978-3-030-63422-3_17
207. Vijayakumar CR, Balasubramani DP, Azamathulla HM (2022) Assessment of groundwater quality and human health risk associated with chromium exposure in the industrial area of Ranipet, Tamil Nadu, India. J Water SanitIon Hyg Dev 12(1):58–67. https://doi.org/10.2166/washdev.2021.260

208. Vikrma A, Sandhu HAS (2022) Health risk assessment of Gurdaspur, Punjab, India using field experiments and GIS: a groundwater perspective. J Geol Soc India 98(7):933–936. https://doi.org/10.1007/s12594-022-2097-8
209. Vinnarasi F, Srinivasamoorthy K, Saravanan K, Kanna AR, Gopinath S, Prakash R, Ponnumani G, Babu C (2022) Hydrogeochemical characteristics and risk evaluation of potential toxic elements in groundwater from Shanmughanadhi, Tamilnadu, India. Environ Res 204:112199. https://doi.org/10.1016/j.envres.2021.112199
210. Wagh V, Panaskar D, Mukate S, Lolage Y, Muley A (2017) Groundwater quality evaluation by physicochemical characterization and water quality index for Nanded Tehsil, Maharashtra, India. In: Proceedings of the 7th international conference on biology, environment and chemistry, IPCBEE, vol 98
211. WHO (2011) Guidelines for drinking-water quality. World Health Organization, Geneva. https://www.who.int/publications/i/item/9789241549950
212. WHO/UNICEF (2017) Progress on drinking water, sanitation and Hygiene: 2017 update and SDG baselines. https://www.who.int/mediacentre/news/releases/2017/launch-version-report-jmp-watersanitation-hygiene.pdf. accessed 14 Dec 2018
213. Yadav KK, Kumar V, Gupta N, Kumar S, Rezania S, Singh N (2019) Human health risk assessment: study of a population exposed to fluoride through groundwater of Agra city, India. Regul Toxicol Pharmacol 106:68–80. https://doi.org/10.1016/j.yrtph.2019.04.013
214. Yammani S (2007) Groundwater quality suitable zones identification: application of GIS, Chittoor area, Andhra Pradesh, India. Environ Geol 53(1):201–210. https://doi.org/10.1007/s00254-006-0634-1
215. Yenugu SR, Vangala S, Badri S (2020) Groundwater quality evaluation using GIS and water quality index in and around inactive mines, Southwestern parts of Cuddapah basin, Andhra Pradesh, South India. Hydro Res 3:146–157. https://doi.org/10.1016/j.hydres.2020.11.001

Groundwater Monitoring and Assessment

Vulnerability to Pollution of Karstic Aquifers in the Tafna River Basin and Risk Mitigation Strategies (Northwest Algeria)

Fouzia Bensaoula and Bernard Collignon

Abstract Karst aquifers are particularly vulnerable to pollution because the water circulates rapidly without the benefit of the self-cleansing action of slow circulation in the soil. The simplest option is to leave karstic outcrops in their natural state to limit sources of contamination. The town of Tlemcen was built on a small agricultural plain at the foot of karstified hills from which many springs flow. It thus benefited from an abundant, good-quality water resource, as the hills were uninhabited. Over the last century, the population has grown tenfold and the town has expanded towards the karstic relief, bringing with it a host of environmental threats (factories, sewage treatment plants, quarries, illegal waste dumps). Its development is compromising the quality of the water resources that were at the origin of the town´s creation, raising the question: is it possible to reconcile urban development with the protection of groundwater in karstic areas? We inventoried the pollution factors in the urban area and the signs of chemical and bacteriological contamination of the groundwater. The government and the city introduced environmental regulations and built major facilities (wastewater treatment plants) that limit the level of general pollution. However, this is not enough to eliminate the risks because in an environment as heterogeneous as karst, point pollution, such as an uncontrolled dump at the bottom of a sinkhole, can be enough to contaminate a borehole. It is essential to integrate environmental risk into the urban planning strategy to make public action more effective. In karstic environments, this necessarily involves large-scale mapping of areas vulnerable to pollution.

Keywords Tafna river · Groundwater resources · Pollution · Vulnerability mapping · Strategies of water resources protection

F. Bensaoula (✉)
Laboratoire 60: Valorisation Des Ressources en Eau, University of Tlemcen, Tlemcen, Algeria
e-mail: fbensaoula@gmail.com

B. Collignon
Bernard Collignon Consulting, Châteauneuf-de-Gadagne, France
e-mail: collignon@bottombillion.fr

S. Ali and A. M. Armanuos (eds.), *Groundwater in Arid and Semi-Arid Areas*, Earth and Environmental Sciences Library, https://doi.org/10.1007/978-3-031-43348-1_3

1 Introduction

Located in the northwest of Africa and with an area approaching 2.4 million km^2, Algeria is the largest country on the African continent. However, more than 80% of its surface is occupied by the Sahara; the rest is made up of 17 watersheds organized into four hydrographic basins including that of Oranie-Chott Chergui which includes the Tafna basin. Due to its location in the far west of Algeria, the Tafna basin receives relatively low rainfall because the rainfall decreases from East to West in northern Algeria. The socio-economic sector is booming there and agricultural activity is dominant, thanks to the existence of large plains where the fertility of the soil has allowed the creation of large agricultural perimeters such as the plain of Henaya and the plain of Maghnia.

In order to support the economic development of the region, water resources are in high demand and many hydraulic structures have been built. Thus, surface water is mobilized by five large dams, totaling a volume of 353 million cubic meters and groundwater by numerous wells and boreholes. The quality of the mobilized water is good but very threatened by pollution. It should be noted that some water points intended for drinking water supply have been contaminated and cases of water-borne diseases have been recorded. In order to overcome both the insufficiency of water resources and their risk of pollution, many efforts are made by the competent authorities and solutions are provided, however, definitively resolving all the difficulties. The available water resources are insufficient and require effective protection against any risk of contamination without hindering the region's economic and urban development. Adequate solutions must be found for the medium and long term.

This work presents, for the first time, a synthesis on the main groundwater reservoirs of the Tafna basin. The risk of degradation of the quality of the groundwater quality and the actions undertaken by the competent authorities to mitigate the risks of pollution that threaten the water environment of the Tafna basin are particularly highlighted.

2 Study Area

The Tafna River basin extends on more than 7,000 km^2, in the Northwest of Algeria. It is bordered by three mountain ranges (see Fig. 1):

- To the NW, Traras Mountains, a coastal mountain range that culminates at 1081 m (Djebel Fillaoucene (1081 m asl).
- To the North-East, Sebaa Chioukh Mounts whose altitude is around 800 m.
- To the South, Tlemcen Mountains, a karstic mountain range, occupy the upstream part of the basin and occupy nearly 40% of the Tafna basin. This massif culminates in Djebel Tenouchfi (1848 m).

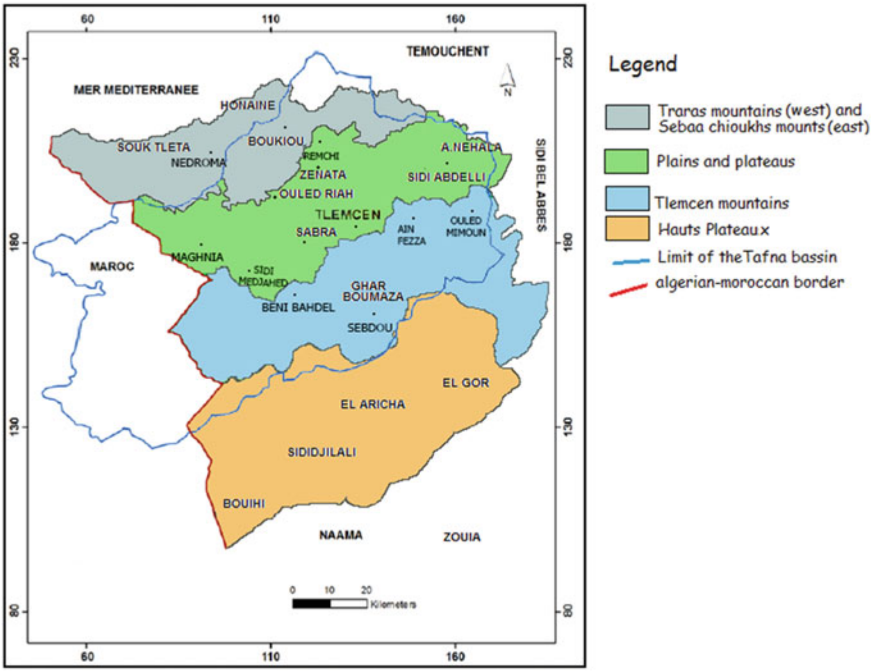


Fig. 1 Geographical constitution of the Tafna basin

The plains and plateaus extending between these mountain ranges include the plain of Maghnia, the plain of Zriga, the plain of Hennaya, the plateau of Zenata and Ouled Riah of Sidi Abdelly and Ain Nehala.

2.1 Geology

The geological formations outcropping in the Tafna basin are very diverse and range from the Primary to the Plio-Quaternary (Fig. 2).

2.1.1 Primary

The primary formations are observed in the Traras Mountains in the northern part as well as in the GharRoubane Mountains on the western edge of the Tlemcen Mountains. These are essentially schisto-quartzite and granitic formations, with limited groundwater potential.

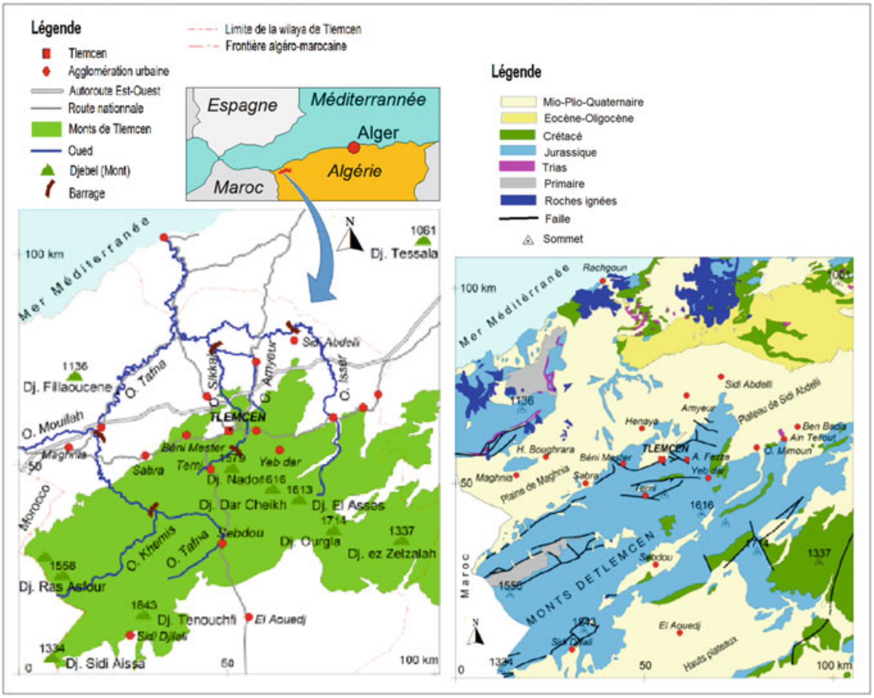


Fig. 2 Geological and geographical context of the Tafna basin [1]

2.1.2 Secondary

The formations of the secondary that spread from the Triassic to Cretaceous, present a lateral change of facies, a variation in thickness and a very irregular dolomitization, through the Mountains of Tlemcen according to the work of Benest [2], Collignon [3] and Bensaoula [4, 5]. The lithostratigraphic description of the formations that outcrop in the basin studied is inspired mainly by the work of Benest [1], Perrodon [6], Guardia [7]. A synthetic log is presented below (Fig. 3).

2.1.3 Tertiary

The middle Miocene is very thick and consists of grey marly clay and sandstone interlayers, while the yellow Tortonian sandstone represents the upper Miocene. They contain a large aquifer on the northern foothills of the Tlemcen Mountains.

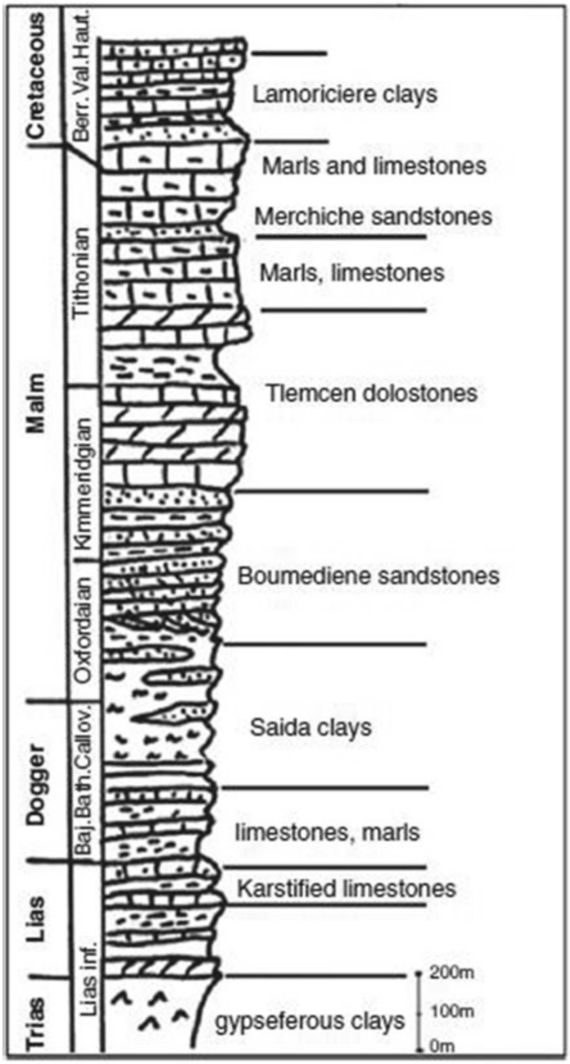


Fig. 3 Synthetic lithostratigraphic log in Tlemcen mountains [8]

2.1.4 Quaternary

The Wadi beds contain continental sediments dating from the Quaternary period (silt, sand, gravel). These sediments contain aquifers of limited extension, but which play an important role in private irrigation. Their recharge is closely linked to surface runoff.

2.2 Climate

The climate in Northern Algeria is typically Mediterranean with cool, wet winters and hot, dry summers. Rainfall is very irregular and agriculture depends on irrigation.

The Tafna basin is located in its western edge, where the climate is the aridest (350 to 650 mm/year). The most watered areas are the Tlemcen Mountains (800 to 1600 m asl), which act as a regional water tower, with annual rainfall between 450 and 650 mm/year (Fig. 4).

Beside the overall regional aridity, the expected impact of climate change in the Mediterranean region is a decrease of rainfall and river flow. Ghenim et al. [9] studied the main changes in rainfall patterns and demonstrated a break in homogeneity between the mid and late 1970s as well as an accentuated occurrence of dry years and the appearance of acute droughts [10].

As a result of this decline in rainfall, dams were no longer filling up sufficiently to cover water needs [11]. The government launched massive investments in other types of water resources: drilling (1980 and 1990s) and finally, seawater desalination from the 2000s onwards.

3 Groundwater Resources in Tafna River Basin

The various surveys carried out across the Tafna basin have revealed permeable hydrogeological formations containing exploitable groundwater. Figure 5 shows the main groundwater reservoirs identified and exploited in the Tafna basin. In what follows, we give the main characteristics of each of them.

3.1 The Lias and Dogger Dolomites

Dolomites and limestones were tested in the border area with Morocco on the northwest slope of the horst of Ghar-Roubane. These formations have very interesting hydrogeological characteristics (Table 1). They are fissured, sometimes karstified, resulting in total mud loss during the performance of hydraulic drilling works. This catchment field includes 22 deep boreholes from 300 to 1240 m totaling more than 15,000 m drilled between 2002 and 2007, with mobilized flow rates of 20 to 50 l/s, sometimes hot water (21 to 47 °C) and a dry residue from 0.65 to 2.8 g/L. The volume produced varies from 20,000m^3/d (July 2016) to 35,000m^3/d intended for the drinking water supply (DWS) of the population of the urban grouping of Tlemcen and the northern corridor of the wilaya (department) of Tlemcen [10].

The waters from these boreholes are relatively loaded with mineral salts compared to the waters contained in the Kimmeridgian and Tithonian carbonate aquifers of the Tlemcen region. The deep water circulations highlighted are probably fed from the

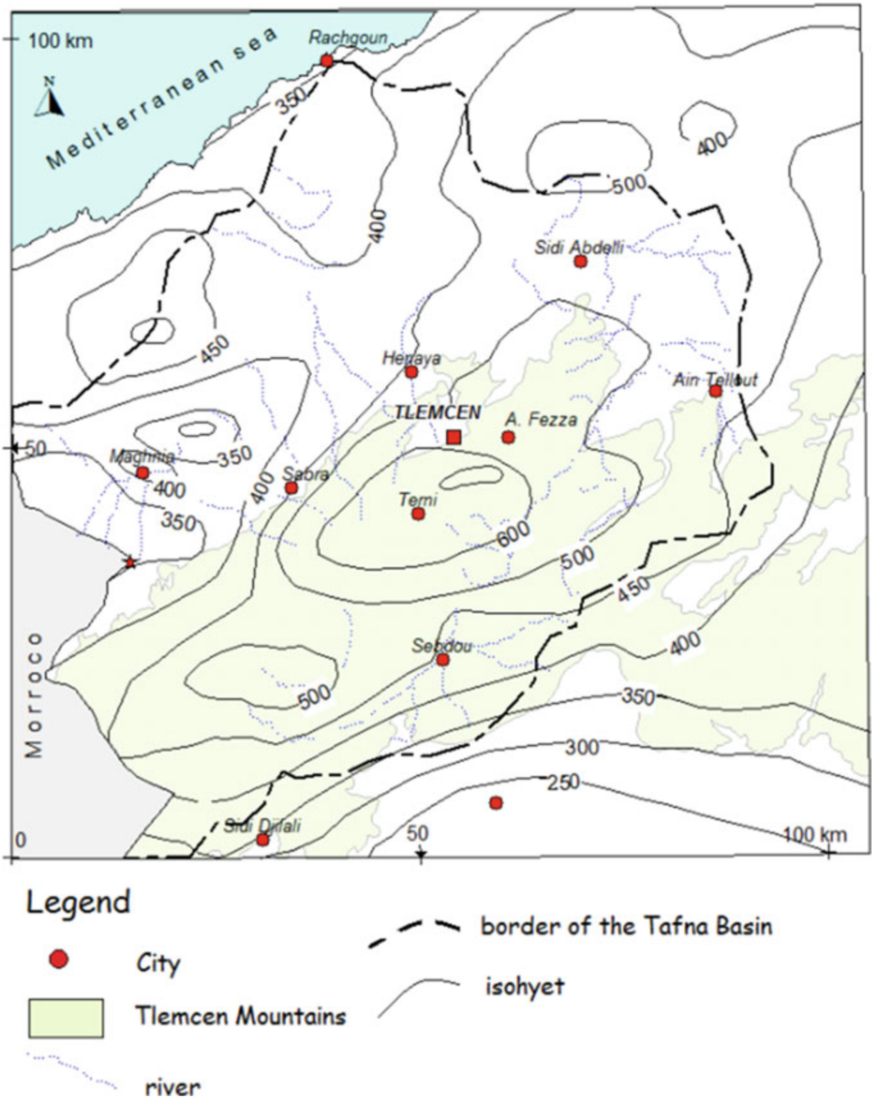


Fig. 4 Yearly rainfall in north-western Algeria (average 1910–2010) [8]

Liassic outcrops located further southwest in Moroccan territory. They, in turn, feed the aquifer of the Maghnia Plain located further north.

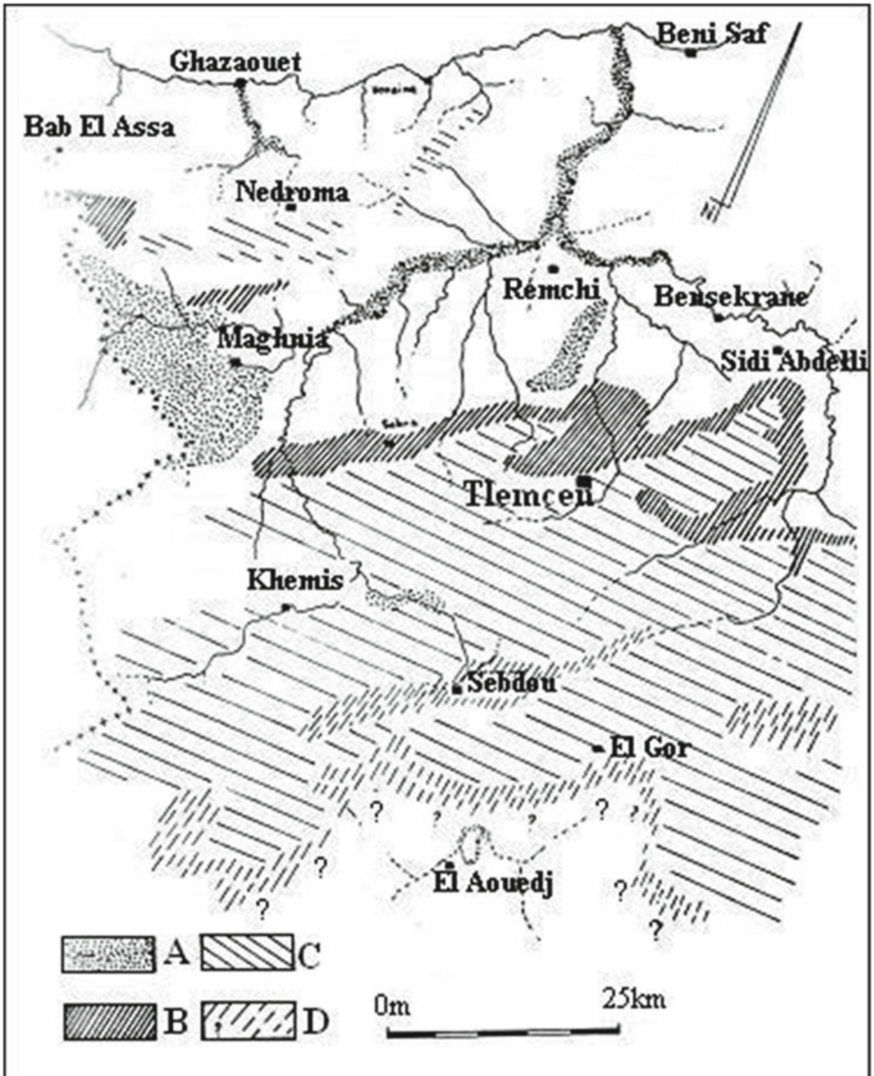


Fig. 5 Main groundwater resources in the Tafna river basin. **A**: Plio-Quaternary sand and gravel aquifers **B**: Miocene sandstones **C**: Jurassic limestones and dolostones **D**: Deeply buried Jurassic carbonates [12]

Table 1 Lithology and aquifers in the mounts of Tlemcen [8]

Geological layer	Lithology	Specific yield (m^3/h per m)*	Bore hole productivity
Miocene's marls north of the Meseta Oranaise (Helvetian)	Marls with thin sandstone	Poor	Many boreholes are productive but with a very limited yield
Ouled Mimoun Marly limestones (Berriasian)	Marly limestone	Very poor	No recorded borehole with a significant yield
Lato limestones, Terni dolostones and Hariga marly limestones (Tithonian)	Limstones and dolostones	Excellent	Majority of high yield wells
Raourai marly limestones (Tithonian)	Marls and marly limestones	Very poor	No recorded borehole with a significant yield
Tlemcen dolostones and Zarifet limestones (Kimmeridgian)	Large banks of limestones and especially dolostones, often with sugar like texture	Excellent	Majority of high yield wells
Boumediene sandstones and limestones	Quartzitic sandstone fine grained highly cemented	Low	Many boreholes are productive but with a very limited yield
Bajocian bathonian dolostones and limestones	Dolostones and limestones	Excellent	Many boreholes are productive but with high yield

3.2 Sequanian Sandstones

It is a thick sandstone sequence with significant water reserves but whose transmissivity is low (10^{-3} to 10^{-5} m^2/s). This does not prevent the existence of small springs with very low flow (2 to 0.5 l/s) [13]. These sandstones were tested by drilling in the region of Tlemcen, the Maghnia plain and the surroundings of the Fillaoucene massif in Nedroma. The well productivity is limited (5 to 100m^3/hr).

3.3 Upper Jurassic Limestones and Dolomites

The Tlemcen Mountains extend over an area of more than 3000 km^2 and occupy the southern part of the Tafna basin. They are very wet (between 500 to 800 mm per year) and contain very large water tables. The Tlemcen Mountains do not constitute a single karstified unit drained by a limited number of important sources, as is the case of the mountains of Saida or Chellala. The many faults that affect the Tlemcen Mountains lead to the formation of compartments that give rise to many small aquifers.

Important layers are contained in the limestone and dolomitic formations which sink under the thick Neogene formations limiting the Tlemcen Mountains on the north side. We cite as an example, the region of Sidi-Abdelli in the North-East and the region of Beni-Mester, Sabra, Bou Hallou in the western part [5].

In the collapsed area of Tlemcen, the many boreholes drilled have revealed great potential for water which supplies a good part of the population of the urban group of Tlemcen [5] oral communication by the water resource services of Tlemcen, 2022].

These aquifers constitute important reserves, particularly at the mounts of Tlemcen and lesser importance at the level of the mounts of Traras. The waters of these aquifers are largely mobilized by a large number of boreholes which have multiplied in recent years (Table 1).

3.4 Tortonian Sandstones

These sandstones feed low-flow springs (0.5 to 4L/s) in Sikkak basin and they have been used for a long time to supply Tlemcen historical city with dug wells. In 2000 there were 720 wells in Tlemcen city only (oral communication by the national land use planning agency of Tlemcen, 2000). In the 80's, deeper boreholes were drilled with limited outcomes.

3.5 Zenata and Remchi Plateau

For a long time, this region was considered as deprived of groundwater resources. Between 1979 and 2002, several geophysical prospections by electrical method, were carried out (Technexportstroy, 1983; Icosium drilling and engineering, 2002; Algeo, 1979 & 1981).

Following these surveys, deep drilling works were carried out (90 to 600 m deep). A deep aquifer in highly fractured Miocene sandstones (manifested by high losses of drilling mud) has been identified. The boreholes are artesian, very productive (20 to 600 m3/h), and the water is abnormally warm (26 to 46 °C). All this suggests a communication at great depth with the karstified reliefs of the Tlemcen Mountains.

3.6 Plio-Quaternary

These are heterogeneous layers of sand, gravel, pebbles, silt and clays filling the bottom of most valleys. They contain local aquifers that are important for irrigation. The main ones are: Maghnia aquifer, Hennaya aquifer, Sidi Senouci aquifer, Ain

Nehala plain aquifer, the Boukiou aquifer and Sebdou aquifer. The water is mostly used for irrigation and also for domestic water supply. The physicochemical and microbiological quality is often poor. This does not prevent some rural inhabitants from consuming it in the absence of other resources.

3.6.1 Maghnia Aquifer

Maghnia Plain is a basin filled by alluvial deposits dated from the Plio-Quaternary that rest on the Miocene marl. The groundwater is mainly used for agricultural purposes. It is fed mainly by rainfall infiltration and by underground flows coming from the Jurassic carbonates which border the plain on the southern side. The water table is shallow (between 10 and 20 m), it is therefore accessible by simple wells or by shallow boreholes (120 to 150 m). The flow is generally from South to North, and in the western part, it is slightly SW-NE, highlighting a supply from the Moroccan side [14]. The water table dropped by 10 m on average during the period 1950–1995 [14] because of the dramatic increase in the number of private wells (>3000 wells, (oral communication by the national land use planning agency of Tlemcen, 2000).

This is aggravated by a decrease in recharge due to a long period of drought that has plagued the region in recent decades and the water of this aquifer is relatively mineralized in some places (2 g/l) [15]. Nitrate levels tend to increase towards the center of the plain with levels exceeding 50 mg/L. It is a direct consequence of excessive use of fertilizers.

3.6.2 The Hennaya Plain Aquifer

Hennaya Plain contains an alluvial aquifer extending on 29km^2. It is part of the Oued Sikkak basin and is located about 10 km North of Tlemcen. Technoexporstroy performed an in-depth geophysical survey in 1969, mapping the water table and aquifer thickness (oral communication). Groundwater flows towards the North and North-East. A more recent water table map (2012) demonstrated a significant water table drop in 30 years (−2.18 to −9.35 m). This is a consequence of the increasing use of groundwater for irrigation. The overall use of fertilizers also impacts groundwater quality: nitrate concentration exceeds human consumption standards (50 mg/L) [16, 17].

4 Population and Water Facilities

4.1 Administrative Framework and Population

The Tafna basin extends to 37 municipalities out of 53 in the wilaya of Tlemcen (region). It shelters 77% of its population, i.e. more than 900,000 inhabitants.

4.2 Mobilization of Water Resources and Drinking Water Supply

Significant investments were performed in water supply to tackle water scarcity. It began in the 1950s with the construction of large dams [10]. The increasing population and water demand led the local and central governments to implement drilling campaigns to extract karstic groundwater in the Tlemcen and Ghar Roubane Mountains. More than 100 boreholes have been installed directly in the Tlemcen Mountains or on their northern foothills, with a cumulative production capacity of 30 Mm^3/year [10]. In the catchment area of Zouia, on the western foothills of the Tlemcen Mounts and the Moroccan border, 22 deep boreholes (300 to 1240 m) were drilled between 2002 and 2007, with very high yield (70 to 200m^3/h) for a cumulative production capacity of 10 Mm^3/year (oral communication by water resource services of Tlemcen, 2018).

4.3 Seawater Desalination

The study area is a semi-arid and densely populated region. Most of the surface water resources have already been mobilized through the construction of dams. The groundwater resources are already overexploited, inducing a significant drop in the piezometric surface. In order to meet the growing demand for water, the government has launched an ambitious policy of desalination of seawater. In the Tlemcen region, this materialized by the construction of two plants in Honaine and Souk Tlata over the last decade. These plants already produce 63 Mm^3/year, with a long-term objective of 140 Mm^3/year. The commissioning of these plants has reduced the pressure on groundwater resources and put some boreholes on standby, aiming to restore the original water table [10].

4.4 Sanitation

Central and local governments invested much in sanitation during the last 30 years. More than 1,700 km of sewerage and a half dozen of modern wastewater treatment plants were commissioned by 2009. Domestic connection rate varies from 65 to 100% among all the municipalities in the Tafna River basin [18].

The connection rate to the sewerage system is on track, but it is not the same for the treatment of collected wastewater. In fact, untreated wastewater is discharged into the natural environment in many municipalities and 35% of domestic water only is treated properly in a wastewater treatment plant (WWTP).

The water from these treatment plants is generally discharged into the natural Environment.

Only those leaving the Ain El Hout WWTP are routed to the Hennaya irrigated zone (912 ha).

5 Present and Potential Sources of Groundwater Contamination

5.1 Documented Contamination of Groundwater Across Tafna Basin

Overall groundwater quality in Tafna basin is presently rather good but it is increasingly threatened by anthropogenic pollution as illustrated by three areas in Tafna basin.

5.1.1 Tlemcen City Area

The poor urban planning associated with the rapid urban growth within the T.U.G. (Tlemcen Urban Grouping–i.e. Tlemcen, Mansourah and Chetouane municipalities) has increased the level of groundwater pollution and, consequently, could have a harmful effect on the public health [19].

Many groundwater analysis campaigns have been carried out throughout the study area. Several water points have been shut down because of nitrate levels above WHO standards or poor bacteriological quality (Table 2).

Other water points in the T.U.G were analyzed in 2016 by A.N.R.H. and A.D.E (water services) and revealed frequently nitrates in excess (>50 mg/L). Out of 25 spring and borehole checked, 50% were found to be non-drinkable [20].

Table 2 Water supply points that were shut down following documented pollution in the Tlemcen area [19]

Water supply point	Type	Reasons for shutting down the water points	Year of shuttings
Koudia (F1)	Borehole	High level of nitrates (70 mg/L) and bacterial contamination	2005
Birouana (F2)	Borehole	Green colored water with bad smell and bacterial contamination	2005
A.Defla (F3)	Borehole	High level of nitrates (83 mg/L)	2007
Oudjlida (F4)	Borehole	Bacterial contamination (Coliforms & E.Coli)	
A.Bendou (S1)	Spring	High level of nitrates (110 mg/L)	2007
A. Mokdad (S2), A. Kobet El Djouz (S3), A. El Ançor (S4), A. El Houtz (S5)	Springs	High level of nitrates (64 to 104 mg/L)	2013
A. Sidi El Haloui (S7), A.Karadja (S6), A. Sidi Lahcen (S8), A. Dar Dbagh1 (S9)	Springs	Bacterial contamination (Coliforms & E. Coli)	2014

5.1.2 Groundwater in Hennaya Plain

Groundwater is mainly used here for irrigation but also for small hamlets drinking water supply. Overall bacteriological quality is good (Table 3), but nitrate concentrations largely exceed WHO standards and should be considered non-drinkable. The main nitrogen source is the intensive use of chemical fertilizers and irrigation with treated and untreated wastewater.

5.1.3 The Karstic System of GharBoumaza

Several water points belonging to the karstic system of GharBoumaza have been tested for bacteriological quality (Table 4). Water bacteriological quality varies along the year, as it is frequent with karstic springs [21]. Bir Dar Maamar and Ain Kbira water points were shut down because of such contamination.

5.2 Water-Borne Diseases

Groundwater contamination has a direct impact on public health. Tlemcen region experienced water-borne diseases for several decades, reflecting the poor hygiene conditions of some water resources (Fig. 6a).

Table 3 Bacteriological quality of some water points in the Hennaya aquifer [16]

Date	Water point	Total Coliforms (UFC/ 100 mls)	E.Coli (UFC/ 100 ml)	Intestinal enterococci(UFC/ 100 ml)	FaecalColiforms (UFC/100 ml)
27/04/ 2011	P102 P7	6.10^4 2.10^4	Absence Absence	Absence Absence	X X
3/07/ 2011	P02 P7 P32 P64	2.10^4 10^4 8.10^3 3.10^4	Absence Absence Absence Absence	Absence Absence Absence Absence	X X X X
26/06/ 2011	P33 P13 P14	7.10^4 10^4 5.10^3	Absence Absence Absence	Absence Absence Absence	X X X
14/08/ 2011	A.Boukora P17 P26	10^4 8.10^3 3.10^4	Absence Absence Absence	Absence Absence Absence	X X X
28/08/ 2011	P10 P09	400 80	X X	X X	Absence Absence

*: Analyses carried out at the veterinary laboratory in Tlemcen-**: Analyses carried out at the laboratory of the Pasteur Institute in Algiers-X: Analysis not carried out

Table 4 Contaminated water supply points in Ghar Boumaza karstic system [21]

Sampling location	Date of analysis	Results of the bacteriological analysis				Quality assessment according to the hygiene service of terni municipality
		Col.TCol.F	E.Coli	Salm	Strept	
Ain Taga	22/07/2014[b]	6 0	0	0	0	Water to monitor
	19/01/2016[b]	22 3	0	0	0	Suspicious water (to be treated)
	14/03/2016[a]	92 5	0	0	35	Dirty water-not drinkable
	3/12/2017[a]	0 0	–	–	–	Water of acceptable bacteriological quality subject to verification
Ouled Bounouar	19/01/2016[a]	4 0	0	0	0	Potable water
Bir dar maamar	5/02/2016	–	–	–	–	Intake closed due to pollution
A. lakbira	5/022016	–	–	–	–	Intake closed due to pollution

Col.T: Total coliforms, Col.F: Faecal coliforms, Salm. Salmonella, Strept. Streptococcus, [a]: samples and analyses carried out by the authors, [b]: samples and analyses carried out by the hygiene service of Terni Municipality, –: elements not analysed.

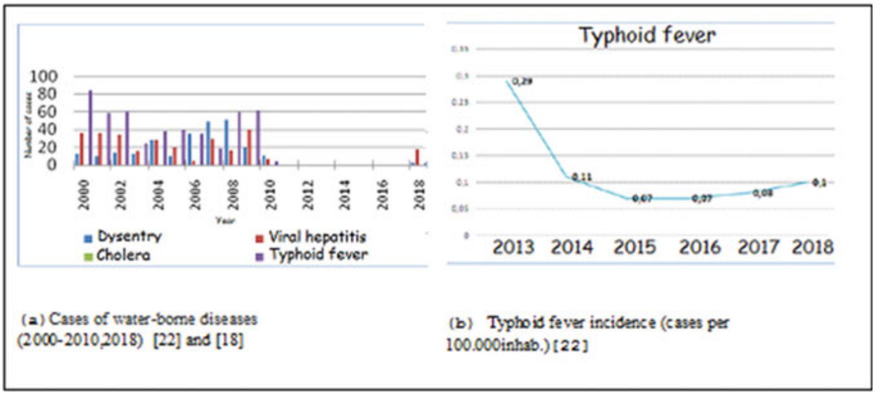


Fig. 6 Waterborne diseases in the wilaya of Tlemcen

Additional investments have been made by local governments, particularly for the improvement of sewerage. 2020 km of sewerage pipes have been installed throughout the whole region and household connection rate is now over 80% (oral communication by the national sanitation office, 2022). Incidence of typhoid fever over the period 2013–2018 has decreased significantly from 0.29 to 0.1per 100,000 inhabitants [22] (Fig. 6b).

5.3 *Classification of Threats to Groundwater*

Despite huge public investment in wastewater collection and treatment, small localities still have an issue discharging untreated wastewater into the natural Environment. In addition, there are other potential sources of groundwater pollution: industry and agriculture (see Table 5).

5.3.1 Domestic and Industrial Wastewater Discharges

In spite of the few wastewater treatment plants built downstream of the region's major agglomerations, untreated wastewater discharges are present almost everywhere and are discharged directly into watercourses, representing the most threatening sources of pollution for surface and groundwater. More than 120 discharges into the natural Environment have been listed, including about 40 within a radius of 10 km from the city of Tlemcen (the largest agglomeration in theTafna basin) [18], see Fig. 7.

The industrial zones of Tlemcen, Maghnia and Sebdou generate dangerous pollution which must be taken into consideration. Wastewater from these industries contains toxic chemicals and heavy metals that are often released directly in the natural Environment without pre-treatment.

Table 5 Tafna basin hazards and their weight according to European cost action 620 methodology [21, 23]

Hazard class	Hazards	Hazard weight
Wastewater	Individual houses without sanitation	45
	Septic tank, cesspool, latrine	45
	Treated and untreated wastewater release in non-perennial rivers	45
Transport	Insecured road	40
Diverse	Graveyard	25
	Active or disused military facilities	35
Industry	Aggregate quarries	25
Livestock and agriculture	Animal barn (shed, shelter, stable)	30
	Battery or intensive farming	30
	Spreading of organic fertilizers	45
	Intensive grazing area	25

5.3.2 Solid Waste Disposal

According to Algerian regulation, solid waste includes three main categories: household and similar waste, special waste (industrial, agricultural, healthcare, etc.) and inert waste.

The improvement of municipal management of solid waste is considered as a priority by the ministry in charge of Environment. For this purpose, a set of regulations and organizations have been implemented. Human and technical resources have been committed since 2001 to improve the service [24]. According to the Directorate of Environment of Tlemcen (2020), the waste generated by the population is estimated at 887 T/d of which only 82% is properly collected and disposed.

The study area includes two industrial zones (Maghnia and Chetouane) and 4 activity zones (Terni, Beni Boussaid, Remchi and Hennaya). The amount of specific waste is estimated at 13,000 T/year. The amount of used oil is estimated at 85,000L/year. The latter are recovered by Naftal (the national petrochemicals marketing company). It should also be noted that significant quantities of special waste (74,000L of obsolete pesticides) are stored in Sidi El Djilali (southwest of the Tlemcen Mountains).

5.3.3 Fuel Loading Stations

According to the Directorate of Energy of the Wilaya of Tlemcen, 74 fuel loading stations in the study area (including car washing and lubrication) generate more than 12m^3/year of used oil (oral communication from the Directorate of Energy of Tlemcen). The average is 1 to 2 stations per municipality. These service stations are

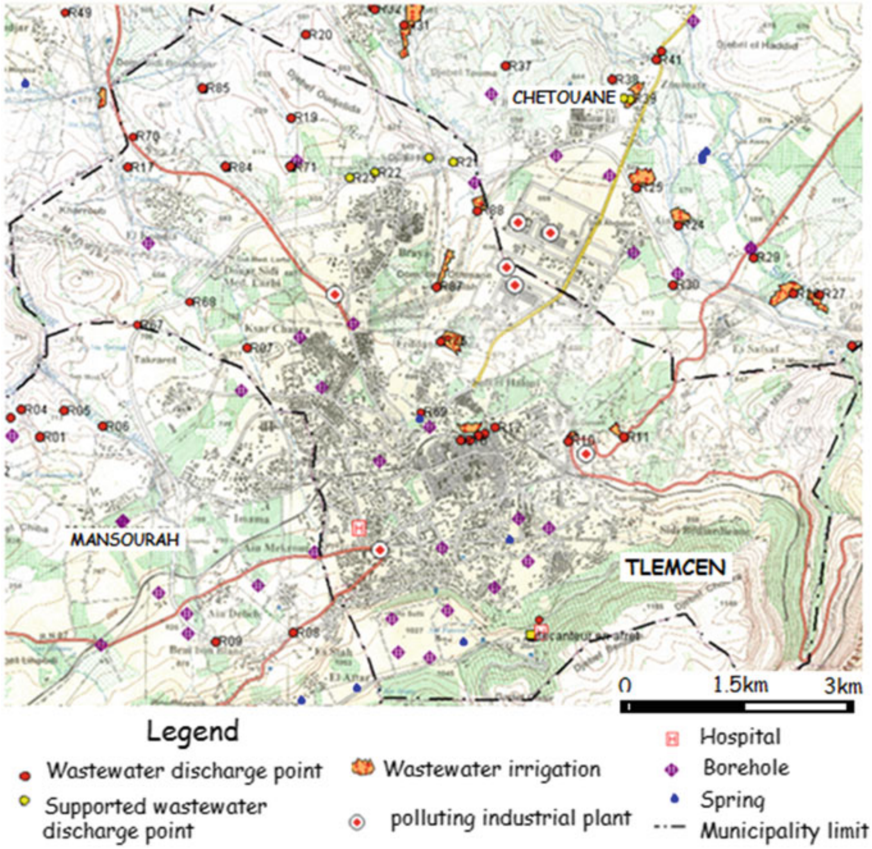


Fig. 7 Water sources and environmental hazards in Tlemcen city area [18]

supplied by tanker trucks from the storage area located in Remchi (in the center of the Tafna basin). The storage tanks at these stations are underground with a total capacity of at least 90m^3 of liquid fuel (diesel, petrol and other) and 10m^3 of gas fuel. Some of these tanks are corroded and local residents have reported cases of significant groundwater contamination. Indeed, several such accidents were reported during the 1980 and 2000s in the region of Remchi, not far from the oil storage area, in Mansourah and recently (summer 2022) in the border area with Morocco (oral communication from the Tlemcen Energy Directorate). It should also be added that hydrocarbons are transported from Arzew to Remchi by means of pipelines that cross the study area over 167 km.

For groundwater protection, the respect of safety instructions during transport and storage is essential, especially in karst areas.

5.3.4 Freight Transport

The study area has an extensive road network extending on 4,188 km, including 100 km of the East–West highway. However, the railway network is poorly developed, with a single functional rail line. The impact of these networks on groundwater depends on the nature of the freight. Hydrocarbons are the most dangerous as they can spread rapidly on the ground in the event of an accident. This is a high risk of groundwater contamination, especially in karstic environments.

5.3.5 Quarries

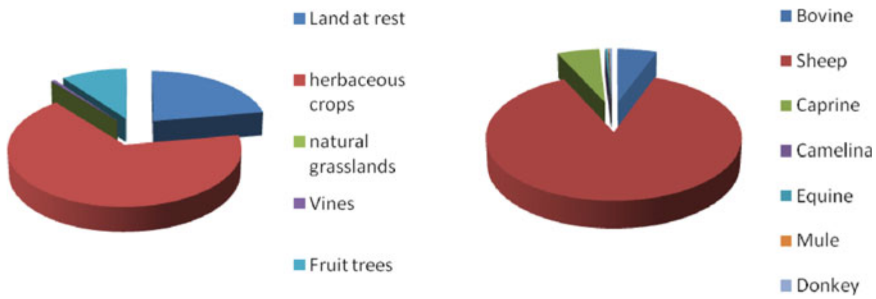
Aggregate quarries are the most widespread in the Tafna basin. All of them are located on limestone and dolomite outcrops, i.e., in karstic areas. Some of these quarries (Koudia, Sidi Abdelli) are gigantic as they supply most large construction sites in the region such as dams, roads or public building.

At the end of their working life, former quarries often become unauthorized dumping fields and become a dangerous source of groundwater pollution [19].

5.3.6 Agriculture

Since the Tafna basin is almost included in the Tlemcen wilaya, the data on the agricultural activity of the latter will be considered.

The total agricultural area (S.A.T) of the Tlemcen wilaya is estimated at 5,400 km^2 [25]. The agricultural area represents 65.2% of the total land area. Figure 8a shows that herbaceous crops are dominant. Regarding livestock farming, Fig. 8b illustrates the predominance of sheep farming.



(a) Distribution of the different types of crops making up the UAA in the wilaya of Tlemcen(2019)

(b) Farmed animal species (number of heads in 2019)

Fig. 8 Agricultural and livestock data (year 2019) [25]

6 Strategies of Protection and Risk Mitigation

A region's socio-economic development depends on availability and quality of water resources. Therefore, their protection is a key for sustainable regional development. Several actions are carried out by the competent authorities and local communities as well as by ordinary citizens concerned about the preservation of their Environment.

6.1 Regulation and Institution Building

Algeria Parliament has enacted several laws and by-laws dealing with the water sector, the environmental protection and land use planning. Three of these laws deal specifically with water resources protection:

- Law 83–17 of July 1983 [26] is dedicated to the fight against water pollution, including protection area for boreholes. In addition to water facilities, the vulnerable parts of groundwater must also be protected.
- Water law of August 2005 (Art. 38) [27] provided more details on creating and implementing protection areas.
- The 2007 decree on qualitative protection (Art.10) [28] recommends conducting geological and hydrogeological studies to assess groundwater's vulnerability to pollution.

The Oranie-Chott Chergui Water Basin Agency manages the water resources of Tafna basin. This is a public establishment under the supervision of the Ministry of Water Resources whose mission is the integrated and collaborative management of water resources on the scale of a natural hydrographic unit.

Another important institution is the National Sanitation Office (N.S.O.) whose mission is to organize the protection of the water environment throughout the country and the implementation of the sanitation policy in consultation with local authorities. The eradication of untreated wastewater discharges into the natural Environment is its main objective thanks to the construction of wastewater treatment plants (WWTP).

6.2 Implementing Groundwater Protection Regulation

6.2.1 The Prohibition of Irrigation with Untreated Wastewater

Although irrigation with untreated wastewater is strictly forbidden by the regulation (Water Act, 1983) [26], in 2003, the Tlemcen agricultural department recorded 272 ha of farming land irrigated with untreated wastewater. It was mostly used for market gardening and arboriculture [29]. By 2011, 83 ha only were recorded, mostly in peri-urban areas [16], suggesting that the regulation is step by step implemented.

This improvement is due to (a) an improvement in regulation implementation and (b) the start-up of Maghnia and Tlemcen WWTPs, reducing availability of untreated wastewater.

On the other hand, the national water sector strategy supports treated wastewater reuse for agricultural development, particularly arboriculture. 10 km downstream Tlemcen WWTP, the Hennaya irrigated area (912 ha) uses treated wastewater for the irrigation of fruit trees.

6.2.2 Mapping Groundwater Vulnerability to Pollution

Groundwater quality in the Tafna basin is generally rather good. However, this quality can be locally impaired, especially near urban areas. Groundwater vulnerability to pollution is becoming problematic as the urban areas are expanding more and more on karstic areas.

Mapping these resources' vulnerability is essential to better guide the development of urban centers [30].

Numerous methods for determining the vulnerability of groundwater have been developed worldwide, ranging from the most complex with models considering physical, chemical and biological processes in the saturated zone, to more qualitative methods considering different criteria affecting vulnerability [31].

To date, little work on intrinsic vulnerability has been carried out in Tafna basin. Several methods of vulnerability mapping have been applied, sometimes with great difficulty. The lack of hydrogeological data, geological mapping at an adequate scale and soil data has often discouraged attempts at vulnerability mapping. On the other hand, the use of GIS (Geographic Information System) for mapping has helped a lot as it facilitates data processing. Several methods were tested: G.O.D [32], D.R.A.S.T.I.C. [33], O.C.P.K. [23], C.O.P. [23], R.I.S.K. [34] and R.I.S.K.E. [35] methods.

The G.O.D. method (Ground water occurrence, Overall lithology of aquifer class, Depth to ground water table) was used for the assessment of vulnerability to ground water pollution in Hennaya plain. The application of this method is simple. The vulnerability index is the product of the three factors and five vulnerability classes are defined (very low, low, moderate, high and extreme). More than 48% of the mapped area was found to be moderately vulnerable, 43.7% was highly vulnerable and only 7.8% of the area was extremely vulnerable [16]. It is also worth noting that the outlets of this aquifer are located in this last zone, where high levels of nitrates have been measured.

The D.R.A.S.T.I.C. method (Depth to groundwater table (D), Recharge of the aquifer (R), Aquifer type (A), soil (S), topography (T), vadose zone (I) and hydraulic conductivity (C) of the aquifer) considers 7 parameters and therefore requires a lot of data. Applied to the Maghnia aquifer, it suggested that 49% half of the mapped area has a low or very low vulnerability, whereas 51% has a moderate vulnerability, high and very high vulnerability (Fig. 9b) [15]. On the other hand, the G.O.D. method applied for the same aquifer provided a different picture, with 98% of the area

(a) (b)

(c)

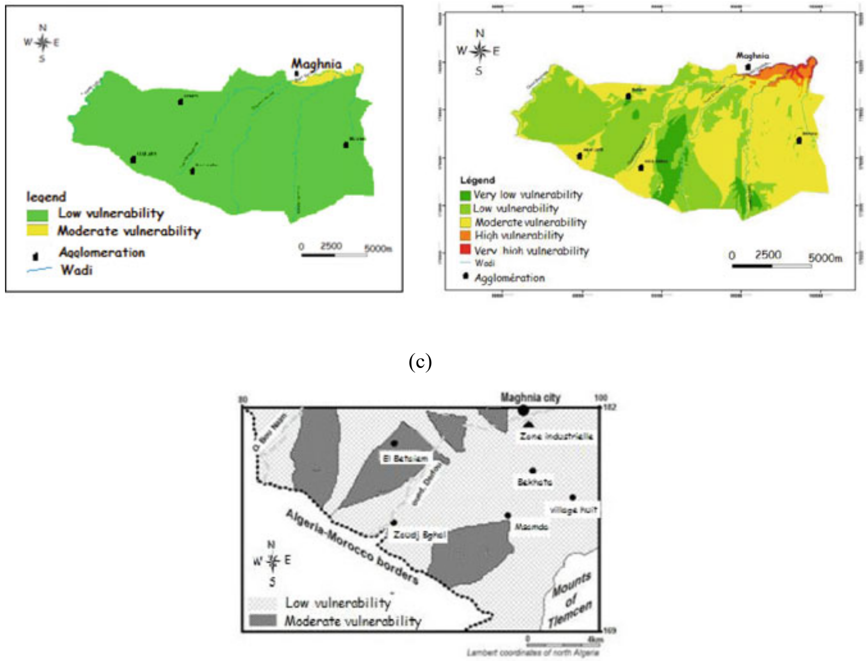


Fig. 9 Maghnia aquifer vulnerability mapping **a** DRASTIC method [15], **b** GOD method [15], **c** DRASTIC method [36]

classified in low vulnerability (Fig. 9a). These large differences illustrate the great uncertainty of the maps that can be constructed with these methods, which are based on a rather summary classification of soils and geological substratum. The absence of large-scale soil maps exacerbates this fragility.

6.2.3 Mapping Vulnerability of Karstic Aquifers

By nature, karst aquifers are extremely vulnerable to pollution. These aquifers are also very heterogeneous [37], so it is important to provide planners with detailed maps of the most vulnerable areas. However, drawing such maps comes up against an obstacle: the intrinsic heterogeneity of karst aquifers makes their modelling much more difficult than that of porous rock aquifers. The construction of maps must therefore be based on a combination of theoretical infiltration models and naturalistic observations, such as the inventory of karst phenomena [37].

Mapping of vulnerability to pollution of karstic groundwater was carried out on several sites, using the COP methodology [23]: Tlemcen area[30], Ghar Boumaza karst system [21], Beni Add caves [38] and the Meffrouch basin [39]. Such maps are worthy of being used as decision-making tools in the scope of land development projects.

What are the main challenges in making such maps? The soil features are the most difficult to map given the absence of detailed soil maps of the whole Tafna River basin. Indeed, only the irrigated areas have benefited from a detailed pedological study (Maghnia plain and Hennaya plain). The determination of the *soil factor* is based on in situ measurements of soil layers, determination from the type of vegetation, and evaluations from soil sampling carried out in the framework of other works in areas bordering or similar to the study area [21].

The *karst factor* is, in some areas, difficult to assess, particularly in poorly prospected regions. The inventory of large karst features (caves, pits, sinkholes, Underground River) would greatly help map this factor.

6.2.4 Implementing Protection Areas for Water Sources

Protection areas are mandatory under Algerian Water Act. However, only the immediate protection perimeter is systematically established. Close and distant protection areas are often still lacking.

The local governments enacted two regulations aiming to improve protection of groundwater resources in Tlemcen wilaya:

- Wilaya by-law n°276–2014 define close protection areas for 36 boreholes and 18 springs in the Tlemcen Mountains;
- Wilaya regulation prohibits heavy goods vehicles (including fuel tankers) from using the national road RN22 that connects Tlemcen to Sebdou and crosses a highly karstified environment that is very vulnerable to pollution. This directive has been applied since 2020 following accidents on this very dangerous road, which caused large volumes of hydrocarbons to be spilled into the natural environment.

6.3 Working Towards a Better Delineation of the Karstic Flow Paths in an Urban Environment

Encourage actions that work towards a better understanding of the karst environment, such as speleological explorations. Indeed, the Tlemcen mounts, essentially carbonate, are home to numerous karstic forms including caves and underground rivers (of international renown) explored since the 1940s. Since 2014, explorations have been carried out by researchers from the University of Tlemcen in collaboration with Algiers Speleology Club to complete the inventory of existing karst caves. A complete version of this inventory has just been published by Bensaoula and Collignon [1]. This will allow, in the future, refining the mapping of vulnerability to pollution as well as the fight against potential sources of pollution in relation to karst cavities.

7 Conclusion and Recommendations

Tlemcen City historically grew up in a small alluvial plain where hundreds of wells were dug. It then gradually expanded onto the surrounding hills because they had limited agricultural potential. This choice was perfectly rational from an economic perspective, preserving a large share of the regional agricultural potential. However, it has inevitably led to environmental risks: these hills are made up of highly karstified limestone and all or part of the wastewater from the new districts seeps into the subsoil and threatens the groundwater resources. At the same time, the city has needed additional boreholes to meet the growing water demand. The most productive boreholes are those that tap into karst aquifers, the quality of which is threatened by city expansion.

The planning of the future development of the urban area of Tlemcen will face the same difficulty: how to accompany city growth while improving the protection of karstic aquifers from which it draws its drinking water?

This will necessarily involve reducing the sources of pollution by improving urban sanitation (collection and treatment of wastewater and household waste). To optimise investments, it will be necessary to produce increasingly detailed maps of vulnerable areas and to model flows through the karst (direction of flows and transit time).

The aquifers located in the agricultural plains of Maghnia and Hennaya are already heavily contaminated by nitrates and should only be used for irrigation or industry. However, they are already overexploited, and the observed drop in piezometric levels compromises their sustainable exploitation.

We cannot finish this work without making some recommendations in order to preserve the karstic water resources of the Tafna basin. Many actions can be carried out for this purpose:

- Large-scale mapping of the vulnerability to pollution of water resources.
- The generalization of the construction of wastewater treatment plants downstream of large agglomerations with more than 20,000 inhabitants.
- Strengthening the water policy for better application of the regulations, particularly the law relating to water of 2005 which requires the establishment of a protection perimeter for groundwater catchment works.
- Strengthen the monitoring network of water points located in vulnerable areas.

Acknowledgements The authors are grateful to the reviewers and the editors for their valuable suggestions and constructive comments. Thanks also goes to the water resource services, the National Sanitation Office and Directorate of Energy of the city of Tlemcen.

References

1. Bensaoula F, Collignon B (2022) Les monts de Tlemcen. In: Collignon B (ed) Karsts et Grottes d'Algérie. Karstologia Mémoires, vol 27. pp 155–186
2. Benest M (1985) Evolution de la plate-forme de l'Ouest Algérien et du Nord-est Marocain au cours du Jurassique supérieur et au début du Crétacé: Stratigraphie milieux de dépôts et dynamique sédimentaire. Thèse université de Lyon.
3. Collignon B (1986) Hydrogéologie appliquée des aquifères karstiques des monts de Tlemcen. Thèse de Doctorat, université d´Avignon.
4. Bensaoula F (1992) Carte hydrogéologique d'Ouled-Mimoun et notice explicative au 1/50000 Thèse de Magister en hydrogéologie, université d'Es-Sénia, Oran.
5. Bensaoula F (2006) Karstification, hydrogéologie et vulnérabilité des eaux karstiques-Mise au point d'outils pour leur protection (Application aux Monts de Tlemcen–Ouest Oranais). Thèse d'état, université de Tlemcen.
6. Perrodon A (1957) Etude géologique des bassins néogènes sublittoraux de l'Algérie occidentale. Bulletin du service de la carte géologique de l'Algérie. 12:43–44
7. Guardia P (1975) Géodynamique de la Marge Alpine du continent Africain d´après l´étude de l´Oranie nord Occidentale relations structurales et paléogéographiques entre le rif externe le tell et l´avant pays atlasique. Thèse de doctorat, université de Nice.
8. Bensaoula F, Collignon B, Adjim M (2020) Assessment of groundwater resources in the Jurassic horst (Western Algeria). In: Negm AM, Bouderbala A, Chenchouni H, Barceló D (eds) Water resources in Algeria-Part I: assessment of surface and groundwater resources, Hdb Env Chem. © Springer Nature Switzerland AG, pp 225–266.https://doi.org/10.1007/698_2019_406
9. Ghenim AN, Megnounif A, Djelloul Smir SM (2014) Evaluation des changements dans la pluviométrie du bassin versant de la Tafna (Nord Ouest de l'Algérie). Sécheresse. https://doi.org/10.1684/sec.2013.0380TO
10. Collignon B, Bensaoula F (2019) L'exploitation des aquifères karstiques des Monts de Tlemcen (Algérie) comme réserve stratégique en cas de sécheresse pluriannuelle grave. Colloque Sécheresses, étiages et déficits en eau. UNESCO, Paris. https://doi.org/10.5281/zenodo.7038399
11. Assaba M, Laborde J, Rezak S (2013) Les effets d'une baisse de la pluviométrie sur les volumes regularisables des barrages d'Algérie. Revue scientifique et technique, le journal de l´eau et de l´environnement. 21 et 22, 10–19
12. Bensaoula F, Collignon B (1986) Evaluation des coûts de production de l´eau selon divers types d´ouvrages hydrauliques. Les donnés récentes dans la wilaya de Tlemcen, Colloque sur les ressources en eau et l´aménagement du territoire, Oran
13. Hayane SM (1983) Contribution à l'étude géologique et hydrogéologique du bassin versant de l'oued Sikkak (région de Tlemcen). Thèse de doctorat, université Oran
14. Babahamed K (2007) Hydrodynamique et modélisation d´une nappe alluviale, validation par l´approche géostatistique. Thèse, université de Tlemcen, Application à la nappe de la plaine de Maghnia (NW algérien)
15. Matène N (2016) Etude comparative des méthodes d'évaluation de la vulnérabilité intrinsèque des aquifères à la pollution-Application à la nappe de Maghnia. Mémoire de magister, université de Tlemcen.
16. Bemmoussat (2012) A Impact de l'activité agricole sur la qualité des eaux souterraines à travers le bassin de la Tafna. Mémoire de Magister université de Tlemcen
17. Bemmoussat A (2020) Méthodologie de protection des ressources en eau souterraines en région à climat semi-aride. Thèse université de Tlemcen.
18. Hamza Cherif C (2011) Epuration des eaux usées par les Macrophytes. Mémoire de Magister, université de Tlemcen.
19. Fellah HS, Adjim M, Bensaoula F (2014) Identification and cartography of potential groundwater polluters in Tlemcen urban area (northwest of Algeria). Desalination Water Treat. https://doi.org/10.1080/19443994.2014.992971

20. Belbachir A, Bendaoud I (2020) Contribution à l'étude hydrogéochimique des eaux souterraines du groupement urbain de Tlemcen (Nord-Ouest algérien).Mémoire de Master, université de Tlemcen
21. Bensaoula F, Adjim M, Benazzouz B, Khatir O, Bouchama A, Harkat M, Fellah HS (2018) Vulnérabilité et risque de pollution du système karstique de Ghar Boumaza (Monts de Tlemcen, Nord-Ouest algérien)–Application de la méthode R.I.S.K. Karstologia 70:53–62
22. Observatoire régional de la santé Oran : bilan région Ouest, année 2018. https://www.insp.dz/images/PDF/ORS%20Oran/bilan%20de%20R%C3%A9gion%20Ouest%20ann%C3%A9e%20%202018.pdf
23. Zwahlen F (2004) Vulnerability and risk mapping for the protection on carbonate (karst) aquifers-COST 620. European commission, directorate-general XII Science Research and development, Brussels, p 297. https://orbi.uliege.be›FinalReportCOST620
24. Djemaci B (2012) La gestion des déchets municipaux en Algérie: analyse prospective et éléments d'efficacité. Thèse de doctorat, université de Rouen
25. Direction des statistiques agricoles et des systèmes d´information (DSASI) 2019 Statistiques agricoles superficies et productions, "Série B"
26. Journal officiel de la république algérienne démocratique et populaire (1983) Loi portant Code des eaux.
27. Journal officiel de la république algérienne démocratique et populaire (2005) Loi relative à l'eau
28. Journal officiel de la république algérienne démocratique et populaire (2007) Décret exécutif 07–399 relatif aux périmètres de protection qualitative des ressources en eau
29. Bensaoula F, Adjim M, Adjim H (2003) Les périmètres de protection des eaux souterraines et les difficultés d'application du code des eaux. Cas de la wilaya de Tlemcen. Colloque international sur l´eau, Biskra-Algérie,
30. Bensaoula F, Bensalah M (2007) Etude de la vulnérabilité des eaux karstiques de la région de Tlemcen Int. conf. of renewable energies and sustainable development (ICRESD) Tlemcen, Algérie.
31. Gogu RC, Dassargues A (1998) A short overview on groundwater vulnerability assessment (basic statements for use in the framework of the COST 620 (Action). Workshop: Vulnérabilité et protection des eaux karstiques. Neuchâtel (Suisse)
32. Foster SSD (1987) Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy, vol 38. TNO Committee on Hydrological Research, Proceedings and Information, Den Haag, pp 69–86
33. Aller T, Bennett LJH, Petty RJ, Hackett G (1987) *DRASTIC:* a standardised system for evaluating groundwater pollution potential using hydrogeologic settings. US Environmental Protection Agency, EPA/600/2–87–035
34. Dörfliger N, Mettetal JP (2005) Cartographie de la vulnérabilité en vue de la délimitation des périmètres de protection en milieu karstique. Guide méthodologique, BRGM (ed)
35. Petelet-Giraud E, Dörfliger N, Crochet P (2000) RISKE: Méthode d'évaluation multicritère de la cartographie de la vulnérabilité des aquifères karstiques. Applications aux systèmes des Fontanilles et Cent-Fonts (Hérault, France). Hydrogéologie 4:71–88
36. Adjim M, Bensaoula F (2013) Application of the DRASTIC groundwater vulnerability mapping to the aquifer of Maghnia (North West of Algeria). Larhyss J 16:21–30
37. Collignon B (2018) L'aquifère karstique, objet d'études mathématiques ou naturalistes? Karstologia 71:53–60
38. Morsli S, Dahmani R (2016) Contribution à l'aménagement hydraulique d'un site karstique cas des grottes de Béni Add. Mémoire de master, université de Tlemcen.
39. Bensaoula F, Adjim N, Adjim M, Collignon B, Zeghid K (2016) First application of the COP method to vulnerability mapping in the Meffrouch catchment (Northwest of Algeria). Larhyss J 26:45–59

Effect of Urbanization on Water Resources: Challenges and Prospects

Esra Bilgiç and Alper Baba

Abstract Rapid urbanization due to population migration to cities has led to various natural hazards in recent decades. Urbanization has various consequences such as flooding, reduced recharge surface due to construction, pollution of water resources, etc. In this study, we investigated the effects of urbanization on water resources globally. Here, we documented the effects of urbanization on hydrological processes. The result shows that urbanization enhances flooding, over-extraction of groundwater, increase in impervious surfaces due to construction, water pollution, and the degradation of water quality due to the accumulation of pollutants derived from industrial and agricultural activities, waste disposal, and sewage. This study mainly highlights the importance of sustainable water management to protect and conserve water resources in urban areas.

Keywords Water resources · Urbanization · Modelling · Flooding · Groundwater management

1 Introduction

The population of the Earth has passed the 8 billion mark [116]. In recent decades, industrialization has brought many immigrants to cities. Therefore, rapid urbanization has been observed worldwide. Mbata and Anthony [60] state that the first dominant urbanization occurred in the 1950s. In 1950, more than two-thirds of the world's population lived in rural settlements, about 30% (nearly 750 million) of the remaining population lived in cities [60]. Ten years later, the world population was

E. Bilgiç (✉) · A. Baba
Civil Engineering Department, Izmir Institute of Technology, Izmir, Türkiye
e-mail: esrabilgic@iyte.edu.tr

A. Baba
e-mail: alperbaba@iyte.edu.tr

A. Baba
Department of International Water Sources, Izmir Institute of Technology, Izmir, Türkiye

S. Ali and A. M. Armanuos (eds.), *Groundwater in Arid and Semi-Arid Areas*, Earth and Environmental Sciences Library, https://doi.org/10.1007/978-3-031-43348-1_4

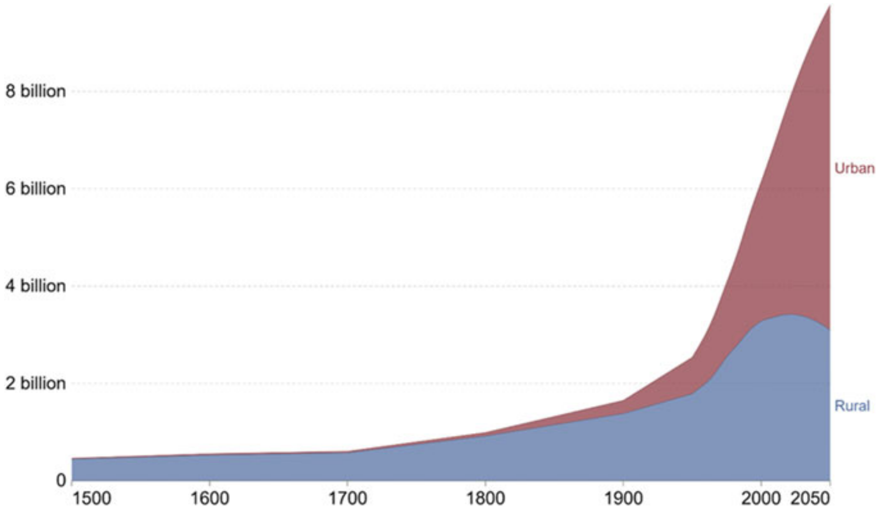


Fig. 1 Population projections for the world from 1500 to 2050 in urban and rural areas (Adopted from [87])

settled at 3.1 billion, and the urban population accounted for 34% of the total population [59, 63, 95, 99, 105, 112, 113]. For the first time in history, the global urban population exceeded the global rural population, and the number of urban residents increased faster than the rural population in 2007 (Fig. 1; [87]). It was estimated that more than 4.3 billion population live in metropolitan areas in 2018 [87]. This means that nearly more than half of the world's population (55%) now lives in cities.

North America has the highest urbanization rate, with more than four-fifths of the population living in cities. North America (82.75%), Latin America and the Caribbean (81.5%), Europe (75%), and Oceania (67%) are the most urbanized regions. In Asia, the urbanization rate is now approaching 52% [102]. In contrast, Africa remains largely rural, with only 44% of the population living in cities. Change at the global level is mainly driven by rural population dynamics in Africa and Asia (Fig. 2; [102]). By 2030, the proportion of the world's population living in urban areas is expected to reach 60%, and by 2050, it was projected that more than two-thirds of the world's population is expected to live in cities (68%) [58–61, 60, 61, 63, 78, 87, 95, 99, 105].

The global urbanization trend greatly varies around the world. In Japan, for example, the urbanization rate has levelled off at about 91.7% over the past decade. This means that less than 10% of Japan's 126 million inhabitants live outside cities. The majority of Japanese give the "comfortable lifestyle" and the "many entertainment options" as reasons for preferring an urban residential area. Japan is significantly more urbanized than the global average of 55% [87]. Japan is also known for its high population density-347.78 people per square kilometre in 2017-despite not even being one of the twenty most populous countries in the world [87]. Monaco tops the list, followed by China and Singapore, as shown in Fig. 3. By 2021, Africa

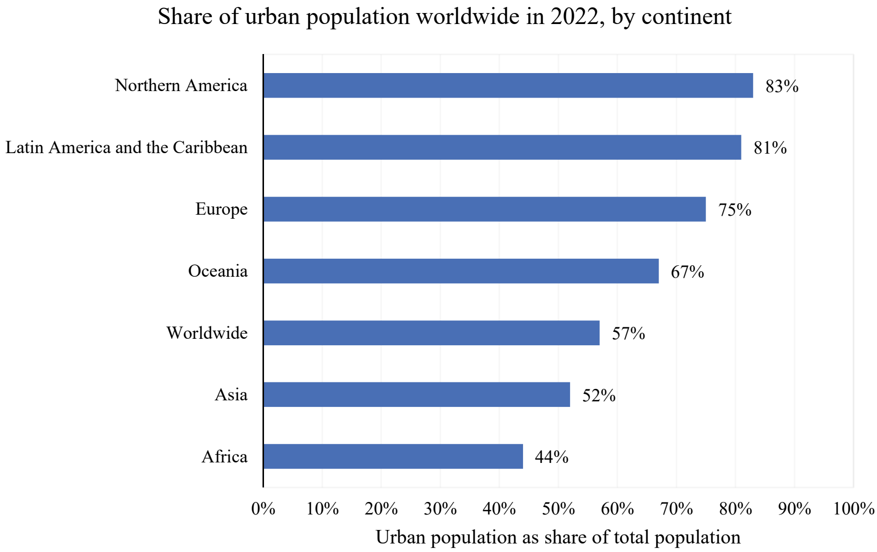


Fig. 2 Global urban population in 2022, by continent (Adopted from [102])

is expected to have an urbanization rate of over 44% [103]. Since 2000, urbanization has gradually expanded on the continent when urbanization accounted for 35% of the total population. This proportion will continue to increase in the coming years. However, the proportion of people living in rural and urban areas varies widely across the continent. Gabon and Libya were the most urbanized countries in Africa in 2019, with 80% each. In comparison, Burundi and Niger, which had urbanization rates of only 13% and 17%, respectively, had roughly the same proportion of their populations living in rural areas [103]. In addition, China experienced a period of rapid urbanization after the late 1970s. In 1980, the proportion of the population living in urban areas was about 20% [104]. In Asia, this rate increased to about 60% in 2018. In Türkiye, the number of people living in cities accounted for only 44% of the total population in the 1980s, while this proportion reached 59% in 1990. In 2019, 92.8% of people lived in provinces and districts, and in 2019 and 2020, it reached 93% [92, 108].

Numerous factors often determine migration from rural areas to urban areas. For example, Egypt plans to move the new capital city, which is located about 45 km from the existing Cairo and is generally referred to as the "New Administrative Capital". The goal is to create many opportunities for housing and employment and to eliminate the crowdedness that is one of the biggest problems now in Cairo because of the increasing population [35]. People are drawn to urban centres because they find better education, job opportunities, health care, access to electricity and advanced sewage systems, a more equitable system, and a higher standard of living [63, 120]. Urbanization is a product of nature's mobility, but if this situation is not systematically developed and planned, it can have significant negative consequences.

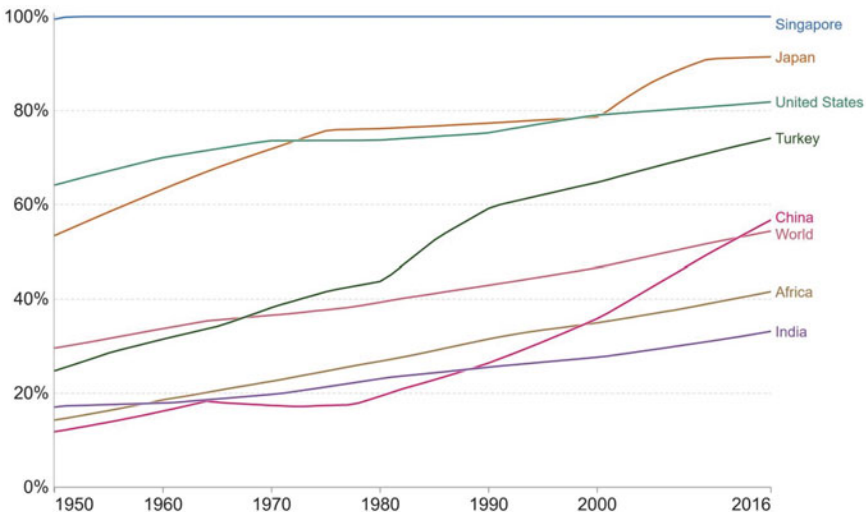


Fig. 3 Graph showing a trend of urbanization in the last 50 years, from 1950 to 2016 (Adopted from [87])

Thus, this chapter examines the various impacts of urbanization on water resources, focusing on urban water management strategies to mitigate these impacts.

2 Impact of Urbanization

Urbanization has various impacts on the environment, mainly air pollution, ecosystems, land use/land cover, biogeochemical cycles, water pollution, solid waste management, and the climate. Here, we documented the major effects of excessive urbanization on water resources which are presented below.

The first impact of urbanization on water resources is an increase in demand for drinking water. As cities grow, more people require clean drinking water as well as water for sanitation, hygiene, and other domestic purposes. This demand can strain existing water sources and lead to water shortages if not properly managed.

Second, urbanization can lead to water pollution. Industrial and agricultural activities, as well as runoff from urban roads, can introduce various toxic pollutants into surface and groundwater sources. These pollutants can range from heavy metals to fertilizers and other chemicals. This can lead to health problems for people who consume contaminated water and can potentially affect aquatic ecosystems.

Third, urbanization can lead to flooding and waterlogging. The more densely populated cities are; the less open land can be available to absorb precipitation. This can lead to increased storm water runoff, which can cause flooding and waterlogging.

These events can cause serious property damage, disruption of public services, and health risks to residents of affected areas.

Finally, urbanization can lead to an increased risk of waterborne diseases. The more densely populated cities are, the greater the risk of waterborne diseases. Poor sanitation, inadequate wastewater treatment, and polluted water sources can contribute to the spread of waterborne diseases.

Unplanned urbanization alters the city's microclimate, surface water dynamics, stream geomorphology, groundwater recharge biogeochemistry, and stream ecology as shown in Fig. 4.

2.1 Effects of Urbanization on Surface Water Resources

Natural disasters and human activities are depleting water supplies around the world. Urbanization, population growth, and rising standards of living are increasing water stress and pollution of water supplies, mainly due to anthropogenic activities. The changes in urban streams, the shape of the drainage hydrograph, the functions of the river structure and the increase in peak flows, total runoff volume, the extent of flooding, full flow, water velocities, frequency of flooding, and pollution of river systems. On the other hand, it can be defined as a decrease in infiltration rate, time of runoff concentration, base flow, erosion of downstream channels, groundwater recharge, dry season water levels, water quality, and changes in an aquatic environment.

Increased impermeable surface directly affects the ability and amount of water to penetrate into the soil, subsequent accumulation of water bodies, surface runoff, and groundwater. Land-use changes in hydrological areas can change the maximum and total discharge, water quality, hydrological capabilities, or appearance of river channels [78, 79]. There are numerous studies investigating about effects of urbanization on water resources. One of them was implemented in the Northwest region of China [12]. It has faced the problem of increasing water scarcity during the rapid urbanization process in recent years. Therefore, the researchers studied the spatial panel econometric model to investigate the spatial effect of urbanization on water resource usage and its driving mechanism. Researchers concluded that urbanization and water ecological footprint showed a spatially clustered trend from 2005 to 2017 [109]. In addition, by using historical topographic maps, satellite pictures, census data, and aerial photography, other researchers have examined how land usage has changed in an urbanized area [5, 11, 95, 107, 115]. Especially, changes in the land use-land cover of urbanization can cause water shortages and significant flash floods. The U.S. Office of Research and Development Washington conducted one of the land cover modification studies in June 1999. The studies show that changes in land use and land cover do not only affect the local and regional level [36, 95]. Another study was performed on the effects of urbanization on water resources in Portland, Oregon, USA. The study concluded that green roofs, seepage areas, permeable physical properties, and other similar techniques help treat water resources sustainably

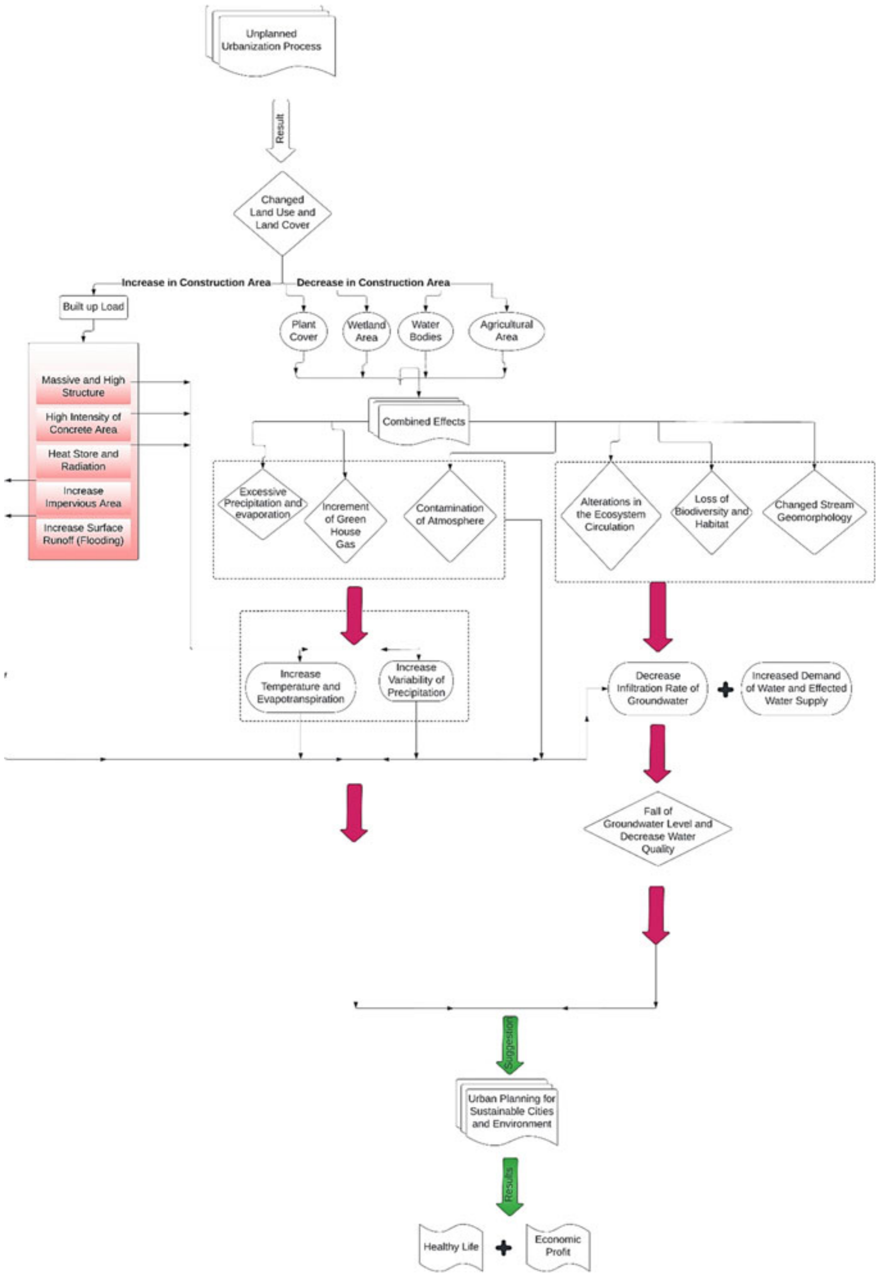


Fig. 4 Effects of unplanned urbanization process (Modified from [79])

and can improve the appearance of this city when combined with site planning or landscape architecture [59, 105, 110]. In addition, a similar study was conducted for the Küçükçekmece basin in Türkiye. The study concluded that urban sprawl in the watershed altered the variability and amplitude of hydrological components based on land-use patterns. It also concluded that subsequent land use planning research should be included a conservation strategy [24].

The impacts of urbanization on floods, droughts, and overall river regimes have been investigated in the past few decades [7]. The study produced a threshold for the effects of urbanization on imperviousness. High, low, and average flows were affected by the threshold of 10% of the total impervious area. Also, it concluded that an increase in the average catchment incompatibility of more than 10% outweighs the modelling uncertainties of the hydrological effect of urbanization [75]. Evaluation of changes in land use and land cover (LULC) in hydrology is essential for developing sustainable water resource strategies. An integrated approach of hydrological modelling and multiple regression analysis was performed to quantify the changes in hydrological components on defined LULC (Land Use Land Cover) classes in the upper San Pedro watershed, which is originates in Sonora (Mexico) and flows north into south-eastern Arizona (USA), by using the Soil and Water Assessment Tool (SWAT) [72].

In conclusion, urbanization seriously impacts the quantity and quality of water resources. Urbanization often leads to the contamination of water sources through industrial activities, wastewater discharge, and leakage from underground storage tanks. Drainage problems: Increased runoff from impervious surfaces (e.g. buildings and roads) can lead to flooding and water pollution. The other effects are aquifer depletion. Withdrawal of huge groundwater for urban use can lead to the depletion of aquifers, especially in areas with lesser rainfall. Urban expansion often leads to the destruction of wetlands, which play a crucial role in maintaining water quality and protecting against floods.

There are several solutions to mitigate the impacts of urbanization on water resources. Therefore, groundwater management should be considered. Changing the urban land area impacts the hydrological cycle and its components; infiltration, runoff, evaporation, etc. These changes affect water quantity and quality (nutrient, sediment, and pollutant levels).

2.2 Impact on the Groundwater

It is well known that groundwater, the world's most important drinking water reserve, is severely affected by urbanization [37, 63, 66, 67, 70]. Urbanization is a necessary geomorphic process that affects both surface and groundwater systems. As the world population increases, this resource will likely be used more intensively [30, 31, 66, 96]. Compared to natural conditions, urbanization affects groundwater recharge sources and flow routes [39, 66, 117, 119]. Increasing water demand can affect groundwater levels as the population increases, as shown in Figs. 5 and 6. Accordingly, excessive groundwater use can lead to land subsidence. An example of this situation is the sinkholes that occurred in Konya, Türkiye as shown in Fig. 7.

The rapid growth of the urban area has two basic effects on groundwater resources such as effects on the natural recharge of aquifers due to the sealing of ground with concrete and pollution of groundwater due to leakage from anthropogenic factors [19, 55–55, 81, 117]. Price [83] emphasized the integrated significance of the urban surface, the presence of water and drainage networks, and the broader characteristics of the catchment area in highlighting the multidimensional scale of the link between urbanization and groundwater flow dynamics. The second one is increased water supply and the construction of sewer networks [20, 66]. A study found that the

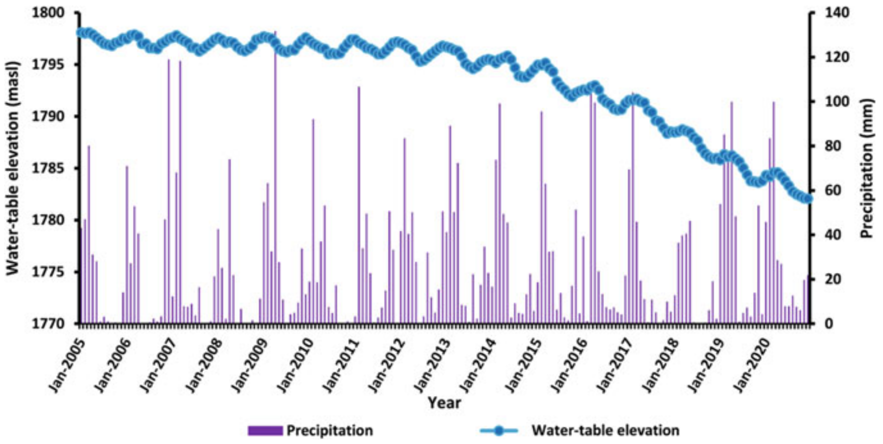


Fig. 5 Fall of groundwater level in the Kabul Plain (2005–2020) [119]

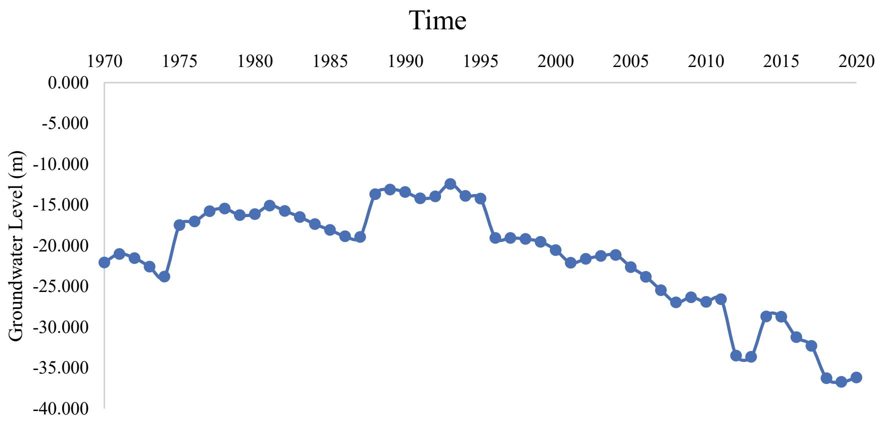


Fig. 6 Fall of groundwater level in Konya Plain, Türkiye (Data from DMI station, 1970–2020)

Fig. 7 İnoba Sinkhole in Konya Plain, Türkiye [118]

presence of significant infrastructure below the city surface can affect groundwater dynamics [47]. As a result, infiltration from the water supply and sewage infrastructure contributes to groundwater recharge while reducing groundwater aquifers' ability to self-clean. It can prevent water entering sewer systems from reaching groundwater [66]. A related study predicted that it might contribute between 15 and 55% of total sewage flow [43]. Other studies in Lima (Peru) and Hong Kong showed the importance of recharging, with leakage accounting for 30% and 50% of the total charge, respectively [56, 55]. Furthermore, a study found a noticeable link between the sewer system's fundamental flow and the city of Lyon's groundwater level [89]. Rising groundwater levels in metropolitan areas frequently cause flooding in low-lying areas such as basements and cellars, particularly in places with limestone bedrock or sand and gravel coverings [63]. The urbanized surface influences groundwater recharge, which higher urbanized areas would be less recharge under paved areas and artificial recharge from storm runoff. A septic tank system could be used to recharge groundwater.

According to several studies, the most important factor for groundwater recharge is leakage from the water supply and sewage systems [51]. As a result of a further literature study carried out in this context, it found that 138 mm/year of existing groundwater recharge, which in Nottingham, England, was 211 mm/year, is due to the leaking water network and 10 mm/year to leaking sewage [117]. Researchers estimated the recharge of groundwater using several chemical tracers in the city of Barcelona, Spain. It found that 30% through seepage from sewage, 22% from seepage from the water supply, 20% from seepage from runoff, 17% from precipitation and 11% from water were caused by Beso River [112]. Other researchers concluded a study of groundwater recharge from a leaky water delivery system in Seoul, which accounts for 93% of total groundwater recharge [52]. On the other hand, other researchers [26, 72] found that a 20–40% decrease in available groundwater recharge is due to an 18% increase in an urbanized area in Vermillion River Catchment, Minnesota, USA. Research published in the literature found that rising groundwater levels in the Copenhagen region of Denmark could only be explained by increased precipitation over the historical period (1850–2003) [49]. Without the increased rainfall, the water table would have fallen due to urbanization. As a result, as the density of urbanization increases, the total flow volume increases. The results may indicate that an increase in impermeable cover increases surface water flow, while an increase in urban irrigation and terrestrial karst leads to an increase in groundwater recharge [26, 47, 49, 51, 52, 56, 72, 89, 96].

In addition, the effects of urbanization on groundwater resources were performed in the city of Merida, Yucatan, Mexico, where the dependence on groundwater is very high. It concluded that urbanization affects the city's groundwater quality [37]. Another researcher used their findings to estimate the recharge process: the impact of urbanization on water recharges in Dübendorf, Switzerland [66]. The Monte Carlo (MC) approach was applied to account for the uncertainty of the parametric values included in this calculation in this region [66]. The study concluded that groundwater recharge rates and the size of the metropolitan area had a strong positive relationship [66]. In the study, urban areas in the study area expanded from 6% in 1880 to 44% in 2009, increasing the average groundwater recharge rate. However, it reported that the increase in recharge rate is variable, ranging from 29 to 67%, depending on the parameter combination derived from the Monte Carlo approach [66]. Another study stated that according to water balance calculations, the conversion of natural landscapes into impermeable areas leads to increased groundwater recharge rates through reduced evaporation. In addition, more significant water infiltration into the ground contributes to increased recharge rates. However, several other studies concluded that new formations in urban areas could be reduced because surface sealing prevents seepage and increases surface water runoff compared to natural landscapes [39, 41, 66, 88].

In a similar investigation, water levels in urban wells were found to be much lower than those in non-urban wells in a region near Atlanta, USA [88]. Also, other researchers discovered a 23% decline in groundwater recharge owing to surface sealing in Dresden, Germany [39]. Similar finding data were also found for Austin in US Garcia-Fresca [32, 66]. The researchers concluded that the groundwater recharge rate for the year 2000 was nearly double the suburban rate due to the lower impervious area, as well as in another study from Perth, Australia [13, 32, 66]. In Beijing, another study on the effects of urbanization on groundwater was conducted. According to a study conducted by the University of Texas at Austin in 2006, Curve Number (CN) levels near 100 indicate high flow, whereas low to moderate CN values suggest reduced flow in the study area. Also, it stated that developed land with a higher level of the impermeable area has higher curve numbers corresponding to higher flow. The impervious surfaces reduce the permeability of the earth's surface and filtration at the site to briefly the total volume of runoff increases when the urbanization density increases [22]. Increased water impermeability can raise surface water flow, whereas increased urban irrigation and subterranean karst can increase groundwater recharge. In summary, it is difficult to assess the net effect of urbanization on groundwater recharge because each city has a unique ecosystem and, in many cases, unique weather patterns [22, 95].

Urbanization also causes significant changes in groundwater recharge frequency, volume, and quality, modifying existing recharge mechanisms. These urbanization effects on water quality can result from sewage and industrial effluent overflow. In turn, these changes have long-term impacts on groundwater levels, resources, and quality in underlying aquifers. There have been several researchers investigating the degradation of urban water quality due to sudden and fast urbanization processes [29, 38, 46, 54, 64, 65, 78, 80, 81, 109, 114]. For example, in Asia, there have serious pollution problems in both coastal and urban areas. In this scope, there is a study to investigate the effects of urbanization on contaminant transport in groundwater. The research areas were located around Bangkok, Thailand, and Jakarta, Indonesia, with approximately 8 and 12 million populations. Each metropolitan city is located on a river delta and is adjacent to a bay [29, 38, 46, 54, 63–65, 65, 78, 80, 81, 109]. To do that, the water levels were measured, and collected water samples at boreholes at multiple depths (100–200 m) in 2004 and 2006 in Bangkok and Jakarta, respectively. The study's results emphasized that changes in groundwater flow and pollutant transport caused by urbanization need to be validated to prevent adverse impacts of urbanization on groundwater quality. It is important to recognize the possibility of future contaminant transport with deep groundwater discharge into the sea after recovering groundwater potential in the coastal areas [74]. In addition to their study results, the groundwater potential had declined, and subsidence had occurred due to intensive groundwater pumping in urban areas. Another study conducted for Delhi in India used ARC-INFO and ArcView GIS, to investigate the effects of urbanization on changes in groundwater quantity and quality. This research calculated the net groundwater amount in some urbanized areas near Delhi. It also concluded that groundwater from urbanization and human pollution in urban areas west and northwest of Delhi might be toxic [93, 95, 99, 110].

2.3 Impact on Hydrological Cycle

Water may circulate between the surface, atmosphere, and oceans due to the hydrological cycle. Moisture, evapotranspiration, condensation, and precipitation are the four basic processes that transfer water. Hydrology has developed over the past few decades to help clarify some of the urban expansion on natural hydrological systems [29, 48, 63, 73]. It reduces the amount of water in the ground and increases surface runoff. It can also alter rainfall into runoff at the surface. According to a study, urbanization alters the natural water cycle as building concentration rises and larger neighbourhood areas develop [65]. It is observed that evaporation and surface runoff increase with urbanization at approximately the same precipitation levels. For example, when the urbanization rate is 6%, the impact of urbanization on water resources is reflected on several parameters, namely, (a) the infiltration amount is 245.1 mm, (b) the surface water flow is 29 mm, and (c) the evaporation amount is 678.9 mm. When the urbanization rate is increased to 44%, the infiltration amount is 332.2 mm, the surface water flow is 121 mm, and the evaporation amount is 494.1 mm. The hydrological cycle can be impressed by several parameters like land use, land cover, amount of precipitation, climate change, etc. [95]. The main parameter is land-use changes. The land-use changes in the hydrology of an area affect peak flow characteristics, total runoff, quality of water, and hydrologic amenities or appearance of river channels [63]. The main reasons these parameters change is suddenly changing flow regime, percentage of impervious area, and water transmission rate from land to flow channels. There are two keynote factors governing the flow regime, one of them is the percentage of the area made waterproof, and the other one is the rate at which water is transmitted across the land to stream channels. The rate of water transferred into the water channel or sewerage depends on the density, volume, surface runoff, soil type characteristics, vegetation cover, and land slope [63, 95, 105]. The large impermeable surfaces can alter the seepage dynamic and have opposite effects on base flow behaviour at various scales [114]. Another parameter that influences the hydrological cycle is urban development or change. Some metropolitan areas reduce infiltration and recharge because of extensive soil sealing. In contrast, some porous areas within the urban landscape facilitate water transfer from the surface to the groundwater. It was discovered that an increase of 1% in the urban area led to a reduction of 41% in overall infiltration in an experimental basin in the Gaza Strip [28]. It emphasized that about 10% of the annual precipitation seeps into the road network for a test site in the south of England [33, 63, 84]. Because significant changes in the physical pathways of the water cycle can be (a) the elimination of natural plant drainage patterns, (b) the disappearance of natural basins temporarily storing surface waters, (c) the loss of the soil's ability to absorb precipitation, (d) the creation of impervious zones, and (d) providing artificial drainage systems (e.g., storm drains, canals, settling ponds). According to a study, sudden hydrologic effects occur when land is developed for housing or other urban uses. These effects increase the area with low or no infiltration rate and boost the effectiveness or speed of water transport through conduits or streams. The extent to which formerly natural surfaces are replaced with designed, permeable ones is the most obvious change in landscape-level alteration [9, 95]. When buildings and paved surfaces replace vegetation and soil, the capacity for infiltration of precipitation is significantly decreased. It causes increased surface runoff, a shorter lag time, and a higher peak discharge in streams and highways, which results in flash floods and ponding [16, 95]. The other study provides a better understanding of the relationship between local hydrological parameters in urban settings and the physical transformation of land covers as impermeable built-ups. It helps to acquire knowledge of how one component affects another. It will allow urban planners in the physical design of new and existing development in an area to achieve optimum sustainability in the city by predicting and projecting changes in hydrological cycles owing to land use/ land cover alteration [55–55, 63, 95].

2.4 Climate Change

According to the Intergovernmental Panel on Climate Change (IPCC) report, it is evident that urban land area has increased, directly affecting the hydrologic cycle [46, 55–55, 55, 63]. Climate change is expected to exacerbate worldwide hazards in nearly all sectors and sub-regions [46]. Extreme weather events are expected to exacerbate the devastating impacts of storms, severe flooding, and coastal inundation due to heavy rainfall, rising temperatures, altered exposure, and vulnerability. Seepage, surface flow, and evaporation are the affected hydrological cycle components. In contrast, land use, land cover, withdrawal, urban developments, and climate components that cause the change in the hydrological cycle [101]. According to another IPCC report [45], human activities and urbanization can influence climate change and cause extreme weather events [45, 95]. These variations may cause damage to soil erosion, crops, land degradation, low yields, and cultivable land. For example, rapid urban and industrial developments and the expansion of irrigated farmland have doubled water demand. To examine the effects of climate change on several flood risks and recommend an adaptation strategy, a regional risk assessment (RRA) methodology was created and implemented in the urban area of the municipality of Venice. The RRA enables the identification and prioritization of goals and sub-areas that are more likely to be affected by various flood hazards owing to heavy rain events in 2041–2050 in the future scenario, based on an integrated analysis of hazard exposure, vulnerability, and risk. Due to the topography's high density and low inclination, all targets (e.g., residential, commercial, industrial sectors, and infrastructures) are prone to heavy flooding [101]. According to a study conducted in this context, several researchers have studied flooding in Africa resulting from climate change and urbanization. In the study, urban areas can facilitate strong storm activity. Built areas can reach higher temperatures than non-construction areas, and it can create local air circulation due to the urban heat island effect. Research linked urbanization and rainfall, as well as the consequences of urbanization on the climate [98, 100]. During the warm season, the researchers discovered a 28% increase in rainfall downwind in six cities in the southern United States, with a more modest rise (5.6%) in metropolitan areas, which indicates that rainfall has far-reaching consequences beyond the local urban scale [98, 100]. Furthermore, some researchers have found that Urban Heat Island (UHI) plays a pivotal role in the frequency of convective summer thunderstorms in Atlanta and the resulting increase in precipitation [10, 14, 17, 98]. It emphasizes the scalability of micro fluid fluctuations on regional climate dynamics in downwind areas once more [10, 14, 17, 63, 98]. Other studies were performed on the effects of urbanization on evapotranspiration. The research concluded that urbanization affects peak and bottom flows because of reduced evapotranspiration

[78, 95, 105]. Converting forest lands to urban usage increases surface albedo (solar radiation reflection), decreases net radiation, diminishes latent heat, raises summer storm severity, and generates heat island effects [78]. To conclude, the urban landscape has a variety of effects on the local climate, including decreased average wind speed because of the blocking effect of buildings and increased frequency of flash floods because of a higher proportion of ground sealed with concrete and asphalt and a corresponding decrease in the natural drainage network. The most significant consequence of urbanization on the hydrological cycle regarding water infiltration is it resulted in excess runoff [98, 100].

2.5 Flooding

The climate regime and the degree of disturbance reflected in the total impervious area determine how urbanization and land use change affect streamflow hydrographs. For instance, after urbanization, watersheds with 43% impervious surface area might triple their discharge. According to research, water depletion occurs on 40–50% of the impervious land cover in California. Flow alterations have been observed in around 20% of impermeable land covers, according to research conducted in Israel, the United States, and the United Kingdom [21, 54, 95, 98, 100, 105]. Climate and land-use changes affect the occurrence of large-scale to low-frequency floods in many parts of the world [3, 23, 34, 54, 82, 91, 106]. To cope with this increased flooding and associated socio-economic damage, there is growing interest in developing flood warning and flood mapping systems [34, 50, 94]. Another study used data recorded at river runoff stations to provide information on past floods and future forecasting using various statistical/stochastic methods [18]. Imperviousness increases the area with limited or no infiltration capacity and improves the efficiency or speed of water transport in channels or conduits [9]. Because impervious surfaces lower the permeability of the land surface and infiltration at the site, developed areas with higher degrees of the impervious area have higher curve numbers (CN), which equate to increased surface runoff. A study concluded that CN values near 100 represent larger flow rates, while CN values in the low to middle range reflect lower flow rates [22, 44]. Besides increasing imperviousness owing to roads, residences, parking lots, and buildings, removing vegetation and soil, grading the land surface, and installing drainage networks which enhance runoff volumes and reduce runoff time into streams from rainfall and snowmelt as shown in Fig. 8. The greater soil's permeability, or ability to permeate rainfall into its bottom strata, the less runoff is produced [44, 95]. Soils and geology are also important considerations when evaluating the effects of urbanization. Urban runoff is influenced by the amount and duration of precipitation, soil conditions, soil thickness, permeability, and moisture level in the soil [44, 95]. Rainwater can be absorbed by the earth's surface, prevented by vegetation, directly trapped in various surface structures ranging from minor depressions to vast lakes and seas, or seeped into groundwater via surface and underground soils. To summarize, when buildings and asphalt pavements replace vegetation and soil, the ability for precipitation infiltration is dramatically diminished, resulting in the increased runoff, shorter lag times, and higher peak discharge, culminating in flash floods and road flooding. The increase in total runoff and storm hydrograph brightness is the most significant consequence of urban expansion on water resources [23, 44, 91, 95]. Hydrological changes can have positive consequences in some aspects and negative ones in others. For example, an increase in annual flow can increase renewable water resources, creating some benefits for both in-stream and off-stream water users, but at the same time. The volume of rainwater in the city's catchments and the frequency of extreme hydrological events have increased dramatically due to urban expansion. Increased runoff leads to more extreme local flooding, whereas dry weather leads to longer and more severe droughts [6, 69]. As a result, greater peak water flows and flood frequency are consequences of urban development. As cities grow, the maximum yearly flow in a stream will increase, although major annual storm variations can sometimes mask this growth. The effects of urban watershed development are most evident during moderate storms that follow dry spells. In rural watersheds, like in urban watersheds, the soil becomes saturated during strong storms and wet seasons, resulting in more precipitation or melting [6, 53, 69]. The literature describes a detailed numerical simulation of flood hydrograph that utilizes one-dimensional model software (such as HEC-RAS). HEC-RAS includes calculations of inundation areas, flood wave travel durations, water depths, water levels, flow velocities, and overflow volumes by simulating the hydraulic behaviour [8]. The study discovered that determining the upper limit of the peak discharge hydrograph entering the Evros river reduces flooding. Because a significant increase in the profile of the free water surface occurs with an increase in the height of the water at the junction, an additional flooding of the adjacent territories resulted in due to the subcritical flow. It also found that this result was important in dealing with floods in the Evros River's downstream section, which is a considerably larger river with several tributaries [8]. Using LiDAR data and HEC-RAS, another study was conducted in the Grand River in Ohio, USA [36]. In order to determine the travel duration of a flood event and the amount of its flooding, this study will compute the predictive power of one-dimensional (1D), two-dimensional (2D), and HEC-RAS models. According to the analysis, the 2D model continuously performs better than the 1D and mixed 1D/2D models. According to the sensitivity analysis, the combined 1D/2D and 1D models are also substantially more sensitive to inputs than the 2D model. The estimated travel time for the 1D model was 20% more than that of the other 2D models. Additionally, it was discovered that the flooding area predicted by the 1D model was slightly higher (4.1%) than predicted by the 2D model. Because it is crucial to establish a flood warning system to issue evacuation times to safeguard lives and property, the forecast of flood travel time, and the extent of the flooded area [36]. Another study, Ertürk and Kaya [27], concluded that preventive measures should be taken such as (a) the establishment of early warning systems in case of floods and (b) the construction of flood control facilities. These preventive measures were carried out for Kirazlı Stream, located in the Vakıfkebir district of Trabzon province in the Eastern Black Sea Region. It also concluded that one of the most important disasters to be prepared for is flooding, which can be caused by topographic conditions like slope, soil type, etc., as well as climate conditions like it can have meteorologically heavy rainfall. If the water transmission capacity of the riverbed is reduced for various reasons, or if more water comes than the riverbed, it can hold during the flood, which causes loss of life and property by overflowing the riverbed [27]. Another study was carried out on the Tavukçu Stream, a sub-basin of Ataköy Basin [76]. The risk of flooding increases in densely populated areas. Because the soil surface is covered due to urbanization, water cannot infiltrate into the soil and starts to flow from the surface. When potable water is added to this, the amount of water coming into the streams increases greatly [105].

Intervention in floods in settled areas is more difficult for various reasons. The first is that the creek bed is smaller than the required dimensions and cannot be expanded. Expropriation problems, excessive concrete area, and the inadequacy of infrastructure systems can be listed as other obstacles. According to research, basements should not be built in buildings within the flood-proof construction band [76]. However, in cases where a basement floor is considered obligatory in terms of ground and construction techniques, these floors, which are exposed to high flood risk, can be used as residences, warehouses, parking lots, etc. Still, they should not be used for any commercial or non-commercial activity. In the buildings within the flood-proof construction band, the flooding elevation at any point is perpendicular to the stream section from this point and +1.50 m. must be high. The research concluded that the basement and ground floors of the buildings (if any) within the flood-preventive zoning band should be insured against the risk of flood disaster [76].

Another study was conducted to identify flood risk areas for the Artvin region in north-eastern Türkiye. The multi-criteria decision analysis (MCDM) method was used, taking into account slope, land use, soil characteristics, orientation, geology, maximum precipitation, and distance to a river with GIS. As a result of this study, risk maps were prepared. Based on the created risk map, it was determined that areas with “very high” and “high” flood risk are located in the settlement area [77]. These areas were chosen as the places with the highest probability of damage in a possible flood [77]. It is well known that as the density of urbanization increases, the total flow volume increases. The results of all these problems are that increasing the impermeable coating increases cities’ surface water flow and irrigation, and an increase in underground karst leads to an increase in groundwater recharge. Saturated conditions in groundwater and floodplains can lead to longer and deeper floods than low-intensity but prolonged floods [90, 91]. To understand the combined effects of hydrology on the surface and soil hydrodynamics on stream formation and subsequent flooding, a study that used an integrated surface water and groundwater (SW-GW) approach to simulate flood conditions [91]. It resulted in more intense precipitation would increase the percentage of runoff and overload the capacity of sewerage systems and wastewater treatment plants [91, 95]. All of them are responsible for the pollution of water resources. There are a lot of studies about urbanization’s impacts on the surface flow regime. One of them is suggested replicating natural drainage systems to prevent flooding, enhance urban aesthetics, and maintain water quantity and quality standards for receiving water bodies. It also showed how natural drainage

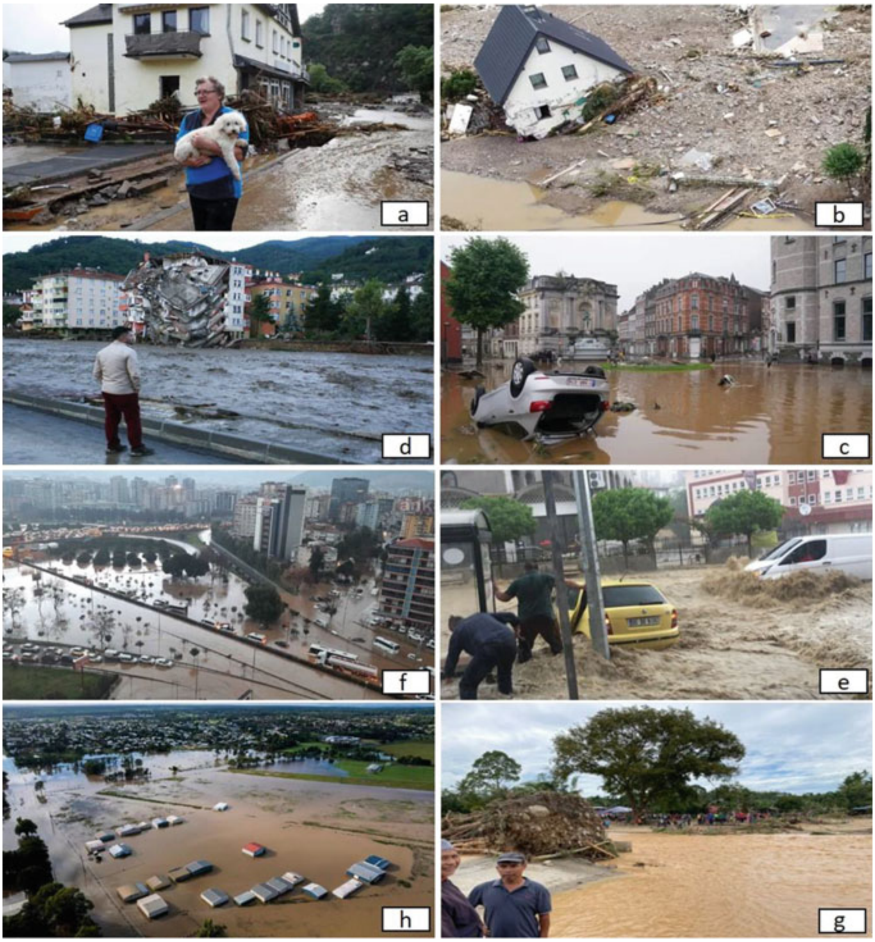


Fig. 8 Flooding problem in the world: **a** flooding damage in the Schuld, Germany [85], **b** flooding damage in the Schuld, Germany [85], **c** flooding damage in the Verviers, Belgium [85], **d** flooding damage in the Kastamonu, Türkiye [1], **e** flooding damage in the Ankara [25], Türkiye, **f** flooding damage in the İzmir, Türkiye [2], **g** flooding damage in the Baling, Kedah, Malaysia [71], **h** flooding damage in the Grafton in northern New South Wales, Australia [86]

processes could be incorporated into urban areas while maintaining a natural or pre-built hydrological regime. The other study is related to severe flood simulations in the Upper Wabash River Basin in Indiana, the USA, which show that floodplain hydrodynamics are more accurately modelled using the SW-GW 2D integrated model without the need for extensive calibration [91, 95]. In addition, the integrated model provides more realistic simulations of flood dynamics for various previous ground conditions. In particular, the results show that the river flow, flood stages, and flood area obtained for the dry scenario are significantly lower compared to the saturation scenario; understanding the dynamic relationship between the hydrosphere and landscape essentially begins with precipitation [90, 91, 95].

Nowadays, urban planners and engineers are assessing the local response of urban areas to precipitation and evaluating the fate of precipitation at the building and street scale. Researchers have studied how moisture, precipitation, and heat move on building surfaces to evaluate their effects. The study concluded that wind-induced rain leads to the wetting of building facades, whereby opposing materials react differently to the subsequent dynamics [15, 68]. For instance, mainly glass buildings create a smooth facade, which leads to a rapid movement of water into flowing. In contrast, buildings with predominantly brick or concrete construction, ancient buildings with supporting and hollow walls, have porous areas in which water can penetrate the structure and be viewed as water loss. Also, it emphasized that the effects of these dynamics on the water balance of the wider basin are unclear; however, the risk of local flooding can be exacerbated by buildings made of certain materials and inadequate supporting drainage infrastructure [63]. According to another study on the uncertainty of water dynamics, researchers found that 30% of rainfall that lands on rooftops in the south of the UK is either intercepted or evaporated [33, 63, 84]. To avoid losing this rainfall, it proposed that converting rain into a sustainable resource and volumetric understanding is critical to the design of collection tanks. It emphasized increasing interest in modelling the amount of water converted into runoff from urban roofs [33, 63]. Other researchers have argued that roofs help accelerate flow-generating processes in urban environments during storms by emphasizing the rate of precipitation conversion [63, 97]. Additionally, some other researchers discovered that a minor increase in enclosed surface area causes much greater peak discharges [111]. The study especially claimed true in urban periphery watersheds, where EIAs (Environmental Impact Assessments) collect to divert runoff to underground drainage networks and finally to neighbouring runoff channels [63, 111].

2.6 Geomorphology

Connected permeable and impermeable surfaces contribute to diverse sediment balance and canal morphology changes [3, 63]. Structures in the floodplain, such as bridges, can cause floods upstream by narrowing the canal and increasing the drag. As a result, the water flows past the obstruction and rises, causing stagnant water that floods a bigger region upstream [53]. This study observed an increase of 2–2.5 times in canal capacity after the urbanization region of Monks Creek in the south of England [38]. Researchers concluded that the adjustment of the channels resulted in an increase in width of up to 2.2 times and a bed cut of up to 0.4 m [38, 63]. Several studies have also shown that canal widening in response to urbanization can lead to a 2 to eightfold increase in cross-sectional area compared to suburban conditions. Another research was performed to study the temporal river geomorphic response to urbanization. The researcher proposed that urbanization affects watersheds and geographical units that consider important in the environment's form and function. A researcher has also studied how changes in canal networks occur due to impermeable surfaces [53]. Floodwaters can also constrict the channel and cause floods by carrying debris and precipitation. This hazard is greatest in the upstream of culverts, bridges, or other places where debris collects. For example, small streams can be filled with sediment or clogged with debris due to insufficient ventilation holes [53]. Another effect of urbanization is the erosion of urban rivers. Channel and coastal erosion are increased by frequent flooding of urban streams. The flow rate will rise when the channels are levelled and vegetation is removed from the channel banks, allowing the stream to carry more material. In many urban areas, riverbank erosion constantly threatens roads, bridges, and other structures and is difficult to control even by strengthening the riverbank [53]. The stripping of impermeable surfaces and coastal vegetation, along with the loss of coarse sediments, leads to higher runoff power and a faster storm water runoff response, increasing erosive flows during flash rains [53]. Previous research has shown that urbanization often leads to a widening urban canal cross-section [42, 78], stream channel interruption, and separation from the riparian zone [40]. According to the researcher who stated that in developed countries, engineering solutions are frequently applied to mediate the effects of erosion in urban streams, causing channels to be artificially lined with concrete, rock, or geomembrane materials (for example, LLDPE, reinforced polyethene and XR-5) [40, 63]. Although there has been a recent movement toward stream restoration, streams flowing under urban areas reduce the risk of surface flooding. Often destroying urban river ecosystems are culverts in concrete canals and attempts to restore in-stream urban ecosystems are culverts in concrete canals [19]. Also, other researchers concluded that another problem about the depletion of groundwater through over-pumping, which also removes the supporting buoyancy of groundwater, leads to the emergence of underground voids under densely populated urban areas, triggering the emergence of large sinkholes [4]. Therefore, it stressed an urgent need for more pragmatic landscape design and groundwater management mainly in developing countries due to the substantial geomorphological risk linked with the lack of control in these places. Streams also suffer from habitat loss, floodplain connection, bank stability, and decreasing water levels, with over 25% of their surface area impervious [4, 63].

3 Conclusion

Urbanization potentially impacts the quality and quantity of water resources. Water levels, temperature, and pollutant loads are likely to be affected by urbanization. The most common problem in urban areas are flooding due to reduced imperviousness. As a result, the extent and frequency of flooding increase, and there is an increased risk of flooding. In addition, urbanization has multiple impacts on the groundwater system. Effective and feasible groundwater resource planning is essential for a green and sustainable city. It can be suggested that in order to slow down and reduce runoff in urban areas and new developments, green infrastructures such as reducing impervious surfaces, renaturalizing streambeds, designing flooded parks to create storm water reserves, and collecting and storing rainwater should be used.

To mitigate the impact of urbanization on water resources, cities must adopt effective water management strategies. These strategies should include water conservation measures, water reuse, wastewater treatment, and water quality monitoring. In addition, cities should strive to reduce their reliance on freshwater sources by promoting the use of recycled water, rainwater harvesting, and rainwater capture. Furthermore, the migration of the population to urban areas should be checked by providing various facilities to rural areas. Finally, cities should implement green infrastructure measures to reduce flooding and waterlogging. Through these measures, cities can manage their water resources more effectively and reduce the environmental impacts of urbanization.

4 Recommendations

First, measures like water conservation; implementing water conservation measures, such as low-flow fixtures and landscaping, can reduce water demand. Other challenges should be in storm water management by implementing green infrastructure such as permeable pavements, rain gardens, and green roofs that can help reduce runoff, improve water quality, and increase groundwater recharge. Implementing sustainable groundwater management practices, such as aquifer recharge and surface and groundwater sharing, can help ensure long-term water security. Rainwater harvesting may be suggested for surface water management. Rainwater harvesting can help promote sustainability and resilience in urban areas, as it is a water conservation technique that collects, stores, and uses rainwater for various purposes. It relates to the design and construction of buildings, roads, bridges, and other infrastructure that can withstand and adapt to the impacts of climate change. It also includes measures to reduce the risk of damage from extreme weather events such as hurricanes, floods, and droughts. Building climate-resilient infrastructure helps in reducing the risk of damage to critical infrastructure, and reduce the economic costs of extreme weather events, so it can be suggested to solve the effects of urbanization on the water resources. In addition, sponge cities can be used to describe urban areas that are designed to manage and conserve water resources in a sustainable way. The concept is based on the idea of a sponge, which absorbs and retains water, and applies this principle to the design of urban infrastructure. The concept of sponge cities has been implemented in several countries around the world. For example, in 2015, the Chinese government launched a "sponge city" initiative to promote sustainable urban water management in cities across the country. Over 100 cities in China are now working to adopt sponge city principles. Other country is Singapore which has a long history of innovative water management, including the use of green infrastructure to manage water resources. The city-state is a leader in the development of sponge cities and is implementing a range of measures to conserve and reuse water. This concept has continued to sprawl in Japan, India, the Netherlands, France, and the UK. Another suggestion is public education. Raising public awareness about the importance of water conservation and the impacts of urbanization on water resources can encourage more sustainable practices.

There are several ways to increase groundwater recharge in urban areas. One of them is rainwater harvesting. This involves capturing rainwater and storing it for later use, such as irrigation, thereby reducing the need for freshwater and increasing groundwater recharge. Permeable pavements such as pervious concrete or permeable pavers can be improved to allow storm water to infiltrate into the soil and recharge groundwater, and green roofs can improve water retention and increase groundwater recharge. Artificial recharge systems such as injection wells or distribution basins can also be used to selectively recharge groundwater. Watershed management may consider measures such as stabilizing streambanks to improve water quality and increase groundwater recharge or installing recharge wells, which are special wells used to recharge groundwater by injecting water directly into an aquifer. These solutions can help increase groundwater recharge in urban areas and promote sustainable water management. By improving water retention and increasing groundwater recharge, cities can.

There are several ways to improve water quality in urban areas. Green roofs are a great way to reduce storm water runoff and improve water quality. Planting vegetation on rooftops can reduce runoff by up to 75%. Permeable pavement is designed to absorb and filter out pollutants from storm water runoff. This can help reduce contaminants entering local waterways. Bioswales are shallow channels that are planted with vegetation and designed to capture and filter storm water runoff. They are an effective way to reduce pollutants entering local waterways. Water conservation measures can help reduce the amount of water being used and reduce the amount of pollutants entering local waterways. Regular water quality testing can help identify pollutants entering local waters and source control measures can be taken to reduce nonpoint source pollution. Educating the public about the importance of water quality can help reduce the amount of pollutants entering local waters. These solutions can help improve water quality in urban areas and promote sustainable water management. By reducing pollution and improving water quality, cities can reduce the risk of water scarcity and improve their health and resilience.

Urbanization can considerably impact the water cycle, but if appropriate decisions are made during development, the damage can be reduced and our future water supply secured [63]. To solve the effects of urbanization climate change, constructing energy-efficient buildings, with features such as high-efficiency heating and cooling systems, double-paned windows, and green roofs, to reduce greenhouse gas emissions and energy use. Increasing the use of renewable energy sources, such as solar, wind, and geothermal, to reduce greenhouse gas emissions and dependence on fossil fuels. Promoting sustainable transportation, such as public transit, cycling, and walking, to reduce greenhouse gas emissions and air pollution from transportation and implementing carbon pricing mechanisms, such as cap-and-trade systems or carbon taxes, to reduce greenhouse gas emissions and encourage investment in clean energy and energy efficiency. These solutions can help to reduce the impact of urbanization on the climate and promote sustainability in urban areas. By reducing greenhouse gas emissions and improving energy efficiency, cities can help to mitigate the impacts of climate change and promote a more sustainable future. Reduce the impact of urbanization on surface flooding and promote sustainable water management in urban areas by introducing green infrastructure, such as parks, green roofs, and permeable pavements, to improve water retention and reduce runoff. Implement storm water management systems, and construct flood control facilities such as levees and walls to reduce flood risk and protect communities, e.g., detention basins and swales, to reduce runoff and improve water quality. Implement sustainable urban planning, e.g., reduce impervious surfaces and promote compact development to reduce the impact of urbanization on flooding. Implement flood-resistant building codes, such as elevating buildings above the potential flood level, using flood-resistant materials, and using storm water: Collecting and using storm water for non-potable purposes.

Acknowledgements We would like to thank the editors for their support and for reviewing this chapter.

References

1. AA (2021) The intensity of the flood disaster in Bozkurt was revealed in the morning twilight-Kastamonu News. Sabah Gazetesi, Anadolu Agency (AA). https://www.sabah.com.tr/kastamonu/2021/08/12/bozkurttaki-sel-felaketinin-boyutu-gun-agarinca-ortaya-cikti (in Turkish). Accessed 22 November 2022
2. AH (2021) Izmir under flood waters: more severe than the 1995 disaster. a3haber.com (AH). https://www.a3haber.com/2021/02/02/izmir-sel-sulari-altinda-1995-felaketinden-daha-agir/, A News (AH) (in Turkish). Accessed 22 November 2022
3. Akpan AE, Ilori AO, Essien NU (2015) Geophysical investigation of Obot Ekpo landslide site, cross river state, Nigeria. J Afr Earth Sci 109:154–167. https://doi.org/10.1016/j.jafrearsci.2015.05.015
4. Al-Kouri O, Al-Fugara A, Al-Rawashdeh S, Sadoun B, Pradhan B (2013) Geospatial modeling for sinkholes hazard map based on GIS and RS data. J Geogr Inf Syst 5(6):584–592. https://doi.org/10.4236/jgis.2013.56055
5. Alaghmand S, Abdullah RB, Abustan I, Vosoogh B (2010) GIS-based river flood hazard mapping in urban area (a case study in Kayu Ara River Basin, Malaysia). Int J Eng Technol 2:488–500. ISSN: 0975-4024
6. Anderson DG (1970) Effects of urban development on floods in northern Virginia. Water Supply Paper. https://doi.org/10.3133/WSP01C
7. Angelakis AN, Antoniou G, Voudouris K, Kazakis N, Dalezios N, Dercas N (2020) History of floods in Greece: causes and measures for protection. Nat Hazards 101:833–852. https://doi.org/10.1007/s11069-020-03898-w
8. Angelidis P, Maris F, Kopasakis K, Vasileiou A, Kotsovinos N (2018) Overflow discharges and flooding areas from flood hydrographs routing in Arda River, Greece. Hydrology 5(3):31. https://doi.org/10.3390/hydrology5030031
9. Arnold CL, Gibbons CJ (1996) Impervious surface coverage: the emergence of a key environmental indicator. J Am Plann Assoc 62(2):243–258. https://doi.org/10.1080/01944369608975688

10. Ashley W, Bentley M, Stallins J (2012) Urban-induced thunderstorm modification in the Southeast United States. Clim Change 113(2):481–498. https://doi.org/10.1007/s10584-011-0324-1
11. Avashia V, Garg A (2020) Implications of land use transitions and climate change on local flooding in urban areas: an assessment of 42 Indian cities. Land Use Policy 95:104571. https://doi.org/10.1016/j.landusepol.2020.104571
12. Bao C, Fang CL (2011) Water resources flows related to urbanization in China: challenges and perspectives for water management and urban development. Water Resour Manag 26(2):531–552. https://doi.org/10.1007/s11269-011-9930-y
13. Barron OV, Donn MJ, Barr AD (2013) Urbanisation and shallow groundwater: predicting changes in catchment hydrological responses. Water Resour Manag 27(1):95–115. https://doi.org/10.1007/s11269-012-0168-0
14. Bentley ML, Ashley WS, Stallins AJ (2010) Climatological radar delineation of urban convection for Atlanta, Georgia. Int J Climatol 30(11):1589–1594. https://doi.org/10.1002/joc.2020
15. Blocken B, Derome D, Carmeliet J (2013) Rainwater runoff from building facades: a review. Build Environ 60:339–361. https://doi.org/10.1016/j.buildenv.2012.10.008
16. Booth D (1991) Urbanization and the natural drainage system – impacts, solutions, and prognoses. Northwest Environ J 7:93–118. ISSN: 07497962
17. Bornstein RD, Lin Q (2000) Urban heat islands and summertime convective thunderstorms in Atlanta: three case studies. Atmos Environ 34:507–516. https://doi.org/10.1016/S1352-2310(99)00374-X
18. Bourdin DR, Fleming SW, Stull RB (2012) Streamflow modelling: a primer on applications, approaches and challenges. Atmos Ocean 50(4):507–536. https://doi.org/10.1080/07055900.2012.734276
19. Broadhead A, Horn R, Lerner DN (2013) Captured streams and springs in combined sewers: a review of the evidence, consequences and opportunities. Water Res 47(13):4752–4766. https://doi.org/10.1016/j.watres.2013.05.020
20. Campo M, Esteller M, Expósito JL, Hirata R (2014) Impacts of urbanization on groundwater hydrodynamics and hydrochemistry of the Toluca Valley aquifer (Mexico). Environ Monit Assess 186:2979–2999. https://doi.org/10.1007/s10661-013-3595-3
21. Chatterji PC, Singh S, Qureshi ZH (1978) Hydrogeomorphology of the central Luni basin, Western Rajasthan, (India). Geoforum 9:211–224. https://doi.org/10.1016/0016-7185(78)90011-8
22. Cohen S, Brakenridge GR, Kettner A, Bates B, Nelson JM et al (2018) Estimating floodwater depths from flood inundation maps and topography. J Am Water Resour Assoc 54(4):847–858. https://doi.org/10.1111/1752-1688.12609
23. Cook A, Merwade V (2009) Effect of topographic data, geometric configuration, and modelling approach on flood inundation mapping. J Hydrol 377(1):131–142. https://doi.org/10.1016/j.jhydrol.2009.08.015
24. Coskun HG, Alganci U, Usta G (2008) Analysis of land use change and urbanization in the Kücükçekmece water basin (İstanbul, Türkiye) with temporal satellite data using remote sensing and GIS. Sensors 8(11):7213–7223. https://doi.org/10.3390/s8117213
25. DHA (2018) Flood disaster in Ankara: 6 injured. NTV Haber, Demirören News Agency (DHA). https://www.ntv.com.tr/galeri/turkiye/ankarada-sel-felaketi-6-yarali,FUacrbMh4E2Hfxu_btslFA/8l3YOnkpXEuFVWnvGSm4zw (in Turkish). Accessed 22 November 2022
26. Erickson TO, Stefan HG (2009) Natural groundwater recharge response to urbanization: Vermillion River watershed, Minnesota. J Water Resour Plan Manag 135:512–520. https://doi.org/10.1061/(ASCE)0733-9496(2009)135:6(512)
27. Ertürk E, Kaya N (2019) Taşkın tehlike alanlarının oluşturulması: Trabzon ili Vakfıkebir ilçesi Kirazlı Deresi örneği. Fırat Üniversitesi Mühendislik Bilimleri Dergisi 31(2):337–344. https://doi.org/10.35234/fumbd.613291 (inTurkish)

28. Eshtawi T, Evers M, Tischbein B (2016) Quantifying the impact of urban area expansion on groundwater recharge and surface runoff. Hydrol Sci J 61(5):826–843. https://doi.org/10.1080/02626667.2014.1000916
29. Fletcher TD, Andrieu H, Hamel P (2013) Understanding, management and modelling of urban hydrology and its consequences for receiving waters: a state of the art. Adv Water Resour 51:261–279. https://doi.org/10.1016/j.advwatres.2012.09.001
30. Foster SSD (1988) Impacts of urbanisation on groundwater. CEPIS, pp D1–D24
31. Foster SSD (2001) The interdependence of groundwater and urbanisation in rapidly developing cities. Urban Water 3(3):185–192. https://doi.org/10.1016/S1462-0758(01)00043-7
32. Garcia-Fresca B (2007) Urban-enhanced groundwater recharge: review and case study of Austin, Texas, USA. In: Urban groundwater, meeting the challenge. CRC Press, pp 19–34. eBook ISBN: 9780429224386
33. Gash JHC, Rosier PTW, Ragab R (2008) A note on estimating urban roof runoff with a forest evaporation model. Hydrol Process 22(8):1230–1233. https://doi.org/10.1002/hyp.6683
34. Gaughan AE, Waylen PR (2012) Spatial and temporal precipitation variability in the Okavango–Kwando–Zambezi catchment, southern Africa. J Arid Environ 82:19–30. https://doi.org/10.1016/j.jaridenv.2012.02.007
35. Ghalib H, El-Khorazaty MT, Serag Y (2021) New capital cities as tools of development and nation-building: review of Astana and Egypt's new administrative capital city. Ain Shams Eng J 12(3):3405–3409. https://doi.org/10.1016/j.asej.2020.11.014
36. Ghimire E, Sharma S, Lamichhane N (2022) Evaluation of one-dimensional and two-dimensional HEC-RAS models to predict flood travel time and inundation area for flood warning system. ISH J Hydraul Eng 28(1):110–126. https://doi.org/10.1080/09715010.2020.1824621
37. Graniel CE, Morris LB, Carrillo-Rivera JJ (1999) Effects of urbanization on groundwater resources of Merida, Yucatan, Mexico. Environ Geol 37(4):303–312. https://doi.org/10.1007/s002540050388
38. Gregory JH, Dukes M, Jones P, Miller G (2006) Effect of urban soil compaction on infiltration rate. J Soil Water Conserv 61(3):117–124. Online ISSN: 1941-3300
39. Grischek T, Nestler W, Piechniczek D, Fischer T (1996) Urban groundwater in Dresden, Germany. Hydrogeol J 4(1):48–63. https://doi.org/10.1007/s100400050088
40. Groffman PM, BainDJ, Band LE, Belt KT, Brush GS et al (2003) Down by the riverside: urban riparian ecology. Front Ecol Environ 1(6):315–321. https://doi.org/10.1890/1540-9295(2003)001[0315:DBTRUR]2.0.CO;2
41. Hardison EC, O'Driscoll MA, DeLoatch JP, Howard RJ, Brinson MM (2009) Urban land use, channel ıncision, and water table decline along coastal plain streams, North Carolina1. JAWRA J Am Water Resour Assoc 45(4):1032–1046. https://doi.org/10.1111/j.1752-1688.2009.00345.x
42. Hession WC, Pizzuto JE, Johnson TE, Horwitz RJ (2003) Influence of bank vegetation on channel morphology in rural and urban watersheds. Geology 31(2):147–150. https://doi.org/10.1130/0091-7613(2003)031%3c0147:IOBVOC%3e2.0.CO;2
43. Heywood H (1997) Accounting for infiltration: a more explicit approach. In: Paper presented at CIWEM metropolitan branch meeting. Chartered Institution of Water Environmental Management, London, UK
44. Hu S, Fan Y, Zhang T (2020) Assessing the effect of land use change on surface runoff in a rapidly urbanized city: a case study of the central area of Beijing. Land 9(1):17. https://doi.org/10.3390/land9010017
45. Intergovernmental Panel on Climate Change (IPCC) (2007) Climate change 2007: synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri RK, Reisinger A (eds)]. IPCC, Geneva, Switzerland, p 104
46. Intergovernmental Panel on Climate Change (IPCC) (2014) Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the

Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri RK, Meyer LA (eds)]. IPCC, Geneva, Switzerland, p 151
47. Jacobson CR (2011) Identification and quantification of the hydrological impacts of imperviousness in urban catchments: a review. J Environ Manag 92(6):1438–1448. https://doi.org/10.1016/j.jenvman.2011.01.018
48. Jasechko S (2019) Global isotope hydrogeology-review. Rev Geophys 57:835–965. https://doi.org/10.1029/2018RG000627
49. Jeppesen J, Christensen S, Ladekarl UL (2011) Modelling the historical water cycle of the Copenhagen area 1850–2003. J Hydrol 404(3):117–129. https://doi.org/10.1016/j.jhydrol.2010.12.022
50. Kauffeldt A, Wetterhall F, Pappenberger F, Salamon P, Thielen J (2016) Technical review of large-scale hydrological models for implementation in operational flood forecasting schemes on continental level. Environ Model Softw 75:68–76. https://doi.org/10.1016/j.envsoft.2015.09.009
51. Kidmose J, Troldborg L, Refsgaard JC, Bischoff N (2015) Coupling of a distributed hydrological model with an urban storm water model for impact analysis of forced infiltration. J Hydrol 525:506–520. https://doi.org/10.1016/j.jhydrol.2015.04.007
52. Kim YY, Lee KK, Sung I (2001) Urbanization and the groundwater budget, metropolitan Seoul area, Korea. Hydrogeol J 9(4):401–412. https://doi.org/10.1007/s100400100139
53. Konrad CP (2003) Effects of urban development on floods. US Department of the Interior, US Geological Survey Tacoma, WA, USA
54. Kundzewicz ZW, Mata LJ, Arnell NW, Döll P, Jiménez B et al (2008) The implications of projected climate change for freshwater resources and their management. Hydrol Sci J 53(1):3–10. https://doi.org/10.1623/hysj.53.1.3
55. Lerner DN (2002) Identifying and quantifying urban recharge: a review. Hydrogeol J 10(1):143–152. https://doi.org/10.1007/s10040-001-0177-1
56. Lerner DN (1986) Leaking pipes recharge groundwater. Groundwater 24(5):654–662. https://doi.org/10.1111/j.1745-6584.1986.tb03714.x
57. Lerner DN (1990) Groundwater recharge in urban areas. Atmos Environ Part B: Urban Atmos 24(1):29–33. https://doi.org/10.1016/0957-1272(90)90006-G
58. Li E, Endter-Wada J, Li S (2015) Characterizing and contextualizing the water challenges of megacities. JAWRA J Am Water Resour Assoc 51(3):589–613. https://doi.org/10.1111/1752-1688.12310
59. Ma H, Chou NT, Wang L (2016) Dynamic coupling analysis of urbanization and water resource utilization systems in China. Sustainability 8(11):1–18. https://EconPapers.repec.org/RePEc:gam:jsusta:v:8:y:2016:i:11:p:1176-:d:82879
60. Mbata RI, Anthony ED (2021) Sustainable mixed-use development: a case study of life hub; daning neighborhood, Zhabei district, Shanghai, China. Glob Sci J 9(2):991–1002
61. McDonald RI, Green P, Balk D, Fekete BM, Revenga C et al (2011) Urban growth, climate change, and freshwater availability. Proc Natl Acad Sci 108(15):6312–6317
62. McDonald RI, Weber K, Padowski J, Flörke M, Schneider C et al (2014) Water on an urban planet: urbanization and the reach of urban water infrastructure. Glob Environ Change 27:96–105. https://doi.org/10.1016/j.gloenvcha.2014.04.022
63. McGrane SJ (2016) Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. Hydrol Sci J 61(13):2295–2311. https://doi.org/10.1080/02626667.2015.1128084
64. Meyer JL, Paul MJ, Taulbee WK (2005) Stream ecosystem function in urbanizing landscapes. J N Am Benthol Soc 24(3):602–612. https://doi.org/10.1899/04-021.1
65. Miller JD, Kim H, Kjeldsen TR, Packman J, Grebby S et al (2014) Assessing the impact of urbanization on storm runoff in a peri-urban catchment using historical change in impervious cover. J Hydrol 515:59–70. https://doi.org/10.1016/j.jhydrol.2014.04.011
66. Minnig M, Moeck C, RadnyD, Schirmer M (2018) Impact of urbanization on groundwater recharge rates in Dübendorf, Switzerland. J Hydrol 563:1135–1146. https://doi.org/10.1016/j.jhydrol.2017.09.058

67. Moeck C, Radny D, Popp A, Brennwald M, Stoll S et al (2017) Characterization of a managed aquifer recharge system using multiple tracers. Sci Total Environ 609:701–714. https://doi.org/10.1016/j.scitotenv.2017.07.211
68. Montazeri H, Blocken B (2013) CFD simulation of wind-induced pressure coefficients on buildings with and without balconies: validation and sensitivity analysis. Build Environ 60:137–149. https://doi.org/10.1016/j.buildenv.2012.11.012
69. Moreira AA, Ruhoff AL, Roberti DR, Souza VA, Rocha HR et al (2019) Assessment of terrestrial water balance using remote sensing data in South America. J Hydrol 575:131–147. https://doi.org/10.1016/j.jhydrol.2019.05.021
70. Morris B, Rueedi J, Cronin AA, Diaper C, DeSilva D (2007) Using linked process models to improve urban groundwater management: an example from Doncaster England. Water Environ J 21(4):229–240. https://doi.org/10.1111/j.1747-6593.2006.00067.x
71. NADMA (2022) Malaysia–Deadly flash floods in Kedah. Agensi Pengurusan Bencana Negara in Malaysia, National Disaster Management Agency (NADMA) Floodlist.com. https://floodlist.com/asia/malaysia-floods-kedah-july-2022. Accessed 22 November 2022
72. Nie W, Yuan Y, Kepner W, Nash MS, Jackson M et al (2011) Assessing impacts of landuse and landcover changes on hydrology for the upper San Pedro watershed. J Hydrol 407(1–4):105–114. https://doi.org/10.1016/j.jhydrol.2011.07.012
73. Niemczynowicz J (1999) Urban hydrology and water management present and future challenges. Urban Water 1:1–14. https://doi.org/10.1016/S1462-0758(99)00009-6
74. Onodera S, Saito M, Sawano M, Hosono T, Taniguchi M et al (2008) Effects of intensive urbanization on the intrusion of shallow groundwater into deep groundwater: examples from Bangkok and Jakarta. Sci Total Environ 404(2):401–410. https://doi.org/10.1016/j.scitotenv.2008.08.003
75. Oudin L, Salavati B, Furusho-Percot C, Ribstein P, Saadi M (2018) Hydrological impacts of urbanization at the catchment scale. J Hydrol 559:774–786. https://doi.org/10.1016/j.jhydrol.2018.02.064
76. Özalp D (2009) Dere taşkın risk haritalarının CBS kullanılarak oluşturulması ve CBS ile taşkın risk analizi. Doctoral dissertation, Fen Bilimleri Enstitüsü
77. Oğuz K, Oguz E, Coşkun M (2016) Coğrafi bilgi sistemleri ile taşkın risk alanlarının belirlenmesi: Artvin ili örneği. In: Conference paper. Conference: 4. Ulusal Taşkın Sempozyumu at: Rize (in Turkish)
78. O'Driscoll M, Clinton S, Jefferson A, Manda A, McMillan S (2010) Urbanization effects on watershed hydrology and ın-stream processes in the southern United States. Water 2(3):605–648. https://doi.org/10.3390/w2030605
79. Patra S, Sahoo S, Mishra, P, Mahapatra SC (2018) Impacts of urbanization on land use/cover changes and its probable implications on local climate and groundwater level. J Urban Manag 7(2):70–84. https://doi.org/10.1016/j.jum.2018.04.006
80. Paul MJ, Meyer JL (2001) Streams in the urban landscape. Annu Rev Ecol Syst 32(1):333–365. https://doi.org/10.1146/annurev.ecolsys.32.081501.114040
81. Paulachok GN (1991) Geohydrology and ground-water resources of Philadelphia, Pennsylvania, U.S. Geological Survey Water
82. Peduzzi P, Dao H, Herold C, Mouton F (2009) Assessing global exposure and vulnerability towards natural hazards: the disaster risk index. Nat Hazard 9(4):1149–1159. https://doi.org/10.5194/nhess-9-1149-2009
83. Price K (2011) Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: a review. Prog Phys Geogr 35:465–492. https://doi.org/10.1177/0309133311402714
84. Ragab R, Rosier P, Dixon A, Bromley J, Cooper J (2003) Experimental study of water fluxes in a residential area: 2. Road infiltration, runoff and evaporation. Hydrol Process 17:2423–2437. https://doi.org/10.1002/hyp.1251
85. Reuters (2021) Flood disaster in Europe: Many deaths in Germany and Belgium, evacuation works started in some cities. BBC News Turkish. https://www.bbc.com/turkce/haberler-dunya-57849860 (in Turkish). Accessed 15 July 2021

86. Reuters (2022) Sydney faces more rain as the death toll from Australian floods rises. Edition.cnn.com. https://edition.cnn.com/2022/03/06/asia/sydney-australia-flood-intl-hnk/index.html. Accessed 22 November 2022
87. Ritchie H, Roser M (2018) Urbanization Published online at OurWorldInData.org. https://ourworldindata.org/urbanization
88. Rose S, Peters NE (2001) Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach. Hydrol Process 15(8):1441–1457. https://doi.org/10.1002/hyp.218
89. Ruban V, Rodriguez F, Rosant JM, Larrarte F, Joannis C et al (2007) Hydrologic and energetic experimental survey of a small urban watershed. In: Novatech 2007–6ème Conférence sur les techniques et stratégies durables pour la gestion des eaux urbaines par temps de pluie/Sixth international conference on sustainable techniques and strategies in urban water management. GRAIE, Lyon, France. https://hal.archives-ouvertes.fr/hal-03238905
90. Saksena S, Merwade V (2015) Incorporating the effect of DEM resolution and accuracy for improved flood inundation mapping. J Hydrol 530:180–194. https://doi.org/10.1016/j.jhydrol.2015.09.069
91. Saksena S, Merwade V (2017) Integrated modeling of surface-subsurface processes to understand river-floodplain hydrodynamics in the upper Wabash River basin. World Environ Water Resour Congr 2017:60–68. https://doi.org/10.1061/9780784480595.006
92. Salata S, Velibeyoğlu K, Baba A, Saygin N, Couch VT, Uzelli T (2022) Adapting cities to pluvial flooding: the case of Izmir (Turkey). Sustainability 14(24):16418. https://doi.org/10.3390/su142416418
93. Sarkar A, Ali S, Kumar S, Shekhar S, Rao SVN (2016) Groundwater environment in Delhi, India. In: Shrestha S, Pandey V, Thatikonda S, Shivakoti B (eds) Groundwater environment in Asian cities. Elsevier, pp 77–108. ISBN: 978-0-12-803166-7. https://doi.org/10.1016/B978-0-12-803166-7.00005-2
94. Schumann G, Matgen P, Hoffmann L, Hostache R, Pappenberger F et al (2007) Deriving distributed roughness values from satellite radar data for flood inundation modelling. J Hydrol 344(1):96–111. https://doi.org/10.1016/j.jhydrol.2007.06.024
95. Sharma S (2017) Effects of urbanization on water resources-facts and figures. Int J Sci Eng Res 8(4):433–459. ISSN 2229-5518
96. Sharp JM (2010) The impacts of urbanization on groundwater systems and recharge. AQUA Mundi 1(3):51–56. https://doi.org/10.4409/Am-004-10-0008
97. Shaw E (2005) Hydrology in practice. CRC Press
98. Shem W, Shepherd M (2009) On the impact of urbanization on summertime thunderstorms in Atlanta: two numerical model case studies. Atmos Res 92:172–189. https://doi.org/10.1016/j.atmosres.2008.09.013
99. Shen Y, Tang C, Xiao J, Oki T, Shinjiro K (2005) Sustainable water management solutions for large cities. In: Proceedings of symposium S2 held during the seventh IAHS scientific assembly at Foz do Iguaçu, Brazil, vol 293. IAHS Publication
100. Shepherd JM (2005) A review of current ınvestigations of urban-ınduced rainfall and recommendations for the future. Earth Interact 9(12):1–27. https://doi.org/10.1175/EI156.1
101. Sperotto A, Torresan S, Gallina V, Coppola E, Critto A et al (2016) A multi-disciplinary approach to evaluate pluvial floods risk under changing climate: the case study of the municipality of Venice (Italy). Sci Total Environ 562:1031–1043. https://doi.org/10.1016/j.scitotenv.2016.03.150
102. Statista (2022) Degree of urbanization 2022, by continent. In: Statista. https://www.statista.com/statistics/270860/urbanization-by-continent/. Accessed 22 November 2022
103. Statista (2022) Degree of urbanization 2022, by continent. In: Statista. https://www.statista.com/statistics/1226106/urbanization-rate-in-africa/. Accessed 20 December 2022
104. Statista (2022) Degree of urbanization 2022, by continent. In: Statista. https://www.statista.com/statistics/270162/urbanization-in-china/. Accessed 20 December 2022
105. Sun G, Caldwell P (2015) Impacts of urbanization on stream water quantity and quality in the United States. Water Resour Impact 17(1):17–20. https://www.fs.usda.gov/treesearch/pubs/47460

106. Syvitski J, Brakenridge R (2013) Causation and avoidance of catastrophic flooding along the Indus River, Pakistan. GSA Today 23:4–10. https://doi.org/10.1130/GSATG165A.1
107. Theobald DM (2001) Land-use dynamics beyond the American urban fringe. Geogr Rev 91(3):544–564. https://doi.org/10.1111/j.1931-0846.2001.tb00240.x
108. Turkish Statistical Institute (2021) Results of the address-based population registration system, 2020. Ministry of interior, directorate general of population and citizenship affairs. https://data.tuik.gov.tr/Bulten/Index?p=Adrese-Dayali-Nufus-Kayit-Sistemi-Sonuclari-2020-37210 (in Turkish). Accessed 4 February 2021
109. Ullah KA, Jiang J, Wang P (2018) Land use impacts on surface water quality by statistical approaches. Glob J Environ Sci Manag 4(2):231–250. https://doi.org/10.22034/gjesm.2018.04.02.010
110. Vasudevan C, Mahamad S, Palanisamy R, Boopathy V (2017) Impact of urbanization on water bodies using remote sensing techniques-a case study of the shrinking Ambattur Lake, Chennai, Tamilnadu, India, pp 29–35. http://orcid.org/0000-0002-8908-5754
111. Verbeiren B, van de Voorde T, Canters F, Binard M, Yves C et al (2013) Assessing urbanization effects on rainfall-runoff using a remote sensing supported modeling strategy. Int J Appl Earth Obs Geoinf 21:92–102. https://doi.org/10.1016/j.jag.2012.08.011
112. Vázquez-Suñé E, Carrera J, Tubau I, Sánchez-Vila X, Soler A (2010) An approach to identify urban groundwater recharge. Hydrol Earth Syst Sci 14(10):2085–2097. https://doi.org/10.5194/hess-14-2085-2010
113. WB (2022) World Bank based on World Population Prospects—UN Population Division (2018), World Development Indicators, World Bank (WB). https://datacatalog.worldbank.org/search/dataset/0037712/World-Development-Indicators
114. Walsh CJ, Roy AH, Feminella JW, Cottingham PD, Groffman PM et al (2005) The urban stream syndrome: current knowledge and the search for a cure. J N Am Benthol Soc 24(3):706–723. https://doi.org/10.1899/04-028.1
115. Weng Q (2002) Land use change analysis in the Zhujiang Delta of China using satellite remote sensing, GIS and stochastic modelling. J Environ Manag 64(3):273–284. https://doi.org/10.1006/jema.2001.0509
116. Worldometers (2023) The world population. https://www.worldometers.info/world-population
117. Yang Y, Lerner DN, Barrett MH, Tellam JH (1999) Quantification of groundwater recharge in the city of Nottingham, UK. Environ Geol 38(3):183–198. https://doi.org/10.1007/s002540050414
118. Yılmaz M (2010) Karapınar Çevresinde Yeraltı Suyu Seviye Değisimlerinin Yaratmış Olduğu Çevre Sorunları (Environmental Problems Caused by Groundwater Level Changes Around Karapınar). Ankara Üniversitesi Çevrebilimleri Dergisi (Ankara University J Environ Sci) 2(2):145–163. https://doi.org/10.1501/Csaum_0000000033
119. Zaryab A, Nassery HR, Alijani F (2022) The effects of urbanization on the groundwater system of the Kabul shallow aquifers, Afghanistan. Hydrogeol J 30(2):429–443. https://doi.org/10.1007/s10040-021-02445-6
120. Zhou D, Zhao S, Zhang L, Sun G, Liu Y (2015) The footprint of urban heat island effect in China. Sci Rep 5(1):11160. https://doi.org/10.1038/srep11160

Understanding the Challenges: Sustainable Usage of Groundwater Resources in Türkiye

Alper Baba and Nilüfer Tirol

Abstract Groundwater resources are essential to the environment's sustainability because they supply water to humans and are important in maintaining a country's socio-economic development. Concerns about groundwater depletion and ecosystem degradation have introduced the concept of sustainable use of groundwater. In this perspective, Türkiye is currently experiencing water stress and is likely to be among the countries that may experience water scarcity in the future. Nearly, 67% of the annual amount of water consumed in Türkiye, the world's seventh largest agricultural producer, is used for agricultural irrigation. Approximately 32% of the agricultural irrigation need is satisfied from groundwater resources. Water withdrawal from unlicensed wells is one of the most critical problems affecting Türkiye's groundwater resources. It is estimated that there are over 100 thousand unlicensed wells in the country, more than 60 thousand of which are located in the Konya Closed Basin. In addition, the sustainable management of groundwater consumption becomes more difficult due to climate change, rapid population growth and urbanization, pollution of water resources, over-exploitation, and sea-water intrusion. This chapter summarizes the challenges faced in the sustainable management of groundwater resources in Türkiye.

Keywords Groundwater management · Groundwater resources in Türkiye · Sustainable use of water · Groundwater pollutants in Türkiye · Seawater intrusion

---

A. Baba (✉)
Department of International Water Sources, Graduate School of Engineering and Sciences, Izmir Institute of Technology, Izmir, Türkiye
e-mail: alperbaba@iyte.edu.tr

N. Tirol
Department of Environmental Engineering, Faculty of Engineering, Izmir Institute of Technology, Izmir, Türkiye
e-mail: nilufertirol@iyte.edu.tr

S. Ali and A. M. Armanuos (eds.), *Groundwater in Arid and Semi-Arid Areas*, Earth and Environmental Sciences Library, https://doi.org/10.1007/978-3-031-43348-1_5

1 Introduction

Although, water is the most abundant liquid on Earth, most of its sources are saline. The estimated global freshwater volume is 10.6 million km^3, corresponding to less than 1% of all water on Earth [59]. Approximately, 99% of this volume consists of groundwater sources. Groundwater resources are essential for environmental sustainability because they provide water for human needs and support economic activities [24, 30, 41, 52]. With the effect of technological developments (especially the use of efficient pumps and the electrification of rural areas), there has been an increase in global groundwater withdrawal. Globally, groundwater withdrawals increased from 312 km^3 in the 1960s to 743 km^3 in 2000 and 959 km^3 in 2017 [68, 77]. On a global scale, a staggering 1.5–3 billion individuals rely on groundwater as a source of sustenance, with irrigation accounting for approximately 60–70% of its utilization [3, 35]. However, groundwater exploitation has exceeded 650 km^3 per year [28], and the increasing usage of groundwater resources leads to the depletion of groundwater levels by 4500 km^3 between 1900 and 2008 [24].

Freshwater volume is unevenly distributed across continents; the differences in continent size and average freshwater volume per unit area explain this unevenness. Asia's estimated groundwater withdrawal amount was 657 km^3 in 2017 [68]. This value corresponds to 68% of the total groundwater withdrawals globally. Out of the ten countries that have the greatest proportion of the global groundwater withdrawals, eight are located in Asia, including India, China, Pakistan, Iran, Indonesia, Bangladesh, Saudi Arabia, and Türkiye. Due to regional differences playing an effective role in meeting water demand, countries in many parts of the world are facing water stress. It is estimated that more than 2 billion people (35% of the world population) are experiencing severe water stress today [2, 75].

This chapter aims to understand the challenges that Türkiye, which is one of the countries with the highest groundwater withdrawals globally, faces in its effort to sustainably use its groundwater resources. In particular, it explored the current state of the groundwater resources in the country and the challenges facing sustainable groundwater management. Finally, potential solutions for the effective management of groundwater resources in the country are discussed.

2 Study Area

2.1 Location and Climate

Türkiye is located in the northern subtropical zone of the Earth, between latitudes 36–42° N and longitudes 26–45° E. Its climate varies depending on location, with a Mediterranean climate along the coast and a continental climate in the interior. The country's total area is 779,500 km^2 and its average annual precipitation is 450 billion m^3. The amount of precipitation in Türkiye differs from region to region, from

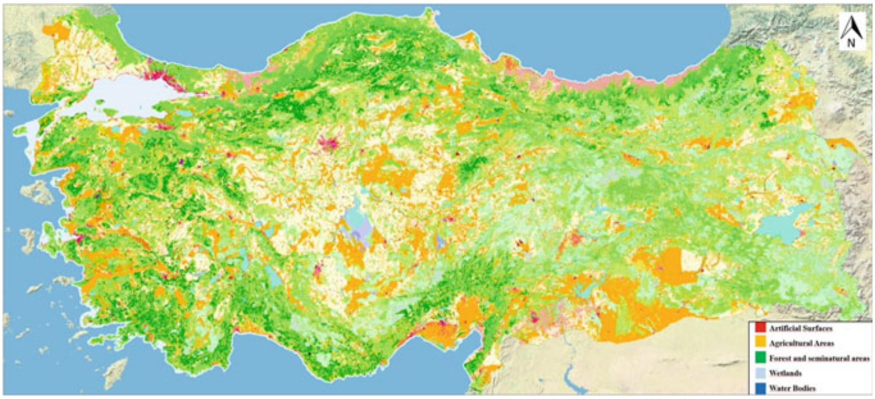


Fig. 1 Türkiye's land use/cover classes [46]

250 mm in the central area to over 3,000 mm in the northeast Black Sea region [23]. Figure 1 represents Türkiye's land use/cover classes. This map was prepared using CORINE 2018 data [46]. The map shows that 50.3% of Türkiye is forest and semi-natural areas, 42.3% is agricultural areas, 5% is water bodies, 1.94% is artificial areas and 0.5% consists of wetlands. In recent years, Türkiye has experienced a surge in population, economic growth, and urbanization, resulting in a substantial transformation of the country's land use/land cover.

2.2 Hydrogeology

Türkiye consists of 25 river basins. Most of the rivers in the country arise from within the borders of the country and pour into the sea within the country. The most important rivers are the Euphrates (1263), Kızılırmak (1151 km), Sakarya (824 km), Büyük Menderes (584 km), Seyhan (560 km), Aras (548 km), Yeşilırmak (519 km), Tigris (512), Ceyhan (509 km), Çoruh (354), Gediz (275 km), and Küçük Menderes (129 km) rivers [55]. The General Directorate of Nature Conservation and National Parks, several studies indicated that 320 natural lakes in Türkiye. Some of these lakes are seasonal and filled with winter precipitation and dry up due to lack of precipitation in summer. Among the lakes in Türkiye, Lake Van (3713 km^2), Salt Lake (1 300 km^2), Beyşehir Lake (656 km^2), and Eğirdir Lake (482 km^2) are the largest lakes in size. There are 861 dams in operation in Türkiye. Among the dams in Türkiye, Atatürk Dam has 817 km^2, Keban Dam 675 km^2, Ilısu Dam 313 km^2, Karakaya Dam 268 km^2, Hirfanlı Dam has a surface area of 263 km^2 [55].

Groundwater reservoirs in Türkiye can be divided into two main categories: alluvial plain aquifers and highly karstified carbonate rock aquifers. Approximately, one third of Türkiye is covered by carbonate formations (mainly limestone) that date back to geological times. These formations are the most productive aquifers in the

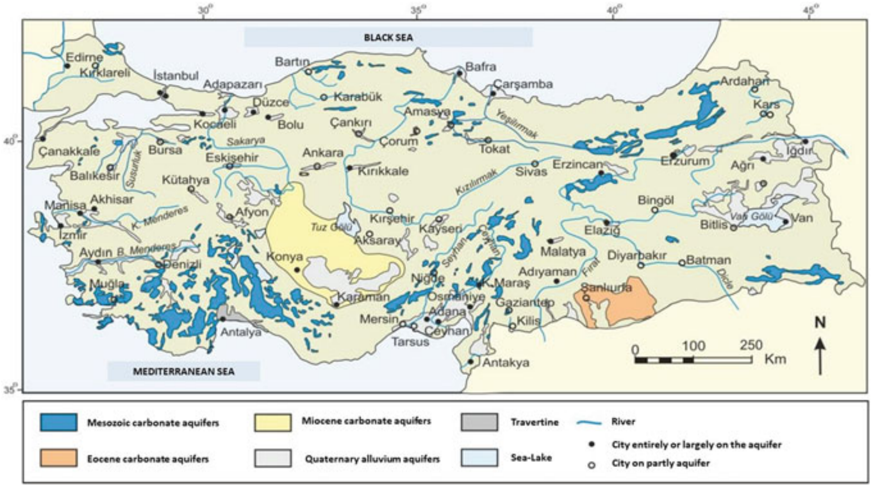


Fig. 2 Major aquifers in Türkiye (Modified from Apaydın [4])

country, with significant groundwater potential for local and regional needs, located mainly in the Taurus Range, the Aegean and Mediterranean coasts, and some highland areas. Alluvial deposits in fault-controlled and broad valleys are also reliable groundwater sources. Other aquifers of local importance include basalts and tuffs. Most of Türkiye's cities are situated on or near alluvial plains, and out of 81 cities, 52 are situated partly or entirely over aquifers of high yield. In addition, 55% of the population lives in large cities (provincial capitals) that are either completely or partly covered by aquifers [4]. Figure 2 shows the major aquifers in Türkiye.

3 Groundwater Resources of Türkiye-Current Usage and Future Expectations

Groundwater resources are essential for the survival of humans and are instrumental in providing life-sustaining water. Türkiye is home to many of these important resources, and ensuring the sustainability of these resources is of paramount importance to the future of the country.

The total available surface and groundwater potential of Türkiye is 112 km^3; the amount of available surface water is 94 km^3 and the amount of available groundwater is 18 km^3. Türkiye's annual water consumption has reached 54 billion m^3, this value is equivalent to 48% of the total freshwater potential of Türkiye [54]. The majority of the water, i.e. 40 billion cubic meters, is allocated for irrigation purposes. 7 billion cubic meters of it is for drinking and domestic purposes, with the remaining 7 billion cubic meters being used for industrial purposes. For 2017, 39 billion m^3 (72.2%) of the water consumed was supplied from surface water, and 15,45 billion m^3 (27.8%)

from groundwater. At the end of 2017, the total amount of groundwater available was 15.45 billion cubic meters, and it was distributed among four sectors. About 26% of this water was allocated to the state-operated cooperatives, State Hydraulic Works (SHW) Irrigations, and TIGEM. About 39% was reserved for personal irrigation, 26% was designated for drinking and domestic use, and the remaining 9% went to industry.

Türkiye's groundwater usage grows year after year [54]. Figure 3 indicates the groundwater allocations in Türkiye between 1995 and 2018. As can be seen, groundwater resources are mainly consumed for irrigation purposes in Türkiye. While the share of groundwater used in irrigation in total groundwater allocation was around 55% in 1995, this value increased to 67% in 2019 [54]. This situation proves that the primary user of groundwater resources in Türkiye is the agricultural sector. Türkiye is the seventh largest agricultural producer in the world [49]. The water footprint of production in Türkiye is approximately 139.6 billion m^3/year, with 89% of this coming from the agricultural sector [74]. It is predicted that climate change will increase the need for irrigation water in the Mediterranean region by 4–18%, which has already shown an increasing trend [26].

The challenges facing Türkiye's groundwater resources are substantial and growing. Projections using State Hydraulic Works datashow that the annual allocation of groundwater will increase from 18 km^3 in 2025 to 25 km^3 in 2050 (Fig. 4), a situation that could lead to significant shortages of this essential resource.

Upon further examination of the groundwater discharge and operating reserve values based on the basin, it is evident that many of them have operating reserves close to groundwater's annual recharge (Fig. 5). This means that due to the other pressures

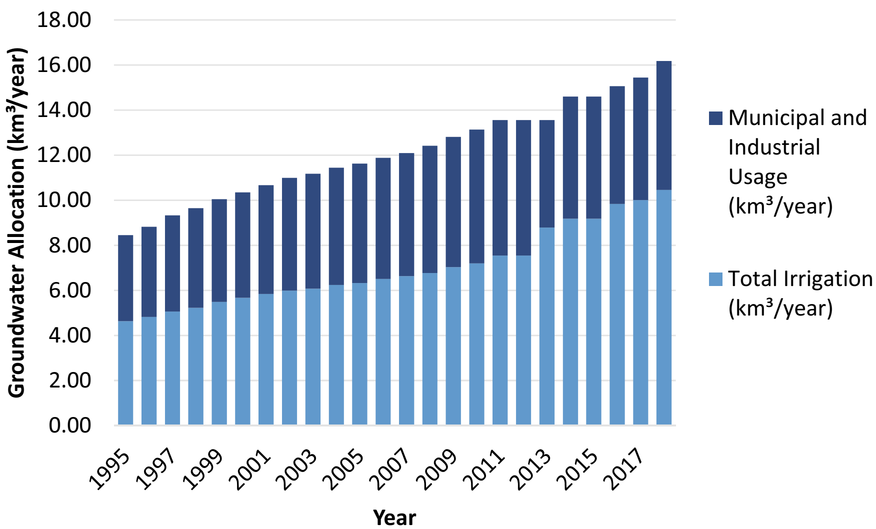


Fig. 3 Groundwater allocations in Türkiye (1995–2019) [54]

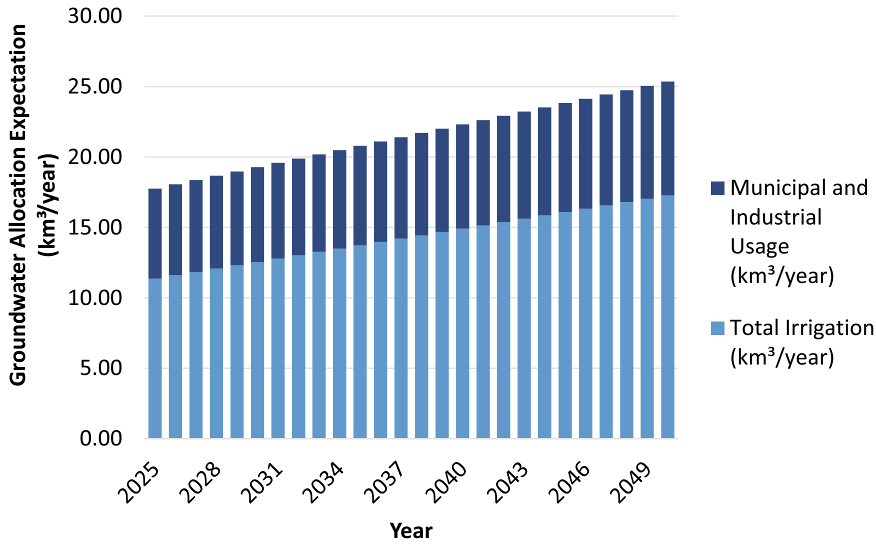


Fig. 4 Groundwater allocation expectation in Türkiye by using state hydraulic works data (2025–2050)

that population increase and other developing sectors will put on water sources, as well as changes in climate, it is likely that the groundwater operating reserves will surpass the annual recharge shortly. In such a situation, it can be impossible to manage the groundwater in Türkiye.

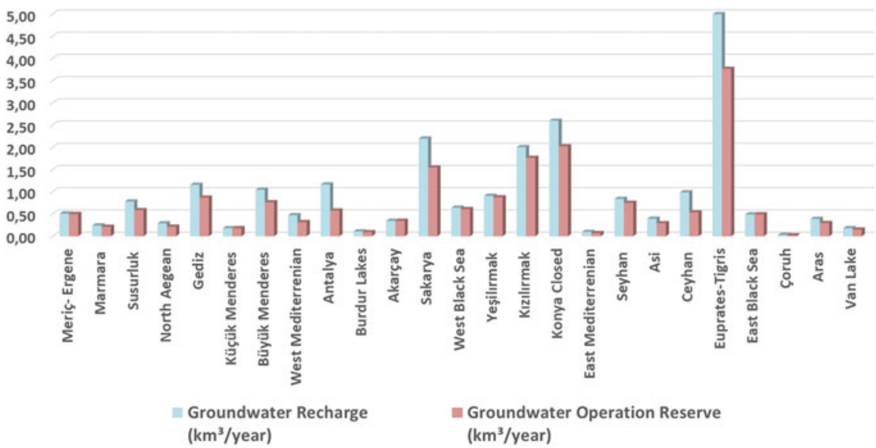


Fig. 5 Basin-based groundwater recharge and groundwater operation reserve values for 2017 [54]

4 Challenges in Sustainable Management of Groundwater in Türkiye

Some of the vital challenges in the Türkiye are rapid growth of population, urbanization, climate change, over exploitation of groundwater and sea water intrusion along the coast, and discussed in the subsequent sections.

4.1 Population

The main reason for the significant increase in the consumption of water resources is rapid population growth and accordingly increasing needs. In 1960, the population of Türkiye was approximately 25 million, but by 2020, it had grown to over 84 million and likely to be increased in the future. Figure 6 illustrates the population development in Türkiye.

Rapid population growth was the result of a combination of factors, including the decline in infant mortality, improved access to healthcare, and an increase in the number of women receiving an education. Moreover, the number of immigrants from other countries has also noticeably contributed to the population growth in Türkiye. As a result, Türkiye has become the world's 18th most populous country [73]. Figure 7 shows the population distribution of Türkiye.

As seen in the Fig. 7, 54% live along the coastal areas [62]. The population density in the nation's coastal regions has caused an increase in water usage, resulting in more seawater entering the groundwater resources. This has put additional stress on

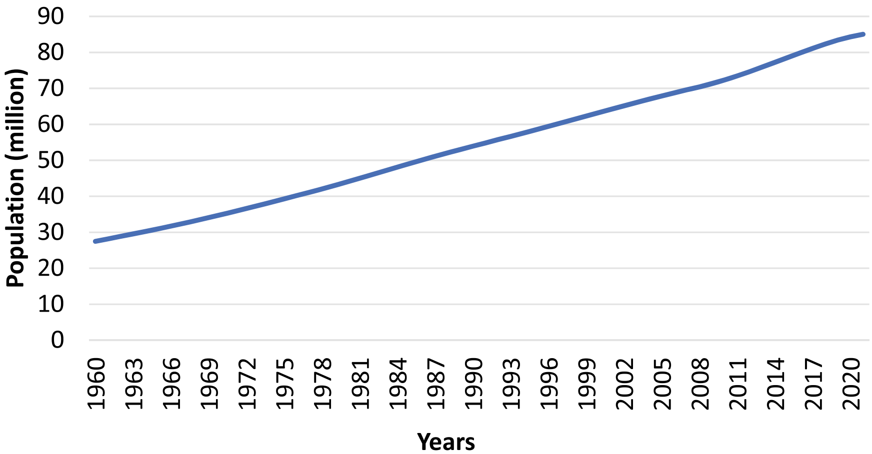


Fig. 6 Population development in Türkiye since 1960 (data in millions of inhabitants) [73]

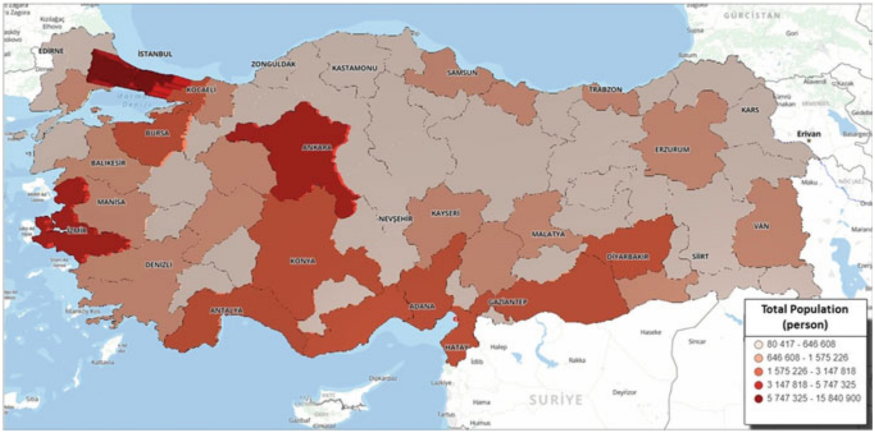


Fig. 7 Population distribution map in Türkiye [62]. (*Note* The highly populated regions are Istanbul, Izmir, and Ankara)

groundwater resources' already diminishing quantity and quality. It is also recommended that other areas excluding Istanbul, Izmir, and Ankara should be developed so that the segregation of the population in these cities can be minimized.

4.2 *Urbanization*

Türkiye is a nation with a rapidly growing population, and with this population comes a rapid increase in urbanization. In 1960, only 32% of the total population lived in cities, and the urban population has increased steadily over the years and by 2021 it had reached 77% [73]. This growth is putting a strain on its natural resources, particularly its groundwater resources. Türkiye is facing over-exploitation and pollution problems related to urbanization [64].

Urbanization often means increased impermeable surfaces, such as roads and buildings, which reduce the amount of water that can be absorbed into the ground. This can cause a decrease in the amount of water reaching the groundwater aquifers and, thus, lead to fewer renewable groundwater resources [11]. Additionally, urbanization can also cause increased runoff, leading to higher water levels in streams and rivers, which can further reduce the amount of water reaching the aquifers.

Several factors, including lithology, morphotectonics, degree of weathering, slope, drainage patterns, land use/cover, and climate heavily influence urban groundwater circulation. In addition, the intricate system of man-made infrastructures and impervious surfaces and/or cover areas have a decisive influence on circulation [25]. Reforestation, on the other hand, can reduce total runoff, but its impact on groundwater recharge is based on the area is undocumented. Groundwater use is determined by the amount of recharge and also constrained by hydrogeological characteristics [42].

Considering all these reasons, in Türkiye, where urbanization is increasing rapidly, it is essential to validate a management tool that combines the protection of groundwater with the planning process, taking into account the financial evaluation of different management scenarios in different media, with varying pressures and socioeconomic conditions. This tool must be linked to and incorporated into master plans to support groundwater resource protection and quality conservation planning, policy, and strategy [31, 61].

4.3 Climate Change

Carbon dioxide levels in the atmosphere have been steadily increasing since the 1950s. Today, the concentration of carbon dioxide in the atmosphere has reached 415.67 ppm [48]. Increasing carbon dioxide levels have many effects on the hydrological cycle, as they increase the temperature. Furthermore, there is a consensus that even with various measures taken, the warming and these changes will continue for decades [32, 67]. Considering the reflections of the changing climate in Türkiye, it has been observed that temperatures in the summer have risen considerably [56, 57]. Since 1950, there has been an increase in the number of heatwaves in Türkiye and they have also been lasting for longer periods of time [21, 40]. There are also clear differences in the amount of precipitation between the winter and fall seasons in Türkiye. Over the course of the last 50 years, winter precipitation in the western provinces has decreased sharply, while fall precipitation has risen in the northern regions of central Anatolia [69].

Climate conditions have a significant impact on the availability of groundwater resources. The Mediterranean region is likely to be strongly affected by climate change's negative impacts on water supply [13, 34, 44]. Climate change has the potential to influence groundwater resources through varying means, including altering recharge processes and magnifying the need to draw from groundwater sources during periods of drought. This can be unsustainable in regions where droughts are expected to become more frequent and longer. The Intergovernmental Panel on Climate Change (IPCC)'s R6 [33] outlines a brief account of groundwater. It has been observed that the groundwater levels in many aquifers globally have been decreasing in recent times as a result of overuse of the resource and a decrease in natural replenishment [14, 15, 33]. Rising sea levels due to climate change will also pose a threat to coastal groundwater aquifers, particularly those that have been oversalted due to overuse [35].

Türkiye is experiencing an increase in temperatures due to climate change [63]. As seen in Fig. 8 compares the temperatures of the capital of Türkiye and five other selected cities between 1985–2000 and 2001–2016. Figure 8 shows that the average values for the second period (2001–2016) are higher for each city. The average temperature increase for Ankara is 1.08°, for İstanbul it is 0.99°, for İzmir it is 0.67°, for Antalya it is 0.87°, for Artvin it is 0.94°, and for Şanlıurfa, it is 0.67°.

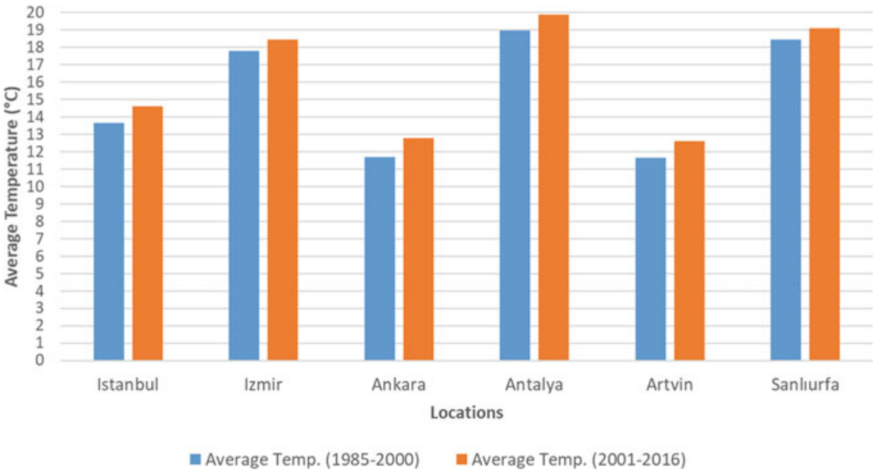


Fig. 8 Average temperature values for the periods of 1985–2000 and 2001–2016

Many studies have been conducted to understand how water resources may be impacted by climate change, but these have mostly focused on surface-water systems [3, 41, 52]. However, forecasting the future of groundwater is not as hard since all water cycle components are linked. Temperature increases and shifts in precipitation patterns in Türkiye will lead to reduced water availability and increased extreme weather events. Consequently, managing water resources is increasingly important in light of these challenges. Although it's not seen a serious change in the precipitation regime in general (Fig. 9), the amount of precipitation decreased in the last ten years in some of the cities such as Antalya and Şanlıurfa.

Climate conditions, directly and indirectly, affect hydrological systems. The two main elements of climate, temperature and precipitation trends, affect regional drought, flood frequency, flood intensity, surface flow rates, vegetation growth, groundwater recharge, and discharge rates [17]. Groundwater aquifers are replenished by precipitation and surface water, so changes in these factors due to climate can affect the quantity of groundwater storage [3, 17, 41]. Climate also impacts groundwater's recharge and discharge rates, which are determined by feedback processes in the water cycle [17]. The residence time of water in the hydrosphere varies according to the environment. For example, while the water in the atmosphere can be renewed in 8 days, groundwater resources are renewed in 1400 years [59].

4.4 Groundwater Pollution

Türkiye is a nation that is developing at a faster rate. Rapid industrialization and urbanization have threatened the water resources in the country [64]. Groundwater

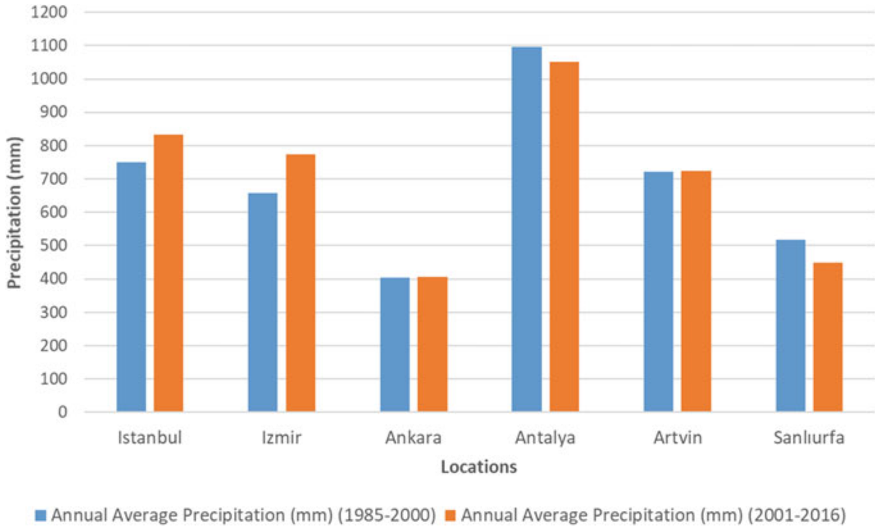


Fig. 9 Annual average precipitation for the periods of 1985–2000 and 2001–2016 (mm)

contamination is caused by pollutants that enter the aquifer system, resulting in an unsafe and unhealthy water supply.

Sources of groundwater pollution can be split into two major groups: natural and anthropogenic. As a result of the dissolution of naturally occurring mineral deposits in the Earth's crust, there are also many contaminants of a geogenic (natural) origin [8, 43]. In Türkiye, natural causes of groundwater contamination include geological formations, seawater intrusion, and geothermal fluids. Türkiye has a complex geology. Considering active faults, its position is the most active region in the world. This leads to an increase in natural groundwater contamination from the leaching of heavy metals from ore deposits, hardness from carbonate rocks, and various harmful elements from geothermal fluids [7]. On the other hand, population growth, urbanization, industrialization, and unscientific farming have all caused a rise in contaminants of anthropogenic origin [7, 43]. Pollutants of anthropogenic origin may consist of organic, inorganic, and/or biological pollutants. The results of the studies conducted in Türkiye are summarized in Table 1, which outlines the locations of the areas where pollution has been detected in groundwater aquifers, as well as the sources of the pollution in those regions (citations are in Table 1). As can be seen from the table, there are areas where groundwater quality has been affected due to different pollutant sources in almost all parts of Türkiye.

Table 1 Major pollutants and their sources detected in some groundwater aquifers in Türkiye (a: Baba and Tayfur [7], b: Tokatlı [66], c: Esmeray and Gökcekli [22], d: Yetis et al. [78], e: Varol et al. [70], f: Varol et al. [71], g: Davraz and Batur [19])

	Source	Pollutant	Contaminated regions	References
Natural	Geogenic factors	As	Aksaray, İzmir, Manisa, Nevşehir, Kırklareli, Kütahya, Balıkesir, Van, Afyon, Isparta	[7, 19, 70, 71]
		Fluoride	Ağrı, Edirne, Van,	[8, 51, 58]
		Salt, gypsum, anhydrite	Çorum, ˙Iskenderun, Sivas	[7]
	Geothermal fluids	Na, K, Cl, Li, B	Afyon	[7]
		B	Denizli, Çankırı, Düzce, Aydın, Manisa, Çanakkale	[9, 10]
	Surface water	Mn, Zn	Elmalı drinking water reservoir	[7]
		Fe	The river Büyükmelen	[53]
Anthropogenic	Agriculture	Nitrate	İzmir, Bursa, Manisa, Mersin, Niğde, Şanlıurfa	[7]
		Pesticides	Mersin, İstanbul	[7]
		Phospate, heavy metals	Adana, Hatay	[7]
		Pathogens	Thrace region	[7]
		As	Tekirdağ, Kırklareli, Isparta	[19, 66]
		Sulfate	Karabük	[22]
		TDS	Burdur	[71]
	Industry	Organic contaminants	İzmir, Eskişehir	[7]
		Iron	Karabük	[22]
	Mining	Mercury	Manisa, İzmir	[7]
		Acidification	Çanakkale, Balıkesir	[7]
		Pb, Cr, Cu and S	Balıkesir, İzmir	[7]
		Cu, Cr, Pb, Co, Ni, Zn	Elazığ	[7]
		B, BO_2	Balıkesir	[7]
		As	Balıkesir, Kütahya	[27, 29]

(continued)

Table 1 (continued)

	Source	Pollutant	Contaminated regions	References
		Ca, Mg, SO_4, Al	Çanakkale	[7]
	Coal-burning power plants	Heavy metals	Muğla, Kütahya	[7]
	Septic tanks and sewage discharge	Organic, inorganic and biological contaminants	Eskişehir, Isparta, Antalya, İstanbul, Büyük Menderes Valley, Ankara, Bursa	[7, 20]

4.5 Over Exploitation of Groundwater and the Consequences

In Türkiye, the excessive use of groundwater aquifers is becoming a serious issue, particularly in certain areas, resulting in a decrease in water levels and a rise in the cost of extraction [5, 38]. There are registered and certified 450 thousand wells in the State Hydraulic Works inventory. About 389 thousand of these wells are used for irrigation, and 11,930 hm^3 of irrigation water is consumed annually [39]. The water withdrawal from unlicensed wells is one of the most critical problems affecting Türkiye's groundwater resources [72]. The approximate number of unlicensed wells in the nation is thought to be over 100,000, with more than 60,000 of those located in the Konya Closed Basin [39]. Konya Closed Basin is an ideal spot for growing crops because of its wide plains, and it has been a major supplier of grain for Türkiye for an extended period of time. The majority of the farming land in the basin is still watered with a flood irrigation system. Open channel transmission lines are employed for surface irrigation. Due to the problems in the distribution of water in these areas, the water can not be delivered to the farmer when requested, so the farmers in these areas also irrigate with wells, most of which are unlicensed [76].

There has been a significant decrease in groundwater, especially in the Central Anatolian, Aegean and Meric-Ergene regions. These basins are also densely populated areas with high agricultural and industrial activities. Figure 10 shows the decline in groundwater levels for the Konya Closed Basin over the years. As can be seen, significant drops in levels are noticeable for most wells. Negligible decreases are observed in a few numbers of wells. The reason for this can be explained as the agricultural or domestic water withdrawals from those wells are lower than the other wells.

The consequences of over-exploited groundwater can be devastating. As water is pumped out of the aquifer, it often leaves behind a layer of sediment that can reduce the aquifer's capacity to store water. As the water level in the aquifer drops, groundwater sources can dry up, leading to water shortages. In addition, over-exploitation can lead to land subsidence [16, 37, 50]. For example, sinkholes in the city of Konya, Türkiye have been a cause for concern in recent years. An estimated 2,500 sinkholes have been discovered in the area (Fig. 11). These sinkholes are caused by a variety of

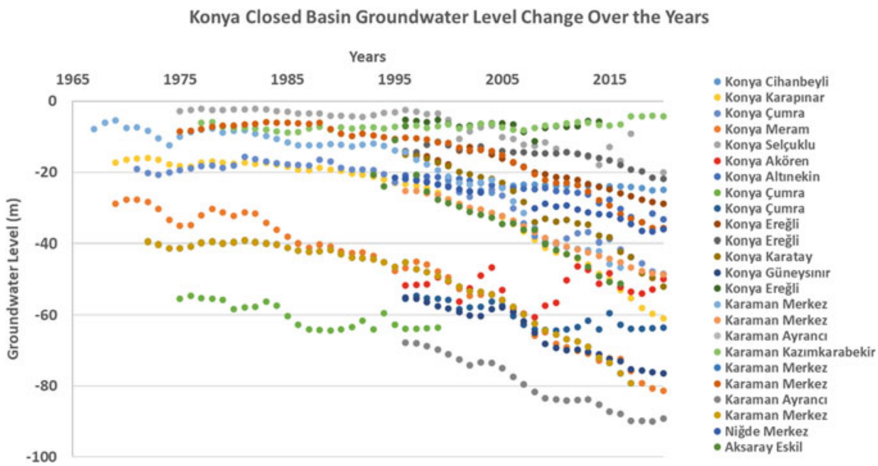


Fig. 10 Groundwater level change in Konya Closed Basin. (*Note* A significant drop in groundwater level is observed from 1995 in many wells)

factors. It can be said that the changing climate and the resulting increased groundwater use have a combined effect on the formation of the sinkhole. With decreasing annual rainfall, crops have been left dry and many farmers have resorted to using wells to irrigate their land, resulting in a weakening of the soil that can ultimately lead to collapse. This is a major serious issue in Türkiye, as sinkholes can cause immense damage to infrastructure and the environment. Additionally, they can undermine the stability of the ground, leading to serious safety hazards for the people living in the area. It is therefore essential that measures are taken to prevent the formation of sinkholes and protect against the risks associated with them.

Fig. 11 Sinkholes in Konya **a** Sinkhole locations [6], **b** Konya [36], **c** Karapınar, Konya [18]

4.6 Sea-Water Intrusion

Seawater intrusion is another major problem affecting groundwater resources in Türkiye. Seawater intrusion occurs in coastal regions when seawater infiltrates the groundwater system, contaminating and depleting the underlying freshwater resources. This phenomenon is a result of an imbalance between the amount of freshwater and seawater in an area, as well as physical and chemical processes that cause the seawater to move inland. This is due to the combination of groundwater over-exploitation, inadequate water management practices, and a lack of regulation and enforcement of existing laws and regulations. In Türkiye, seawater intrusion has been a major problem for many years, resulting in the loss and contamination of valuable groundwater resources.

Seawater intrusion can occur due to excessive extraction of groundwater from coastal wells, leading to contamination in areas (such as Çeşme, Karaburun-İzmir, Gökçeada-Çanakkale, Azmak, Bodrum, Marmaris-Mugla, Çanakkale, Erzin-Hatay, Kazanlı-Mersin, and Turgutreis-Mugla) [1, 7, 12, 47, 60]. This can have negative impacts on the environment, such as increased coastal erosion, increased salinity of the groundwater, and higher concentrations of pollutants and toxins. The effects of human activity can be reduced and partially offset on a local level, however, global climate change remains an unavoidable danger to the sustainability of coastal water systems. Seawater intrusions, especially in the Mediterranean region where coastal karst aquifers are particularly vulnerable, are becoming increasingly common [45, 65].

5 Conclusion

This study revealed that Türkiye witnessed a significant decline in groundwater levels, particularly in areas with high agricultural production and population density. Türkiye's groundwater supply is facing a multitude of threats due to urban expansion, contaminants both natural and caused by humans, climate change, saltwater infiltration, and overuse of groundwater. For quick intervention in possible adverse situations, it is important to monitor regularly production wells in terms of both quality and quantity. With the implementation of effective management and conservation strategies, Türkiye can ensure that its groundwater resources remain sustainable for future generations.

6 Possible Solutions and Recommendations

The groundwater resources of Türkiye are under pressure due to urbanization, natural and human-induced pollutants, climate change, seawater intrusion, and over-extraction. In Türkiye, the agricultural sector, which uses more than 60% of the country's groundwater resources, should be the main focus for efficient water use. In recent years, various methods for sustainable water use have been developed, such as installing water meters in wells and introducing more effective irrigation techniques. Education and information programs can teach farmers how to use water more effectively to save both water and money. In addition, reusing treated wastewater in agriculture and other industries can create additional sources of freshwater. Reuse of treated water also has the potential to expand groundwater reserves.

On the other hand, accurate groundwater recharge estimation is important for the sustainability of surficial aquifers under the over-exploitation pressure. The Turkish government has taken steps to tackle the issue of unlicensed wells, such as introducing legislation to improve the monitoring, regulation of drilling activities, and setting up a national licensing system. However, more needs to be done to effectively address the problem, such as creating a stronger regulatory system and providing resources for enforcement. Additionally, further research is required to assess the extent of the issue and develop better solutions. Artificial recharge techniques can be used to increase the aquifer's recharge rate. These techniques include the use of surface water for irrigation or the injection of water into the aquifer from surface sources. In addition, reducing the amount of water lost through leakage or evaporation from irrigation canals can also help to increase the aquifer's recharge rate. It is also critical to monitor the aquifer's water level and water quality. This can be done through the use of sensors and other monitoring equipment. Regular monitoring can help to detect changes in the aquifer's water level and water quality, which can then be used to make informed decisions about how to best manage the aquifer.

Insights into the effects of climate change on groundwater are critical for sustainable water resource management. Data analysis, management, remote sensing, and modeling can reduce uncertainties and support planning. In addition, rapid technological advances have enabled exploration of various approaches to analyzing groundwater levels and contamination, including geophysical and geoinformatics techniques. GIS remote sensing, artificial intelligence, data analysis, drone surveys, and molecular and stable isotope analysis have proven extremely useful in advancing groundwater research.

Below are summarized all suggestions for the sustainable management of groundwater resources in Türkiye:

- The development of integrated water management,
- Increasing the number of monitoring wells in over-abstraction regions,
- The extension of the observation network,
- Increasing incentives for the protection and improvement of groundwater resources for all sectors,
- Controlling withdrawals with measuring systems,

- Increasing aquifer recharge through artificial recharge structures and rain water harvesting,
- Prohibiting unauthorized wells and controlling over-extraction through new legal regulations,
- Properly managing the balance between water supply and demand,
- Treating and reusing contaminated water sources,
- Better coordination among various governing institutions,
- Implementing water-saving technologies, such as low-flow fixtures, water-efficient appliances etc.,
- Educating the public about the decision-making processes,
- The development of water pricing policies,
- Water conservation campaigns, and
- Willingness of the governing institutions.

Acknowledgements The authors wish to thank the General Drectorate of State Hydraulic Works for the collaboration and data sharing. The authors also thanks the editors for their critical constructive comments on this chapter.

References

1. Acikel S, Ekmekci M (2018) Assessment of groundwater quality using multivariate statistical techniques in the Azmak Spring Zone, Mugla, Turkey. Environ Earth Sci 77:753. https://doi.org/10.1007/s12665-018-7937-x
2. Alcamo J, Henrichs T, Rösch T (2000) World water in 2025–Global modeling scenario analysis for the World Commission on Water for the 21st Century. World Water Series Report 2, Center for Environmental Systems Research, University of Kassel, Germany. http://www.env-edu.gr/Documents/World%20Water%20in%202025.pdf
3. Amanambu AC, Obarein OA, Mossa J, Li L, Ayeni SS, Balogun O, Oyebamiji A, Ochege FU (2020) Groundwater system and climate change: present status and future considerations. J Hydrol (Elsevier B.V.) 589. https://doi.org/10.1016/j.jhydrol.2020.125163
4. Apaydın A (2018) Kentleşmenin yeraltısuyu beslenimine etkileri ve türkiye'de kentleşme-yeraltısuyu ilişkisi üzerine bir değerlendirme. DSİ Teknik Bülteni 129. https://cdniys.tarimorman.gov.tr/api/File/GetGaleriFile/425/DosyaGaleri/600/tb129.pdf
5. Arslan H (2013) Application of multivariate statistical techniques in the assessment of groundwater quality in seawater intrusion area in Bafra Plain, Türkiye. Environ Monit Assess 185(3):2439–2452. https://doi.org/10.1007/s10661-012-2722-x
6. BBC (2021) Konya'daki obruklar neyin işareti? (2021, Nov 29), BBC News Türkçe. https://www.bbc.com/
7. Baba A, Tayfur G (2011) Groundwater contamination and its effect on health in Türkiye. Environ Monit Assess 183(1–4):77–94. https://doi.org/10.1007/s10661-011-1907-z
8. Baba A, Ayyildiz O (2006) Urban groundwater pollutıon in Türkiye. In: Tellam JH, Rivett MO, Israfilov RG, Herringshaw LG (eds), Urban groundwater management and sustainability. Springer, Netherlands, pp 93–110
9. Baba A, Ármannsson H (2006) Environmental impact of the utilization of geothermal areas. Energy Sour Part B 1(3):267–278. https://doi.org/10.1080/15567240500397943

10. Baba A, Özcan H, Deniz O (2005) Environmental impact by spill of geothermal fluids at the geothermal field of Tuzla, Canakkale-Turkey. In: Proceedings world geothermal congress. Antalya, Turkey, 24–29 April 2005, pp. 1–8
11. Baba A, Yazdani H (2017) Effect of urbanization on groundwater resources of İzmir city. https://www.hidropolitikakademi.org/uploads/wp/2019/02/Effect-of-Urbanization-on-Groundwater-Resources-of-Izmir-City.pdf
12. Baba A, Gündüz O, Şimşek C, Elçi A, Murathan A, Sözbilir H (2017) Investigation of sea water intrusion in the Ildırı Region (Çeşme-Turkey) coastal aquifer. In: 2nd international conference on civil and environmental engineering (ICOCEE-Cappadocia). Nevşehir Hacı Bektaş Veli Üniversitesi
13. Bangash RF, Passuello A, Sanchez-Canales M, Terrado M, López A, Elorza FJ, Ziv G, Acuña V, Schuhmacher M (2013) Ecosystem services in Mediterranean river basin: climate change impact on water provisioning and erosion control. Sci Total Environ 458–460:246–255. https://doi.org/10.1016/j.scitotenv.2013.04.025
14. Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (eds) (2008) Climate change and water. Technical paper of the intergovernmental panel on climate change, IPCC Secretariat, Geneva, p 210
15. Bouderbala A (2019) The impact of climate change on groundwater resources in coastal aquifers: case of the alluvial aquifer of Mitidja in Algeria. Environ Earth Sci 78:698. https://doi.org/10.1007/s12665-019-8702-5
16. Caló F, Notti D, Galve J, Abdikan S, Görüm T, Pepe A, Balik Şanli F (2017) DInSAR-based detection of land subsidence and correlation with groundwater depletion in Konya plain, Türkiye. Remote Sens 9(1):83. https://doi.org/10.3390/rs9010083
17. Cuthbert MO, Gleeson T, Moosdorf N, Befus KM, Schneider A, Hartmann J, Lehner B (2019) Global patterns and dynamics of climate–groundwater interactions. Nat Clim Chang 9(2):137–141. https://doi.org/10.1038/s41558-018-0386-4
18. DS (2021) Sinkholes proliferate in Türkiye's Konya (2021, Feb 11), Daily Sabah. https://www.dailysabah.com
19. Davraz A, Batur B (2021) Hydrogeochemistry characteristics of groundwater and health risk assessment in Yalvaç-Gelendost basin (Türkiye). Appl Water Sci 11:67. https://doi.org/10.1007/s13201-021-01401-9
20. Ekmekçi M (2005) Pesticide and nutrient contamination in the Kestel polje–Kirkgoz karst springs, Southern Türkiye. Environ Geol 49:19–29
21. Erlat E, Türkeş M, Aydin-Kandemir F (2021) Observed changes and trends in heatwave characteristics in Turkey since 1950. Theor Appl Climatol 145:137–157. https://doi.org/10.1007/s00704-021-03620-1
22. Esmeray E, Gökcekli C (2020) Assessment of groundwater quality for drinking and irrigation purposes in Karabuk province, Türkiye. Environ Earth Sci 79:325. https://doi.org/10.1007/s12665-020-09074-4
23. FAO (2016) Türkiye Water along the food chain. Towards water-smart agrifood policies: the case of red meat processing. Rome, Italy. https://www.fao.org/3/i5991e/i5991e.pdf
24. Frappart F, Ramillien G (2018) Monitoring groundwater storage changes using the gravity recovery and climate experiment (GRACE) satellite mission: a review. Remote Sens 10(6). MDPI AG. https://doi.org/10.3390/rs10060829
25. Freitas L, Afonso MJ, Pereira AJSC, Delerue-Matos C, Chaminé HI (2019) Assessment of sustainability of groundwater in urban areas (Porto, NW Portugal): a GIS mapping approach to evaluate vulnerability, infiltration and recharge. Environ Earth Sci 78(5). https://doi.org/10.1007/s12665-019-8167-6
26. Galeotti M (2020) The economic impacts of climate change in the Mediterranean. Mediterranean Yearbook (IEMed)
27. Gemici Ü, Tarcan G, Helvaci C, Somay AM (2008) High arsenic and boron concentrations in groundwaters related to mining activity in the Bigadic borate deposits (Western Türkiye). Appl Geochem 23:2462–2476

28. Giordano M (2009) Global groundwater? Issues and solutions. Annu Rev Environ Resour 34:153–178. https://doi.org/10.1146/annurev.environ.030308.100251
29. Gündüz O, Simsek C, Hasozbek A (2009) Arsenic pollution in the groundwater of Simav Plain, Türkiye: Its impact on water quality and human health. Water Air Soil Pollut 205:43–62
30. Holman IP, Allen DM, Cuthbert MO, Goderniaux P (2012) Towards best practice for assessing the impacts of climate change on groundwater. Hydrogeol J 20(1):1–4. https://doi.org/10.1007/s10040-011-0805-3
31. Howard KWF (2015) Sustainable cities and the groundwater govern-ance challenge. Environ Earth Sci 73(6):2543–2554. https://doi.org/10.1007/s12665-014-3370-y
32. IPCC (2007) Climate change 2007: Synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri RK, Reisinger A (eds)]. IPCC, Geneva, Switzerland, 104 pp
33. IPCC (2022) Climate change 2022: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Pörtner HO, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, Rama B (eds)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp. https://doi.org/10.1017/9781009325844
34. Iglesias A, Garrote L, Flores F, Moneo M (2007) Challenges to manage the risk of water scarcity and climate change in the Mediterranean. Water Resour Manage 21(5):775–788. https://doi.org/10.1007/s11269-006-9111-6
35. Jakeman AJ, Barreteau O, Hunt RJ, Rinaudo JD, Ross A, Arshad M, Hamilton S (2016) Integrated groundwater management: an overview of concepts and challenges. In: Anthony J, Jakeman O, Barreteau RJ, Hunt JD, Rinaudo JD, Ross A (eds) Integrated groundwater management: concepts, approaches and challenges. Springer, Heidelberg, Germany. https://doi.org/10.1007/978-3-319-23576-9_1
36. Joyner T (2022) Welcome to Sinkhole village. Türkiye's mysterious craters are swallowing up fertile farming land in the nation's breadbasket. ABC. https://www.abc.net.au/news/2022-08-12/sinkholes-in-Türkiye-are-swallowing-up-fertile-farming-land/101310474
37. Khorrami B, Arik F, Gunduz O (2021) Land deformation and sinkhole occurrence in response to the fluctuations of groundwater storage: an integrated assessment of GRACE gravity measurements, ICESat/ICESat-2 altimetry data, and hydrologic models. GISci Remote Sens 58(8):1518–1542. https://doi.org/10.1080/15481603.2021.2000349
38. Khorrami B, Gunduz O (2021) Evaluation of the temporal variations of groundwater storage and its interactions with climatic variables using GRACE data and hydrological models: a study from Türkiye. Hydrol Process 35(3). https://doi.org/10.1002/hyp.14076
39. Koçbay A (2022) Türkiye'de Yeraltı Suyu Yönetimi. TMMOB Jeoloji Mühendisleri Odası https://www.youtube.com/watch?v=YhVNx-Cm_hw. Accessed 01 May 2022
40. Kuglitsch FG, Toreti A, Xoplaki E, Della-Marta PM, Zerefos CS, Türkeş M, Luterbacher J (2010) Heat wave changes in the eastern Mediterranean since 1960. Geophys Res Lett 37. https://doi.org/10.1029/2009GL041841
41. Kumar CP (2012) Climate change and its impact on groundwater resources. Res Invent Int J Eng Sci 1(5):43–60. www.researchinventy.com
42. Kundzewicz ZW, Döll P (2009) Will groundwater ease freshwater stress under climate change? Hydrol Sci J 54(4):665–675. https://doi.org/10.1623/hysj.54.4.665
43. Li P, Karunanidhi D, Subramani T, Srinivasamoorthy K (2021) Sources and consequences of groundwater contamination. In: Archives of environmental contamination and toxicology, vol 80, no 1. Springer. https://doi.org/10.1007/s00244-020-00805-z
44. Lionello P, Scarascia L (2018) The relation between climate change in the Mediterranean region and global warming. Reg Environ Change 18(5):1481–1493. https://doi.org/10.1007/s10113-018-1290-1
45. Lukač Reberski J, Rubinić J, Terzić J, Radišić M (2020) Climate change impacts on groundwater resources in the coastal karstic Adriatic area: a case study from the Dinaric karst. Nat Resour Res 29(3):1975–1988. https://doi.org/10.1007/s11053-019-09558-6

46. MAF (2023) Republic of Türkiye ministry of agriculture and forestry, corine project. https://corinecbs.tarimorman.gov.tr/. Accessed 16 January 2023
47. Mansour AYS, Baba A, Gunduz O et al (2017) Modeling of seawater intrusion in a coastal aquifer of Karaburun Peninsula, western Turkey. Environ Earth Sci 76:775. https://doi.org/10.1007/s12665-017-7124-5
48. NOAA (2022) National oceanic and atmospheric administration, carbon dioxide now more than 50% higher than pre-industrial levels, (2022 June 3). https://www.noaa.gov/news-release/carbon-dioxide-now-more-than-50-higher-than-pre-industrial-levels
49. OECD (2011) Evaluation of agricultural policy reforms in Türkiye. OECD Publishing, Paris. https://doi.org/10.1787/9789264113220-en
50. Orhan O (2021) Monitoring of land subsidence due to excessive groundwater extraction using small baseline subset technique in Konya, Türkiye. Environ Monit Assess 193(4):174. https://doi.org/10.1007/s10661-021-08962-x
51. Oruç N (1977) Preliminary study on the effect of water-borne fluoride on the fluoride content of soils and plants: in seminar on problems of high fuoride waters. CENTO Sci Prob Rep (28)
52. Patil NS, Chetan NL, Nataraja M, Suthar S (2020) Climate change scenarios and its effect on groundwater level in the Hiranyakeshi watershed. Groundw Sustain Dev 10. https://doi.org/10.1016/J.GSD.2019.100323
53. Pehlivan R, Yılmaz O (2005) Water quality and hydrogeochemical characteristics of the River Buyukmelen, Duzce, Turkey. Hydrol Process 19(20):3947–3971
54. SHW (2020) State hydraulic works. Istastic of water resources. https://www.dsi.gov.tr/Sayfa/Detay/1344. Accessed 28 April 2022
55. SHW (2022) State hydraulic works. https://www.dsi.gov.tr/Sayfa/Detay/754. Accessed 20 December 2022
56. Şen ÖL (2013) Türkiye'de iklim değişikliğinin bütünsel resmi. (A holistic picture of climate change in Turkey) Türkiye'de İklim Değişikliği Kongresi (Climate Change Congress in Turkey) (TİKDEK 2013). Haziran, İstanbul, pp 3–5
57. Şensoy S, Türkoğlu N, Akçakaya A, Ekici M, Demircan M, Ulupinar Y, Atay H, Tüvan A, Demirbaş H (2013) Trends in Turkey climate indices from 1960 to 2010. In: 6th Atmospheric science symposium, Istanbul, Turkey, 3–5 June 2013
58. Sendil Ç, Baysu N (1973) İnsan ve hayvanlarda Ağrı ili Doğubeyazıt ilçesi köylerinde görülen flor zehirlenmesi ve bunu Van ili Muradiye ilçesi köylerinde de saptamamızla ilgili ilk tebliğ. (The first report on fluorine poisoning in humans and animals in the villages of Doğubeyazıt district of Ağrı province and our detection in the villages of Muradiye district of Van province) Ankara Üniv Vet Fak Derg 10:474–489
59. Shiklomanov IA, Rodda CJ (2003) World water resources at the beginning of the twenty first century. Cambridge University Press, Cambridge
60. Somay MA, Gemici Ü (2009) Assessment of the salinization process at the coastal area with hydrogeochemical tools and geographical information systems (GIS): Selçuk Plain, Izmir, Turkey. Water Air Soil Pollut 201:55–74
61. Srinivasan V, Seto KC, Emerson R, Gorelick SM (2013) The impact of urbanization on water vulnerability: a coupled human–environ-ment system approach for Chennai, India. Glob Environ Change 23:229–239. https://doi.org/10.1016/j.gloenvcha.2012.10.002
62. TSI (2022) Population of Türkiye, Turkish Statistical Institute. https://data.tuik.gov.tr/
63. Tayanç M, İm U, Doğruel M, Karaca M (2009) Climate change in Türkiye for the last half century. Clim Change 94(3):483–502. https://doi.org/10.1007/s10584-008-9511-0
64. Tayfur G, Kirer T, Baba A (2008) Groundwater quality and hydrogeochemical properties of Torbali Region, İzmir, Türkiye. Environ Monit Assess 146(1–3):157–169. https://doi.org/10.1007/s10661-007-0068-6
65. Terzić J, Peh Z, Marković T (2010) Hydrochemical properties of transition zone between fresh groundwater and seawater in karst environment of the Adriatic islands, Croatia. Environ Earth Sci 59(8):1629–1642
66. Tokatli C (2021) Health risk assessment of toxic metals in surface and groundwater resources of a significant agriculture and industry zone in Türkiye. Environ Earth Sci 80:156. https://doi.org/10.1007/s12665-021-09467-z

67. Trenberth KY, Fasullo JT, Shepherd TG (2015) Attribution of climate extreme events. Nat Clim Change 5:725–730. https://doi.org/10.1038/nclimate2657
68. UN (2022) Groundwater: making the invisible visible. World Water Development Report. https://unesdoc.unesco.org/ark:/48223/pf0000380721
69. UNDP (2013) Climate change and Turkey: impacts, sectoral analyses, socio-economic dimensions. Ankara, Turkey. https://www.undp.org/turkiye/publications/climate-change-and-turkey
70. Varol S, Davraz A, Şener Ş, Şener E, Aksever F, Kırkan B, Tokgözlü A (2021) Assessment of groundwater quality and usability of Salda Lake Basin (Burdur/Turkey) and health risk related to arsenic pollution. J Environ Health Sci Eng 19(1):681–706. https://doi.org/10.1007/s40201-021-00638-5
71. Varol S, Şener Ş, Şener E (2021) Assessment of groundwater quality and human health risk related to arsenic using index methods and GIS: a case of Şuhut Plain (Afyonkarahisar/Türkiye). Environ Res 202:111623. https://doi.org/10.1016/j.envres.2021.111623
72. Velibeyoğlu K, Yazdani H, Baba A (2018) Groundwater in local development strategies: case of İzmir. Water Sci Technol Water Supply 18(4):1339–1349. https://doi.org/10.2166/ws.2017.199
73. WB (World Bank) (2022) The World Bank. https://data.worldbank.org/
74. WB (World Bank) (2016) Valuing water resources in Türkiye: a methodological overview and case study. https://openknowledge.worldbank.org/handle/10986/25291
75. WRI (Water Resource Institute) (2022). https://www.wri.org/applications/aqueduct/water-risk-atlas
76. WWF (2014) Konya'da Suyun Bugünü Raporu. https://wwftr.awsassets.panda.org/downloads/konya_da_suyun_bugnu_raporu.pdf
77. Wada Y, van Beek LPH, van Kempen CM, Reckman JWTM, Vasak S, Bierkens MFP (2010) Global depletion of groundwater resources. Geophys Res Lett 37:L20402. https://doi.org/10.1029/2010GL044571
78. Yetis AD, Kahraman N, Yesilnacar MI, Kara H (2021) Groundwater quality assessment using gis based on some pollution indicators over the past 10 years (2005–2015): a case study from semi-arid Harran Plain, Türkiye. Water Air Soil Pollut 232(11). https://doi.org/10.1007/s11270-020-04963-7

Application of Geospatial Multicriteria Decision Analysis in the Evaluation of Groundwater Quality for Irrigation in the Northern Sector of Gabes Region (SE Tunisia)

Fatma Ben Brahim, Zeinab Rhayma, and Salem Bouri

Abstract Groundwater resources in arid and semi-arid regions are of limited availability and variable quality, which impacts the agricultural development. Indeed, the sustainable use of water resources for agricultural, domestic and industrial purposes is confronted with serious challenges in the context of climate change and rapid population growth. In this study, an attempt was made to provide groundwater management focusing primarily on the sustainability of irrigation in the North Gabes (Tunisia) phreatic aquifer to provide baseline information on the groundwater suitability for agricultural purposes. The analytical physicochemical data and the associated hazards to soil characteristics and crop yield, were evaluated and then processed with the hybrid GIS-Multi-Criteria Decision Analysis (MCDA) techniques, as well as by the hierarchical clustering technique (HCA). The hydrochemical study indicated that evaporative processes and the reverse effect of ion exchange through water–rock interactions govern the increase in the groundwater mineralization. The irrigation water quality index (IWQI) obtained from the weighted overlay index analysis reveals two classes of suitability for irrigation of which 29.12% of the study area has a low quality, while 70.88% are classified as moderately suitable. The results will be highly helpful for agricultural planning and could also guide decision-makers to take proactive actions to protect and preserve groundwater resources from pollution risks in Gabes region of Tunisia.

Keywords Groundwater · Irrigation Water Quality Index (IWQI) · GIS-MCDA · HCA · Water Resources Management · Groundwater Quality in Tunisia

F. B. Brahim (✉) · S. Bouri
Water, Energy and Environment Laboratory (LR3E), National School of the Engineers, B.P.W.3038 Sfax, Tunisia
e-mail: bfatma27@yahoo.fr

F. B. Brahim · Z. Rhayma · S. Bouri
Department of Earth Sciences, Faculty of Sciences of Gabes, University of Gabes, Gabes, Tunisia

S. Ali and A. M. Armanuos (eds.), *Groundwater in Arid and Semi-Arid Areas*, Earth and Environmental Sciences Library, https://doi.org/10.1007/978-3-031-43348-1_6

1 Introduction

In arid and semi-arid regions, groundwater has played a major role in irrigation, which accounts for about 70% of groundwater withdrawn globally [60]. Approximately 1500 km^3/year of groundwater was extracted around the world in the 2012s. Water withdrawals for irrigation are the key contributor to groundwater depletion worldwide [22]. Groundwater used for irrigation resulting in the over-abstraction of groundwater resources. This is indeed the example of countries located on the southern shore of the Mediterranean basin, including Tunisia [4, 9, 19, 20, 23, 24, 64, 65, 70]. The simulation of groundwater flow is one of the most widely used solutions to understand prevention and protection of groundwater resources. Therefore, several authors have implemented various tools worldwide for the sustanable development of water resources [16, 17, 23, 31, 38, 39, 67]. In Tunisia, the scarcity of surface water resources is a main constraint for agricultural development. This scarcity is the direct consequence of an extreme arid climate with less than 100 mm annual rainfall. Under this condition, the groundwater constitutes the dominant long-term water resource for meeting water requirements of an intensive agriculture. The dependence on groundwater in areas of southern Tunisia is greater in northern areas of the country.

Therefore, groundwater is only water available for irrigation in the Gabes region. Thus, it is necessary to investigate the study area to ensure effective water management for the sustainable food production in Tunisia. Further, excessive pumping leads to overexploitation of this aquifer, which can degrade the quality of groundwater and could permanently desaturate the aquifers. In addition, overuse of the agricultural fertilizers in the area means that this aquifer is at risks of contamination by phosphate [14]. Further, various industries in the region are sources of the reason of various contamination in the groundwater. Therefore, use of such unsafe groundwater for irrigation may lead to the transport of detrimental contaminants into the soil, which, over time, may alter the soil's physio-chemical properties and as a whole affect the soil's fertility [12, 18].

Approximately 74.5% and 16.4% of groundwater in the Gabes region is used for irrigation and drinking respectively [27]. To maintain a sustainable environment in the area, it is crucial to monitor and evaluate groundwater quality regularly. Indeed, the water quality challenge depends on water resources management strategy. Undoubtedly, water pollution assessment has led to the development of numerous water quality indexes (WQI), as water quality monitoring tools [59]. In this context, numerous authors used mathematical tools to characterize the water quality; those methods are based solely on the potential parameters related to the water application [73].

Therefore, various approaches were used globally such as the Oregon Water Quality Index (OWQI) [28], the National Sanitation Foundation Water Quality Index [55], and the Water Quality Index (WQI) [41]. For the current study, WQI is used as a ranking system of water quality by numerical means since it has been widely used for assessing the water quality in coastal and inland areas and potentialy helpful. WQI combines multiple water quality variables into a single number by normalizing values to subjective rating curves [1]. Further, multivariate statistical analyses were used to examine the factors controlling groundwater quality and its suitability for drinking and irrigation [52].

Various studies were conducted on the evaluation of the water quality index in the North Gabes region. However, this study represents the first work that is based on the hybrid GIS-MCDA approach integrating with multivariate statistical analysis. This survey attempts to assess the hydrogeochemistry of the waters, to define the groundwater evolution processes and to assess the suitability of groundwater quality for irrigation purposes in the northern sector of Gabes region. The findings provide a reference for the better management of groundwater resources and for the rational exploitation of the natural resources in the study area.

2 Study Area

2.1 Location

The Northern Gabes, is a coastal area located in the southeastern of Tunisia. It occupies the northeastern part of pre-Saharan Tunisia and opens at the same time to the Mediterranean through the Gulf of Gabes (Fig. 1). It lies between longitudes 9°51′E and 10°6′E and latitudes 33°52′30″N and 34°13′30″N and cover an area of about 408.4 km^2. It encompasses the localities of Ghannouch, Metouia, Oudhref, El Akarit, El Hicha and El Mida. This coastal zone is characterized by flat and monotonous reliefs and not exceeding 150 m above msl [61].

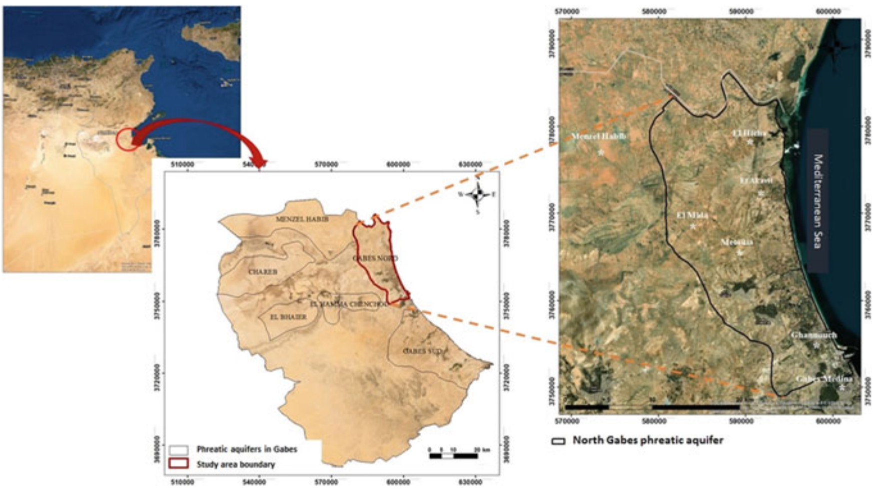


Fig. 1 Location map of North Gabes phreatic aquifer

2.2 Climate

The coastal section has a Mediterranean climate and receives an annual average rainfall of 175 mm, but the western part has an arid climate, with dry and hot summers (June, July, and August) and rainy and chilly winters (November, and December) [3, 14]. There are no perennial rivers in the Gabes area; nevertheless, large storms may cause surface runoff, which is discharged via wadis including Oued El Akarit, Oued Jir, and Oued El Hamma. The proximity of the Mediterranean sea highly influences it. The water resource potential also depends on the climatic characteristics of the study area [43, 45, 50].

2.3 Geology and Hydrogeology Settings

The geology and geomorphology of the area played an important role in the geometry and hydrodynamics of the Djeffara aquifer system. The aquifers of the Gabes sector have continuity outside this study area. These aquifer levels are differentiated in two categories: (i) Phreatic and (ii) Deep aquifers (Fig. 2).

(i) the phreatic aquifer of Plio-Quaternary age: This aquifer underlies part of the study area and consists of a 15–50 m-thick sequence of Pliocene–Quaternary sand-clay sediments [53]. It extends over the entire coastal plain, and the groundwater has a natural gradient flowing toward the sea. In the northern part of Ghannouch-and Methouia, this aquifer is locally in direct hydraulic contact with the underlying Djeffara aquifer [26]. Recharge to the aquifer is mostly provided by rainwater infiltration. Some recharge to the aquifer may also take place by seepage from the El Akarit and Demna wadis during periods of flooding [57]. In the Ghannouch region, the aquifer is also receive recharge from return of irrigation water.

The total groundwater resource equivalent to the aquifer recharge was estimated about 3.71 Mm^3/year, and consumption has been estimated about 3.3 Mm^3/year [30]. Several previous studies have shown that this coastal aquifer was threatened by overexploitation [15, 34, 51].

As Tunisia is subject to the influence of two climates, one Mediterranean in the North and the other Saharan in the South, which are the cause of a spatio-temporal variability of water resources. Thus, this apparent paradox shows us the regional specificity of resources: surface water almost exclusively in the North, groundwater in the Center and South.

Indeed, the highest concentration of wells exploiting this aquifer is located at Ghannouch and along the coast towards north (46% of wells). This shows that the availability of water is very limited and that the zone of high exploitation also corresponds to the sector where the water table is the most vulnerable due to the presence of

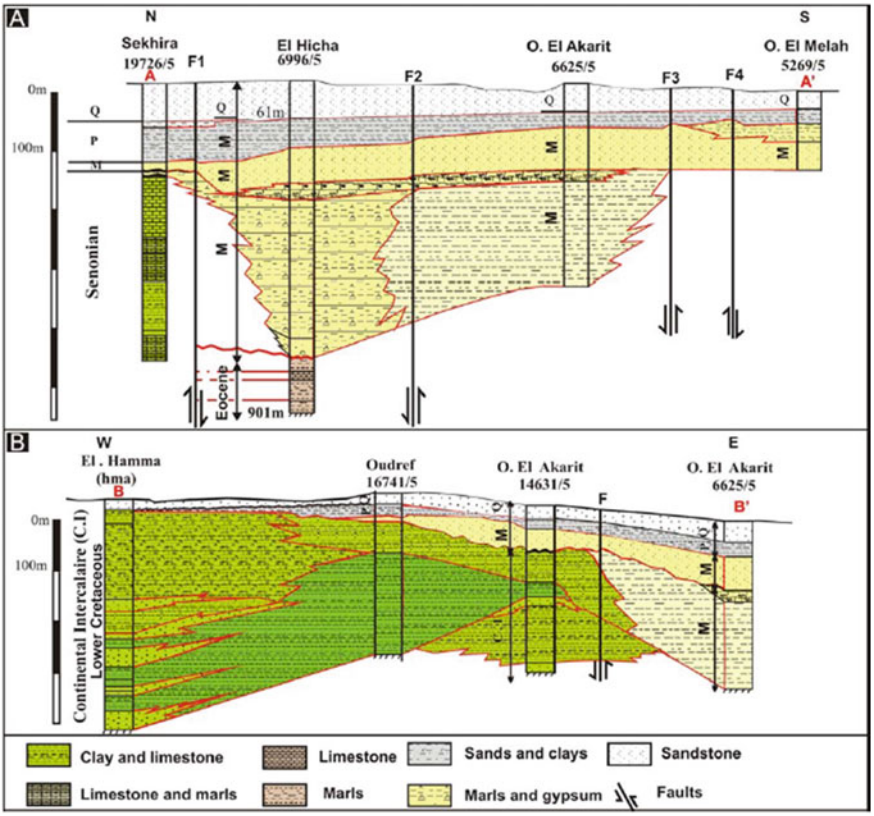


Fig. 2 Geological sections showing the litho-stratigraphic correlation of North Gabes region [21]

sebkhas, the proximity of the sea and the increase in salinity. All of these phenomena resulted in the salinization of the groundwater in the Ghannouch locality.

Their location on the coast requires great caution regarding their exploitation to prevent the risk of degradation of water quality due to marine intrusion [29]. Its location on the coastline requires great attention as to its exploitation to prevent the risk of water quality degradation due to marine intrusion [29].

(ii) the deep aquifer of Lower Senonian age: This aquifer is located in the dolomitic limestones, it is highly karstified. It covers a marly-gypsum complex. Its top is formed by a Mio-Plio-Quaternary cover. The thickness of this layer varies from 200 to 400 m, the limestone of the lower Senonian disappear completely in Wadi El Melah, Bsissi and Wadi Akarit which are located in the northern sector of Gabes region. This variation in thickness is mainly due to geological processes which largely affecting the Jeffara plain of Gabes (Fig. 2).

Indeed, the latter is bordered on all sides by faults which have contributed to leveling the superficial formations of Horst and preserving that of the Graben [62].

3 Materials and Methods

3.1 Sample Collection and Analysis

For this study, groundwater samples were collected from 13 shallow wells, following continuous purging for 20 min to avoid stagnant water in the pipelines during October 2021 (Fig. 3). Samples were collected and stored in pre-washed polyethylene containers and filtered in the laboratory through 0.45-μm membrane filters. The Hach Series of Portable meters and electrodes performed in-situ measurements of temperature, pH, TDS and EC. The collected samples were analyzed at the Laboratory of Physico-chemical Analyses of Soil and Water in the Regional Commissariat of Agricultural Development of Gabes for major ions using standard procedures. The Complexometric titration method was used to determine bicarbonates (HCO_3^-), chlorides (Cl^-), hardness and alkalinity of the samples [6]. Cations like calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K) were determined by Inductively Coupled Plasma Atomic Emission Spectroscopy. Sulfates (SO_4^{2-}) and nitrates (NO_3^-) were determined in the field using a portable meter (LAQUAtwin B-743) after two-point calibration. Using a potentiometric ion selective electrode, fluoride (F^-) was determined. Ionic Balance Error (IBE) was carried out for all groundwater samples to ensure a high level of standardization and minimize manual error. The IBE did not exceed the permissible limit of $\pm 5\%$. To display their spatial distributions, data from the measured ions and elements were interpolated using the Inverse Distance Weighting (IDW) interpolation methods in ArcGIS 10.8 and ArcGIS Pro. Statistical analyses, correlation analyses, and graphical representations were used to evaluate the hydrogeochemical reactions and basic hydrogeochemical processes utilizing Origin and Phreeqc software 3.5.0.

3.2 Geochemical Modeling of Groundwater Quality and Identification of Possible Mineralization Processes

The Whiskers of a Tukey's box plot, are used to represent schematically the distribution of some variable. This graphical representation can be a tool to approach abstract concepts of statistics, if one practices its use on different data sets [48]. In this study, they were plotted using the SPSS 26 software.

Gibbs [35] proposed TDS versus Na + K/(Na + K + Ca) for cations and TDS versus Cl/(Cl + HCO_3) for anions to establish the natural mechanism controlling groundwater chemistry. The concentrations units are in milliequivalents per liter (meq/L).

The saturation indices (SI) with respect to carbonate and evaporate minerals versus TDS were also examined, respectively. The saturation index (SI) was calculated by PHREEQC geochemical equilibrium modeling [5, 58], The SI varies from -1.5 to $+1.5$. When SI < 0, the minerals in the aqueous solution do not reach saturation and fall

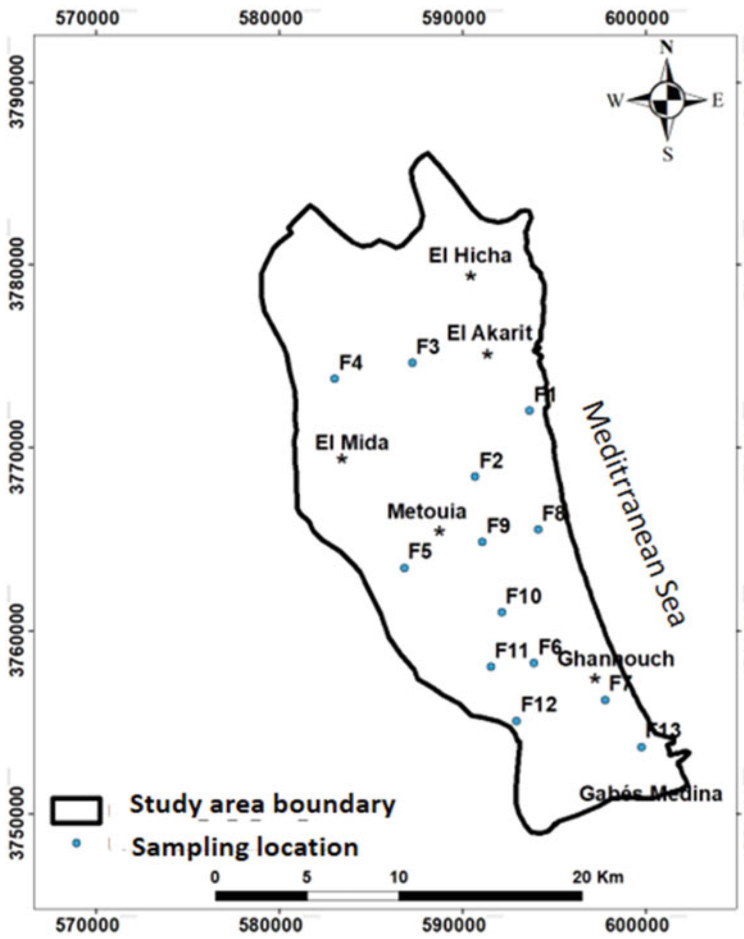


Fig. 3 Location map of sampled water points

into dissolution. Otherwise, in case of SI > 0, the minerals come to the supersaturated state and turn into the deposition state [49].

3.3 *Statistical Analysis*

3.3.1 Cluster Analysis

The hierarchical cluster analysis (HCA) Q-mode is a method for assembling individuals or objects into unknown groups having common characteristics. Many studies widely use HCA to successfully classify water samples [8, 13, 32, 33, 46]. Comparisons based on multi-parameters methods from different samples were made and the samples were grouped according to their 'similarity' to each other (known as Q-mode classifications).

In this paper, Q-mode cluster analysis was used on the water chemistry data on 13 measured hydrochemical variables: electrical conductivity (EC), TDS, pH, Ca, Mg, Na, K, Cl, SO_4, HCO_3, NO_3, Br^- and F^- to group the samples as water quality clusters [36]. The present work used Q-mode HCA to categorize the samples into separate hydrochemical groups using Ward's linkage method [72]. For statistical analysis, all the variables were log-transformed and more closely correspond to normally distributed data. Subsequently, the data were standardized to their standard scores (z-scores) as described by [37].

3.3.2 Factor Analysis

PCA/FA are usually applied to determine the relationships between measured properties that were originally considered independent sources of groundwater hydrochemical data to determine the most important factors. This analysis aim to decrease the data with minimal loss of information and play an important role in confirming temporal and spatial variations caused by natural and anthropogenic issues [54, 66]. Furthermore, multivariate statistical analyses such as principal component analysis (PCA), are applied for the explanation of the reaction process and complex water quality data in the study area.

In this work, PCA/FA are applied to hydrochemical data from the North Gabes groundwater to extract the principal factors corresponding to the different sources of variation and to identify the spatial interrelationships within a set of variables in the study area [7, 40]. PCs with eigen value >1 are only taken into consideration [44]. A Varimax rotation was executed on this PC to help the interpretation of factors based on hydrochemical or anthropogenic processes controlling groundwater quality. Hydrochemical statistical analysis of all samples was performed with SPSS.26 software.

3.4 Application of Weighted Overlay Analysis to Determine Groundwater Suitability for Irrigation

The hazards affecting irrigation water quality include: (a) salinity hazard; (b) infiltration and permeability hazard; (c) specific ion toxicity hazard; (d) trace element toxicity hazard and; (e) hazard due to miscellaneous impacts on sensitive crops [10]. A linear combination of these hazards forming an index, known as the irrigation water quality index (IWQI) as described below, is used to assess the suitability of irrigation water. The spatial maps of irrigation water quality parameters for the development of IWQI in this study were prepared from the following formula:

The salinity hazard index (G_1) is formulated as:

$$G_1 = W_1 \times r_1 \tag{1}$$

where:

($W_1 \times r_1$): the weight multiplied by the rating of the salinity risk index which is designed by the parameter of EC as shown in Table 1.

The infiltration and permeability hazard index (G_2) is expressed as:

$$G_2 = W_2 \times r_2 \tag{2}$$

Table 1 IWQ index parameters classification [19, 69]

Irrigation water hazard	Weight	Parameter	Range	Rating (r)	Quality classes
Salinity hazard (G_1)	5	EC (μS/cm)	<700	3	High
			$700 \le EC \le 3000$	2	Medium
			$EC > 3000$	1	Low
Infiltration and permeability hazard (G_2)	4	See Table 2 for details			
Specific ion toxicity (G_3)	3	SAR (meq/L)	$SAR < 3$	3	High
			$3 \le SAR \le 9$	2	Medium
			$SAR > 9$	1	Low
		Chloride (mg/L)	$Cl < 140$	3	High
			$140 \le Cl \le 350$	2	Medium
			$Cl > 350$	1	Low
Trace element toxicity (G_4)	2	Fluoride (mg/L)	$F < 1$	3	High
			$1 \le F \le 15$	2	Medium
			$F > 15$	1	Low
Miscellaneous effects to sensitive crops (G_5)	1	Nitrate-nitrogen (mg/L)	$NO_3 < 5$	3	High
			$5 \le NO_3 \le 30$	2	Medium
			$NO_3 > 30$	1	Low
		Bicarbonate (mg/L)	$HCO_3 < 90$	3	High
			$90 \le HCO_3 \le 500$	2	Medium
			$HCO_3 > 500$	1	Low
		pH	$7 \le pH \le 8$	3	High
			$6.5 \le pH < 7$ and $8 < pH \le 8.5$	2	Medium
			$pH < 6.5$ or $pH > 8.5$	1	Low

($W_2 \times r_2$): is the weight multiplied by the rating of the second hazard group G_2 that refers to the combination parameters represented by EC and SAR as shown in Table 2.

The specific ion toxicity hazard index (G_3) is obtained as the weighted average of influencing toxic specific ions (SAR and Cl^-) as:

$$G_3 = \frac{W_3}{n} \sum_{j=1}^{n} rj \tag{3}$$

where n = number of influencing parameters.

W_3 is the weight and r_j is the rating of each parameter of the third group G_3 represented by SAR and chloride ions in the groundwater as explained in Table 1.

j is an incremental index, and $n$is a number of influencing parameters.

The trace element toxicity (G_4) is determined as:

$$G_4 = \frac{W_4}{N} \sum_{m=1}^{N} r_m \tag{4}$$

where, m is an incremental index, N is the total number of trace elements available for the analysis, W_4 is the weight value of this group and r_m is the rating value of each parameter as given in Table 1.

The hazard index (G_5) due to miscellaneous effects is calculated as the weighted average of influencing parameters (pH, HCO_3 and NO_3) as:

$$G_5 = \frac{W_5}{3} \sum_{k=1}^{n} r_k \tag{5}$$

where W_5 is the weight and r_k is the rating of pH, HCO_3 and NO_3 related to the last group of the hazard index G_5. k is an incremental index, n is the number of trace elements and r is the rating of each parameter as explained in Table 1.

The final IWQI is expressed as linear combination of the hazards from the following formula 6 [18, 19, 42, 69]:

Table 2 Infiltration and permeability hazard classification [19, 69]

	SAR (meq/L)					Rating (r)	Quality classes
	<3	3–6	6–12	12–20	>20		
EC (μS/cm)	>700	>1200	>1900	>2900	>5000	3	High
	700–200	1200–300	1900–500	2900–1300	5000–2900	2	Medium
	<200	<300	<500	<1300	<2900	1	Low

$$IWQI = \sum_{i=1}^{5} G_i \tag{6}$$

where:

G_i: is the contribution of each hazard groups.

i: is an incremental index.

The hazard groups were assigned weights of 1 to 5 depending on their influence in the irrigation water quality assessment and assigned suitability ratings of 3, 2, 1 for high, medium and low suitability of irrigation water, respectively (Table 1). The final computed IWQI values are classified into three categories as high water (>37), medium water (22–37) and low water (<22) for irrigation water suitability [19, 69].

4 Results and Discussion

4.1 Major Ions Chemistry and Water Type

Major ions like, Na, Ca, Mg and K were found to be varies from 240.063 to 678; 69.213 to 286; 31.2 to 268.2 and 12 to 76 mg/L, respectively (Fig. 4). However, the abundance of the anions were of the following order: $SO_4^{2-} > Cl^- > HCO_3^- > NO_3^-$ thus their range of variation is from 471.894 to 1380; from 349.523 to 1313; from 121 to 152 and from 0.01 to 44 mg/L, respectively. Accordingly, these results show that almost all the water points have a hydrochemical facies of the chloride and sulfated calcium and sodium type. The high concentrations of Na^+ and Cl^- may indicate a local source of pollution from anthropogenic activities such as the use of agricultural chemical and effluents from private and municipal septic systems [63]. Therefore, the sulfate ion could result from the decomposition of organic substances in the weathered soils, leachable sulfate from fertilizers and other human influences, such as sulfuric salts in domestic wastewater [68, 71]. However, the presence of high Cl^- level in groundwater is generally due to the return of evaporated irrigation flow. In addition, the evaporition levels in the region could increase the Cl^- concentration in the groundwater [2].

Gibbs [35] suggested that a simple plot of the ratio of dominant $Na^+/(Na^+ + Ca^{2+})$ cations and $Cl^-/(Cl^- + HCO_3^-)$ anions against TDS could provide information on the relative importance of the major natural mechanisms for controlling water chemistry. The study area has an arid climate, and thus evaporation may also contribute to the variation in water chemistry. This is clearly indicated in the Gibbs plot (Fig. 5), which shows a trend toward the evaporation pole and the other pole of seawater intrusion. Indeed, the evaporation of surface water and moisture in the unsaturate has been considered as the process that influences the development of the chemical composition of groundwater. However, evaporation concentrates the

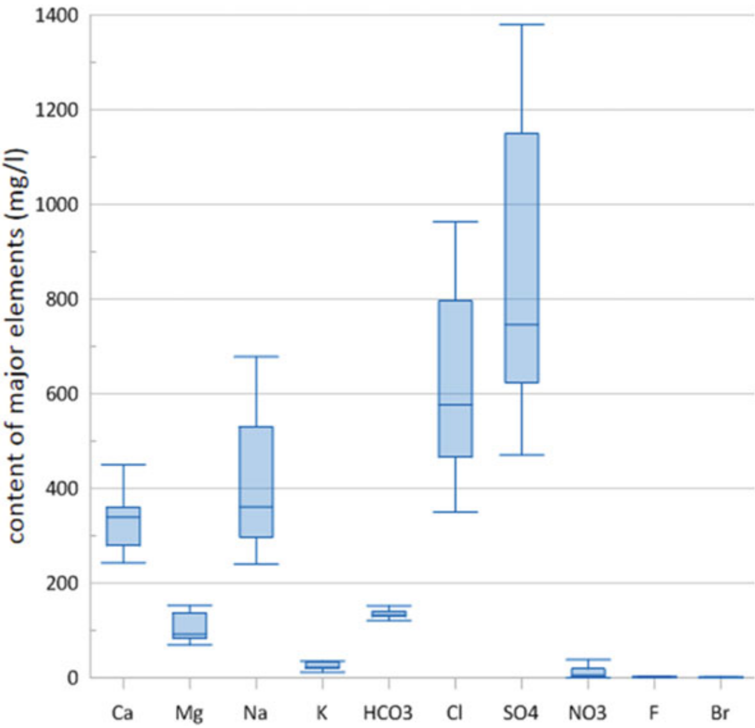


Fig. 4 Box–Whisker diagrams of ionic concentrations of the Mio-Plio-Quaternary in North Gabes region

remaining water and drives the evaporative deposit which is eventually leached into the saturated zone. It is also well known that the groundwater salinity is amplified in arid lands like the study area, due to the high evaporation rate and low rainfall which promote the above process and also reduce the effect of dilution on the soil [56].

4.2 Geochemical Modelling

In the Mio-Plio-Quaternary aquifer of Northern Gabes (Fig. 6), groundwater is found to be significantly supersaturated with respect to calcite ($CaCO_3$), aragonite ($CaCO_3$) and dolomite (Ca, $Mg(CO_3)^{2-}$) (carbonate minerals). Back and Hanshaw [11] and Langmuir [47] suggest that the dissolution of traces of gypsum causes this and that the supersaturation condition is maintained by an imbalance in the rates of dissolution of gypsum relative to the rates of precipitation of calcium carbonate (calcite or aragonite). On the other hand, the evaporitic minerals (halite (NaCl), gypsum ($CaSO_4$ $2H_2O$), and anhydrite ($CaSO_4$)) are in the state of under-saturation, this is explained

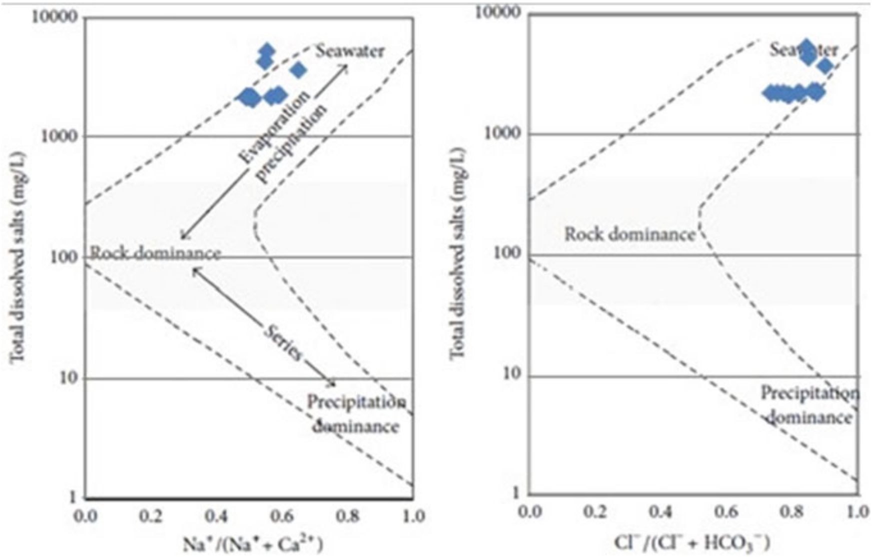


Fig. 5 Gibbs diagrams of groundwater samples in North-Gabes region

by the effect of the high values of the equilibrium constant of evaporitic minerals which allow evaporitic elements to occur in water at high concentrations [25].

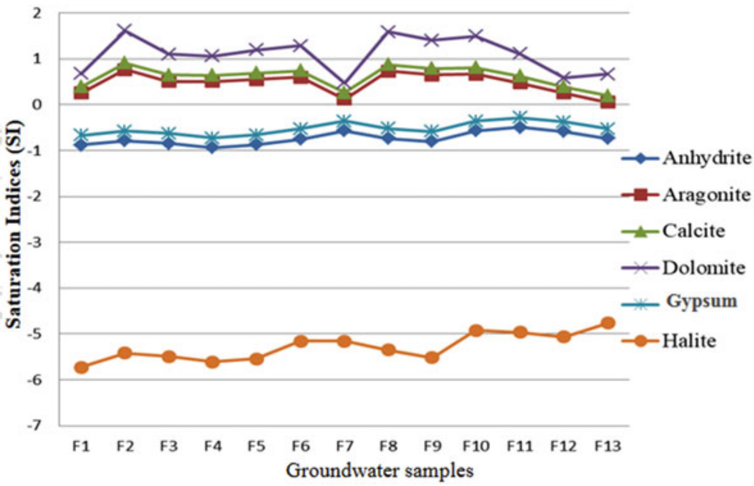


Fig. 6 Saturation indices values of the North Gabes groundwater samples with respect to minerals (carbonate and evaporite)

4.3 Multivariate Statistical Analysis

4.3.1 Correlation Matrix

Pearson correlation matrix was performed in this study to identify the relationships that exist among the individual hydrochemical parameters and their origins (Table 3). A very strong positive correlation is observed between TDS and EC ($r^2 = 0.99$), Cl^- ($r^2 = 0.98$), $SO_4{}^{2-}$ (r = 0.99), Ca^{2+} ($r^2 = 0.9$), Mg^{2+} ($r^2 = 0.7$), Na^+ ($r^2 = 0.98$) and K^+ ($r^2 = 0.6$), but represents low correlations with $HCO_3{}^-$ ($r^2 = 0.14$), F^- ($r^2 = -0.5$), $NO_3{}^-$ ($r^2 = 0.26$) and Br^- ($r^2 = -0.3$). This suggests that these elements may have two different origins of mineralization: water–rock interaction and anthropogenic pollution.

In addition, Na^+ displays very strong positive correlations with Cl^- ($r^2 = 0.963$), Ca^{2+} ($r^2 = 0.899$) and $SO_4{}^{2-}$ ($r^2 = 0.892$) indicating an anthropogenic input to groundwater or some unique form of reverse ion exchange.

4.3.2 Hierarchical Clustering Analysis (HCA)

Using SPSS.26 software, we can apply the hierarchical classification of individuals' boreholes of the study area using Ward's aggregation criterion (Table 4). The obtained results are visualized under the two dendrograms (C1 and C2) according to their squared Euclidean distance (Fig. 7).

- The first cluster (C1) includes 7 boreholes (n°. 1, 2, 3, 4, 5, 8 and 9) characterized by medium saline water (spatially located at the northern portions of the plain). The surrounding rocks influence this on the one hand, and on the other hand by the infiltration of irrigation water. These waters are generally used for irrigation in the study area.
- The second cluster (C2) is mainly located toward the southeastern and the east of the study area (Fig. 7). It correspond to the water samples characterized by a very high content of major chemical elements, which can be influenced by agricultural and industrial activities (boreholes n° 6, 7, 10, 11,12 and 13). These waters reflect the increase in mineralization in the water table in the southern part of the study area. Groundwater samples in this cluster could be classified as unsuitable and would generally not meet the irrigation water standard for these parameters.

4.3.3 Factor Analysis

To differentiate and support the identified hydrochemical processes, the method of multivariate statistical of Q-mode factor analysis was applied to the groundwater quality data. Three significant factors were eventually retained which explains 85.7% of the total variance. The factor analysis and loading diagram results for the first two factors are presented in Fig. 8 and Table 5.

Table 3 Correlation matrix of physico-chemical elements

Variables		TDS	pH	EC	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	NO_3^{-}	F^{-}	Br^{-}
Relation	TDS	1.000												
	pH	0.441	1.000											
	EC	0.999	0.414	1.000										
	Ca^{2+}	0.900	0.222	0.239	1.000									
	Mg^{2+}	0.700	0.350	0.377	0.507	1.000								
	Na^{+}	0.980	0.512	0.938	0.899	0.902	1.000							
	K^{+}	0.600	0.057	−0.109	0.784	0.389	0.874	1.000						
	HCO_3^{-}	0.140	0.393	0.118	0.335	0.484	0.240	0.450	1.000					
	Cl^{-}	0.980	−0.515	0.901	0.856	0.880	0.963	0.859	0.432	1.000				
	SO_4^{2-}	0.990	−0.523	0.936	0.908	0.910	0.892	0.949	0.350	0.867	1.000			
	NO_3^{-}	0.260	0.395	−0.043	0.183	0.124	−0.277	0.193	0.434	0.207	−0.147	1.000		
	F^{-}	−0.500	−0.477	0.037	0.405	0.392	0.298	0.512	0.448	0.144	0.376	0.444	1.000	
	Br^{-}	−0.300	0.093	0.180	−0.091	−0.418	−0.181	−0.352	−0.169	−0.221	−0.131	−0.468	−0.418	1.000

Table 4 Chain of variable distance aggregations

Stage	Class grouping		Coefficients	Class spawn stage		Next stage
	Class 1	Class 2		Class 1	Class 2	
1	12	13	0.000	0	0	2
2	2	12	0.000	0	1	4
3	7	11	0.003	0	0	4
4	2	7	0.012	2	3	7
5	5	8	0.026	0	0	7
6	4	6	0.105	0	0	9
7	2	5	0.324	4	5	11
8	9	10	0.710	0	0	9
9	4	9	2.641	6	8	11
10	1	3	6.638	0	0	12
11	2	4	15.492	7	9	12
12	1	2	156.000	10	11	0

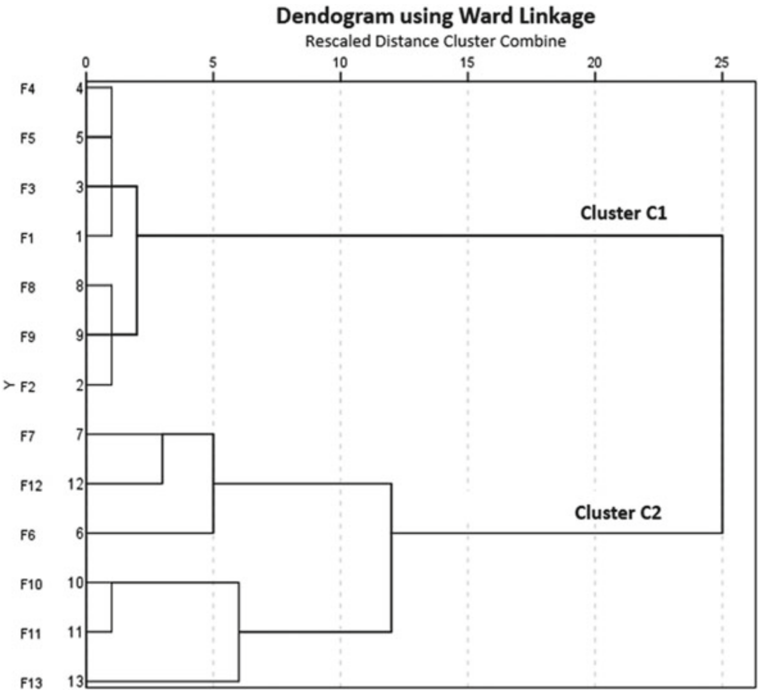


Fig.7 Dendrogram of HCA for individuals (water samples)

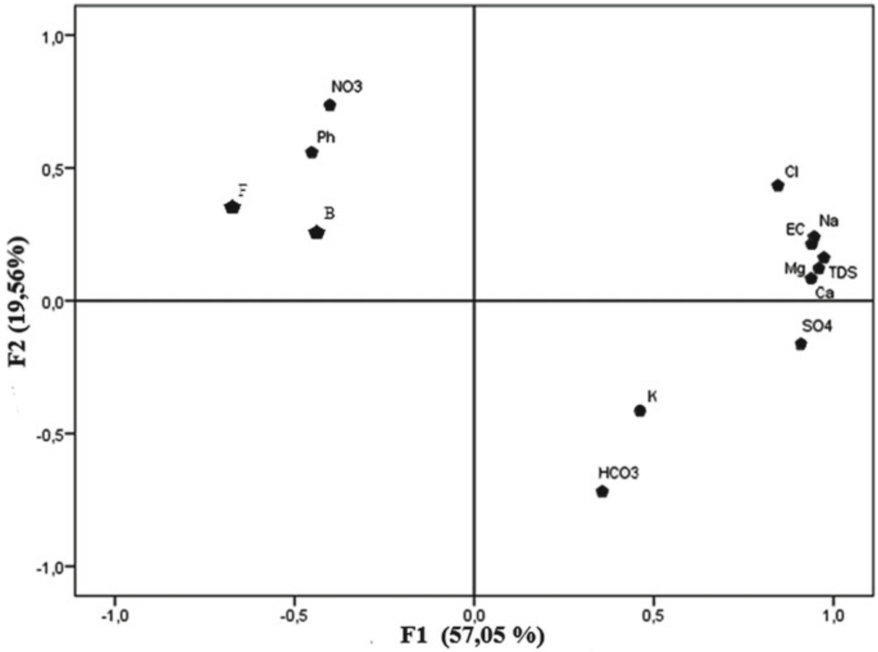


Fig. 8 Projection des variables sur le plan factoriel F1 × F2

The first principal component (FA1) presents 57.047% of the total variance, it is expressed by the highest positive loads of EC, Mg^{2+}, Ca^{2+}, Na^{+}, K, $SO_4{}^{2-}$, Cl^{-}, HCO_3 and TDS (Table 3), this reveals their involvement in the mineralization of groundwater. The second principal component (FA2) explains 19.56% of the total variance in water quality in the studied aquifer. It is articulated around the variables $NO_3{}^{-}$, F^{-}, Br^{-} and pH, which reflects another mineralization origin: the anthropogenic pollution. Thus, the contamination of the water may be carried out by fertilizers (agricultural activities) and the transfer of pollution by the wells implanted in an uncontrolled way (domestic and industrial activities).

Furthermore, the representation of the statistical units shows globally two groups of water (Fig. 9):

Group I: represents waters characterized by medium mineralization, taken from boreholes No. 1, 2, 3, 4, 5, 8 and 9. These waters are used for irrigation.

Group II: represents highly mineralized waters, taken from boreholes n° 6, 7, 10, 11, 12 and 13, are characterized by very high contents of all chemical elements and are located in the southern part of the study area.

Based on these results, it can be considered that the PCA/FA has confirmed the results of the HCA of the analyzed elements.

Table 5 Total variance of the studied variables of the North Gabes phreatic aquifer

Total variance explained						
Component	Initial eigenvalues			Extraction sums of the squares of the retained factors		
	Total	% of variance	% cumulated	Total	% of variance	% cumulated
1	7.416	57.047	57.047	7.416	57.047	57.047
2	2.543	19.560	76.607	2.543	19.560	76.607
3	1.181	9.085	85.692	1.181	9.085	85.692
4	0.800	6.153	91.845			
5	0.602	4.630	96.475			
6	0.313	2.408	98.883			
7	0.092	0.704	99.587			
8	0.030	0.234	99.820			
9	0.014	0.104	99.924			
10	0.009	0.073	99.997			
11	0.000	0.002	99.999			
12	0.000	0.001	100.000			
13	−1.000E−013	−1.000E−013	100.000			

Extraction method: Principal component analysis

4.4 Groundwater Suitability for Irrigation

ArcGIS Spatial Analyst extension was used to carry out the spatial integration for groundwater suitability mapping. The Irrigation Water Quality Index (*IWQI*) was generated by overlapping the thematic maps for the individual hazard groups (G_1, G_2, G_3, G_4, and G_5) discussed in previous sections (Eq. 6).

4.4.1 Salinity Hazard (G_1)

The EC values of the North Gabes groundwaters range from 2810 to 6820 μS/cm. The spatial distribution map of EC in the study area (Fig. 10 G_1) shows that the lowest values are measured in the eastern part of the locality of Metouia (F1, F2, F8). The low conductivity could be the result of the infiltration of fresh water in this sector. The highest values were reported at wells F7 and F6 at Ghannouch locality. As EC demonstrates the salinity hazard, one can conclude that 85% of the water samples belong to the moderate salinity class (2) whose conductivity is less than 3000 μS/cm and 25% of the area belongs to the high salinity rate (1) whose conductivity is greater than 3000 μS/cm (Fig. 10 G_1).

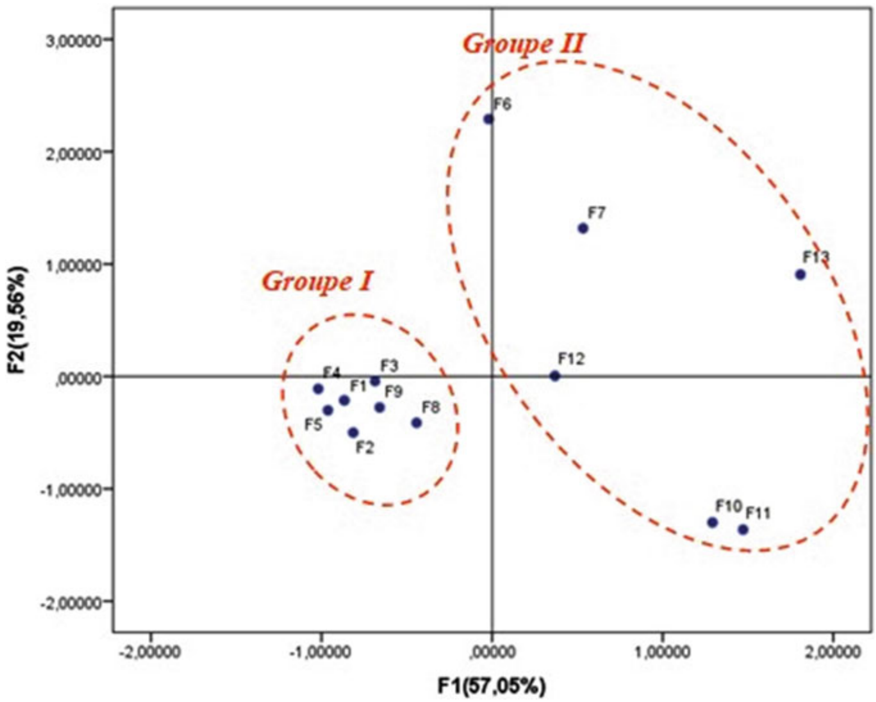


Fig. 9 Projection of individuals on the factorial plane F1 × F2

4.4.2 Infiltration and Permeability Hazard (G_2)

The combined EC-SAR maps were prepared, rasterized and reclassified into irrigation suitable classes as medium and low with areal extent of 89% and 11% respectively (Fig. 10 G_2). It has been found out that these areas where groundwater is affected from the anthropogenic effluents are low suitable areas for irrigation water extraction as high SAR and EC values counter balance their respective negative effects.

4.4.3 Specific Ion Toxicity (G_3)

In addition to SAR distribution map, the chloride content was taken into account to define the specific ion toxicity group (Fig. 10 G_3) Chloride concentrations are found to be higher throughout the areal extent of the study area with concentration values of 139,2 and 1313 mg/l. Thus, 92% of the water samples exceed the lower limit of 140 mg/l representing low quality of irrigation waterand the remaining occupy a medium quality characterizing the F1, F4 and F5 boreholes.

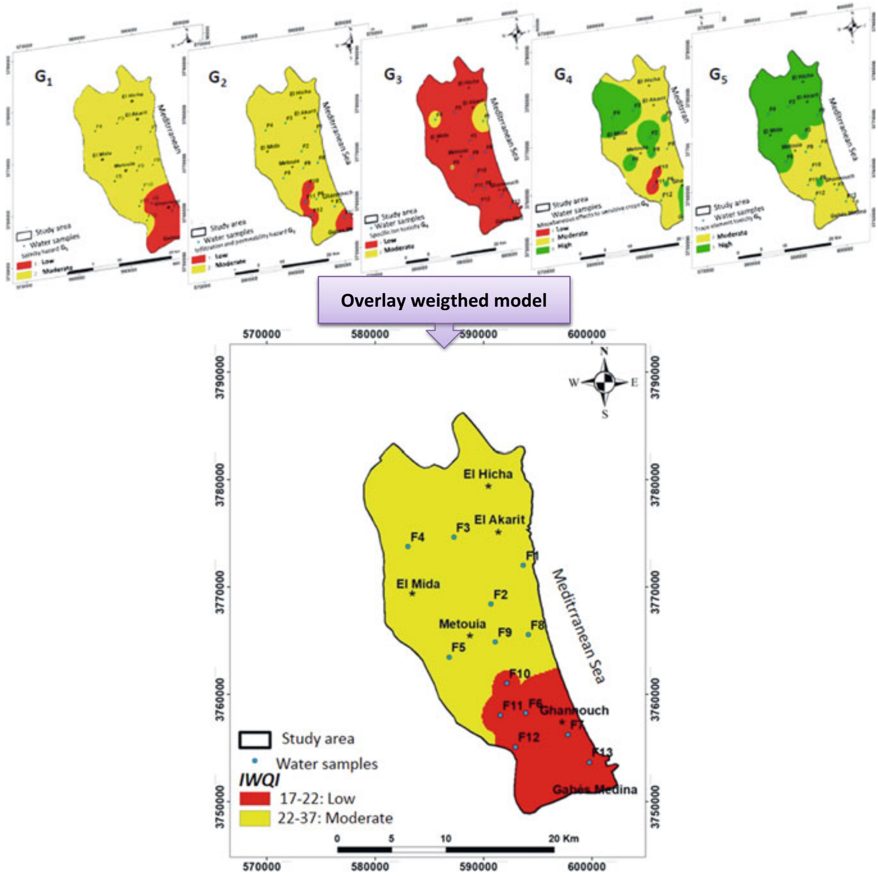


Fig. 10 Final irrigation water qualiti map of the North Gabes phreatic aquifer

4.4.4 Miscellaneous Effects to Sensitive Crops (G_4)

Miscellaneous crop hazards may arise due to additional irrigation water parameters that must be studied to assess the suitability of water for irrigation purposes. These parameters including pH, bicarbonate, and nitrate were mapped, rasterized and reclassified into high, medium and low class irrigation suitability (Fig. 10 G_4).

4.4.5 Risk of Trace Element Toxicity (G_5)

These values vary between 0.45 and 2.67 mg/l with an average of 1.29 mg/l. The groundwater quality in the North Gabes region shows two categories of irrigation water (Fig. 10 G_5): a high quality class (<1 mg/l), in the northern part of the study area and the other of medium quality (1–15 mg/l) in the southern part.

4.4.6 Calculation and Mapping of the IWQI

The final spatial distribution map of the IWQI of the Mio-Plio-Quaternary aquifer varied from medium to low class for the quality of irrigation water (Fig. 10). Indeed, the dominant class covers 70.88% of the areal extent of the study area. It revealed an index comprised between 22 and 37 indicating a "medium suitability" of groundwater, while the second class with only 29.12% of the study area represents "low suitability" and an index varying between 17 and 22.

4.5 Validation of the Results

In addition, hierarchical cluster analysis (HCA) was applied to validate the final quality index maps obtained from the applied multi-criteria decision analysis (MCDA) model. As shown in Fig. 11, cluster (group) C1, which represents about 54% of the groundwater samples and is classified as being of acceptable quality, coincides with the areas of medium suitability, while the remaining 46% of the groundwater samples characterized by high contents of TDS, Cl, SO_4, and NO_3 and classified as water unsuitable for irrigation, are located in areas of low quality and unsuitable for irrigation delineated by this MCDA model.

The correlation between the distribution of boreholes classified according to HCA and the final IQEI/IWQI maps is considered an indicator of the effectiveness of the adopted methods. Indeed, the boreholes of cluster C1 are located in areas with moderate water quality. This distribution is significant and demonstrates consistency between the groundwater quality assessment and HCA analysis results. According to these results, the model of [69] seems the best method to determine the IWQI which can provide a more accurate suggestion for the selection of suitable areas for water pumping for agricultural purposes in the study area.

5 Conclusions

Evaluation of groundwater quality suitability for irrigation purposes using the irrigation water quality index (IWQI) is utmost in combining many irrigation hazards and indices to provide straight forwardly understandable information to the stakeholders. Salinity-hazard, infiltration and permeability hazard, specific ion toxicity-hazard, trace element toxicity, and miscellaneous hazards were considered to compute IWQI.

The final groundwater suitability map for irrigation revealed that the groundwater samples located in Gannouch, Gabes medina localities and the southern parts of the Gabes arid region are of a low suitability class mainly due the salinity effects. Therefore, a threat to the soil structure and crops productivity.

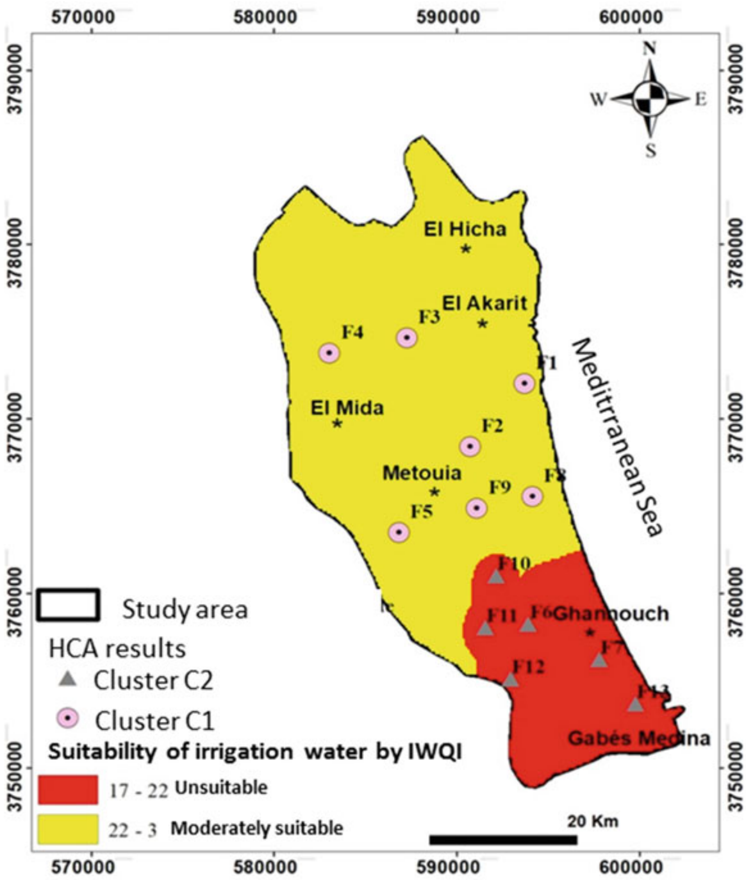


Fig. 11 Grouping analysis of the samples of HCA results on the final IWQI map

The obtained results of IWQI by applying the MCDA method associated to the grouping of the HCA was superimposed. It shows the influence of natural and anthropogenic factors, such as the salinization process and the uncontrolled various agricultural practices which controls variability in groundwater chemistry. The results of this study demonstrated the ability of geographical information systems to model and help locate suitable area for irrigation purposes.

Hence, this chapter has produced a very valuable tool for management and planning, as it gives complete indications of the quality of groundwater and promotes measures for the sustainable protection of this resource for better living conditions for the people of Tunisia.

6 Recommendations

To ensure sustainable use of groundwater, few recommendations were proposed to manage and protect the groundwater resource of Gabes-North which can be summarized as follow:

- Raise awareness and responsibility of the inhabitants to preserve water resources with affordable water pricing,
- Encourage environmental and economic studies of water resources, and monitor all progress in this field to preserve them and ensure sustainable development in the region,
- Stricter state control over chemicals used in agriculture sector and also on wastewater discharges which is another important mechanism of pollution of aquifers,
- Promoting environmentally friendly green technologies of manures in the agriculture over existing high phosphatic fertilizers,
- Avoiding the location of potential future human activities in areas of low vulnerability to limit their negative impact on groundwater resources.

Acknowlegments The author thanks the Directorate of Water Resources of the Regional Commissariat of Agricultural Development (CRDA) of Gabes region for the collaboration and the valuable contributions concerning the data availability. We acknowledges editors for their useful and constructive comments and their meaningful suggestions which are helpful to improve the quality of the chapter.

References

1. Adimalla N, Qian H (2022) Evaluation of non-carcinogenic causing health risks (NCHR) associated with exposure of fluoride and nitrate contaminated groundwater from a semi-arid region of south India. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-022-21771-0
2. Adimalla N, Li P, Venkatayogi S (2018) Hydrogeochemical evaluation of groundwater quality for drinking and irrigation purposes and integrated interpretation with water quality index studies. Environ Process 5:363–383. https://doi.org/10.1007/s40710-018-0297-4
3. Agoubi B (2018) Assessing hydrothermal groundwater flow path using Kohonen's SOM, geochemical data, and groundwater temperature cooling trend. Environ Sci Pollut Res 25:13597–13610. https://doi.org/10.1007/s11356-018-1525-1
4. Agoubi B, Souid F, Kharroubi A, Abdallaoui A (2016) Assessment of hot groundwater in an arid area in Tunisia using geochemical and fuzzy logic approaches. Environ Earth Sci. https://doi.org/10.1007/s12665-016-6296-8
5. Ali S, Shekhar S, Chandrasekhar T, Yadav AK, Arora NK, Kashyap CA, Bhattacharya P, Rai SP, Pande P, Chandrasekharam D (2021) Influence of the water–sediment interaction on the major ions chemistry and fluoride pollution in groundwater of the Older Alluvial Plains of Delhi, India. J Earth Syst Sci 130(98):1–16. https://doi.org/10.1007/s12040-021-01585-3
6. Ali S, Shekhar S, Bhattacharya P, Verma G, Chandrasekhar T, Chandrashekhar AK (2018) Elevated fluoride in groundwater of Siwani Block, Western Haryana, India: a potential concern

for sustainable water supplies for drinking and irrigation. Groundw Sustain Dev 7:410–420. https://doi.org/10.1016/j.gsd.2018.05.008
7. Awaleh MO, Hoch FB, Boschetti T, Soubaneh YD, Egueh NM, Elmi SA, Mohamed J, Khaireh MA (2015) The geothermal resources of the Republic of Djibouti—II: Geochemical study of the Lake Abhe geothermal field. J Geochem Explor 159:129–147. https://doi.org/10.1016/j.gexplo.2015.08.011
8. Ayadi Y, Mokadem N, Besser H, Redhaounia B, Khelifi F, Harabi S, Nasri T, Hamed Y (2018) Statistical and geochemical assessment of groundwater quality in Teboursouk area (Northwestern Tunisian Atlas). Environ Earth Sci 77:208. https://doi.org/10.1007/s12665-018-7523-2
9. Ayed B, Jmal I, Sahal S, Mokadem N, Saidi S, Boughariou E, Bouri S (2017) Hydrochemical characterization of groundwater using multivariate statistical analysis: the Maritime Djeffara shallow aquifer (Southeastern Tunisia). Environ Earth Sci 76:1–22. https://doi.org/10.1007/s12665-017-7168-6
10. Ayers RS, Westcot DW (1985) Water quality for agriculture, vol 29. Food and Agriculture Organization of the United Nation, Rome
11. Back W, Hanshaw BB (1970) Comparison of chemical hydrogeology of the carbonate peninsulas of Florida and Yucatan. J Hydrol 10(4):330–368. https://doi.org/10.1016/0022-1694(70)90222-2
12. Batabyal AK, Gupta S (2017) Fluoride-contaminated groundwater of Birbhum district, West Bengal, India: interpretation of drinking and irrigation suitability and major geochemical processes using principal component analysis. Environ Monit Assess 189:369. https://doi.org/10.1007/s10661-017-6041-0
13. Belkhiri L, Boudoukha A, Mouni L, Baouz T (2010) Application of multivariate statistical methods and inverse geochemical modeling for characterization of groundwater a case study: Ain Azel plain (Algeria). Geoderma 159(3–4):390–398. https://doi.org/10.1016/j.geoderma.2010.08.016
14. Ben Alaya M, Zemni T, Mamou A, Zargouni F (2014) Acquisition de salinité et qualité des eaux d'une nappe profonde en Tunisie: approche statistique et géochimique. Hydrol Sci J 59(2):395–419. https://doi.org/10.1080/02626667.2013.870663
15. Ben Baccar B (1982) Contribution à l'étude hydrogéologique de l'aquifère multicouche de Gabès-Sud. Thèse de 3éme cycle, Paris-Sud (Orsay) (191p)
16. Ben Brahim F (2006) Actualisation de l'étude hydrogéologique des nappes phréatiques d'El Hencha, Djebeniana et El Amra : Cartographie, Synthèse, Relation et Gestion. Mastère en Géosciences Appliquées aux Ressources et Environnements Naturels, Faculté des Sciences de Sfax
17. Ben Brahim F, Bouri S (2015) Transfert hydraulique entre les aquifères profonds du sillon des Chotts, Sud-Ouest tunisien. Int Water J de La Houille Blanche 4(2015):65–73. https://doi.org/10.1051/lhb/20150048
18. Ben Brahim F, Boughariou E, Bouri S (2021) Multicriteria-analysis of deep groundwater quality using WQI and fuzzy logic tool in GIS: a case study of Kebilli region, SW Tunisia. J Afr Earth Sci 180:104224. https://doi.org/10.1016/j.jafrearsci.2021.104224
19. Ben Brahim F, Msaddki H, Bouri S (2022a) Groundwater quality index mapping for irrigation purposes in the "El Hezma-El Hmila" (Medenine, Tunisia). CLEAN-Soil, Air, Water J. https://doi.org/10.1002/clen.202100203
20. Ben Brahim F, Boughariou E, Hajji S, Bouri S (2022b) Assessment of groundwater quality with analytic hierarchy process, boolean logic and clustering analysis using GIS platform in the Kebilli's complex terminal groundwater. SW Tunisia Environ Earth Sci J. https://doi.org/10.1007/s12665-022-10541-3
21. Ben Hamouda MF, Mamou A, Bejaoui J, Klaus, Froehlich K (2013) Hydrochemical and isotopic study of groundwater in the North Djeffara aquifer, Gulf of Gabès, Southern Tunisia. Int J Geosci 4:1–10. https://doi.org/10.4236/ijg.2013.48A001
22. Boretti A, Rosa L (2019) Reassessing the projections of the world water development report. NPJ Clean Water 2:15. https://doi.org/10.1038/s41545-019-0039-9

23. Boughariou E, Allouche N, Jmal I, Mokadem N (2018) Modeling aquifer behaviour under climate change and high consumption: case study of the Sfax region, southeast Tunisia. J Afr Earth Sci 141. https://doi.org/10.1016/j.jafrearsci.2018.02.006
24. Boughariou E, Allouche N, Ben Brahim F, Nasri G (2021) Delineation of groundwater potentials of Sfax region, Tunisia, using fuzzy analytical hierarchy process, frequency ratio, and weights of evidence models. Environ Develop Sustain. https://doi.org/10.1007/s10668-021-01270-x
25. Chemseddine F, Boudoukha A, Rouabhia A, Salameh E (2009) 2009) Caractérisation hydrogéochimique des eaux souterraines du complexe aquifère Morsott-Laouinet (Région Nord de Tébessa, Sud-Est algérien. Afrique Science 05(2):217–231. https://doi.org/10.4314/afsci.v5i2.61732
26. Chandoul IR, Bouaziz S, Ben Dhia H (2014) Utilisation des SIG pour l'évaluation de la sensibilité à la désertification par l'approche MEDALUS. Application région de Gabès
27. CRDA Gabés (2022) Commissariat Régional du Développement Agricole Gabés. Le rapport annuel de l'année 2021, Arrondissement des eaux
28. Cude CG (2001) Oregon water quality index a tool for evaluating water quality management effectiveness 1. JAWRA J Am Water Resour Assoc 37(1):125–137
29. DG/ACTA (2021) Etude de la planification des aménagements CES dans le gouvernorat de Gabès
30. DGRE (Direction Générale des Ressources en Eau) (2008) Situation de l'exploitation des nappes phréatiques en 2008. Publ. DGRE, Tunis, Tunisie
31. Ebrahimi H, Rajaee T (2017) Simulation of groundwater level variations using wavelet combined with neural network, linear regression and support vector machine. Environ Sci. https://doi.org/10.1016/j.gloplacha.2016.11.014
32. Farnham IM, Stetzenbach KJ, Singh AK, Johannesson KH (2000) Math Geol 32:943–968. https://doi.org/10.1023/A:1007522519268
33. Foued B, Hénia D, Lazhar B, Nabil M, Nabil C (2017) Hydrogeochemistry and geothermometry of thermal springs from the Guelma region, Algeria. J Geol Soc India 90:226–232. https://doi.org/10.1007/s12594-017-0703-y
34. Gaaloul N, Alexandre H-D, Cheng (2003) Hydrogeological and hydrochemical investigation of coastal aquifers in Tunisia-Crisis in overexploitation and salinization. In: Second international conference on saltwater intrusion and coastal aquifers monitoring, modeling, and management. Merida, Mexico, March 30–April 2
35. Gibbs RJ (1970) Mechanisms controlling world water chemistry. Science 170(3962):1088–1090
36. Grande JA, Carro B, Borrego J, de La Torre ML, Santisteban M (2013) Hydrogeochemical variables regionalization: applying cluster analysis for a seasonal evolution model from an estuarinesystem affected by AMD. Mar Pollut Bull 69:150–156. https://doi.org/10.1016/j.marpolbul.2013.01.022
37. Guler C, Thyne GD, McCray JE, Turner AK (2002) Evaluation of graphical and multivariate statistical methods for classification of water chemistry data. Hydrogeol J 10:455–474. https://doi.org/10.1007/s10040-002-0196-6
38. Haj-Amor Z, Araya T, Kim DG, Bouri S (2023) Climate change effects on soil salinity in rainfed maize areas: a case study from South Africa. Water Supply. https://doi.org/10.2166/ws.2023.138
39. Haj-Amor Z, Araya T, Acharjee TK, Bouri S, Anlauf R (2023) Soil-water modeling as a tool for sustainable soil resources management: progress and future directions. In: Water, land, and forest susceptibility and sustainability. Academic Press, pp 71–96. https://doi.org/10.1016/B978-0-443-15847-6.00001-X
40. Hamad A, Baali F, Hadji R, Zerrouki H, Besser H, Mokadem N, Hamed Y (2018) Hydrogeochemical characterization of water mineralization in Tebessa-Kasserine karst system (Tuniso-Algerian Transboundry basin). Euro-Mediterr J Environ Integr 3(1):7. https://doi.org/10.1007/s41207-017-0045-6

41. Horton RK (1965) An index number system for rating water quality. J Water Pollut Control Fed 37(3):300–306
42. Jasmin I, Mallikarjuna P (2015) Delineation of groundwater potential zones in Araniar River basin, Tamil Nadu, India: an integrated remote sensing and geographical information system approach. Environ Earth Sci 73(7):3833–3847. https://doi.org/10.1007/s12665-014-3666-y
43. Jedoui Y (2000) Sédimentologie et géochronologie des dépôts littoraux quaternaires: reconstitution des variations des paléoclimats et du niveau marin dans le Sud-Est tunisien. Thèse de doctorat des-sciences géologiques, université de Tunis II
44. Kaiser HF (1960) The application of electronic computers to factor analysis. EducPsychol Meas 20:141–151. https://doi.org/10.1177/001316446002000116
45. Kerrit O (2021) Contribution de l'analyse multicritère de la télédétection et des SIG à la cartographie des zones potentielles de la recharge dans la région de Gabès-Sud. Mémoire de Mastère de recherche en Géologie des Bassins Sédimentaires et du Changement Climatique à la Faculté des Sciences de Gabès (FSG) (Juin 2021, 119p) (in french language)
46. Khelif S, Boudoukha A (2018) Multivariate statistical characterization of groundwater quality in Fesdis, East of Algeria. J Water Land Dev 37:65–74. https://doi.org/10.2478/jwld-2018-0026
47. Langmuir D (1971) Particle size effect on the reaction goethite = hematite + water. Am J Sci 271(2):147–156. https://doi.org/10.2475/ajs.271.2.147
48. Le Guen M (2008) La boîte à moustaches de TUKEY, un outil pour initier à la Statistique. Statistiquement Votre - SFDS, 2001, pp 1–3. ffhalshs-00287697f
49. Li P, Qian H, Wu J, Zhang Y, Zhang H (2013) Major ion chemistry of shallow groundwater in the Dongsheng Coalfield, Ordos Basin. Mine Water Environ 32:195–206. https://doi.org/10.1007/s10230-013-0234-8
50. Makni J (2012) Contribution des approches hydrogéologique, hydrochimique et géothermique à l'étude des systèmes aquifères du Sud-est tunisien Etude du transfert d'eaux souterraines inter-aquifères profonds. Université de Sfax, Thèse de doctorat en Sciences géologiques
51. Mammou A (1990) Caractéristiques et évaluation des ressources en eau du sud tunisien. Thèse de doctorat d'état des sciences naturelles, 426 p. (in french language)
52. Megahed HA (2020) GIS-based assessment of groundwater quality and suitability for drinking and irrigationpurposes in the outlet and central parts of Wadi El-Assiuti, Assiut Governorate, Egypt. Bull Natl Res Cent 44:187. https://doi.org/10.1186/s42269-020-00428-3
53. Mekrazi AF (1975) Contribution à l'étude géologique et hydrogéologique de la région de gabes nord. Thèse de doctorat sciences géologiques université bordeaux I, 230 p. (in french language)
54. Mustapha A, Aris AZ (2012) Multivariate statistical analysis and environmental modeling of heavy metals pollution by industries. Pol J Environ Stud 21(5):1359–1367
55. Noori R, Berndtsson R, Adamowski JF, Abyaneh MR (2018) Temporal and depth variation of water quality due to thermal stratification in Karkheh Reservoir, Iran. J Hydrol Reg Stud 19:279–286. https://doi.org/10.1016/j.ejrh.2018.10.003
56. Nsiri M, Ben Brahim F, Khlifi M, Bouri S (2021) Assessment of the effects of anthropogenic activities on the El Arich groundwater using hydrogeochemistry, GIS and multivariate statistical techniques: a case study of the semiarid Kasserine region, Tunisia. Environ Qual Manage J. http://dx.doi.org/10.1002/tqem.21810
57. OSS (2008) Observatoire du Sahara et du Sahel: the great green wall initiative for the Sahara and the Sahel\OSS; CEN-SAD. Introductory Note Number 3. OSS: Tunis, 44 pp
58. Parkhurst DL, Appelo CAJ (2013) Description of input and examples for PHREEQC version 3: a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. U.S. Geol Surv Tec. Methods. https://doi.org/10.3133/tm6A43
59. Prasad M, Sunitha V, Reddy YS, Suvarna B, Reddy BM, Reddy MR (2019) Data on water quality index development for groundwater quality assessment from Obulavaripalli Mandal, YSR district, AP India. Data Brief 24:103846. https://doi.org/10.1016/j.dib.2019.103846
60. Pointet T (2022) The United Nations world water development report 2022 on groundwater, a synthesis. LHB 108:1. https://doi.org/10.1080/27678490.2022.2090867

61. Rhayma Z (2022) Contribution de l'approche hybride SIG-Analyse de décision multicritères (MCDA) à l'évaluation de l'aptitude des eaux souterraines à l'irrigation: cas de la nappe phréatique de Gabès-Nord. Mémoire de Mastère de Recherche en Géologie des Bassins Sédimentaires et du Changement climatique, FSG, 135 p
62. Rouabti R (1967) Contribution à l'étude hydrogéologique du Karst en Terre de Gabès Sud. Thèse de Doctorat, Montpellier
63. Saadali B, Zerrouki H, Hamzi A, Bouhdid C, Khiari A (2019) Geochemical assessment of water quality and its suitability for agricultural use in the Djedra wadi subwatershed, northeast Algeria. Euro-Mediterr J Environ Integr 4(1):33. https://doi.org/10.1007/s41207-019-0121-1
64. Saidi S, Bouri S, Ben Dhia H (2013) Groundwater management based on GIS techniques, chemical indicators and vulnerability to seawater intrusion modelling: application to the Mahdia-Ksour Essaf aquifer, Tunisia. Environ Earth Sci 70(4):1551–1568. https://doi.org/10.1007/s12665-013-2241-2
65. Saidi S, Hosni S, Mannai H, Jelassi F, Bouri S, Anselme B (2017) GIS-based multi-criteria analysis and vulnerability method for the potential groundwater recharge delineation, case study of Manouba phreatic aquifer, NE Tunisia. Environ Earth Sci 76:1–20. https://doi.org/10.1007/s12665-017-6840-1
66. Schaefer K, Einax JW (2010) Analytical and chemometric characterization of the Cruces River in South Chile. Environ Sci Pollut Res 17(1):115–123. https://doi.org/10.1007/s11356-009-0116-6
67. Sendide O (2002) Etude qualitative des eaux de la nappe phréatique du bassin de Fes-Meknes: Caractérisation, Evolution, Modélisation mathématique et Moyens de protection. Thèse Doctorat, Faculté des Sciences de Tunis, université de Tunis El Manar, 356 p
68. Sener S, Sener E, Davraz A (2017) Evaluation of water quality using water quality index (WQI) method and GIS in Aksu River (SW-Turkey). Sci Total Environ 584:131–144. https://doi.org/10.1016/j.scitotenv.2017.01.102
69. Simsek C, Gunduz O (2007) IWQ index: a GIS-integrated technique to assess irrigation water quality. Environ Monit Assess 128:277–300. https://doi.org/10.1007/s10661-006-9312-8
70. Trabelsi R, Kaceme A, Zouari K, Rozanski K (2009) Quantifying regional groundwater flow between continental intercalaire and djeffara aquifers in southern Tunisia using isotope methods. Environ Geol 58(1):171–183. https://doi.org/10.1007/s00254-008-1503-x
71. Varol S, Davraz A (2015) Evaluation of the groundwater quality with WQI (Water Quality Index) and multivariate analysis: a case study of the Tefenni plain (Burdur/Turkey). Environ Earth Sci. https://doi.org/10.1007/s12665-014-3531-z
72. Ward JH (1963) Hierarchical grouping to optimize an objective function. J Am Stat Assoc 58:236–244
73. Zhao Z, Zhou Y, Wang X, Wang Z, Bai Y (2022) Water quality evolution mechanism modeling and health risk assessment based on stochastic hybrid dynamic systems. Expert Syst Appl 193:116404. https://doi.org/10.1016/j.eswa.2021.116404

Groundwater Modelling

Creation of Rational Groundwater Management Schemes in the Chu Valley of the Kyrgyz Republic Based on Groundwater Modeling

Rafael G. Litvak, Ekaterina I. Nemaltseva, and Aman Ch. Imanaliev

Abstract Groundwater management is understood as the creation of the most rational scenarios for the use of groundwater as an additional source of water resources for irrigation. At the same time, it is necessary to minimize the impact of additional groundwater abstraction on the existing groundwater intakes and environmental damage. In this work, quantitative criteria for evaluating the considered scenarios are proposed. The consideration of management variants is based on groundwater modeling using MODFLOW software package. The Chu valley of Kyrgyzstan is an intermountain depression with complicated natural and water economy conditions. Broadly, the valley is divided into eastern, central and western parts. However, this chapter deals with the largest i.e.,—the central part. The chapter also discusses the issues of minimizing the impact of management actions on cross-border groundwater.

Keyword Groundwater management · Intermountain basin of Chu valley · Water resources for irrigation · Groundwater modeling · Kyrgyzstan · Central Asia

1 Introduction and Task Setting

The territory of the central part of the Chu Valley is characterized by complicated natural and water management conditions. The most important source of livelihood for the population of this region is irrigated agriculture, which may be significantly

R. G. Litvak (✉)
Kyrgyz State Research Institute of Irrigation, Toktonaliev Str. 4a, Bishkek 720055, Kyrgyzstan
e-mail: RLitvak14@gmail.com

E. I. Nemaltseva
Kyrgyz National Academy of Sciences, Institute of Water Problems and Hydropower, Bishkek, Kyrgyzstan

A. Ch. Imanaliev
Hydrogeological Department, State Enterprise "Kyrgyzgeology", Bishkek, Kyrgyzstan
e-mail: imanaliev60@beka.ru

S. Ali and A. M. Armanuos (eds.), *Groundwater in Arid and Semi-Arid Areas*, Earth and Environmental Sciences Library, https://doi.org/10.1007/978-3-031-43348-1_7

affected due to the projected reduction in river flow. Developing scenarios is necessary for mitigating this phenomenon that involves attracting additional water resources for irrigation without any detriment to the environment and water supply to settlements.

In this chapter, groundwater management is considered as the development of the most rational scenarios for groundwater use as an additional source of water resources for irrigation. Meanwhile, any impact on existing groundwater abstractions and environmental damage shall be minimized. It is also necessary to achieve the maximum reclamation effect, i.e. drainage of territories flooded by groundwater using additional water intake.

The Chu valley of Kyrgyzstan is about 250 km in the latitudinal direction and reaches about 100 km in the meridional direction. It is an intermountain valley with complex natural and water management conditions (Fig. 1). The valley is subdivided into eastern, central, and western parts.

In this chapter, the most significant part i.e., the central part, is considered. Bishkek, the capital of the Kyrgyz Republic, is located here. The northern boundary of the studied area is marked by the Chu River, in its southern boundary is the mountain frame.

The initial data source for this study was the long-term work of various organizations in Kyrgyzstan (mainly Kyrgyz Hydrogeology Survey) and scientific centers of the former USSR [4–6, 13]. The upper structural hydrogeological level groundwaters, Quaternary complex, were under consideration. Neogene-Quaternary clay sediments taken as a water confining layer (the lower boundary of the studied area), underlie them. The Quaternary aquifer complex within the central part of the Chu Valleyis divided into four hydrogeological zones [4, 5]: recharge zone, discharge zone, transit flow zone and zone of regional groundwater discharge into the Chu River (Figs. 2 and 3).

Groundwater flow is formed in the piedmont part (in the recharge zone). Here, in loose coarse clastic Quaternary sediments, a united aquifer of 300–500 m total thickness contains groundwater. Somewhat to the south of the WestBigChu Canal, the recharge zone is transformed into the discharge zone and further into transit zones and regional discharge of groundwater flow into the Chu River. Depths of groundwater levels are shown in the Fig. 4.

The boundary between the recharge zone and the discharge zone is characterized by the fact that the flow from the well-permeable grounds of the piedmont plume enters a series of aquifers separated by loamy interlayers. Total water transmissivity in the discharge zone decreases several times. All watered interlayers of the pressure complex and groundwater horizon are hydraulically interconnected and form a single system.

The main goal of the conducted research is to develop some rational schemes of additional water intake that will meet the following conditions:

(1) minimally affect the location zones of existing water intakes;
(2) improve reclamation condition of flooded areas of irrigation systems located in the studied area;

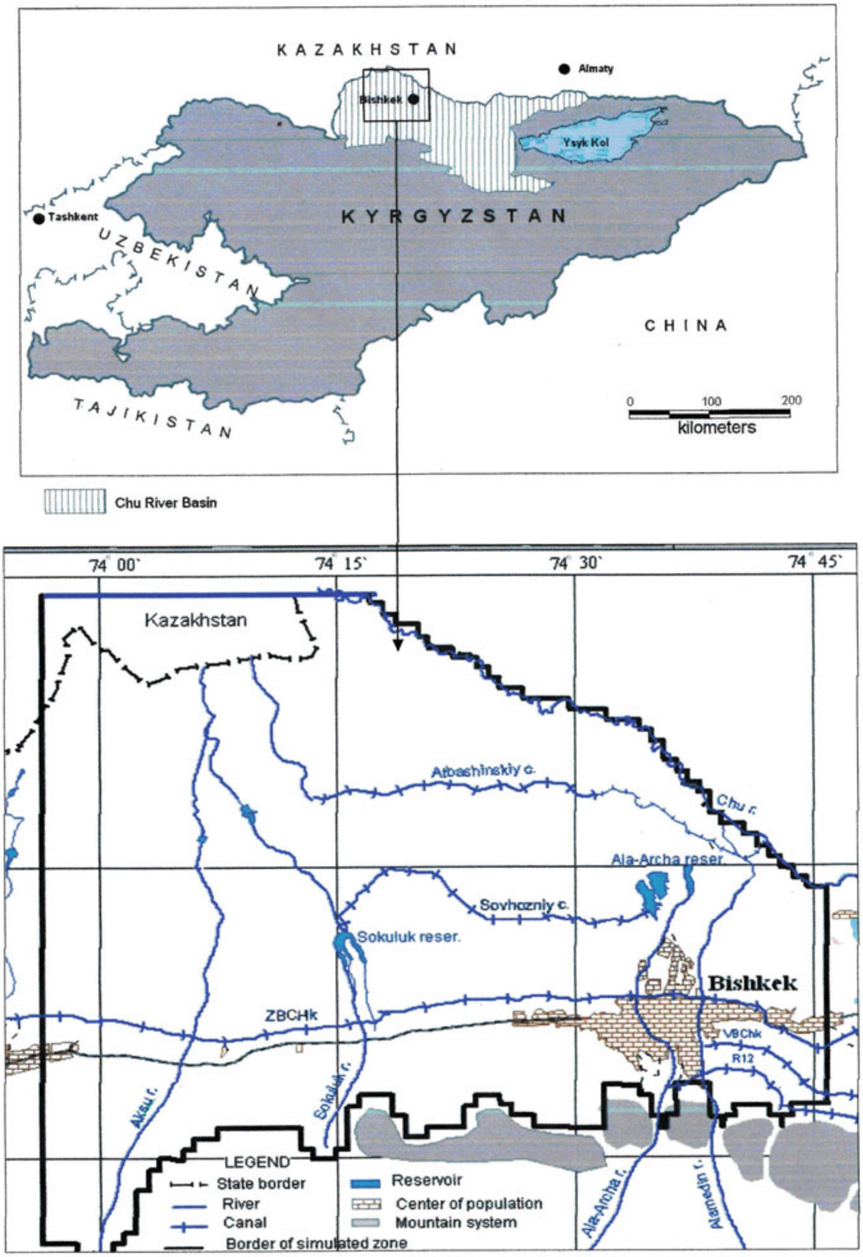


Fig. 1 Location of the study area

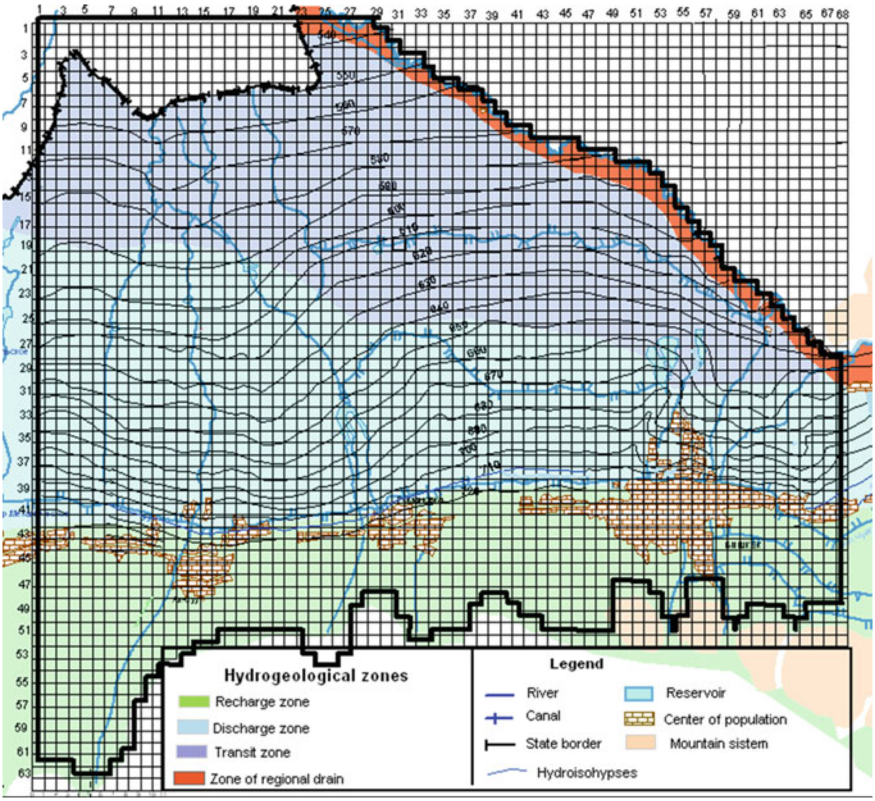


Fig. 2 Hydrogeological zones

(3) minimally affect the initial discharge of groundwater into the Chu River. Significant decrease of this value will lead to deterioration of ecological situation in the lower reaches of the river.

To achieve the above mentioned goal, a volumetric model of the studied area was established and quantitative criteria for comparing the considered scenarios of impact on groundwater were proposed.

Despite the labour-intensiveness of groundwater modeling use to select the best scenarios for solving water management problems related to groundwater, it has been used by many researchers [1–3, 10–12, 14, 16]. In this chapter, the groundwater management problem is formulated and solved as a two-level optimization problem. Meanwhile, the volumetric filtration model created by the authors at such a detailed level, which has not been created in Kyrgyzstan before, is used.

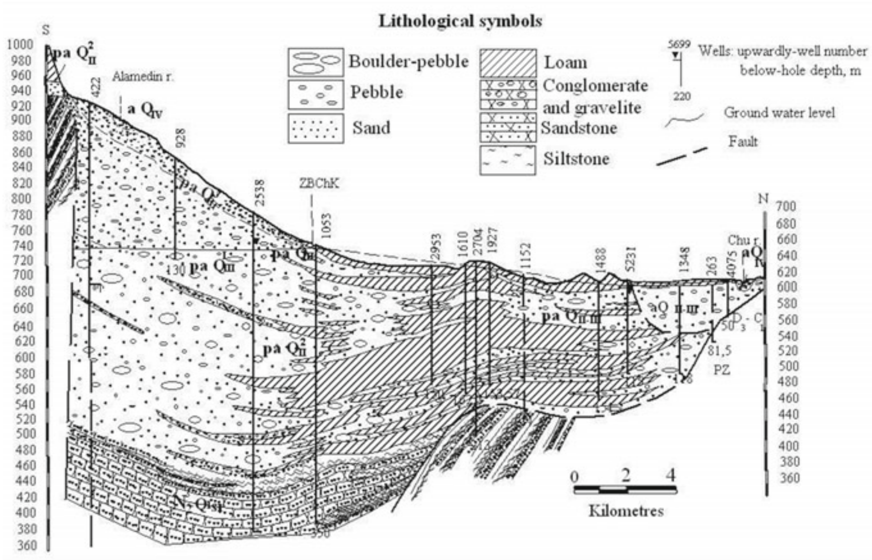


Fig. 3 Schematic hydrogeological cross section

2 Material and Methods

A general target function $F(t, sc)$ is proposed, which characterizes the degree of deviation of hydrogeological and environmental conditions from the optimal situation. Its general form is as follows:

$$FG(t, sc) = a_1 \cdot FW(t, sc) + a_2 \cdot FD(t, sc) + a_3 \cdot FR(t, sc), \quad (1)$$

where

$FW(t, sc)$ target function, minimization of which provides the minimum impact of the considered scenario on the existing groundwater intakes;
t time, (in days);
sc the considered set of scenarios, under which the minimization is performed.

The following dependence for $FW(t, sc)$ is proposed:

$$FW(t, sc) = \frac{QF(t, sc)}{Q} \quad (2)$$

where

$QF(t, sc)$ outflow from the zone of operating water intakes into additional water intake, which depends on time and on the considered scenario, m^3/s;

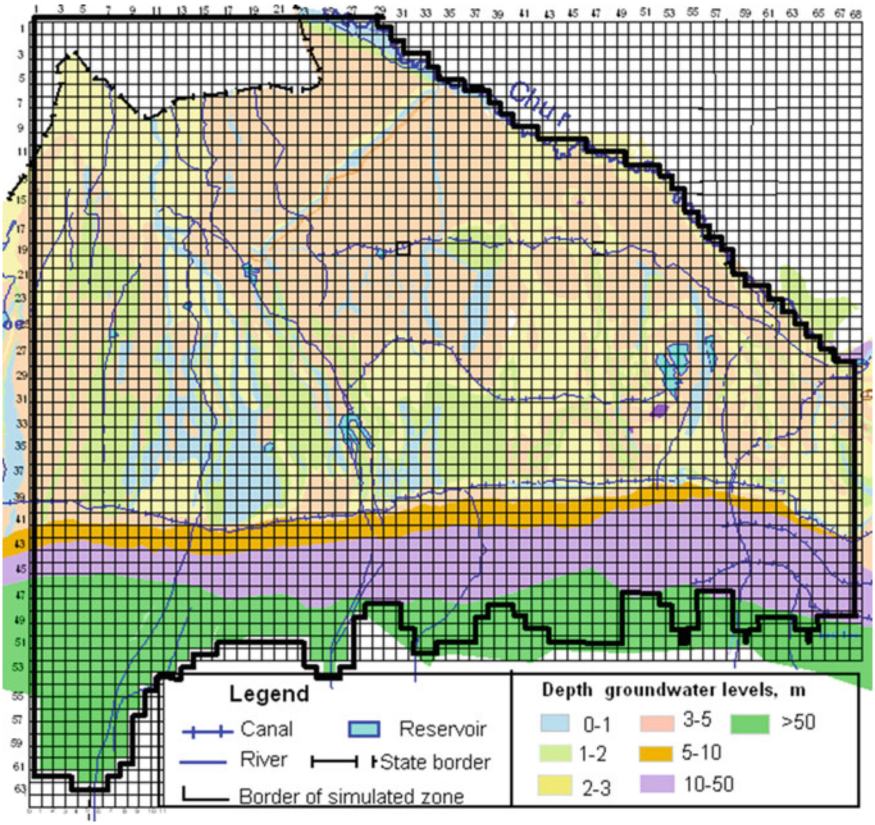


Fig. 4 Groundwater depth and model cells

Q amount of additional water intake, m^3/s.

FD(*t*, *sc*)—target function, minimization of which is related to drainage of under flooded areas. The following dependence for *FD*(*t*, *sc*), which characterizes reclamation effect, is proposed:

$$FD(t, sc) = \frac{E(t, sc)}{E_0} \quad (3)$$

where

E_0 average annual initial evaporation of groundwater in a zone, where the land reclamation status is being assessed, m^3/s;

$E(t, sc)$ predicted evaporation of groundwater in a zone where the land reclamation status is being estimated; its value depends on time, specific scenario, and predicted depth of groundwater levels in each model cell, m^3/s.

Groundwater evaporation was chosen as an integral indicator of the reclamation status of the territory, because this parameter characterizes the intensity of secondary salinization of soil.

The third term of Eq. (1), denoted $FR(t, sc)$, is the target function, minimization of which provides a minimum reduction of groundwater discharge into the Chu River:

$$FR(t, sc) = \frac{QN - Q(t, sc)}{QN} \cdot \Phi(QN - Q(t, sc)) \quad (4)$$

where

QN initial groundwater discharge in the Chu River within the territory under consideration, m^3/s;

$Q(t, sc)$ predicted groundwater discharge in the Chu River as a result of the "sc" considered scenario, m^3/s.

$\Phi(x)$—Heaviside function, $F(x) = 0$ when $x < 0$, $F(x) = 1$ when $x > 0$, this function is needed to zero out the target function in the case of increasing the predicted discharge in the Chu River.

$FR(t, sc)$ represents the relative decrease in discharge in the Chu River comparing to a initial value, and with the unchanged discharge and its increase $FR(t, sc) = 0$, which means the optimal effect of the considered scenario on the groundwater supply to the Chu River.

The proposed dependence (1) includes "weight" coefficients a1, a2, a3. They set the significance of each of the given components of the target function, which are also lower-level target functions. The proposed values of weight coefficients are summarized in Table 1.

Table 1 Weight coefficients of target function $FG(t, sc)$

No	Name of the coefficients	Notation	The value of the weighting coefficients
1	Minimizing the impact on existing groundwater intakes	a1	5
2	Drainage of areas prone to flooding (improvement of the ameliorative state)	a2	3
3	Preservation of the existing groundwater discharge in the river Chu	a3	1

Water-related, environmental and technical conditions impose a number of restrictions on control actions and parameters. Some of them are given below.

1. Limitations related to additional groundwater abstraction.

$$\sum_{i=1}^{n} Q_i < QD \quad S_i < SD \tag{5}$$

where

QD maximum possible additional groundwater abstraction in the whole studied area, m^3/s;
SD maximum possible groundwater table (GWT) decline within zones of operating water intake locations for household and drinking purpose, m.
Q_i, S_i water abstraction and water table decline in water intake area # "i".

2. Limitation related to groundwater discharge into the River Chu

$$\frac{QN - Q(t, sc)}{QN} < QD \tag{6}$$

where

QD maximum possible relative decrease of groundwater discharge into the River Chu. Preliminary estimate of this value is 0.25–0.30.

3. Limitation related to the impact of additional water intakes on existing groundwater abstracts:

$$FW(t, sc) < 0.25 \tag{7}$$

Development and justification of groundwater use schemes as an additional source of irrigation water (as an element of rational groundwater management) includes the following interrelated stages:

1. Establishment of a set of preliminary scenarios for operating additional groundwater intakes (location, flow rate, operation mode, etc.).
2. Predictive groundwater modeling of selected scenarios; preliminary selection of suitable options.
3. Analysis and comparison of options for the use of groundwater as an additional source of water resources using the proposed criteria.

Among many schemes of additional water intake, schemes of wells location along main irrigation canals were considered. These schemes are the most rational ones from the technical point of view. The existing irrigation network can be used (Fig. 5).

While choosing the schemes of water intake locations and their flow rates, the authors sought to minimize the impact on the location zones of existing water intakes and minimize the reduction of groundwater inflow into the River Chu. In addition,

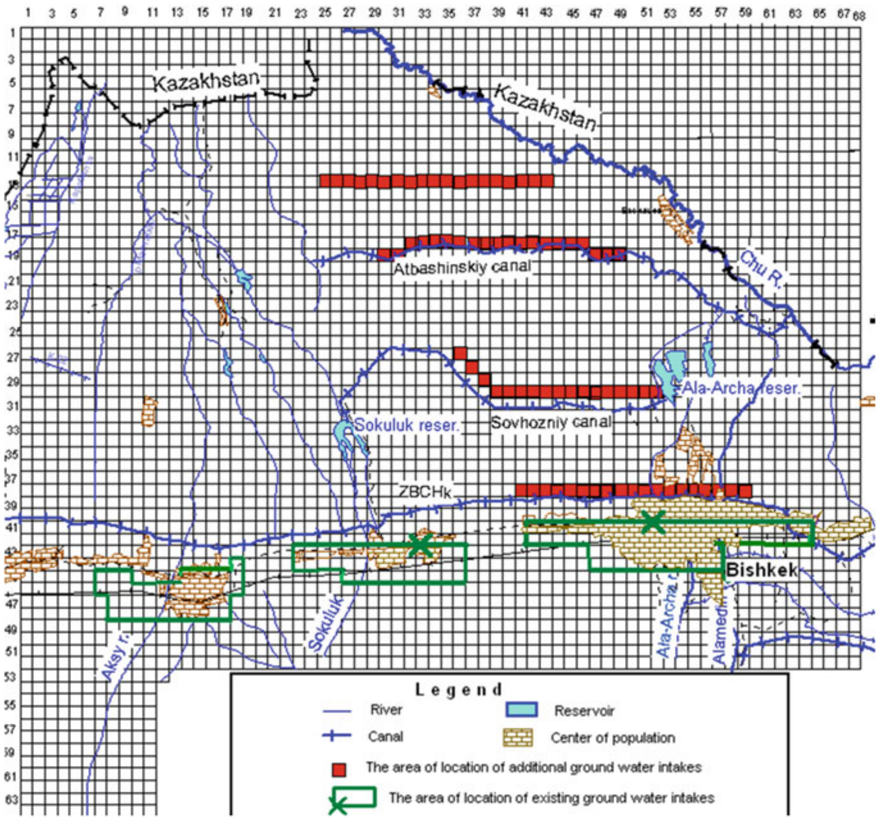


Fig. 5 Location of additional groundwater intakes and zones of existing water intakes

the ameliorative effect was approximately estimated. Most of the interim evaluations are of limited interest and are not given in this chapter, but they helped in producing the final results. The following schemes for obtaining additional water resources for irrigation were selected.

Scheme 1: Linear ground water intake along the Sovkhozny canal, Fig. 5. Average annual flow rate is 1 m^3/s (average vegetation flow rate is about 2 m^3/s).

Scheme 2: Linear ground water intake is located similarly to Scheme 1; average annual and average vegetation flow rates are increased by 1.5 times.

Scheme 3: Ground water intake along the Atbashinsky canal was added to the water intake from Scheme 2, its flow rate is 2 m^3/s. Its length is about 20 km, see Fig. 5.

Scheme 4: The northern line, located about 5 km from the Atbashinsky canal, Fig. 5, was added to the linear water intakes from Scheme 3. Average annual flow rate is 1 m^3/s.

Scheme 5: One line of wells along the ZBChC, Fig. 5. This line's average annual flow rate is 1 m^3/s.

All the listed schemes (scenarios) were simulated using the Modflow program [15]. The number of model cells in the latitudinal direction is 63, in the meridian direction—68 cells. There are 4 layers located in vertical direction. Forecast period is 25 years. The forecasting purpose is determining changes in groundwater head and changes in groundwater balance components in different time periods.

3 Results and Discussion

For each scheme, numerous predictive parameters of the groundwater status, including the dynamics of the selected zones balance were obtained in a variety of ways. The results of modeling and comparative evaluation of all five schemes mentioned above occupies a considerable volume and are given in the scientific report written by the authors [9]. This chapter presents the results for schemes 4 and 5. Scheme 4 provides the largest amount of additional water resources. Scheme 5 is an example of the scenario, the implementation of which will adversely affect the existing groundwater abstractions.

Forecast results for different schemes were compared in the 10th year, because stabilization comes after the disturbing impact of additional groundwater abstraction by this time.

Scheme 4. Groundwater levels‘ decrease in the 10th year of operation of additional water intakes is shown in Fig. 6. There is practically no impact on the operating water intakes.

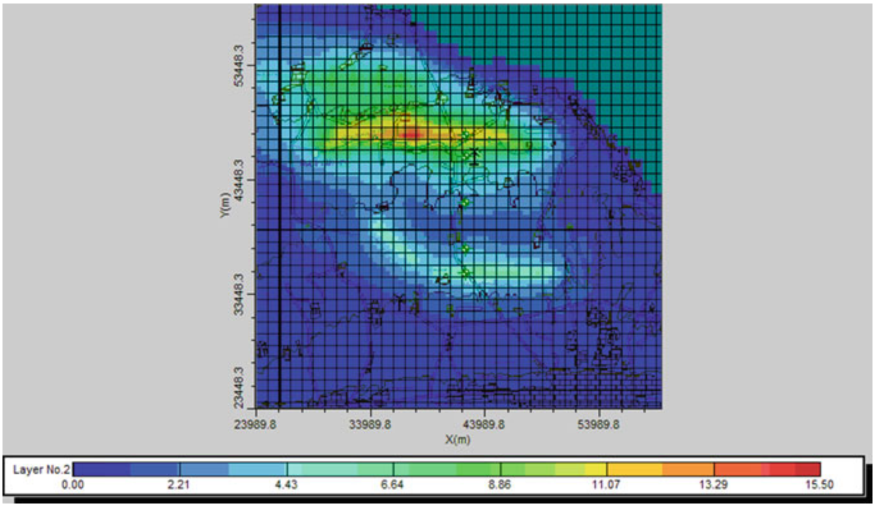


Fig. 6 Scheme 4. Predicted change in groundwater levels in the central part of the Chu Valley under the influence of additional ground water intake, 10th year of operation

Maximum decrease meanings (up to 15 m) are achieved at the ground water intake line along the Atbashinsky canal.

Predicted groundwater evaporation in 2 canal systems decreases from 2.63 to 1.13 m^3/s, i.e. by 1.5 m^3/s. Total additional water intake of all 3 lines is 4.5 m^3/s. Evaporation inversion equal to 1.5 m^3/s covers one third of additional groundwater abstraction. It should be noted that discharge inversion into drains and narrows, equal to about 50% of evaporation, also covers part of additional water intake.

The target function $FD(t, 4)$, at $t = 10$ years, characterizing the reclamation effect and calculated by (3), is equal to 0.43.

The predicted change in groundwater discharge into the River Chu in schemes 1–3 is negligible. It is a noticeable value in scheme 4, Fig. 7. The resulting curve shows that the discharge into the River Chu in the studied area will be reduced by 107,000 m^3 per day, or 1.24 m^3/s, in 10 years.

The initial discharge, as estimated by the authors of this report [7], is approximately equal to 10 m^3/s. Forecasted reduction of inflow is 12–13%, i.e. in the 10th year of the forecast period $FR(3650, 4) = (10 - 8.76)/10 = 0.124$.

Additional ground water intakes of Scheme 4 have no effect on operating water intake zones (Fig. 6). Corresponding water table and head reductions are equal to zero, i.e. $FW(t, 4) = 0$.

The total target function, calculated according to the Eq. (1), is as follows:

$$FG(t, 4) = a_1 \cdot FW(t, 4) + a_2 \cdot FD(t, 4) + a_3 \cdot FR(t, 4) = 0.984 \qquad (8)$$

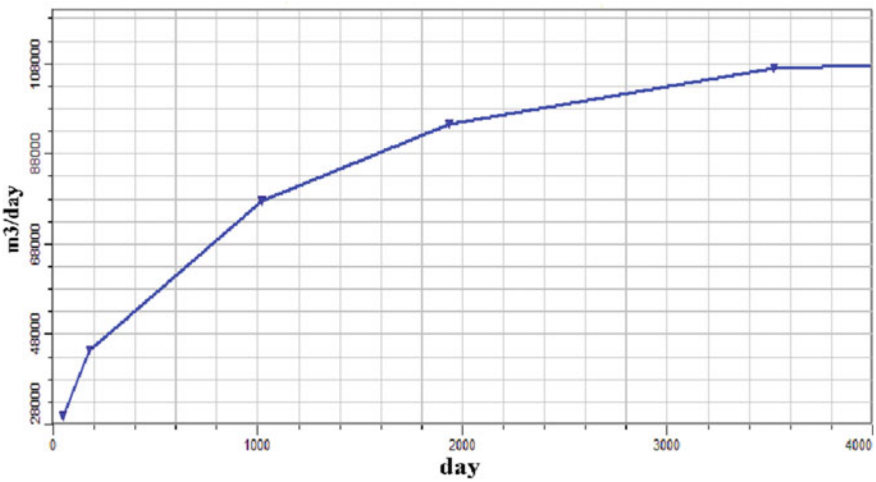


Fig. 7 Scheme 4. Predicted decrease in groundwater discharge in the river Chu under the action of additional water intakes of ground water intakes depending on time

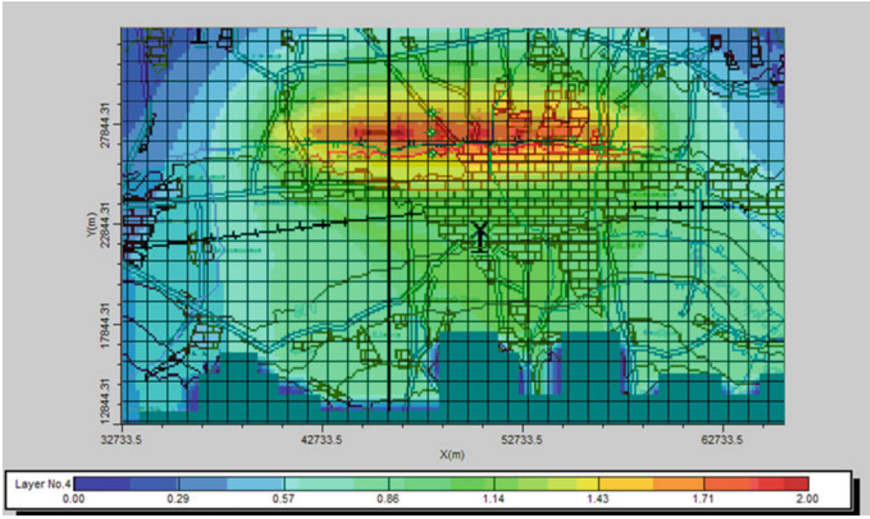


Fig. 8 Scheme 5. Predicted change in groundwater levels in the central part of the Chu Valley under the influence of additional ground water intake, 10th year of operation

This scheme provides the largest additional water resources for irrigation and the largest reclamation effect. However, its implementation will require the highest capital and operational costs.

Scheme 5. Groundwater level decrease in the 10th year of additional water intakes operation is shown in Fig. 8. Level decrease extends to the southern part of Bishkek, which worsens the operating conditions of the existing water intakes. This is mainly due to the close location of the groundwater formation zone, which is characterized by high transmissivity of the aquifer.

An interesting outcome of the considered scenario is the predicted curve of groundwater outflow from Bishkek's active water abstraction zone (Figs. 5 and 9). Maximum outflow towards additional water intake is predicted in a year since it was commissioned. It is equal to 24,000 m ^{3} per day, or 0.28 m^3/s. In 10 years, it will decrease to 16,000 m ^{3} per day, or 0.19 m^3/s. As the flow rate of additional water intake is 1 m^3/s, it will be covered by 20–30% at the expense of existing drinking water intakes, which is unacceptable, $FW(365, 5) = 0.28$. Target function of reclamation effect is $FD(t, 5) = 0.95$. Total target function will be $FG(365, 5) = 3.3$, which indicates low quality of this scheme.

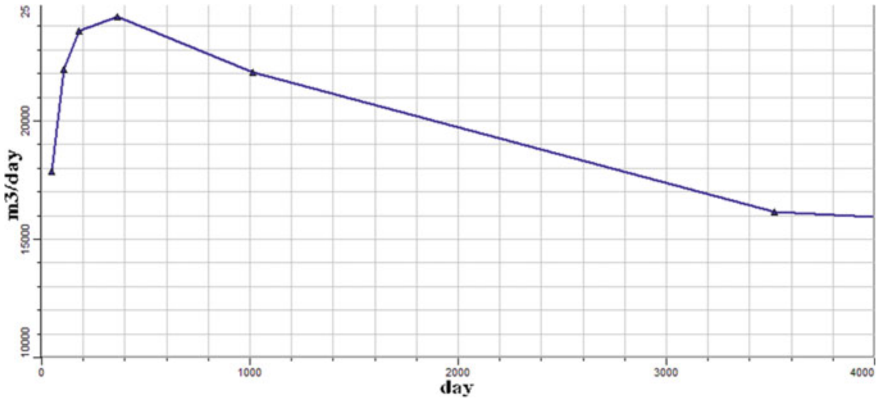


Fig. 9 Scheme 5. Outflow of groundwater from the zone of existing ground water intakes in the southern part of Bishkek under the influence of additional water intake

4 Conclusions

The authors considered 5 schemes of groundwater management to cover the expected deficit of surface water resources. The most rational approach from the technical and ecological points of view is the gradual increase in the volume of additional groundwater use. At the initial stage, it is recommended to use Scheme 1. It provides for the location of one line along the Sovhozny Canal (an average annual flow rate of 1 m^3/s), Fig. 5. With the continued acute shortage of irrigation water, it is advisable to use the second scheme (increase in the flow rate of the water intake line to 1.5 m^3/s). A further increase in water intake is possible in accordance with schemes 3 and 4. Scheme 3—ground water intake along the Atbashinsky canal was added to the water intake from Scheme 2, its flow rate is 2 m^3/s, total—3.5 m^3/c. Scheme 4—the northern line, located about 5 km from the Atbashinsky canal, Fig. 5, was added to the linear water intakes from Scheme 3. Average annual flow rate of this line is 1 m^3/s, total—4.5 m^3/s.

Meanwhile, it is necessary to provide conservation of wells in the periods of sufficient surface water resources. The most perspective options of additional ground water intake locations are the areas of Sovkhozny and Atbashinsky canals‘ systems. It is not rational to locate any additional water intakes in the ZBChC zone. This creates threats to the existing water intakes in the southern part of Bishkek.

5 Recommendations

5.1. Five schemes for groundwater management in the central part of the Chui Valley are proposed and scientifically substantiated, which provide mitigation of the consequences of reduced river flow for irrigated agriculture in the face of climate change. At the same time, in each scheme, was quantitatively studied the influence of additional water intakes on: (1) the existing water intakes of groundwater for domestic and industrial purposes; (2) change in the ameliorative state of irrigated lands in the territory under consideration; (3) preservation of the current inflow of the groundwater to the river Chu to prevent severe environmental consequences in the lower part of the river.

5.2. In addition to the tasks solved within the framework of this chapter, the created groundwater model can be used to develop and justify a wide range of water management solutions in the Chui Valley of Kyrgyzstan.

5.3. Additional groundwater intake along the ZBChK canal (Scheme 5) is not advisable to use for irrigation. However, it can be used to mitigate the shortage of water supply in Bishkek during the summer. This issue was also considered by the authors in [8].

References

1. Costa AC, Dupont F, Bier G et al (2023) Assessment of aquifer recharge and groundwater availability in a semiarid region of Brazilin the context of an interbasin water transfer scheme. Hydrogeol J (Springer. Published online) 02 March 2023, 19 p
2. Costelloe WJ, Peterson TJ (2019) Do groundwater management plans work. Modeling the effectiveness of groundwater management scenarios. Hydrogeol J 27:2447–2470
3. Ebrahim GY, Jonoski A, Al-Maktoumi A, Ahmed M, Mynett A (2016) Simulation-optimization approach for evaluating the feasibility of managed aquifer recharge in the Samail lower catchment, Oman. J Water Resour Plan Manag 2(142):5001–5017
4. Grigorenko PG (1979) The groundwater of' the Chu basin and perspectives use of it. Frunze, Ilim, p 187
5. Hydrogeology of the USSR (1971) Kyrghyz SSR. Nedra, Moscow, vol 40, p 487
6. Kaplinsky MI (1977) Prediction of changing of the drainage runoff under the influence of' the water economical measures. Frunze, Ilim, p 93
7. Litvak RG, Nemaltseva EI (2017) Development of science-based monitoring schemes for transboundary groundwater in the Chui Valley, taking into account climate change. Report KNIIIR, Bishkek, p 52
8. Litvak RG, Nemaltseva EI (2020) Criteria for the rational location of groundwater intakes in the area of Bishkek, the capital of Kyrgyzstan. Sci J Russian Acad Sci Geoecol Eng Geol Hydrogeol 6:14–21
9. Litvak RG, Nemaltseva EI (2022) Development of rational groundwater management schemes for the central part of the Chui valley for sustainable irrigation under climate change conditions based on ground water modeling. Report KNIIIR, Bishkek, p 85
10. Naves A, Samper J, Pisani B, Mon A et al (2021) Hydrogeology and groundwater management in a coastal granitic area with steep slopes in Galicia (Spain). Hydrogeol J (Springer) 29:2655–2669
11. Rasmussen P, Kidmose J, Kallesшe AJ et al (2023) Evaluation of adaptation measures to counteract rising groundwater levels in urban areas in response to climate change. Hydrogeol J (Springer) 31:35–52
12. Stefan C, Fröhlich T, Fuchs L, Junghanns R, Phan HM, Tran VN, Werner P (2012) Sustainable water resources management in the Long Bien district of Hanoi, Vietnam. Water Sci Technol Water Supply 6(12):737–746

13. Tsytsenko KV, Sumarokova VV (1990) Hydrological foundations of irrigated melioration in the basins of the Chu and Talas rivers. Gidrometeoizdat, Leningrad, p 334
14. Va TD, Zhou Y, Stigter TY, Van TP, Hong HD, Uyen TD, Вьюнг Буй Тран (2023) Sustainable groundwater development in the coastal Tra Vinh province in Vietnam under saltwater intrusion and climate change. Hydrogeol J (Springer). Accepted on 28 January 2023, 19 p
15. Visual MODFLOW (2009) User's manual. For professional applications in three-dimensional groundwater flow and contaminant transport modeling. Schlumberger Water Services, Waterloo, Ontario, Canada, N2L 5J2, p 688
16. White EK, Costelloe J, Peterson TJ (2019) Do groundwater management plans work? Modelling the effectiveness of groundwater management scenarios. Hydrogeol J 27:25

Applications of Machine Learning Models for Solving Complex Groundwater Modelling, Monitoring and Management Problems

Alvin Lal, Ravi Naidu, and Bithin Datta

Abstract In recent times, machine learning-based predictive models have been widely used to overcome the shortcomings of conventional numerical models for groundwater level and quality simulation. This chapter demonstrates the application of well trained and validated machine learning-based predictive models for replicating complex groundwater system behaviour and solving key groundwater modelling, monitoring, and management challenges. Specifically, this study validates the successful use of predictive models in several hydrological applications such as (1) making accurate future groundwater quality forecasts; (2) prescribing optimal groundwater management strategies; (3) incorporating aquifer parameter uncertainty in groundwater modelling; (4) selecting optimal monitoring well locations for groundwater contamination detection and, (5) evaluating the impact of each of the dependent variables e.g., assessing impacts of individual pumping rates on groundwater salinity. The input–output datasets for the construction of prediction models are generated using a 3D groundwater numerical simulation model. FEMWATER, a finite element-based groundwater flow and transport modelling package is used to construct 3D groundwater numerical simulation models for different case studies aquifer systems. The input–output datasets are assembled to train, test and validate support vector machine regression (SVMR), Gaussian Process Regression (GPR) and Group Method of Data Handling (GMDH)-based predictive models. These predictive models were used to solve all five key issues discussed. The results prove that validated predictive models can be used to solve the five major shortcomings of

A. Lal (✉) · R. Naidu
Global Centre for Environmental Remediation, College of Engineering Science and Environment, University of Newcastle, Callaghan, NSW 2308, Australia
e-mail: alvin.lal@newcastle.edu.au

R. Naidu
e-mail: ravi.naidu@newcastle.edu.au

B. Datta
Discipline of Civil Engineering, College of Science & Engineering, James Cook University, Townsville, QLD 4811, Australia
e-mail: Bithin.datta@jcu.edu.au

S. Ali and A. M. Armanuos (eds.), *Groundwater in Arid and Semi-Arid Areas*, Earth and Environmental Sciences Library, https://doi.org/10.1007/978-3-031-43348-1_8

a complex groundwater numerical model and are a key for understanding groundwater processes, making future predictions, effective groundwater monitoring, and groundwater resources management. This chapter constitutes an advancement to the field of machine learning-based groundwater modelling by showing that predictive models can simulate complex groundwater systems and assist in effective monitoring, modelling, and management of fragile groundwater resources.

Keywords Groundwater modelling · Machine learning · Predictive models · Groundwater management · Aquifer uncertainty

1 Introduction

Groundwater is an extremely valuable yet scares resource in many parts of the globe, especially in areas where surface water is of limited supply and/or poor quality. It plays a significant role in various aspects of lives on planet earth, such as agriculture, industrial development, and is usually used as a drinking water source. In addition, groundwater serves as a key component of the global water cycle and indirectly affects the environment and communities. The suitability of groundwater for different purposes are depended on its quality and measuring groundwater quality parameters is often a very complex process [12, 20]. Also, groundwater quality parameters are vulnerable to changes due to hydrogeological, environmental, topographical, and climatic conditions. This makes understanding, monitoring, and modelling groundwater quality even more challenging.

A groundwater simulation model is an essential hydrogeological tool that aids in the evaluation, monitoring and management of groundwater quality parameters. A groundwater model replicates the behavior of an aquifer system, which is developed by defining the essential features of the aquifer in some controlled physical or mathematical manner [13]. A range of groundwater modelling software's are available for solving complex coupled groundwater flow and transport processes and aid policymakers and practitioners in water sectors to get better insight into groundwater parameters. These include MODFLOW, SEAWAT, FEMWATER, FEFLOW, HDROGOSPHERE and SUTRA. A groundwater model offers three major advantages including i) a groundwater simulation model provides a quantitative framework for synthesizing field information and for conceptualizing hydrogeologic processes; ii) a groundwater simulation model is the primary quantitative tool available in a groundwater investigation and iii) a groundwater numerical model can be used for making future simulations/predictions enabling sustainable management groundwater resources and reliable decision-making.

Despite its inherent advantages, a complex groundwater numerical simulation model has some obvious disadvantages [18, 23, 28]. A groundwater model is sometimes extraordinarily complex, demands large computational power, and is often cumbersome. Therefore, at times complex groundwater model cannot be easily used for designated hydrological tasks such as:

(1) running a model for a large number of years of often difficult and computationally expensive and therefore it becomes difficult to use a groundwater model to make future predictions and decisions [2],
(2) it is always difficult to couple a 3D groundwater model with an optimization algorithm to find optimal groundwater management strategies [22],
(3) difficult to incorporate aquifer parameter uncertainty in groundwater modelling [25],
(4) difficult to use complex groundwater models for selecting optimal groundwater contamination monitoring locations [26] and
(5) it is sometimes problematic to evaluate the impact of each dependent variable, e.g., pumping on groundwater contamination [6].

In the recent times, machine learning-based prediction models have been widely used to overcome the drawbacks of complex groundwater simulation models [7, 8, 17]. A well-trained and tested machine learning-based prediction model has the potential to mimic groundwater simulation models and predict subsequent effects of some solutions on the groundwater system [1]. Algorithms such as artificial neural network, genetic programming, multivariate adaptive regression splines, adaptive neuro-fuzzy inference system and support vector regressions have been extensively used for developing groundwater prediction models. These algorithms possess certain advantages over each other and have been successfully used in various groundwater level and quality prediction applications.

In this chapter, the practical benefits of employing machine learning models for solving all the major groundwater model-related challenges are demonstrated for the first time. Different case study areas are used to validate each of the listed benefits of utilizing machine learning based predictive models for groundwater simulation. The main goal is to recognize and evaluate the potential capability of machine learning-based predictive models, particularly for their use in groundwater quality monitoring, modelling and management applications. In general, the results presented here highlights that machine learning along with groundwater simulation model is a crucial tool for hydrogeologists, as it has the potential to solve key groundwater-related challenges worldwide.

2 Methods

2.1 Large Simulations for Future Predictions

Executing a complex numerical model for making long-term groundwater quality projections is often difficult, cumbersome, and computationally demanding. Therefore, support vector machine regression (SVMR) models were used to make future groundwater quality (salinity) prediction by mimicking the responses of a complex groundwater model. A 3D numerical model of the study area containing a portion of a multi-layered coastal aquifer was formulated and executed using FEMWATER

[10]. FEMWATER, a finite element-based groundwater flow and transport modelling package is a commercial software extensively used in saltwater intrusion modelling study. The length of the coastline was 2.13 km, and the other two boundaries were 2.04 km (side A) and 2.79 km (side B), respectively. The aquifer of depth 60 m was divided equally into 3 layers. The aquifer is considered heterogeneous vertically based on the different hydraulic conductivity values of the aquifer layers. The study area of 2.53 km^2 incorporated 5 barrier wells (BWS), 8 fresh groundwater pumping production wells (PWS) and 3 monitoring wells (MWS). The PWS are used for extracting groundwater for beneficial use. The BWS are used as hydraulic barriers, which minimizes saltwater encroachment into the aquifer system. The MWS are used to monitoring salt concentration levels in the aquifer. A 3D view of the study area with specific well locations are given in Fig. 1. Also, key details about the aquifer hydraulic parameters can be obtained from Lal and Datta [7, 8]. The 3D transient simulation was commenced from an initial steady state condition of the aquifer, achieved via constant pumping of 300 m^3/day from only 3 of the production wells for 20 years. After 20 years, it was noted that the observed heads at different nodes in the model domain became constant. These resultant heads and concentration were used as initial conditions (initial head and concentration) for aquifer simulation for the specified period of 4 years (4th time step) where pumping from all PWS and BWS were instigated.

The numerical simulation model was used to generate input–output patterns for training and validating the prediction models. Transient pumping (inputs) is obtained from uniform sampling distribution using Latin Hypercube Sampling (LHS) [11] having an upper bound of 1300 m^3/day and lower bound of 0 m^3/day. The resulting salt concentration at each monitoring well was obtained from the numerical model after each set of pumping from all FWS and BWS were fed to the model as inputs.

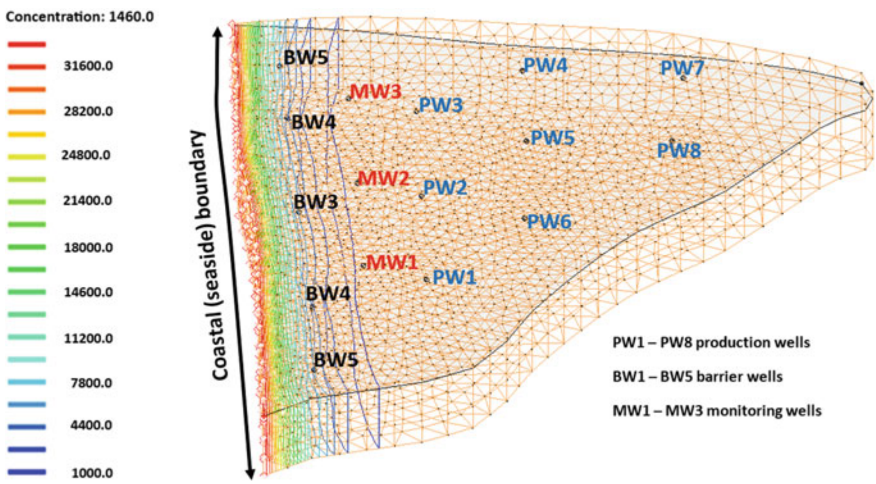


Fig. 1 3D groundwater numerical model illustrating different well locations

Each numerical model took approximately 4–5 min to converge. Seven hundred sets of pumping and resulting output (salt concentrations) were assembled by running the simulation model 700 times. These input–output patterns were later used for the development of individual prediction models.

For cross-validation purpose, generated datasets were partitioned randomly into training, validation, and prediction datasets without replacement, similar to [16]. The training and validation set is used for prediction model development, while the prediction set is used to test model performances. Out of 700 datasets, 400 were used for training, 100 were used for validation, and 200 were used for prediction. The output (salt concentration) is only fed into the model during the training and validation stages. No output is fed into the model at the prediction stage. Three different prediction models were constructed utilising the SVMR algorithm for predicting salt concentrations at the 3 MWS. Calculation of root mean square error (RMSE), mean square error (MSE), relative error (RE), correlation coefficient (r), and the Nash–Sutcliffe efficiency (NSE) were used to appraise the performance of the developed models at the three stages.

2.2 Optimal Groundwater Management Using Machine Learning

Linked simulation–optimization (LSO) is a common methodology used for generating optimal groundwater management strategies. In LSO-based groundwater management model, optimal solutions are generated by a utilised optimization algorithm while the 3D groundwater numerical simulation model evaluates the solution and checks for implemented optimization constraints to be satisfied. This happens in an iterative manner until optimal solution sets are obtained. The major difficulty in using LSO is that linking a complex 3D groundwater flow and transport model with an optimization model is computationally infeasible and challenging. Hence, machine learning-based prediction models capable of mimicking the responses of 3D groundwater model is employed in an LSO framework to generate optimal groundwater pumping strategies for the illustrative case study aquifer system (discussed in Sect. 2.1). SVMR models developed in Sect. 2.1 can be used in the LSO model replacing 3D numerical model. However, newly developed Gaussian Process Regression (GPR) models were used to test the validity of other machine learning algorithms available. GPR provides a probabilistic, non-parametric technique for solving nonlinear regression problems [24]. A complete theoretical background on GPR models is presented in [27] and [19]. Statistical indices such as root mean square error (RMSE), correlation coefficient (r) and Nash–Sutcliffe coefficient (NSE) were used to assess the performances of the developed GPR models. After it was validated that GPR prediction models could effectively mimic 3D groundwater numerical simulation model, it was used to prescribe optimal pumping patterns from respective PWS and BWS and ensure salt levels in the aquifer remain below specified limits.

A multi-objective genetic algorithm (MOGA) [3] was used to solve the multi-objective optimization problem. The trained and tested GPR models were externally coupled to the MOGA via the MATLAB 2017a platform. The prediction models presented candidate groundwater pumping (from PWS and BWS) solutions to the MOGA, allowing the optimization algorithm to search for solutions where the only way to further improve one objective is to incur deterioration in the performance of another conflicting objective. A detailed description and different components of an LSO model is presented in Fig. 2. Mathematical expressions of the objective function, constraints, and bounds are given in what follows.

The multi-objective LSO management model was designed to obtain sets of optimal pumping patterns from the PWS and BWS installed in the aquifer. The PWS are used for extracting groundwater for beneficial use. The BWS are used as hydraulic barriers, which minimizes saltwater encroachment into the aquifer system. Also, the management model intended to keep salt concentrations in the aquifer (monitored at different MWS) within a pre-specified acceptable level.

Objective 1: maximize pumping from PWS

$$f_1(\mathrm{PWS}) = \sum_{n=1}^{N}\sum_{t=1}^{T}\mathrm{PWS}_n^t$$

Objective 2: minimize pumping from BWS

$$f_2(\mathrm{BWS}) = \sum_{m=1}^{M}\sum_{t=1}^{T}\mathrm{BWS}_m^t$$

PWS_n^t, symbolizes pumping from nth freshwater pumping well at the time t, and BWS_m^t denotes pumping from the mth barrier well at time t. N, M and T are the total number of PWS, BWS and time steps in the management model, respectively.

The optimization problem was subjected to a set of constraints, which were as follows.

Constraint 1: Coupling GPR metamodels within the LSO framework

$$c_i = \xi(\mathrm{PWS}, \mathrm{BWS})$$

Constraint 2: Maintaining salt concentrations at each MWS within a pre-specified limit.

$$c_i \leq c_{\max,i} \forall i, t$$

where, c_i represents salt concentration at the ith monitoring well at the end of the management time, t.

The two objective functions were also bounded by limits as specified below.

Bound 1: Maintaining PWS pumping rates within a prespecified range.

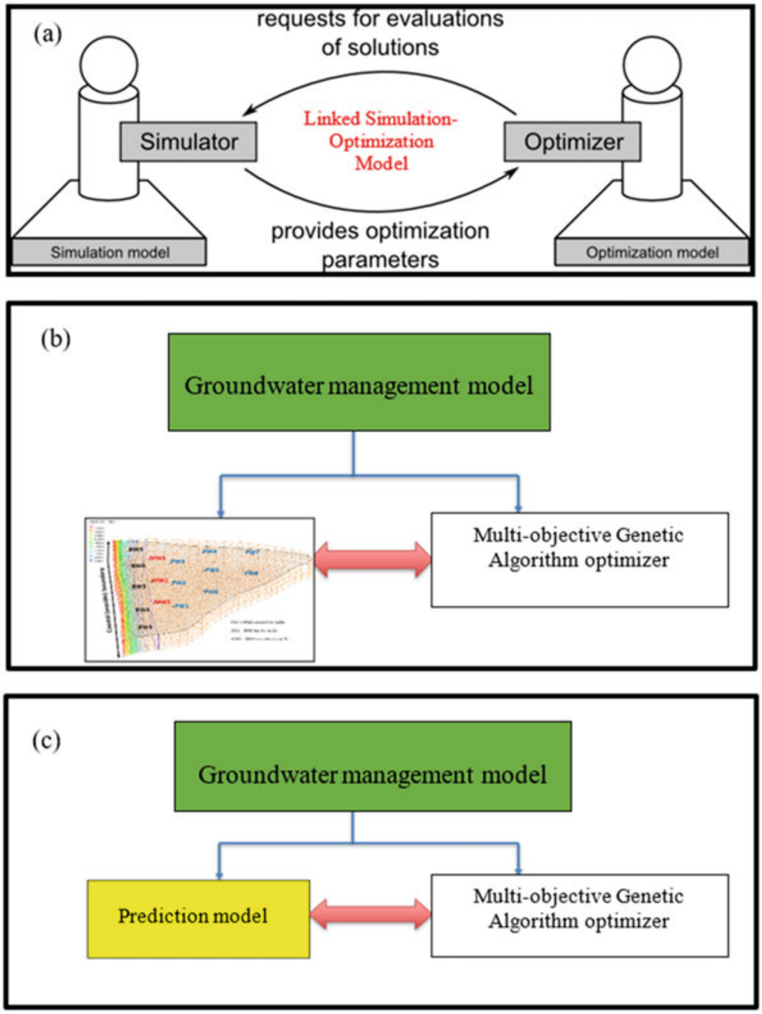


Fig. 2 Predictive model assisted linked simulation–optimization model for groundwater management

$$\mathrm{PWS_{min}} \leq \mathrm{PWS}_n^t \leq \mathrm{PWS_{max}}$$

$\mathrm{PWS_{min}}$ and $\mathrm{PWS_{max}}$ is the minimum and maximum pumping rates from FWS.
Bound 2: Maintaining BWS pumping rates within a prespecified range.

$$\mathrm{BWS_{min}} \leq \mathrm{BWS}_m^t \leq \mathrm{BWS_{max}}$$

$\mathrm{BWS_{min}}$ and $\mathrm{BWS_{max}}$ is the minimum and maximum pumping rates from BWS.

The LSO model incorporated a total of 52 decision variables (yearly pumping rates from all the 8 FWs and 5 BWs for the implemented 4-year management term). The minimum and maximum bounds placed on these decision variables were 0 and 1300 m^3/day, respectively. For constraints, the maximum allowable salt concentrations at MW1, MW2 and MW3 was set to 420, 505 and 625 mg/L, respectively. These permissible concentration limits ensured that water extracted from the FWS were suitable for domestic and agricultural consumptions.

2.3 Incorporating Uncertainties in Groundwater Modelling

The use of ensemble models has recently gained popularity over single prediction models. Ensemble models are a collection of several standalone prediction models combined using standard statistical means. In this study, ensemble predictive models are built using several standalone models developed using different 3D numerical models containing unique sets of aquifer parameters. The values of hydraulic conductivity and porosity were two uncertain aquifer parameters considered while developing the 3D coastal aquifer numerical model. Different combinations of these two uncertain parameters for the respective aquifer layers were implemented into the numerical model, keeping the other parameters constant during the simulation period. A total of 10 numerical models were developed using 10 different sets of hydraulic conductivity and porosity values. The implementation of each set of input pumping patterns into the different numerical model presented different output concentrations for each monitoring location. These input–output datasets (pumping-concentration) from each of these numerical models were used to construct different prediction models. Utilizing the training and testing data from 10 different numerical models led to the development of 10 different prediction models for each monitoring location. Ensembles of these 10 prediction models were developed by combining the predicted output of standalone prediction models in the ensemble using the simple averaging methodology [21]. Each standalone prediction model was tested and validated using methodology discussed in Sect. 2.1.

Once an ensemble model for each of the monitoring locations was built, it was linked to MOGA optimization tool in an LSO framework to generate optimal groundwater pumping patterns from PWS and BWS. A 3D groundwater numerical model for an island aquifer system was developed, calibrated, and used to test this methodology. A thorough discussion of the model development procedure is discussed in Lal and Datta [9]. The developed standalone models are evaluated using key statistical indices such as RMSE, r, NSE and Wilmot's Index (WI). The aquifer had 6 monitoring wells in total. Therefore, a total of 60 standalone SVMR prediction models (10 prediction models corresponding to 10 different numerical models) were developed and validated.

2.4 Effective Groundwater Monitoring

Selecting a monitoring well or borehole installation location for groundwater quality monitoring is a key challenge for groundwater professionals and practitioners. In many cases, groundwater quality data can be collected from numerous locations in the aquifer i.e., any node can be used as a monitoring well location in a 3D groundwater model. However, this may be impractical and economically infeasible due to limited budget allocations for monitoring projects and due to avoid redundancy in collected data. Therefore, for effective monitoring, only a few permissible number of monitoring wells called the optimal monitoring wells (within budgetary limit) best suited for collecting useful and reliable monitoring data is needed. First, a few nodes representative of the entire model domain are selected out of all the nodes in the 3D model domain. These are called candidate monitoring wells. From these candidate monitoring wells, optimal monitoring wells are chosen by utilizing an integer programming framework. To obtain candidate monitoring wells, *k*-means clustering was utilized to obtain locations of candidate monitoring wells representative of the entire model domain. *k*-means clustering is a method of machine learning that involves grouping data points by similarity [15]. Clustering of all existing nodes using the *k*-means clustering methodology ensured that candidate monitoring wells are chosen from the entire area of the model domain. The main idea of using *k*-means clustering is to categorize the set of nodes into *k* disjoint clusters, where *k* is fixed in advance. After convergence, the *k*-means clustering solution offers a centroid for each of the clusters. The node number closest to this centroid is identified, where a candidate monitoring well is to be installed.

In this study, groundwater salinity data at these candidate monitoring wells are obtained after a few prescribed optimal groundwater pumping management strategies are implemented into the system. After implementation, the average of the logarithmic concentration at each candidate monitoring well was maximized to ensure that candidate monitoring wells were placed in high-risk areas (highly concentrated areas). These candidate monitoring wells are now referred to as optimal monitoring wells. An integer programming using the LINGO 17 (Lindo Systems, 1415 North Dayton Street, Chicago, IL, USA) platform was executed with an objective function and respective constraints as described below.

$$\text{Maximize}\frac{\sum_{i=1}^{N}\log(C_i)}{N}Y_i$$

$$\text{subject to; }\sum_{i=1}^{N}Y_i \leq M \text{and} Y_i \in (0, 1)$$

where, C_i is the concentration at the ith candidate monitoring well and Y_i is the decision variable indicating whether to install ($Y_i = 1$) or not to install ($Y_i = 0$) a monitoring well at the ith specified location. The symbol M represents the maximum number of monitoring wells permitted in the monitoring network (due to budgetary

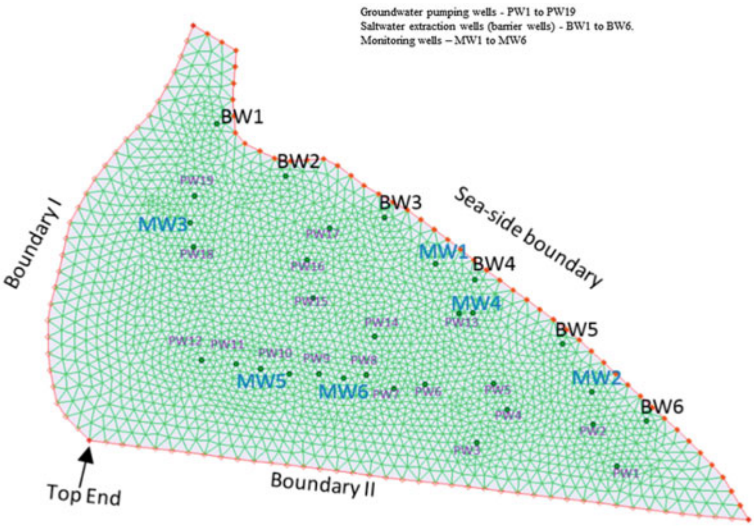


Fig. 3 Top view of the 3D coastal aquifer model with different well locations

or other management limitations). After selecting and installing optimal monitoring wells, initially implemented aquifer pumping management strategy or policy can be modified using concentration data from optimal monitoring wells. Also, these optimal monitoring wells can be used for collecting reliable groundwater salinity data. A 3D coastal groundwater numerical simulation model for an island aquifer system was used to develop and evaluate this methodology. A plan view of the groundwater simulation model is given in Fig. 3. Further details about the model parameters, development procedure, calibration, and validation details are available in [9]. A total of 100 candidate monitoring well locations were chosen using the *k*-means clustering methodology. The *k*-means clustering code was written and executed in the *R* platform. A fixed number of iterations was used as the stopping criteria. In the present case, 50 iterations were considered. Optimal pumping strategy obtained from LSO (method discussed in Sect. 2.3) was implemented and salt concentration data at these 100 candidates monitoring wells were recorded. For budgetary reasons, only 10 ($M = 10$) optimal monitoring well locations out of the 100-candidate monitoring well locations were obtained by implementing the designed monitoring network.

2.5 *Impact of Individual Pumping Rates on Salt Concentration: Assessing Variable Importance*

One of the common challenges of machine learning applications in groundwater modelling is that it is sometimes problematic to evaluate the impact of each dependent variable (e.g., pumping rates) on output groundwater quality (target variable).

Identifying the most important and least important predictor variables (groundwater pumping rates from individual wells) based on their impact on output target variable (salt concentration at respective monitoring wells) is crucial for groundwater planning, monitoring and management perspective. For this purpose, Group Method for Data Handling (GMDH) models are developed to predict groundwater salinity levels at different monitoring wells by mimicking the responses or a complex 3D groundwater simulation model. The GMDH algorithm first suggested by the former Soviet scientist Ivakhnenko, is a method for identifying nonlinear relationships between a set of input and output and possess the ability to identify and present a subset of the most influential input predictor variables [4]. This characteristic allows the user to comprehend the effect of each input groundwater pumping rates on the salt concentration at monitoring wells.

In the present work, GMDH models are trained and tested using input–output dataset from a 3D illustrative coastal aquifer system discussed in Sect. 2.1. GMDH models not only predict groundwater salt concentration in a coastal aquifer, but also help identify and select the most influential pumping rates influencing the groundwater salt concentration levels. A detailed explanation of the GMDH models can be obtained from [5, 14] The 3D numerical simulation model was run for a period of 4 years in a transient state (different yearly pumping rates) using all the operational wells (8 PWS and 5 BWS). Thirteen pumping wells with different yearly pumping values resulted in 52 (13 wells × 4-year simulation period) decision variables. These 52 variables (labelled as × 1, × 2, …, × 52) represented yearly pumping rates from each well over the 4-year simulation period. A total of 800 sets of randomized input pumping patterns were produced and fed to the 3D groundwater model to generate 800 salt concentration values at each of the monitoring wells. Out of the 800 datasets, the development set consisted of 700, and the independent set contained 100. The development set data was used to train and test the GMDH models. Only the input data from the independent dataset was fed into the GMDH models to assess its predictive capability. The predicted output was then compared with the output from the independent dataset. GMDH shell software was used to construct these prediction models. The development (training and testing) and independent prediction using GMDH models took only 0.45 and 0.10 min of CPU time, respectively. Standard mathematical indices such as RMSE, MAE, NSE, coefficient of determination (R^2) and r were employed to assess the performance of each GMDH based groundwater predictive models.

Table 1 Performance evaluation results for SVMR models

Monitoring wells	SVMR model	MSE (mg/L)	RMSE (mg/L)	RE	r	NSE
Training stage						
MW1	SVMR1	0.164	0.405	5.0×10^{-7}	0.997	0.99
MW2	SVMR2	0.057	0.238	1.6×10^{-7}	0.997	0.99
MW3	SVMR3	0.184	0.428	6.7×10^{-8}	0.989	1.00
Testing stage						
MW1	SVMR1	0.202	0.449	1.8×10^{-6}	0.994	0.99
MW2	SVMR2	0.105	0.323	2.6×10^{-7}	0.993	1.00
MW3	SVMR3	0.187	0.432	5.4×10^{-7}	0.989	1.00
Prediction stage (unseen data—future)						
MW1	SVMR1	0.155	0.394	$7.5 \times 10 - 7$	0.997	1.00
MW2	SVMR2	0.073	0.271	$2.9 \times 10 - 7$	0.996	0.99
MW3	SVMR3	0.255	0.505	$1.7 \times 10 - 7$	0.984	1.00

3 Results and Discussion

3.1 Large Simulations for Future Predictions

The performance evaluation results of the SVMR models at the training, validation and prediction stages are given in Table 1. The prediction performances of the developed SVMR models in predicting salinity levels at specified monitoring wells were comparable to the 3D model. At all the MWS, higher r and NSE values and lower MSE, RMSE and RE values were recorded. Overall, the performance evaluation results at all three stages establish that the SVMR model effectively forecasts groundwater salinity at specified wells in the modelled coastal aquifer. In addition, the time taken to train, test and predict using a new data took less than 5 s. This is significantly low when compared to running a complex 3D groundwater numerical model. This result establishes that SVMR models do not only accurately mimic the responses of the groundwater numerical model but also provide quick and efficient approximation of the groundwater quality modelling result.

3.2 Application in Optimal Groundwater Management

The performance prediction results for the GPR models are presented in Table 2. The comparison indices utilised demonstrates that the trained and tested GPR models

Table 2 Performance evaluation results of the GPR models

Monitoring well	GPR model name	Development phase	Assessment indices		
			RMSE	r	NSE
MW1	GPR_1	Training	1.25	0.95	0.99
		Validation	1.02	0.94	1.00
MW2	GPR_2	Training	0.63	0.97	1.00
		Validation	0.31	0.98	1.00
MW3	GPR_3	Training	0.47	0.99	1.00
		Validation	0.35	0.99	1.00

could accurately and efficiently predict concentration at the respective MWS. This result highlighted that GPR models could be used as a replacement for the complex 3D groundwater model in the LSO framework. The GPR predictive model-based LSO model executed in a MATLAB 2017a platform using an Intel(R) Core i7-6700 CPU 16GB RAM computer took approximately 110 min to converge. The multi-objective coastal aquifer management model produced an optimal pareto-front containing a large set of optimal solutions. The Pareto-front is presented in Fig. 4. The Pareto-front consisted of 300 optimal solutions, each defining different trade-offs between FWS and BWS pumping rates. Any of these solutions can be implemented into the aquifer system as a pumping strategy. The decision on selecting a particular optimal solution set depends on the policymakers as it requires analysis of the various trade-offs between PWS and BWS pumping. For example, Solution I (Fig. 4) can be implemented if priority is given to maximizing production well pumping. On the other hand, solution II (Fig. 4) can be chosen and implemented is priority is given on minimizing barrier well pumping.

3.3 Incorporating Uncertainties in Groundwater Modelling

All 10 standalone SVMR models developed for each monitoring location could predict the salt concentrations with reasonable accuracy. The accuracy of the standalone SVMR models presented in Table 3 reflected in the prediction accuracy of the ensemble models. This accuracy and robustness ensured computational efficiency and reliability of the optimal pumping strategies obtained from the executed LSO based coastal aquifer management model. The optimal or non-dominated set of solutions from the developed multi-objective coastal aquifer management model are presented in the form of a Pareto front (Fig. 5). The Pareto front consisted of 600 different solutions defining the trade-offs between the total PWS and BWS pumping rates. Any solution from the optimal pareto-front can be used to sustainably manage the aquifer system as every solution in the pareto-front satisfies the implemented optimization constraints i.e., maintain salt concentration levels below

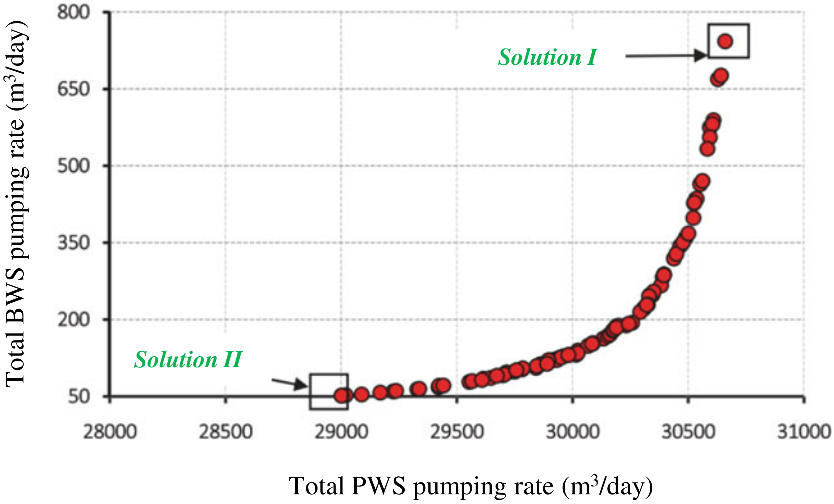


Fig. 4 Optimal pareto-front depicting trade-off between prediction and barrier well pumping wells

the specified limit. Therefore, carefully evaluating each optimal solution is necessary before implementation.

3.4 Effective Groundwater Monitoring

The location of candidate monitoring wells obtained using the *k*-means clustering methodology is presented in Fig. 6a. As per Fig. 6a, it is observed that the clustering methodology ensured that the candidate monitoring wells were scattered over the entire model domain. After identifying the 100 candidate monitoring wells, only 10 were selected as the optimal monitoring wells. These 10 optimal monitoring wells are shown in Fig. 6b. It was observed that the optimal monitoring wells were closer to the sea-side boundary, where salt concentrations as a result of fresh groundwater well pumping was the highest. Also, well-spread optimal monitoring wells were observed, which avoid redundancy of monitoring well installation. These optimal monitoring wells can be used for better groundwater salinity monitoring and designing accurate aquifer management strategies for implementation.

3.5 Variable Importance Analysis

The prediction performance assessment results of the developed GMDH-based predictive models are presented in Table 4.

Table 3 Performance assessment results for the developed SVMR models

3D numerical model	Performance measure	SVMR1	SVMR2	SVMR3	SVMR4	SVMR5	SVMR6
1	*RMSE*	5.10	6.17	3.74	2.95	2.02	1.89
	r	0.96	0.97	0.97	0.97	0.98	0.98
	NS_E	0.97	0.96	0.98	0.97	0.98	0.98
	WI	0.94	0.95	0.95	0.96	0.96	0.96
2	*RMSE*	5.98	5.62	2.82	2.04	1.59	1.33
	r	0.97	0.97	0.98	0.97	0.98	0.98
	NS_E	0.96	0.96	0.96	0.97	0.97	0.97
	WI	0.95	0.94	0.95	0.96	0.96	0.96
3	*RMSE*	4.16	5.22	3.51	4.86	3.02	2.14
	r	0.97	0.96	0.97	0.96	0.98	0.98
	NS_E	0.97	0.97	0.98	0.97	0.98	0.99
	WI	0.94	0.95	0.95	0.94	0.95	0.96
4	*RMSE*	6.60	5.33	5.27	4.65	3.53	3.05
	r	0.97	0.98	0.96	0.97	0.97	0.97
	NS_E	0.97	0.96	0.96	0.97	0.97	0.98
	WI	0.95	0.94	0.93	0.95	0.95	0.96
5	*RMSE*	6.96	7.13	5.12	5.68	4.25	4.56
	r	0.97	0.97	0.97	0.97	0.98	0.97
	NS_E	0.97	0.98	0.98	0.97	0.98	0.97
	WI	0.95	0.94	0.95	0.94	0.96	0.95
6	*RMSE*	7.63	5.32	5.24	5.69	4.25	3.57
	r	0.97	0.98	0.98	0.97	0.99	0.99
	NS_E	0.98	0.98	0.98	0.98	0.98	0.99
	WI	0.96	0.97	0.97	0.97	0.98	0.98
7	*RMSE*	7.26	6.75	6.03	5.87	5.66	5.12
	r	0.97	0.98	0.98	0.98	0.98	0.99
	NS_E	0.97	0.98	0.98	0.98	0.98	0.99
	WI	0.96	0.97	0.97	0.97	0.98	0.98
8	*RMSE*	6.35	7.16	5.57	5.31	5.26	5.19
	r	0.98	0.97	0.98	0.98	0.98	0.98
	NS_E	0.97	0.97	0.97	0.97	0.97	0.97
	WI	0.96	0.95	0.96	0.96	0.96	0.96
9	*RMSE*	7.37	6.89	8.43	6.22	5.32	4.41
	r	0.98	0.98	0.96	0.97	0.97	0.98
	NS_E	0.97	0.97	0.96	0.97	0.97	0.98
	WI	0.95	0.96	0.95	0.96	0.97	0.97

(continued)

Table 3 (continued)

3D numerical model	Performance measure	SVMR1	SVMR2	SVMR3	SVMR4	SVMR5	SVMR6
10	*RMSE*	7.14	6.59	6.91	5.88	4.71	4.28
	r	0.98	0.98	0.98	0.98	0.98	0.99
	NS_E	0.98	0.98	0.98	0.98	0.98	0.99
	WI	0.96	0.97	0.97	0.97	0.97	0.98

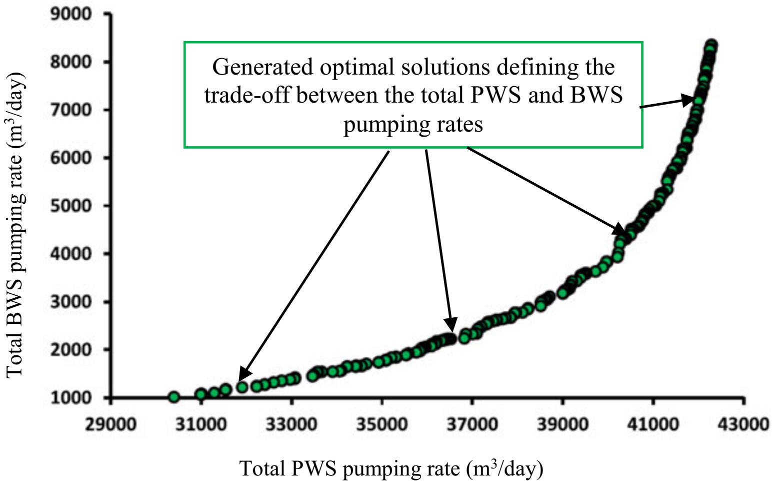


Fig. 5 Optimal solutions defining the trade-off between the total PWS and BWS pumping rates

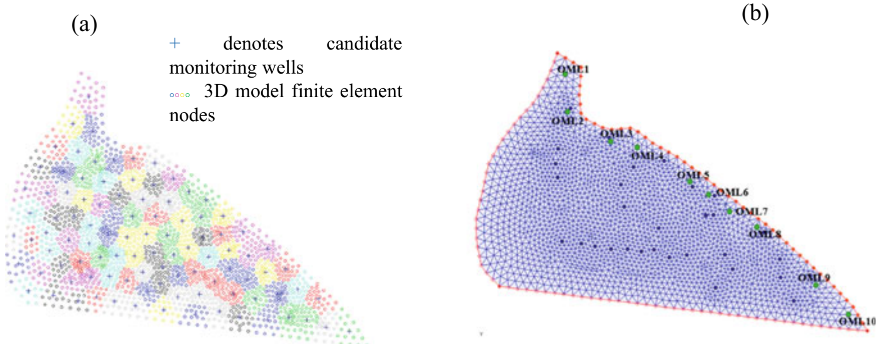


Fig. 6 Candidate monitoring well locations (**a**) and identified optimal monitoring well locations (**b**)

Table 4 Performance assessment result for the developed GMDH models

Model Identity	Development stage	RMSE (mg/L)	MSE (mg/L)	NSE	R^2 (%)	*r*
GMDH_MW1	Training	0.366	0.292	1	99.68	0.997
	Testing	0.358	0.289	1	99.72	0.997
	Independent prediction	0.379	0.299	1	99.61	0.996
GMDH_MW2	Training	0.221	0.175	1	99.67	0.998
	Testing	0.218	0.174	1	99.66	0.998
	Independent prediction	0.243	0.186	1	99.73	0.997
GMDH_MW3	Training	0.440	0.298	1	99.68	0.998
	Testing	0.368	0.293	1	99.69	0.998
	Independent prediction	0.458	0.306	1	99.66	0.996

The data presented in Table 4 establishes the accuracy of the development GMDH models and their ability to accurately predict salt concentration in the aquifer system with reasonable accuracy. This can also be justified using the results from the independent dataset (independent prediction stage). Overall, the performances evaluation results of the GMDH models at the three different stages demonstrate its powerful prediction capability and establishes their usefulness in saltwater intrusion prediction investigations.

In addition, one of the other major benefits of GMDH predictive models was that it provided a subset of most influential groundwater pumping rates that had the most impact on salt concentration levels at respective monitoring wells. For the present study, the most influential pumping rates out of the 52 input pumping rates (ranking for variables × 1 to × 52) for the three GMDH models are presented in Fig. 7. It was observed that only a few individual pumping rates had the most impact on monitoring well salt concentration levels. This information is utmost important for decision-makers as it allows them to focus only on the influential variables for designing better groundwater pumping policies and legislations. The most influential pumping rates can also be modified to control the concentration at respective monitoring wells. Also, the least influential pumping rates can be modified (possibly increased) to maximize total feasible beneficial pumping in the study area, since they do not have much impact on the salinity concentration outcome at specified or critical locations. Also, identifying important and most influential pumping rates can assist in data collection and monitoring. This can help in efficient groundwater monitoring, significantly lower monitoring effort, and cost.

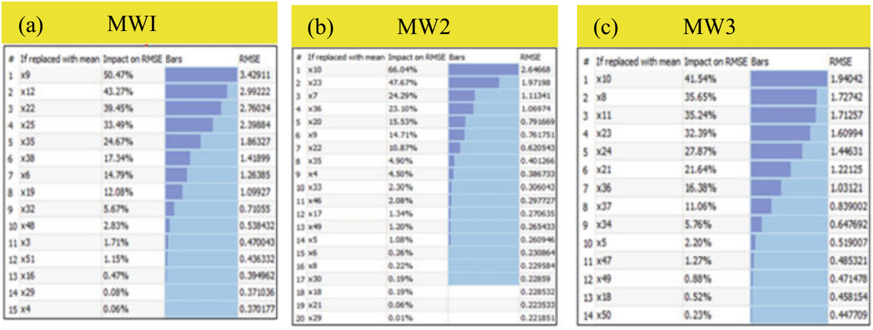


Fig. 7 Most influential pumping rates (important predictor variables) identified by the GMDH models for monitoring wells **a** MW1, **b** MW2 and **c** MW3

4 Conclusions

This study establishes that machine learning is a key for understanding groundwater processes, making future predictions, contamination detection, and managing groundwater resources and therefore, should be made a priority in the current curriculum, research, and industrial applications. Overall, this work illustrates that the problem of complex groundwater monitoring and management can be solved using a groundwater model and a well-trained and tested machine learning based predictive models. While a numerical model of groundwater enables a deeper comprehension of the flow and movement of groundwater in the environment, a well-developed predictive model for groundwater can uncover valuable insights for planning and managing groundwater resources. A machine learning-based predictive model do not require an understanding of the underlying groundwater processes; instead, they identify patterns directly from the data at hand. Therefore, an accurately designed, executed, and implemented groundwater management methodologies based on the two approaches may ultimately prove complementary.

5 Recommendations

This study makes the following future recommendations for utilizing groundwater numerical simulation models and predictive modelling in groundwater monitoring and management. First, it is important to test and validate modelling results incorporating datasets from real study areas. It is imperative that predictive modelling studies are conducted in real-world study areas with diverse hydrogeological conditions. This approach helps validate the applicability of the models to different settings and ensures their practical utility in specific groundwater management contexts. Second, while using predictive modelling, it is crucial to compare results using various AI Algorithms. Modellers should explore the application of different AI algorithms, such as random forests, support vector machines, neural networks, or deep learning models, and compare their performance in groundwater predictive modelling. This comparative analysis can provide insights into the strengths and weaknesses of different algorithms, allowing for more informed algorithm selection. In addition, it is important to utilize different datasets for model training and evaluation. This helps in enhancing the robustness of predictive models, employ a variety of datasets for model training and evaluation. Also, it is advisable to consider dataset from multiple sources, such as groundwater level measurements, hydrological parameters, land use data, and climate variables, to capture the complexity and dynamics of the groundwater system accurately. Furthermore, it is essential to consider and incorporate uncertainty analysis. Conducting an uncertainty analysis helps users and decision-makers quantify and communicate the uncertainties associated with predictive modelling results. Understanding these uncertainties helps decision-makers evaluate the reliability of model predictions and supports effective risk management strategies.

Acknowledgements The authors would like to extend heartfelt appreciation to the anonymous reviewers and editors of this book chapter. Your meticulous reading and thoughtful comments have significantly enriched the content and ensured its accuracy and clarity. We are truly grateful for your time and dedication in providing invaluable feedback that has enhanced the quality of our work.

References

1. Chen C, He W, Zhou H et al (2020) A comparative study among machine learning and numerical models for simulating groundwater dynamics in the Heihe River Basin, northwestern China. Sci Rep 10(1):1–13. https://doi.org/10.1038/s41598-020-60698-9
2. Datta B, Chakrabarty D, Dhar A (2009) Simultaneous identification of unknown groundwater pollution sources and estimation of aquifer parameters. J Hydrol 376(1):48–57. https://doi.org/10.1016/j.jhydrol.2009.07.014
3. Deb, K. (2003). Multi-objective evolutionary algorithms: Introducing bias among Pareto-optimal solutions. Advances in evolutionary computing: theory and applications, pp. 263–292.
4. Farlow SJ (1981) The GMDH algorithm of Ivakhnenko. Am Stat 35(4):210–215. https://doi.org/10.2307/2683292
5. Farlow SJ (2020) Self-organizing methods in modeling: GMDH type algorithms. CRC Press
6. Kumar D, Singh A, Jha RK, et al (2019) A variance decomposition approach for risk assessment of groundwater quality. Expo Health 11(2):139–151. https://doi.org/10.1007/s12403-018-00293-6
7. Lal A, Datta B (2018) Development and implementation of support vector machine regression surrogate models for predicting groundwater pumping-induced saltwater intrusion into coastal aquifers. Water Resour Manage 32(7):2405–2419. https://doi.org/10.1007/s11269-018-1936-2
8. Lal A, Datta B (2018) Multiple objective management strategies for coastal aquifers utilizing new surrogate models. GEOMATE J 15(48):79–85
9. Lal A, Datta B (2019) Multi-objective groundwater management strategy under uncertainties for sustainable control of saltwater intrusion: Solution for an island country in the South Pacific. J Environ Manage 234:115–130. https://doi.org/10.1016/j.jenvman.2018.12.054
10. Lin HCJ, Richards DR, Yeh GT, et al (1997) FEMWATER: a three-dimensional finite element computer model for simulating density-dependent flow and transport in variably saturated media. army engineer waterways experiment station Vicksburg ms coastal hydraulics lab.

11. Loh WL (1996) On Latin hypercube sampling. Ann Stat 24(5):2058–2080
12. Mal U, Adhikari K (2021) Groundwater quality and hydrological stress induced by Lower Gondwana open cast coal mine. J Earth Syst Sci 130(1):1–24. https://doi.org/10.1007/s12040-020-01486-x
13. Martínez-Santos P, Llamas MR, Martínez-Alfaro PE (2008) Vulnerability assessment of groundwater resources: a modelling-based approach to the Mancha Occidental aquifer Spain. Environ Model & Softw 23(9):1145–1162. https://doi.org/10.1016/j.envsoft.2007.12.003
14. Mehra RK (1977) Group method of data handling (GMDH): review and experience. In 1977 IEEE conference on decision and control including the 16th symposium on adaptive processes and a special symposium on fuzzy set theory and applications, pp 29–34
15. Patil P, Karthikeyan A (2020) A survey on k-means clustering for analyzing variation in data. In: Inventive communication and computational technologies: proceedings of ICICCT 2019, pp 317–323
16. Roy DK, Datta B (2017) Fuzzy C-mean clustering-based inference system for saltwater intrusion processes prediction in coastal aquifers. Water Resour Manage 31(1):355–376. https://doi.org/10.1007/s11269-016-1531-3
17. Sahoo S, Russo TA, Elliott J et al (2017) Machine learning algorithms for modeling groundwater level changes in agricultural regions of the US. Water Resour Res 53(5):3878–3895. https://doi.org/10.1002/2016WR019933
18. Samani S, Vadiati M, Nejatijahromi Z et al (2023) Groundwater level response identification by hybrid wavelet–machine learning conjunction models using meteorological data. Environ Sci Pollut Res 30(9):22863–22884. https://doi.org/10.1007/s11356-022-23686-2
19. Schulz E, Speekenbrink M, Krause A (2018) A tutorial on Gaussian process regression: modelling, exploring, and exploiting functions. J Math Psychol 85:1–16. https://doi.org/10.1016/j.jmp.2018.03.001
20. Shanafield M, Bourke SA, Zimmer MA et al (2021) An overview of the hydrology of non-perennial rivers and streams. Wiley Interdiscip Rev Water 8(2):1504
21. Shu C, Burn DH (2004) Artificial neural network ensembles and their application in pooled flood frequency analysis. Water Resour Res 40(9). https://doi.org/10.1029/2003WR002816
22. Sreekanth J, Datta B (2015) Simulation-optimization models for the management and monitoring of coastal aquifers. Hydrogeol J 23(6):1155–1166. https://doi.org/10.1007/s10040-015-1272-z
23. Taghavi N, Niven RK, Paull DJ et al (2022) Groundwater vulnerability assessment: a review including new statistical and hybrid methods. Sci Total Environ 822:153486–153486. https://doi.org/10.1016/j.scitotenv.2022.153486
24. Verrelst J, Rivera JP, Veroustraete F et al (2015) Experimental Sentinel-2 LAI estimation using parametric, non-parametric and physical retrieval methods–a comparison. ISPRS J Photogramm Remote Sens 108:260–272. https://doi.org/10.1016/j.isprsjprs.2015.04.013
25. Wagner BJ, Gorelick SM (1987) Optimal groundwater quality management under parameter uncertainty. Water Resour Res 23(7):1162–1174. https://doi.org/10.1029/WR023i007p01162
26. Wang W, Ahlfeld DP (1994) Optimal groundwater remediation with well location as a decision variable: model development. Water Resour Res 30(5):1605–1618. https://doi.org/10.1029/93WR03552
27. Wilson AG, Knowles DA, Ghahramani Z (2011) Gaussian process regression networks. arXiv preprint arXiv:1110.4411
28. Zeydalinejad N (2022) Artificial neural networks vis-à-vis MODFLOW in the simulation of groundwater: a review. Model Earth Syst Environ 8(3):2911–2932. https://doi.org/10.1007/s40808-022-01365-y

New Trends in Groundwater Contaminant Transport Modelling

Kamilia Hagagg

Abstract Water is one of the essential interactive environmental and vital components for sustaining life on Earth. The increasing awareness about our environment and the recognition of the need for its protection support rational and efficient use of water resources planning qualitatively and quantitatively. In this context, using numerical models as a tool for diagnosing, managing, and predicting groundwater behavior has been gaining considerable importance in recent years. The study of solute transport related to groundwater contamination has become the focus of numerous researchers from many viewpoints, and the resulting achievements are so scattered and extensive. Therefore, this work documents various literature to systematically study the available theoretical and experimental works on groundwater contaminant transport modelling. Here, a simplified systematic and integrative picture of the present status of groundwater contamination is provided to emphasize the new trends and challenges to facilitate future research directions for more comprehensive analyses of the solute transport phenomena, with some recommendations toward solving these challenges.

Keywords Groundwater · Pathways · Contaminants transport modelling · Groundwater contaminants · Challenges in transport modelling

1 Introduction

Water is a vital key component in the development of nations. The efficient use of water resources has become important in future planning especially in arid African regions. In general, groundwater simulation models are mainly used for predicting the changes in groundwater level or in concentration, to test aquifer sustainable use or as protection strategies. In addition to hindcasts concentration changes, to determine the source of contamination or to design a proper monitoring network. The measurement

K. Hagagg (✉)
Siting and Environment Department, Nuclear and Radiological Safety Research Center, Egyptian Atomic Energy Authority, Cairo, Egypt
e-mail: k.hagagg@gmail.com

S. Ali and A. M. Armanuos (eds.), *Groundwater in Arid and Semi-Arid Areas*, Earth and Environmental Sciences Library, https://doi.org/10.1007/978-3-031-43348-1_9

of groundwater flow and pollutant transport is a challenging issue; hence the system of groundwater is dynamic one; predicting groundwater flows and contaminants transport through it is difficult. The characteristics that control groundwater flow and transport in an aquifer include those related to fluid and porous media properties are heterogeneous on large scales (e.g., porosity, permeability, storativity, dispersivity etc.). To simulate these intricate and sophisticated groundwater flow and transport phenomena, numerical models are necessary.

With growing awareness of the importance of protecting our environment, the study of solute transport related to groundwater contamination has become a primary focus for many researchers globally [9, 10, 23, 33, 37–39, 49]. Numerous researchers tried to solve the problem from different perspectives, and the resulting accomplishments are so diverse and dispersed that it appears necessary to inventory the completed works.

This chapter presents a systematic examination of the theoretical and experimental works that are currently available. A comprehensive picture of the problem's current state is also provided. Issues such as uncertainty, verification, and validation of the model output that are still unclear or unaddressed by recent researchers are highlighted to facilitate future research directions for a better understanding and more comprehensive analyses of the solute transport phenomena related to contaminate transport modelling. The chapter aims to identify and elucidate potential sources of contaminants water. In addition to examination of the progress made so far in using dispersion models in order to highlight the key issues and challenges confronting dispersion modelers. Also, it aims to identify future prospects and summarize the key areas requiring additional research to close evidence gaps and improve model performance.

2 Contaminants Sources and Their Pathways to Groundwater System

Any significant physical, chemical, biological, or radiological substance or matter that has a negative impact on air, water, soil, or living organisms is considered as an environmental contaminant, Shane [66] and Jaiswal et al. [41], WHO [80], Zhou et al. [85], Tokatli et al. [73] and Jabbo et al. [40]. Groundwater contaminants come from two categories of sources: point sources and non-point sources (distributed). Landfills, leaking gasoline storage tanks, leaking septic tanks, and accidental spills are examples of point sources. Infiltration from farmland treated with pesticides and fertilizers is an example of a non-point source, [18] as following.

Non-Point Source

- Fertilizers on agricultural land
- Pesticides on agricultural land and forests
- Contaminants in rain, snow, and dry atmospheric fallout.

Point Source

- On-site septic systems
- Leaky tanks or pipelines containing petroleum products
- Leaks or spills of industrial chemicals at manufacturing facilities
- Underground injection wells (industrial waste)
- Municipal landfills
- Livestock wastes
- Leaky sewer lines
- Chemicals used at wood preservation facilities
- Mill tailings in mining areas
- Fly ash from coal-fired power plants
- Sludge disposal areas at petroleum refineries
- Land spreading of sewage or sewage sludge
- Graveyards
- Road salt storage areas
- Wells for disposal of liquid wastes
- Runoff of salt and other chemicals from roads and highways
- Spills related to highway or railway accidents
- Coal tar at old coal gasification sites
- Asphalt production and equipment cleaning sites.

There are several pollution sources that pose risks to groundwater globally. Municipal landfills and industrial waste disposal facilities are two of the more important point sources in sand and gravel shallow aquifers at arid and semi-aridness. Under the risk of more extensive contamination might be enhanced. Septic tanks, petroleum product leaks and spills, and heavy industrial organic liquids are also a few of these risky and common causes of pollution. Bacteria, viruses, detergents etc., are some of the contaminants that can come from septic systems and infiltrate groundwater.

On the other hand, iron, manganese, arsenic, chlorides, fluorides, sulphates, and radionuclides are a few examples of naturally occurring materials that can occur in groundwater [2]. Particles from other naturally occurring substances in our environment, like decomposing organic matter, can migrate through groundwater. The migration of contaminates is mainly controlled by the surrounding environmental condition, such as, soil pH, redox conditions, biotic action, and the amount of water percolating the soil. When taken in large quantities, some pollutants can be harmful to the health. Unless it has been treated to remove the contaminants, ground water that has unacceptable levels should not be utilized for drinking water or other domestic water usage.

The first step is to fully understand groundwater flow and transport processes, taking into account critical parameters such as contamination activity location, intensity, and duration. The establishment of a proper flow and transport model ensures that the correct spatial and temporal distribution of contaminant concentrations is maintained throughout the site. The combined processes of advection and dispersion cause groundwater to move from higher hydraulic head towards areas of lower hydraulic heads, transferring dissolved solutes as well as contaminants. Advection describes the large-scale transportation of solutes by flowing groundwater. Dispersion is the process by which a pollutant plume moves from an area with a high concentration to one with a lower concentration. The advection–dispersion-reaction equation, which describes solute transport in many groundwater transport models, can be used to compute the dispersion coefficients as the total of mechanical dispersion, molecular diffusion, and macro-dispersion.

3 Numerical Modelling of Contaminates Transport

Although groundwater models are a simplification of a more complicated reality, they have consistently been effective tools for addressing a variety of groundwater issues and assisting in decision-making over several decades [44]. Any computer technique approximating an underground water system is known as a numerical groundwater model [5]. Numerical groundwater simulation models have developed into a promising technique in science and engineering during the last few decades for describing, evaluating, and evaluating physical systems and phenomena [44]. Hence, analytical solutions were insufficient to accurately characterize a subsurface system, as a results of the system's inherent heterogeneity; groundwater simulation models have been used to describe hydrologic phenomena to evaluate or forecast the long-term effects of water withdrawals and to investigate different groundwater management options, movement of water and oil in the subsurface, and movement of contaminants in the fields of groundwater hydrology with the goal of identifying a contaminant source and its plume extent. In numerical simulation models; a numerical simulator converts one or more partial differential equations converts one or more partial differential equations into a set of algebraic equations that can be solved for discrete values of the dependent variables. The models are separated into five groups [44] according to the numerical approach taken to solve these equations as following.

1. Finite differences.
2. Finite elements.
3. Integrated finite differences.
4. Boundary elements.
5. Analytical elements.

The most often used techniques for resolving groundwater flow and mass transportation issues are finite differences and finite elements. The collections of algebraic equations (system equations, boundary conditions, and initial conditions) that result from approximating partial differential equations are solved by a computer programme.

A simple protocol for groundwater modelling can be explained that starts with the planning of project problems, or phenomena to be modeled and also the selection of the used model. After that the conceptualization of the modeled system starts. The development of a valid conceptual model is the most important step in a modeling study after the definition of the study objectives, model purpose, and complexity at the scoping stage. A conceptual model is a simplified representation of the physical system's key features and hydrological behavior.

It serves as the foundation for the site-specific computer model; it is subject to some simplifying assumptions. The assumptions are necessary partly because a complete reconstruction of the field system is impossible and partly because there is rarely enough data to fully describe the system. The conceptual model must include all features that are relevant to the problem and the boundaries geometry of the investigated aquifer domain; it should specifically include the following.

- The aquifer matrices structure, homogeneities, and heterogeneities.
- The flow mode and regime in the investigated area.
- The properties of the water (homogenous, viscous, etc.).
- Sources and sinks of water and of relevant contaminants within the domain and their specific geometry.
- Initial conditions within the considered domain; across its boundaries.

The reliability or accuracy of the model is tested in the calibration step, in which the model reproduces or matches historically observed data (hydraulic head) [82]. Based on the results of this step, the key groundwater parameters are then modified and refined. A trial-and-error approach can be used for this process until a satisfactory match to observations is attained. Verification is the process in which the calibrated model can reproduce a set of field observations independent of that used in the model calibration (if they exist) [7]. The sensitivity analysis could be demonstrated through varying inputs over a reasonable range, within uncertainty in the parameter value, and observing the relative change in the model response. The sensitivity of one parameter versus others is also can be evaluated [5].

Now finally, the model can be used to predict the response against future scenarios after completing the calibration process, sensitivity analysis, and field verification. The estimation of the future hydraulic response of a region is important for protection, mitigation, and adaptation to any expected adverse effects [8].

4 New Trends in Groundwater Contamination Modelling

Groundwater contamination risk assessment offers a means for decision support through carefully assessing and ranking the severity of site contamination, helping identify critical issues for mitigation actions [12, 47]. Risk assessment is usually based on using mathematical models by predicting subsurface contaminant behavior into the future [16], although the efficiency of the mathematical modelling efforts usually requires sufficient knowledge of the subsurface hydrogeological conditions throughout a contaminated site. However, this knowledge is often limited by various uncertainties associated with soil and contaminant properties, and the risk is thus inherently linked with uncertainties [35]. It is recognized that the success of contaminated site risk assessment depends significantly on whether the contaminant transport and fate models have appropriately quantified and incorporated the related uncertainties into the simulation processes [48, 53]. Also, source identification and characterization can be more difficult for groundwater than for other environmental pathways. Several factors; the pollution sources' characteristics are difficult to measure due to several factors. Pollution sources that are only present in very small quantities might pose a potentially great health risk, depending on the toxicity of the substances.

4.1 The Remediation of Contaminated Sites

Once contamination has been detected in the subsurface, the pathways and fate of the contaminants must be predicted. This action should be taken as a mandatory response to any plan of mitigation, cleanup operations, or control measures toward planned remediation activities. Similarly, any monitoring or observation network should be based on the anticipated behavior of the system. There are two main strategies: (i) to hinder, modify or remove the migration of the contaminant from the source to the environment [1, 15, 61, 65]; or (ii) to protect the recipients from contamination by filters, barriers or pumping [13, 14, 72]. New techniques are continuously being developed to manipulate the contaminant source, but the latter strategy may be necessary for non-point sources as well as for contaminant plumes that have migrated long distances in the subsurface. When groundwater is used as a supply of drinking water, the management of an artificial aquifer recharge has also proven to be successful in meeting the standards for drinking water quality [30, 34, 70]. However, because of the heterogeneous conditions of the subsurface and the contaminants' adherence to soil particles, there are arguments that once an aquifer has been contaminated, it is difficult, if not impossible, to restore it to its original state [74].

4.2 Vadose Zone Contaminant Transport

The numerical problem for predicting contaminant transport in the vadose zone and in groundwater often becomes extremely demanding of computational power. A literature survey indicates that there has been an increasing tendency for numerical problems to be solved on networks of computers, which are not publicly available. Several studies were implemented on the effectiveness of aquifer remediation [52, 54, 58, 59]. They functioned their studies merely as demonstrators for specific numerical methods, simulators, or various remediation techniques. Therefore, an important research challenge is to focus more broadly on integrating appropriate methodological developments with the realities of field observations at specific sites to help solve real problems of the subsurface environment [31, 37].

4.3 Environmental Isotopes Hydrology

Recent research in this field [33, 55, 64], followed an attempt that used an integrated approach of the hydrogeological setting and the conjugation of the hydrogeochemical data with the stable isotope hydrology for representation of the conceptual model of the modeled area. Those tools give more insights into the characterization of the groundwater system with all relevant boundaries and main recharge sources of the aquifer, which is considered to be the key components in the groundwater modeling process.

4.4 Geochemical Modelling

Many studies combined two approaches to analyzing groundwater quality data: geochemical modeling of concentration profiles [6, 77] and trend detection concerning travel times. Many studies argued the geochemical modelling of nitrate and sulfate concentrations along the vertical component of groundwater flow within the studied aquifer. A notable effort has been made to improve the modelling of the transport and fate of contaminants by coupling transport models with geochemical models [17, 26, 49, 52]. Geochemical models essentially solve various chemical reactions based on mass conservation and chemical equilibrium principles with the aid of thermodynamics. Some of the geochemical models, such as MINEQL, EQ31EQ6, and MlNTEQ, also calculate adsorption/desorption and precipitation/dissolution. For example, the transport model, EXAMS, was coupled to MlNTEQ to form the model MEXAMS, which calculates chemical species of heavy metals, the amounts of adsorption/desorption and precipitation/dissolution, and the migration of heavy metals [43, 46, 81].

4.5 Mining Activities

The primary possible environmental sources of pollution at mining sites are rock waste materials and tailings, which interact with rain and leach into the aquifer. When exposed mining is completed, nature begins to re-establish the basic groundwater and surface water regimes, and the mine floods. Flooding creates pools at lower elevations, causing mine water quality to deteriorate. Groundwater modelling can provide on-site characteristics of the subsurface contaminant source in abandoned mine sites, as well as help to reduce uncertainties that govern groundwater flows and contaminant transport, as well as the most likely location and magnitude of the unknown contamination source. Under these conditions, the MODFLOW (flow) and PHT3D (reactive transport) simulation codes are widely used to predict spatial and temporal flows, as well as the concentration values in a contaminated aquifer [21].

4.6 Seawater Intrusion Studies

In the last decade, there were several density-dependent simulation codes developed based on the commonly-used groundwater model [68], among them, SEAWAT [29], which uses a modified version of MODFLOW [51] to solve the variable density groundwater flow equation and MT3D module [83]. Hagagg [31] and Hussien et al. [38] assessed the lateral extent of the seawater intrusion to predict the future behavior with respect to different stressing scenarios, many researchers used the SEAWAT code, as a useful tool for simulating three-dimensional variable-density groundwater flow.

4.7 Groundwater Management and Sustainability Studies

Management means making decisions to achieve goals without violating specified constraints. Groundwater sustainability was defined as "the development and use of groundwater in some way to meet the needs of present and future demand without causing unacceptable environmental, economic or social consequences" [4]. All such predictions can be obtained within the framework of a considered management problem by constructing and solving mathematical models of the investigated domain and of the flow and solute transport phenomena that take place in it. The determination of groundwater sustainable yield requires providing an optimal and quantitative outcome based on groundwater flow and mass balance principles. Much effort through research has contributed to studies on the definition, methods and factors of sustainable yield, either on an aquifer scale or a basin scale [3, 24, 36, 50, 76, 78, 84]. As a result of some difficulties in the conceptualization of the subsurface aquifer media and because models are often used to physically simplify a complex system and mathematically represent key phenomena of the system [19]. Various models have become the tools employed to understand groundwater systems via simulating and predicting its behavior [79]. Compared with analytical methods, numerical modelling provides a fast and sometimes effective way to evaluate groundwater resources' bulk behavior and quantity [27, 32, 62, 69].

4.8 Data Mining Algorithms

The main aim of using contaminant transport modelling is to understand the contaminant plumes' development and quantify the impacts to water quality. Data mining has recently considered the state of the art in different science applications dealing with large databases. Gaussian Process (GP) were used to predict nitrate (contaminant) and strontium (potential future increasing) concentrations in groundwater using various groundwater quality potential variables such as Temperature, pH, EC, HCO_3^-, F, Cl, SO_4^{2-}, Na^+, K^+, Mg^{2+}, and Ca^{2+} [11]. Different quantitative criteria, as well as a visual comparison approach, were used to assess the modelling capability in this study revealing that the GP algorithm outperforms all other models in predicting nitrate and strontium concentrations, followed by RF, M5P, and RT, respectively, according to the model evaluation criteria. This approach might present a new vision of using a large data set of specific contaminants with different mathematical algorithms to have a predictive future holistic picture of the status and concentration of contaminants.

In addition to that, Artificial Neural Networks (ANN) have recently been used in groundwater management to predict the hydraulic head at a well location and to simulate spatiotemporal groundwater levels [20, 25, 45, 56, 57, 71, 75]. ANNs mimic the hydraulic head using a black box method, incorporating hydrological data like rainfall and temperature as well as hydrogeological ones like pumping rates from neighboring wells. The network is trained using available field data, and the training process is assessed.

4.9 Stochastic Multicomponent Reactive Transport Modelling

In recent years, multicomponent reactive transport modeling (MRTM) has been used specifically to elucidate and simulate the controls of some contaminants to assist decision-makers in quantifying the potential extension contamination in aquifers [22, 26, 42]. Stochastic MRTM are useful tools for estimating the probability of non-exceedance (PNE) of a toxic aquifer compound in the presence of uncertainty [22, 63]. Model input parameters are treated as random spatial functions in stochastic analysis, while model outputs are expressed in terms of probability density functions. These functions' statistical indicators are used as metrics to quantify one or more desired target variables (e.g., the concentration of a polluting aqueous species), [60]. On the other hand, the empirical uncertainty caused by the incomplete mapping of the geochemical initial conditions (GICs) is a critical limitation for the MRTM predictions' reliability, Dalla Libera et al. [22]. When a system is out of chemical equilibrium, its initial geochemical status changes over time due to flow, transport, and geochemical transformations. Setting the correct GICs in each model cell is critical for correctly computing the PNE of a desired toxic compound.

5 Advanced Models in Groundwater Contaminant Transport

Several models were used for the predication and demarcation of contaminated plumes in groundwater systems. Some of them are mentioned in (https://www.epa.gov/land-research/ground-water-modeling-research), see Table 1.

Table 1 Some groundwater contaminant transport prediction models

Model	Specification
3DFATMIC	It simulates subsurface flow, transport, and fate of contaminants that are undergoing chemical or biological transformation. The model is applicable to transient conditions in both saturated and unsaturated zones. This model can almost eliminate spurious oscillation, numerical dispersion, and peak clipping due to advective transport
3DFEMWATER/ 3DLEWASTE	They are related and can be used together to model flow and transport in three dimensional, variably-saturated porous media under transient conditions with multiple distributed and point sources/sinks. These models can be used to apply the assimilative capacity criterion to development of wellhead protection areas
BIOCHLOR,	It is a screening model that simulates remediation by natural attenuation of dissolved solvents at chlorinated solvent release sites. It includes three different model types: Solute transport without decay, solute transport with biotransformation modeled as a sequential first-order decay process, and solute transport with biotransformation modeled as a sequential first-order decay process with two different reaction zones
FOOTPRINT	It is a screening model used to estimate the length and surface area of benzene, toluene, ethylbenzene, and xylene (BTEX) plumes in groundwater, produced from a gasoline spill that contains ethanol
Modular 3-D multi-species transport model (MT3D)	It is a 3D solute transport model for simulation of advection, dispersion, and chemical reactions of dissolved constituents in groundwater systems. The model uses a modular structure similar to that implemented in MODFLOW
Nonaqueous-phase liquid (NAPL) simulator	It conducts a simulation of the contamination of soils and aquifers that results from the release of organic liquids commonly referred to as nonaqueous-phase liquids (NAPLS). The simulator applies to three interrelated zones: a vadose zone in contact with the atmosphere, a capillary zone, and a water-table aquifer zone
WhAEM2000	It is a public domain, groundwater flow model designed to facilitate capture zone delineation and protection area mapping in support of the State's Wellhead Protection Programs (WHPP) and Source Water Assessment Planning (SWAP) for public water supplies in the United States. It provides an interactive computer environment for design of protection areas based on radius methods, well in uniform flow solutions, and hydrological modeling methods

6 Challenges in Groundwater Contaminants Modelling

Most natural groundwater systems exhibit significant heterogeneity in aquifer system that affects on its physical and chemical properties. Groundwater management modelling is hampered by such heterogeneities [67]. There can be no "optimal" management strategies if the aquifer simulation model cannot be reliably calibrated. In fact, regardless of how thoroughly a simulation model is calibrated, there is always some degree of uncertainty in both model input and output. Furthermore, significant uncertainties are always present in economic and policy factors. Thus, since groundwater management modelling became an active field of research, how to adequately accommodate uncertainties in simulation and economic models has long been a focus point. As groundwater management modelling becomes more sophisticated, this topic is likely to remain a major focus of future research. Nevertheless, since there is no other way but to use models in order to predict the future behavior of an investigated system, using whatever data that are available for model calibration (despite of the associated uncertainty). So, a strong monitoring approach to validate and track outcomes is vital and mandatory.

Groundwater management modelling has mainly focused on incorporating simulation with optimization methods to investigate critical issues ranging from contaminant remediation to agricultural irrigation management [28]. Still the broad impacts of global change on aquifer storage and depletion trajectory management that are defendants on surrounding environments need more enhancements. The scope of research efforts is only beginning to address complex interactions using multiagent system models that are not easily formulated as optimization problems and consider a variety of human behavioral responses.

Stochastic MRTM have not been widely used so far as a result of very long computational times regarding solving the nonlinear equations characterizing this type of model, in addition to the number of unknowns and input parameters required to run MRTM.

7 Conclusion

Groundwater flow and solute transport modeling is a vital and mandatory water management tool. It represents a simplified version of the real field site, helping understand the system and predict its behavior. The main goal of modelling in the groundwater field is to predict the value of an unknown variable such as head in an aquifer system or the concentration distribution of a chemical in the aquifer in time and space and predict the future changes of the system. Detection of groundwater contamination is considered to be a vital importance to manage and protect groundwater from anthropogenic pressures. This review introduces a special focus review for modelling the contaminant transport starting from the occurrence of groundwater contaminants including natural and anthropogenic, their movement, mathematical modelling, and recent trends in this topic. It was revealed that till now, issues such as heterogeneity of the modeled system, uncertainty in model input, and limitation of the available data describing the underground system are complicating the accurate estimation. In general, modelling of contaminants' transport in the groundwater system using a real-world simulation has been improved compared to earlier attempts to calibrate a simulation model for the complex flow and transport process. Although, recently, the application of data mining in filling the unknown gaps in modeled information seems to be promising. In addition to the application of data mining in forecasting and prediction problems as hydraulic head might be extended in the future for predicting the behavioral attempt of contaminated plumes.

8 Recommendations

1. Putting more strategies in accurately selecting the model inputs is one of the most important factors that might reduce uncertainties in the output of numerical models.
2. Integrating some advanced models as data mining in predicting attributes and data in unreached areas to facilitate the conceptualization process prior to modeling.
3. Conjugation of several models might compensate for the data gap and decrease the uncertainty of the modelling process.
4. Linking the solute transport in unsaturated zone with subsurface groundwater flow and mass transport might help in knowing the behavior of the contaminants in these zones and hence mitigate their plumes.
5. It is mandatory to trace and link the climatic change on the behavioral of the aquifer response and quality aspects.

Acknowledgements It is a pleasure to acknowledge the technical support provided by Egyptian Atomic Energy Authority. I also acknowledged the editors for their support and critical constructive comments on this chapter.

References

1. Albergaria JT, da Conceicao M, Alvim-Ferraz M, Delerue-Matos C (2006) Remediation efficiency of vapour extraction of sandy soils contaminated with cyclohexane: influence of air flow rate, water and natural organic matter content. Environ Pollut 143(1):146–152
2. Ali S, Thakur SK, Sarkar A, Shekhar S (2016) Worldwide contamination of water by fluoride. Environ Chem Lett 14:291–315. https://doi.org/10.1007/s10311-016-0563-5
3. Alley WM, Leake SA (2004) The journey from safe yield to sustainability. Groundwater 42(1):12–16
4. Alley WM, Reily TE, Franke OL (1999) Sustainability of groundwater resources. U.S. Geological Survey Circular 1186, Denver, CO

5. Anderson MP, Woessner WW (1992) Applied groundwater modeling, simulation of flow and advective transport. Academic Press, San Diego, USA
6. Appelo CAJ, Postma D (2005) Geochemistry, groundwater and pollution. In: Standard guide for conceptualization and characterization of groundwater systems designation: D5979–96 (reapproved 2008)
7. Barnett B, Townley LR, Post V, Evans RE, Hunt RJ, Peeters L, Richardson S, Werner AD, Knapton A, Boronkay A (2012) Australian groundwater modeling guidelines. Waterlines report, National Water Commission, Canberra
8. Barry DA (1992) Modelling contaminant transport in the subsurface: theory and computer programs. In: Ghadiri H, Rose CW (eds) Modelling chemical transport in soil: natural and applied contaminants. Lewis, Publishers, Boca Raton, FL, pp 105–144
9. Bianchi M, Pedretti D (2017) Geological entropy and solute transport in heterogeneous porous media. Water Resour Res 53:4691–4708. https://doi.org/10.1002/2016WR020195
10. Boso F, Bellin A, Dumbser M (2013) Numerical simulations of solute transport in highly heterogeneous formations: a comparison of alternative numerical schemes. Adv Water Resour 52:178–189. https://doi.org/10.1016/j.advwatres.2012.08.006
11. Bui DT, Khosravi K, Karimi M, Busico G, Sheikh Khozani Z, Nguyen H, Mastrocicco M, Tedesco D, Cuoco M, Kazakis N (2020) Enhancing nitrate and strontium concentration prediction in groundwater by using new data mining algorithm. Sci Total Environ 715:136836
12. Carrington CD, Bolger PM (1998) Uncertainty and risk assessment. Hum Ecol Risk Assess 4(2):253–257
13. Chang LC, Chu HJ, Hsiao CT (2007) Optimal planning of a dynamic pump-treat inject groundwater remediation system. J Hydrol 342(3–4):295–304
14. Chang NB, Hossain F, Wanielista M (2010) Filter media for nutrient removal in natural systems and built environments: I-previous trends and perspectives. Environ Eng Sci 27(9):689–706
15. Chang TC, Yen JH (2006) On-site mercury-contaminated soils remediation by using thermal desorption technology. J Hazard Mater 128(2–3):208–217
16. Chen T, Zhang Y-C, Rossow WB (2000) Sensitivity of atmospheric radiative heating rate profiles to variations of cloud layer overlap. J Climate 13:2941–2959. https://doi.org/10.1175/1520-0442(2000)013<2941:SOARHR>2.0.CO;2
17. Chen JS, Lai KH, Liu CW, Ni CF (2012) A novel method for analytically solving multi-species advective-dispersive transport equations sequentially coupled with first-order decay reactions. J Hydrol 420–421:191–204
18. Cherry JA (1987) Groundwater occurrence and contamination in Canada. In: Healey MC, Wallace RR, Canadian Aquatic Resources (eds) Canadian bulletin of fisheries and aquatic sciences, vol 215, p 395. Department of Fisheries and Oceans, Ottawa
19. Chiang WH, Kinzelbach W (2001) 3D groundwater modeling with PWWIN. Springer, Berlin, p 346
20. Coppola EA, Rana AJ, Poulton MM, Szidarovszky F, Uhl VW (2005) A neural network model for predicting aquifer water level elevations. Ground Water 43:231–241
21. Datta B, Petit C, Palliser M, Esfahani H, Prakash O (2017) Linking a simulated annealing based optimization model with PHT3D simulation model for chemically reactive transport processes to optimally characterize unknown contaminant sources in a former mine site in Australia. J Water Resour Protect 9:432–454
22. Dalla Libera N, Pedretti D, Casiraghi G, Markó Á, Piccinini L, Fabbri P (2021) Probability of non-exceedance of arsenic concentration in groundwater estimated using stochastic multicomponent reactive transport modeling. Water 13:3086. https://doi.org/10.3390/w13213086
23. De Barros FP (2018) Evaluating the combined effects of source zone mass release rates and aquifer heterogeneity on solute discharge uncertainty. Adv Water Resour 117:140–150. https://doi.org/10.1016/j.advwatres.2018.05.010
24. Delvin JF, Sophocleous M (2005) The persistence of the water budget myth and its relationship to sustainability. Hydrogeol J 13(4):549

25. Feng S, Kang S, Huo Z, Chen S, Mao X (2008) Neural networks to simulate regional ground water levels affected by human activities. Ground Water 46:80–90
26. Gao ZP, Jia YF, Guo HM, Zhang D, Zhao B (2020) Quantifying geochemical processes of arsenic mobility in groundwater from an inland basin using a reactive transport model. Water Resour Res 56:e2019WR025492
27. Glesson T, Cuthbert M, Ferguson G, Perrone D (2020) Global groundwater sustainability resources, and systems in the anthropocene. Annu Rev Earth Planet Sci 48(431):463
28. Gorelick SM, Zheng C (2015) Global change and the groundwater management challenge. Water Resour Res 51(5):3031–3051. https://doi.org/10.1002/2014WR016825
29. Guo W, Langevin CD (2002) User's guide to SEAWAT-2000: a computer program for simulation of three-dimensional variable-density groundwater flow: technique of water resources investigation. Technique of Water-Resources Investigations, U.S. Geological Survey
30. Hagagg K (2016) Site evaluation for waste disposal site in Eastern Cairo using hydrogeochemical techniques. Faculty of Science, Ain Shams University, Egypt, PhD
31. Hagagg K (2018) Numerical modeling of seawater intrusion in karstic aquifer, Northwestern Coast of Egypt. In: Modeling earth systems and environment. https://doi.org/10.1007/s40808-018-0549-3
32. Hagagg K, Abdallah HR, Sadek M (2023) Numerical modeling constrained by environmental isotopes for sustainable development of partially renewable aquifers in desert area. Carbonates Evaporites 38:30. https://doi.org/10.1007/s13146-023-00850-4
33. Hagagg KH, Sadek MA, Mohamed FA, El-Shahat MF (2018) Use of isotope hydrology in groundwater conceptualization for modeling flow and contaminant transport at northwestern Sinai, Egypt. Environ Monit Assess 90:745.https://doi.org/10.1007/s10661-018-7102-8
34. Hiscock KM, Grischek T (2002) Attenuation of groundwater pollution by bank filtration. J Hydrol 266(3–4):139–144
35. Hoffman FO, Chambers DB, Stager RH (1999) Uncertainty is part of making decisions. Hum Ecol Risk Assess 5(2):255–261
36. Holland M, Witthüser KT (2009) Factors that control sustainable yields in the Achaean basement rock aquifers of the Limpopo province. In: Titus RA, Adams S, Strachan L (eds) The basement aquifers of Southern Africa, WRC report no. TT 428/09, Water Research Commission, Pretoria, South Africa. https://doi.org/10.1016/j.gsd.2017.05.002
37. Hussien R, Hagagg K, El-Aassar AM (2017) Coupling HYDRUS and MODFLOW for studying environmental impact of wastewater ponds in tenth of Ramadan City, Egypt. Int J Eng Sci (IJES) 6(10):41–54
38. Hussien RA, Hagagg K, Rayan RA, El-Aassar A (2022) Groundwater modeling to study brine disposal impact from desalination plant in Sharm El-Sheikh, South Sinai, Egypt 262:1–13. https://doi.org/10.5004/dwt.2022.28507
39. Iori A, Zarlenga A, Jankovic I, Dagan G (2017) Solute transport in aquifers: the comeback of the advection dispersion equation and the first order approximation. Adv Water Resour 110:349–359. https://doi.org/10.1016/j.advwatres.2017.10.025
40. Jabbo JN, Isa NM, Aris AZ, Ramli MF, Abubakar MB (2022) Geochemometric approach to groundwater quality and health risk assessment of heavy metals of Yankari game reserve and its environs, Northeast Nigeria. J Clean Prod 330:129916. https://doi.org/10.1016/j.jclepro.2021.129916
41. Jaiswal DK, Kumar A, Yadav RR (2011) Analytical solution to the one-dimensional advection-diffusion equation with temporally dependent coefficients. J Water Resour Prot 2011:76–84
42. Jakobsen R, Kazmierczak J, Sø HU, Postma D (2018) Spatial variability of groundwater arsenic concentration as controlled by hydrogeology; conceptual analysis using 2-D reactive transport modeling. Water Resour Res 54:10–254
43. Kandil AT, Haggag K, Gamal AA, Abd El-Nasser MG, Mostafa WM (2022) Adverse health and environmental outcomes of sewage treatment plant on surrounding groundwater with emphasis on some mitigation recommendations. Environ Geochem Health. https://doi.org/10.1007/s10653-022-01413-7

44. Kumar CP (2015) Modeling of groundwater flow and data requirements. Int J Mod Sci Eng Technol 2(2):18–27
45. Lallahem S, Mania J, Hani A, Najjar Y (2005) On the use of neural networks to evaluate groundwater levels in fractured media. J Hydrol 307:92–111
46. Lee KE, Barber LB, Schoenfuss HL (2014) Spatial and temporal patterns of endocrine active chemicals in small streams. J Am Water Resour Assoc 50(2):401–419
47. Li JB, Liu L, Huang GH, Zeng GM (2006) A fuzzy-set approach for addressing uncertainties in risk assessment of hydrocarbon-contaminated site. Water Air Soil Pollution 171(1–4):5–18
48. Li JB, Huang GH, Chakma A, Zeng GM (2003) Numerical simulation of dual phase vacuum extraction to remove non-aqueous phase liquids in subsurface. Pract Period Hazard Toxic Radioact Waste Manag (ASCE) 7(2):106–113
49. López-Vizcaíno R, Yustres A, Cabrera V, Navarro V (2021) A worksheet-based tool to implement reactive transport models in COMSOL Multiphysics. Chemosphere 266:129176. https://doi.org/10.1016/j.chemosphere.2020.129176. Epub 2020 Dec 3
50. Maimone M (2004) Defining and managing sustainable yield. Ground Water 6:809–814
51. McDonald MG, Harbaugh AW (1998) A modular three-dimensional finite difference groundwater flow model. US geological survey technique of water resources. U.S. geological survey
52. Maji R, Sudicky EA (2008) Influence of mass transfer characteristics for DNAPL source depletion and contaminant flux in a highly characterized glaciofluvial aquifer. J Contam Hydrol 102(1–2):105–119
53. Maxwell RM (1998) Understanding the effects of uncertainty and variability on groundwater-driven health risk assessment. PhD thesis, University of California, Berkeley, CA, USA
54. Maxwell RM, Carle SF, Tompson AFB (2008) Contamination, risk, and heterogeneity: on the effectiveness of aquifer remediation. Environ Geol 54(8):1771–1786
55. Morgenstern U, Stewart MK, Stenger R (2010) Dating of streamwater using tritium in a post nuclear bomb pulse world: continuous variation of mean transit time with streamflow. Hydrol Earth Syst Sci 14:2289–2301
56. Nayak P, Rao Y, Sudheer K (2006) Groundwater level forecasting in a shallow aquifer using artificial neural network approach. Water Resour Manag 20:77–90
57. Nikolos IK, Stergiadi M, Papadopoulou MP, Karatzas GP (2008) Artificial neural networks as an alternative approach to groundwater numerical modelling and environmental design. Hydrol Process 22:3337–3348
58. Prommer H, Barry DA, Zheng C (2003) MODFLOW/MT3DMS based reactive multicomponent transport modeling. Ground Water 41(2):247–257
59. Rauber M, Stauffer F, Huggenberger P, Dracos T (1998) A numerical three dimensional conditioned/unconditioned stochastic facies type model applied to a remediation well system. Water Resour Res 34(9):2225–2233
60. Rubin Y (2003) Applied stochastic hydrogeology. Oxford University Press, New York, NY, USA
61. Rugner H, Finkel M, Kaschl A, Bittens M (2006) Application of monitored natural attenuation in contaminated land management: a review and recommended approach for Europe. Environ Sci Policy 9(6):568–576
62. Sadek M, Hagagg K (2020) A novel groundwater sustainability index using AHP/GIS approach. Int J Res Environ Sci (IJRES) 6(4):28–40. ISSN: 2454-9444. https://doi.org/10.20431/2454-9444.0604003
63. Sanchez-Vila X, Fernàndez-Garcia D (2016) Debates—Stochastic subsurface hydrology from theory to practice: why stochastic modeling has not yet permeated into practitioners? Water Resour Res 52:9246–9258
64. Sappa G, Barbieri M, Ergul S, Ferranti F (2012) Hydrogeological conceptual model of groundwater from carbonate aquifers using environmental isotopes (18O, 2H) and chemical tracers: a case study in Southern Latium Region, Central Italy. J Water Resour Protect 4(9):695–716. https://doi.org/10.4236/jwarp.2012.49080

65. Seol Y, Zhang H, Schwartz FW (2003) A review of in situ chemical oxidation and heterogeneity. Environ Eng Geosci 9(1):37–49
66. Shane AS (2014) Emerging chemical contaminants: looking for greater harmony. Am Water Work Assoc 108(8):38–52
67. Soltani N, Keshavarzi B, Moore F, Tavakol T, Lahijanzadeh AR, Jaafarzadeh N et al (2015) Ecological and human health hazards of heavy metals and polycyclic aromatic hydrocarbons (PAHs) in road dust of Isfahan metropolis, Iran. Sci Total Environ 505:712–723
68. Sorek S, Pinder GF (1999) Survey of computer codes and case histories. In: Bear J et al (eds) Seawater intrusion in coastal aquifers: concepts, methods, and practices. Kluwer Academic Publishers, Dordrecht, pp 399–461
69. Sophocleous M, Devlin JF (2002) Discussion on the water budget myth revisited: why hydrogeologists model. Ground Water 40(4):340–345
70. Szucs P, Madarasz T, Civan F (2009) Remediating over-produced and contaminated aquifers by artificial recharge from surface waters. Environ Model Assess 14(4):511–520
71. Tapoglou E, Karatzas GP, Trichakis IC, Varouchakis EA (2014) A spatio-temporal hybrid neural network-kriging model for groundwater level simulation. J Hydrol 519:3193–3203. https://doi.org/10.1016/j.jhydrol.2014.10.040
72. Thiruverikatachari R, Vigneswaran S, Naidu R (2008) Permeable reactive barrier for groundwater remediation. J Ind Eng Chem 14(2):145–156
73. Tokatli C, Uğurluoğlu A, Köse E, Çiçek A, Arslan N, Dayioğlu H et al (2021) Ecological risk assessment of toxic metal contamination in a significant mining basin in Turkey. Environ Earth Sci 80:17–19. https://doi.org/10.1007/s12665-020-09333-4
74. Travis CC, Doty CB (1990) Can contaminated aquifers at superfund sites be remediated? Environ Sci Technol 24(10):1464–1466
75. Trichakis IC, Nikolos IK, Karatzas GP (2009) Optimal selection of artificial neural network parameters for the prediction of a karstic aquifer's response. Hydrol Process 23:2956–2969
76. Van Tonder GJ, Botha JF, Chiang WH, Kunstmann H, Xu Y (2001) Estimation of the sustainable yields of boreholes in fractured rock formations. J Hydrol 241:70–90
77. Visser A, Hans Peter Broers AP, Ruth Heerdink R, Bierkens MFP (2009) Trends in pollutant concentrations in relation to time of recharge and reactive transport at the groundwater body scale. J Hydrol. https://doi.org/10.1016/j.jhydrol.2009.02.008
78. Wang M, Kulatilake PHSW, Panda BB, Rucker ML (2001) Groundwater resources case study via discrete fracture flow modelling. Eng Geol 62:267–291. Washington, DC
79. Water Science and Technology Board (1990) Groundwater models: scientific and regulatory application. National Academy Press
80. WHO (2021) A global overview of national regulations and standards for drinking-water quality. World Health Organization, Switzerland
81. Zeng YH, Huai WX (2014) Estimation of longitudinal dispersion coefficient in rivers. J Hydro-Environ Res 8(1):2–8
82. Zheng C, Bennett GD (1995) Applied contaminant transport modeling. Van Nostrand Reinhold, New York
83. Zheng C, Wang PP (1999) MT3DMS, a modular three-dimensional multi-species transport model for simulation of advection, dispersion and chemical reactions of contaminants in groundwater systems. Documentation and user's guide. U.S. Army Engineer Research and Development Center Contract Report SERDP-99-1, Vicksburg, 202 p
84. Zhou Y (2009) A critical review of groundwater budget myth, safe yield and sustainability. J Hydrol 370:207–213
85. Zhou Y, Li P, Chen M, Dong Z, Lu C (2021) Groundwater quality for potable and irrigation uses and associated health risk in southern part of Gu'an County, North China plain. Environ Geochem Health 43:813–835. https://doi.org/10.1007/s10653-020-00553-y

Groundwater Management

Groundwater Environment and Management in Kabul, Afghanistan

Abdulhalim Zaryab, Mohammad Zia Jamal, Mohammad Salem Hussaini, Asadullah Farahmand, and Shakir Ali

Abstract Kabul city is considered as one of the least developed cities of the world regarding access to clean water supply and effective sanitation. Numerous feasibility studies on Kabul Basin's surface and groundwater resources potential have been conducted over the past few decades. However, the Kabul residents are still facing drinking water shortage. The groundwater of Kabul Plain aquifer (KPA) is the primary source of water available in the Kabul for drinking, and widely utilized in agricultural and industrial sectors. Groundwater in the Kabul aquifer has significantly declined due to heavy abstraction of groundwater resulting in drying many shallow wells. The major challenges in groundwater resource management in the KPA are the lack of coordination among concerning organizations, unavailability of monitoring data, and lack of proper management framework. Therefore, strong implementations of proper policies are required for groundwater management in the Kabul Plain. This study highlights the current status of groundwater and various management issues in the Kabul Plain.

Keywords Groundwater · Sanitation in Afghanistan · Groundwater quality · Management of groundwater in Kabul · DPSIR indicators in Kabul

A. Zaryab (✉) · M. Z. Jamal · M. S. Hussaini
Faculty of Geology and Mines, Department of Engineering Geology and Hydrogeology, Kabul Polytechnic University, Kabul, Afghanistan
e-mail: a.zaryab@kpu.edu.af

M. Z. Jamal
e-mail: ziajamal@kpu.edu.af

A. Farahmand
Department of Hydrogeology, Ministry of Energy and Water, Kabul, Afghanistan

S. Ali
Department of Geology, University of Delhi, Delhi 110007, India
e-mail: shakiriitb@gmail.com

S. Ali and A. M. Armanuos (eds.), *Groundwater in Arid and Semi-Arid Areas*, Earth and Environmental Sciences Library, https://doi.org/10.1007/978-3-031-43348-1_10

1 Introduction

Groundwater is an important fundamental resource for socio-economic development of a country and one of the vital resources in the developing countries [2, 8, 11, 16, 19, 22, 26, 29, 33, 37, 38, 40, 46, 50, 53]. The Kabul is the fifth fastest growing city in the world and among in the world's most water-stressed cities [36]. Kabul, capital of Afghanistan has witnessed rapid unplanned urbanization since the last few years. In addition, rapid population growth, increase in gross domestic production (GDP) and drastic changes in land-use/land cover over the past two decades has poses serious thread to water security in Kabul.

The Kabul Plain aquifer is the primary source of water for drinking, agricultural and industrial purposes [7, 9, 25, 35, 38, 39, 45, 48]. Over the past two decades, groundwater tables have significantly declined due to excessive water withdrawal [10, 32, 49]. The groundwater abstraction from Kabul Plain aquifer was more than two times higher than the natural recharge rate [50]. Consequently, rapid urbanization and over-exploitation of groundwater has deteriorated the water quality significantly [13, 14, 28, 39, 50, 52].

Population growth and socio-economic development have resulted in over-abstraction of groundwater from the aquifer, considerable depletion of groundwater storage, and reduction of natural groundwater recharge in the Kabul Plain. Sewage was found to be the main source of nitrate because the city of Kabul has no centralized sewage collection system [50]. The major groundwater contaminants in Kabul Plain aquifer (KPA) are nitrate, salinity, boron, coliform, uranium, chromium and arsenic [31].

Before 2013, the country's management and monitoring of groundwater resource was under the Afghanistan Geological Survey (AGS), which is currently known as the Ministry of Mines and Petroleum. Presently, Ministry of Energy and Water of Afghanistan are responsible for monitoring and management of groundwater resource throughout the country. Rapid unplanned urbanization due to rapid population growth in the Kabul Plain has created a series thread to water security in the city. Poor coordination among various water-related institutions and shareholders leads to mismanagement and weak protection of groundwater resources in the Kabul Plain. Moreover, poor knowledge on law and regulations and lack of institutional framework resulted in poor management of groundwater resources in the Kabul Plain.

In this work, the groundwater resources' status has been documented and groundwater management issues in Kabul city have been highlighted. Here, the DPSIR (Drivers, Pressures, State, Impacts, and Responses) indicators have been employed to evaluate environment and management of groundwater resource of Kabul.

2 Study Area

Kabul is Afghanistan's capital, largest, and most populated city. Kabul city is located in the Kabul Plain in the southeastern part of the Kabul Basin in eastern Afghanistan lying between 69°02′E-69°23′E longitudes and 34°24′N–34°36′N latitudes. The Kabul Plain is divided into western and eastern parts by the Asma-e (TV) and Shire-e Darwaza mountains (Fig. 1). The Kabul city forms one of several districts of Kabul province and this district is further divided into 22 precincts (Fig. 1).

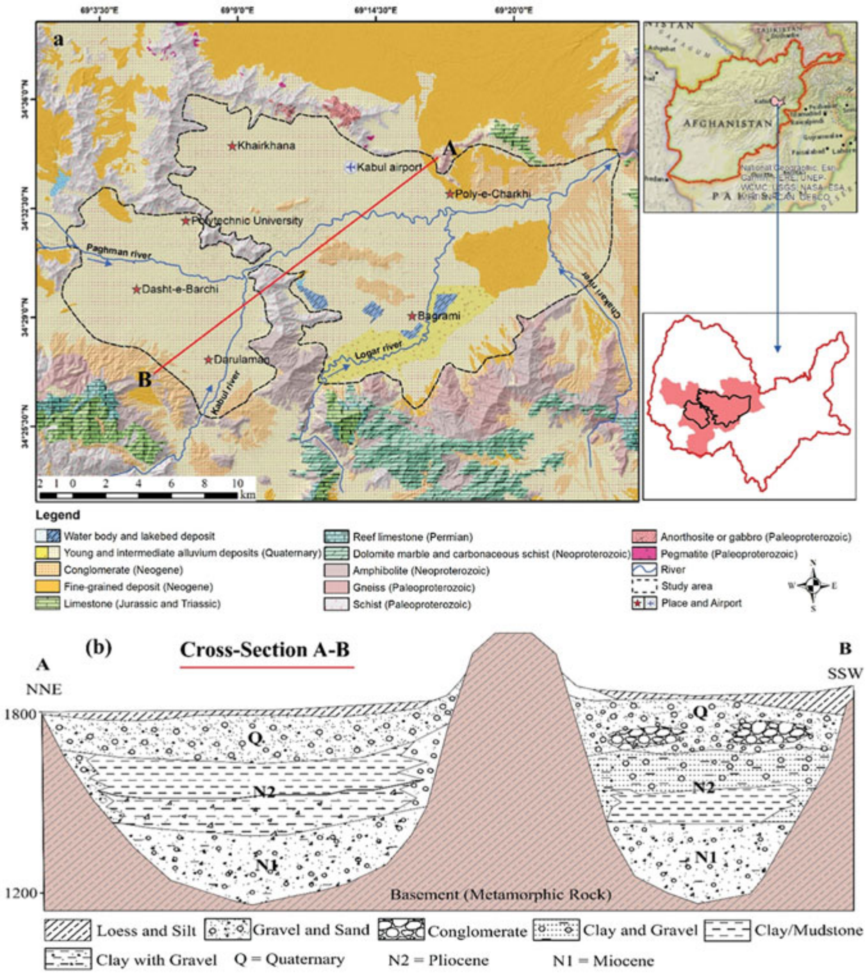


Fig. 1. **a** Geological map of Kabul and adjoining areas. **b** Conceptualized geological cross section of the study area [6, 50]. AB is the cross section profile shown in Fig. 1a.

Kabul Plain is surrounded by various metamorphic rocks such as gneiss, schist, amphibolite; and sedimentary rocks, including limestone and dolomite. The Kabul Plain is underlain by Neogene to Quaternary sedimentary basin and lies at a height of 1,800 m above mean sea level (Fig. 1). The seasonal rivers of Kabul are Paghman and Logar which flow through the Kabul Plain (Fig. 1). The Kabul Plain is characterized by arid and cold climate with an average annual precipitation and temperature of 315 mm and 14 °C, respectively. The current population of Kabul city was estimated to be more than 5.3 million [30].

2.1 Hydrogeology

The shallow aquifer is known as Quaternary aquifer and deep aquifer is known as Neogene aquifer [21]. Shallow aquifers primarily consist of gravels, conglomerates and sandy beds covered partially by loess clay and silts of Quaternary age. The thickness of the shallow aquifer is highly variable with an average thickness of 40 m. The hydraulic conductivity of Quaternary aquifer ranges from 2 to 40 m/day [51]. The deeper aquifers are composed of Neogene sediments and aquitard in nature [12, 21]. The thickness of Neogene sediments ranges from 30 to 600 m [17] and dominantly compose of sand, gravel and conglomerates with low storativity. The bed rocks are primarily metamorphic rocks such as gneiss, schist and amphibolites. Lately, several public and private wells were drilled in the deeper aquifer. The groundwater is extensively abstracted from the aquifers for domestic, agricultural and industrial usage.

3 Drivers

3.1 Population Growth

Kabul is estimated to have had roughly one million residents in 2001 [1]. After the establishment of peace and relative security in the country, thousands of Afghan refugees from Iran and Pakistan retuned to Afghanistan and most of them settled in the Kabul Plain. In addition, migration of people from rural areas to Kabul is also frequent due to employment, better life and good infrastructures. Therefore, there is sudden increase in population in the Kabul Plain, which leads to improper settlement construction in the city [3]. This directly put pressure on the available groundwater resources and presently struggling to provide water to the inhabitants.

Consequently, the population of Kabul city was gradually increased from one million in 2001 to more than 5.38 million in 2021 [30, 43]. Figure 2 shows the population growth in Kabul city over the last fifteen years. The graph clearly depicts that there is rapid increase in the population in Kabul city. However, at the mid of

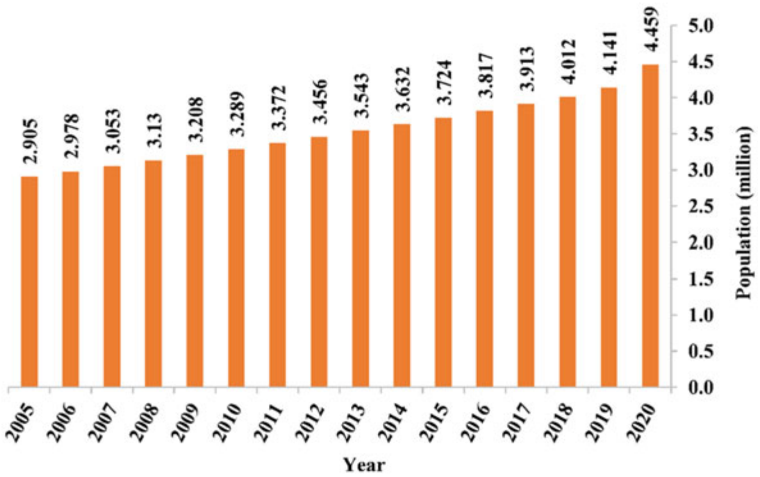


Fig. 2 Annual population growth from 2005 to 2020 in Kabul city [44]

2021, few Afghan people left the Kabul city, however there is no proper record of the number of migrants [4].

3.2 *Urbanization*

The Kabul Plain experienced rapid unplanned urbanization in the past two decades. There is considerable increase in the buildup areas and reduction in the agricultural areas. The primary cause of these changes is due to dramatic population growth in the country.

3.3 *Climate Change*

Based on the United Nations Framework Convention about climate change, Afghanistan is classified among the most vulnerable countries in the world to the adverse impacts of climate change. Afghanistan has witnessed severe impacts of climate change such as increasing temperatures, degradation of land and aquatic systems, and rapid events flash floods. A limited knowledge of climate change-induced various disasters and threats across the country [5].

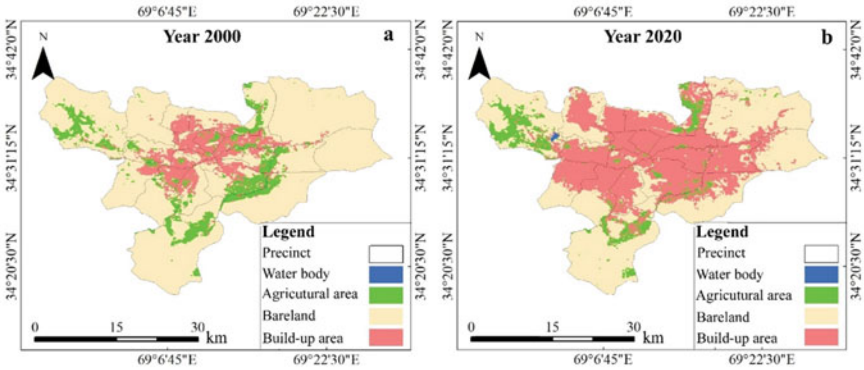


Fig. 3 Decadal land use/land cover change of Kabul city

4 Pressures

4.1 Land Use/Land Cover Changes

In general, four major land-use types were identified in the study area (Fig. 3a, b). According to the land use map, the agricultural lands were decreased remarkably from 106 km^2 in 2001 to 76 km^2 in 2020 whereas, the built-up area was exponentially increased from 161 km^2 in 2005 to 410 km^2 in 2020.

The built-up area development has caused a decline of bare land areas, which shows a decline from 762 to 546 km^2 over the considered period. Notably, over 70% of the Kabul population is estimated to live in informal settlements [50]. The concerned authorities in Afghanistan were not successfully controlled the informal settlements due to the mismanagement and lack of a proper compressive urban master plan for the Kabul Plain. The rapid and primarily unplanned urbanization in the Kabul Plain are major issues and has adversely impact the environmental and social health.

4.2 Utilization of Surface Water and Groundwater

Three rivers such as Paghman, Kabul, Logar rivers are backbone of the Kabul Plain (Fig. 1). These rivers flow during wet season and occasionally run dry during the dry season. Fine materials are accumulated in the river beds and thus decreased infiltration capacity. The river water is partially used for agricultural and green space applications in the Kabul Plain. However, the groundwater is main source of drinking water for Kabul city's inhabitants. The people supply their drinking water through shallow and deep wells. Almost all deep wells are drilled in the past two decades. The number of wells installed in Kabul is unknown and there is no exact information that how much water are annually extracted from the aquifer. Zaryab [51] reported

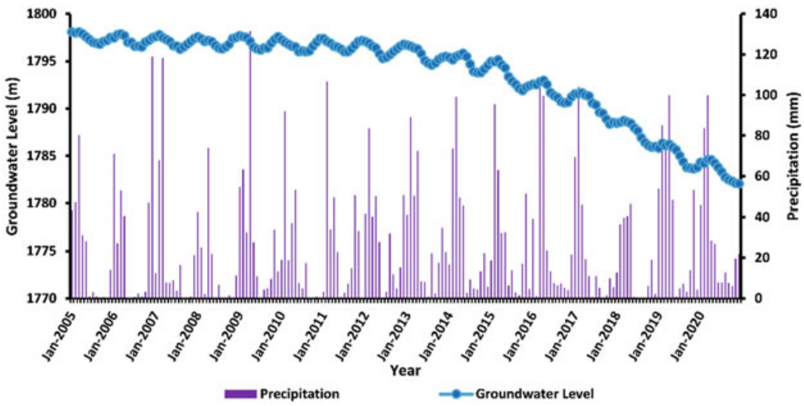


Fig. 4 Decline of groundwater tables in Kabul plain (2005–2020) [50]. *Note* There is also a significant decline of rainfall with time

that about 221 MCM of water are abstracted from the aquifer during the period of October 2020 to September 2021.

5 State

5.1 Water-Table Fluctuations

Presently, monitoring wells are monitored by Ministry of Energy and Water of Afghanistan. The ministry reported that groundwater tables have declined across the plain, particularly in northwest of the eastern plain (Khairkhana) and in southwest of the western plain (Dash-e-Barchi) over the past 13 years (Fig. 5). The mentioned regions are the most densely populated areas in the Kabul city. The hydrograph indicates that the decline in groundwater level has rapidly increased since 2011 (Fig. 4). It is most likely due to population growth, rapid unplanned urbanization, and climate change. Recently, precipitation pattern has changed from snow to rain and likely to be linked to recent climate change and urbanization. Presently, a considerable number of shallow wells and the only remained wetland (Kole Hashmat Khan) have been drilled up over recent years due to extensive groundwater exploitation [41, 50].

5.2 Groundwater Depletion

As mentioned earlier, Kabul witnessed a rapid and mostly unplanned urbanization over the past two decades. The groundwater tables in the Kabul Plain aquifer have

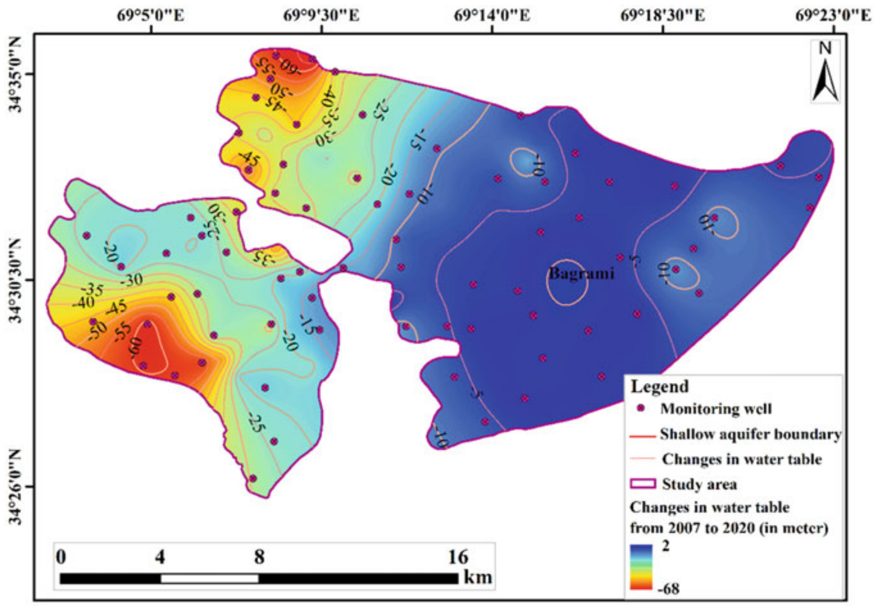


Fig. 5 Changes in groundwater level from November 2007 to November 2020 [50]

considerably declined due to over-abstraction. Figure 5 indicates that from 2007 to 2020, water tables have considerably dropped down all across the plain except in the southeast of the eastern plain. Nevertheless, water table decline is not uniformly distributed all over the plain. The main decline was seen in the northwest and southwest region of the study area (Fig. 5). The average groundwater table decline from 2007 to 2020 is about 16.5 m, and the total area of the aquifer is 271 km^2, and the average specific yield of the aquifer is 0.10 (Fig. 5; [51]). It was estimated that nearly 447,150 million cubic meters (MCM) of groundwater was decreased from the Kabul Plain aquifer over the last 13 years [50].

The past studies indicate that the primary and productive aquifer in the Kabul Plain is Quaternary aquifer (shallow aquifer), but in the most part of the plain, the water table dropped down below the shallow aquifer resulting in drying of shallow wells [20]. The deep aquifer has been identified as fossil water by JICA [17] however, the age of the water has not been investigated. In addition, the storativity of deeper aquifer is very low as compared to shallow aquifer [21]. Rapid abstraction in the Kabul Plain has caused changes in groundwater flow direction. Currently, groundwater flow directions concentrate towards the center of the plains [50]. It is worth mentioning that both public and private concerned stakeholders were ineffective in minimizing over-abstraction.

5.3 Sewage

The Kabul city has no centralized sewerage system. Sewage collection and treatment plants work only at a smaller scale and only restricted to newly developed townships [34]. The Kabul Plain aquifer characterized by aerobic condition, which likely promote nitrification process [50].

5.4 Groundwater Quality

Rapid urbanization in Kabul Plain and excessive use of fertilizers in agricultural areas resulted in groundwater deterioration. The major reported groundwater contaminants in KPA are nitrate, boron, salinity and coliform [15]. Zaryab et al. [50] reported that there is a positive relationship between groundwater-table decline and reducing nitrate concentrations over the years. The authors also observed that urban sewage is the main source of nitrate in KPA followed by soil organic nitrogen and chemical fertilizer. High concentrations of boron are mainly observed in northern KPA [39]. However, a detailed study on boron contamination was not conducted. Zaryab et al. [49] observed that the evaporitic lacustrine deposits are the main source of groundwater salinity in eastern KPA. In terms of other contaminants arsenic, uranium and chromium exceeded WHO guidelines [24]. In general, groundwater quality of western KPA is relatively better than eastern KPA. This is due to presence of evaporitic lacustrine deposits in the eastern Kabul Plain [49].

5.5 Availability of Water in the Kabul Basin

The main potential of surface and groundwater resources within the Kabul Basin are Panjshir river, Loger River, Maidan River, Salang River and Panjshir fan aquifer [31, 48]. Over the past decade, several feasibility studies of surface water and groundwater projects have been carried out by the government of Afghanistan with the technical and financial cooperation of international organizations in Kabul Basin. But still nothing has been performed to supply potable water for Kabul city's residents from other available water resources in the basin. Over the past two decades, groundwater storage was considerably depleted in Kabul Plain due to over-abstraction. Zaryab et al. [50] recently reported that the groundwater abstraction is higher than two fold than the rate of natural recharge. Therefore, an urgent action is required to supply drinking water for Kabul city's residents from other available water resources within the basin for potable water in the future.

6 Impacts

6.1 Land Subsidence

Meldebekova et al. [27] conducted a study on the ground subsidence in the Kabul Plain due to groundwater over-abstraction. Their study revealed an average yearly vertical displacement of up to −5.3 cm/year, from 2014 to 2019. It was concluded that the larger the groundwater level drop, the greater will be the subsidence rates.

7 Responses

7.1 Groundwater Monitoring and Assessment

The groundwater balance is not calculated for the KPA and the annual recharge and discharge is unknown. Before 2013, the AGS was responsible for exploring and managing groundwater resources in Afghanistan. After 2013, the Hydrogeology Department of the Ministry of Energy and Water (MEW) is engaged in monitoring, managing and documentation of groundwater quantity and quality in Afghanistan. The DACAAR organization is also involved in groundwater monitoring in the country. The goal of DACAAR's groundwater monitoring network is to provide long-term scientific data regarding status of groundwater resources in terms of quantity and quality in the country. Currently, the groundwater table in 75 wells is monthly measured by MEW in the Kabul Plain. Groundwater samples are collected on semi-annual basis for groundwater quality analysis. In addition, about 42 monitoring wells also have been drilled and equipped by diver/data logger for automatic measurements of groundwater level, temperature and salinity [21].

Generally, the knowledge of groundwater resources of the country is limited. Although, some projects have been carried out to quantify groundwater resources availability and demand in the Kabul Basin [17, 23]. However, there is no national program to assess the groundwater resources availability and demand annually in the country. Even though, groundwater is the main source for domestic and agricultural purposes, there is lack of proper management of the resource which may be due to groundwater invisible nature and more focus is given on the surface water management particularly in Kabul city.

7.2 Poor Coordination Among Various Water-Related Organizations

The Afghan government working towards water resources management from the beginning of 1960s. Water-related institutions evolved based on changing national priorities. The Afghanistan Water Law of 2009 proposed highly unfeasible regulatory policies which was failed at the ground level. The policies have significant gaps, particularly with regard to the clarity and division of responsibilities among various concerned agencies and stakeholders. With the aid of the World Bank, the Urban Water Supply and Sewerage Corporation (AUWSSC) has been established in 2007. However, the AUWSSC has entirely focused on urban water supply and no centralized sewerage system has yet been established anywhere in the country and in Kabul city by this entity.

There is a lack of measures in current management of water sources, particularly groundwater in Kabul and whole of Afghanistan. The implementation of Integrated Water Resources Management (IWRM) was added to the new Water Affairs Management Law of 2020 as a tool to develop national water resources. However, in practice, insufficient steps have been taken to incorporate IWRM in water resources planning processes in Afghanistan. But poor coordination among different water-related institutions and shareholders leads to mismanagement and weak protection of groundwater resources in the country.

The investment in monitoring groundwater systems is much less than Afghanistan surface water resources. While, the groundwater is the main source for drinking and agriculture. In addition, it seems that major challenges to the successful coordination among groundwater-related organizations can be the lack of data availability and sharing, inter-departmental coordination, poor knowledge on law and regulations and lack of institutional framework and government instability. These challenges are inter-related which are only possible through adequate regulatory/institutional/policy framework. On the other hand, research and development on the groundwater resources is hindered by the limited availability of long-term, accurate and comprehensive hydrological data. Each organization is collecting data and storing it in their-selves database with restrictions for sharing. As most of Afghanistan's major cities, particularly Kabul, are facing diminishing water resources, the multi-sectoral data management in line with the comprehensive approach can boost groundwater resource efficiency. Lack of data sharing hindered making of strong policies for the proper management of water resource.

Water resources development in Afghanistan have been sporadic, fragmented, and project-based rather than sector-based. The water-related institutions and agencies need to consider the transform from project-based development to sector-based and onward to multi-sectoral integrated planning and development. Institutional capacity is the key to successful water management in Afghanistan. Afghanistan has different tiers of government, i.e., central, provincial, and district. However, decision making is highly centralized, therefore, local institutions were not involved in making a better policy.

Currently, there are four governing authorities that are directly involved in the management of water resources in Afghanistan. Ministry of Rural Development and Rehabilitation, Ministry of Urban Development and Lands, Ministry of Agriculture, and Ministry of Water and Energy. A comprehensive database and information systems involving expertise from other sectors should be established to formulate strategy for the rehabilitation of irrigation systems. Appropriate institutional arrangements should be made for proper coordination of different ministries and line agencies involved in the management of water resources. The roles and responsibilities of these organizations should be clearly defined to avoid overlapping and effective water resource management at all levels. Controlling private water supply companies attempt to withdrawal more water and selling to the Kabul residents must be checked. Thus, supervision and control from government side on private water supply companies will be an important step for the management of water resource.

7.3 Water-Scarcity, Conflict and Migration

In Afghanistan, the annual water supply relies largely on winter precipitation in the mountains that accumulates as snow, ice, glaciers, this has resulted in on the worst droughts of the past two decades. About 70% of Afghans lives in rural areas and they depend directly on agriculture for their livelihoods [42]. Water shortages in 2022 have devastated Afghanistan's agriculture and pastures and led to water scarcity for human consumption. The water situation is changing in Kabul Plain due to several factors such as rapid urbanization, population growth, over-exploitation and mismanagement of water resources, and climate change. These stresses can affect 35% or around 8 million of Afghanistan's population living in Kabul basin. Of these, about 5.3 million lives in Kabul city, which is expected to increase to around 8 million by 2050. In the meantime, many people are left with little or no water. The AUWSSC has estimated that about 30% of residents in Kabul city have access to piped water and only around 10% of them receive potable water [18]. The remaining residents supply their drinking water private or private company water supply wells. In some parts of the Kabul city like Chelston, the people do not receive drinking water through private piped water even after 10 days. There is no guarantee from private companies to provide reliable water for the residents. In addition, gradually increase the water cost and the people have to pay for them. Therefore, the Kabul city residents do not rely on private water supply companies. Kabul city facing increased water insecurity and needs an urgent action from the Afghan government to provide drinking water.

7.4 More Cost and Poverty

Reliance on groundwater for irrigation and a growing population have led to greater groundwater use and chronically declining groundwater tables in most parts of the city. This has important implications as more energy is needed to withdraw groundwater from greater depths. As a result, the city is struggling with increased electricity costs associated with groundwater withdrawal, and the cost of drilling depth wells. In addition, increased food prices are expected from higher energy costs and reduced water availability.

8 Conclusion

The rapid population growth in Kabul Plain has resulted in unplanned urbanization in the past two decades. The urbanization put huge pressure on the availability of groundwater which is only the primary source for drinking. Further, considerable reduction in agricultural area and exponential increase of residential areas reduces the recharge into groundwater. Additionally, insufficient rainfall due to climate change significantly reduced the recharge to the groundwater.

The major pollutants in the groundwater are the contaminants such as uranium, chromium, nitrate, salinity, and arsenic. Thus, providing safe water supply to the inhabitants of Kabul is highly challenging to the concerned governing authorities. Moreover, poor knowledge on law and regulations and lack of institutional framework resulted in mismanagement of groundwater resources in the country. The study suggests that the Kabul city's residents will face with a serious drinking water shortage in the upcoming years. Therefore, timely management of groundwater in the Kabul city is required.

9 Recommendations

In most parts of the Kabul, the residents are already faced with drinking water shortages and this problem will certainly increase in the future. Therefore, it is highly recommended to supply drinking water from available safe surface and groundwater resources within the Kabul Basin such as Panjshir river, Maidan River, Salang River and Panjshir alluvial fan aquifer. Water-related institutional policies is the key to successful and sustainable water management in the country.

Conflict of Interest The authors declare no conflict of interest.

Funding This research did not receive any specific grant from funding agencies.

Author Contributions All authors contributed significantly to the study conception and design, data collection, material preparation and data interpretation and were carried out by Abdulhalim Zaryab, Mohammad Zia Jamal, Mohammad Salem Hossaini, Asadullah Farahmand and Shakir Ali. The first draft of the manuscript was written by Abdulhalim Zaryab. All authors read and approved the final manuscript.

References

1. Afghanistan Public Policy Research Organization (APPRO) (2012) Migration and urban development in Kabul: classification or accommodation? Newcomers and host communities in district 5, 7 and 13 in Kabul, Afghanistan
2. Ali S, Kumar S, Shekhar S (2021) Spatio-temporal dynamics of groundwater resources of national capital region, Delhi. In: Adhikary PP, Shit PK, Santra P, Bhunia GS, Tiwari AK, Chaudhary BS (eds) Geostatistics and geospatial technologies for groundwater resources in India. Springer hydrogeology. Springer, Cham, pp 473–484. ISBN: 978-3-030-62396-8. https://doi.org/10.1007/978-3-030-62397-5_24
3. Amiri BA, Lukumwena N (2018) An overview of informal settlement upgrading strategies in Kabul city and the need for an integrated multi-sector upgrading model. SCIRP 6(3):348–365. https://doi.org/10.4236/cus.2018.63019
4. Bathke B (2022) What's the status of displaced Afghans worldwide. https://www.infomigrants.net/en/post/38943/whats-the-status-of-displaced-afghans-worldwide. Accessed Nov 2022
5. Beier AC (2019) Sida's helpdesk for environment and climate change. Afghanistan
6. Bohannon RG (2010) Geologic and topographic maps of the Kabul North 30 × 60 quadrangle, Afghanistan: U.S. Geological survey scientific investigation map 3120, 34 p. pamphlet, 2 map sheets, scale 1: 100,000. http://pubs.usgs.gov/sim/3120
7. Brati MO, Ishihara MI, Higashi O (2019) Groundwater level reduction and pollution in relation to household water management in Kabul, Afghanistan. Sustain Water Resour Manag 5:1315–1325. https://doi.org/10.1007/s40899-019-00312-7
8. Choi B, Yun S, Yu S, Lee P, Park S, Chae G et al (2005) Hydrochemistry and urban groundwater in Seoul, South Korea: effects of land use and pollutant recharge. Environ Geol 48:979–990. https://doi.org/10.1007/s00254-004-1205-y
9. Farahmand A, Hussaini MS, Zaryab A, Aqili SW (2021) Evaluation of hydrogeoethics approach or sustainable management of groundwater resources in the upper Kabul sub-basin, Afghanistan. Sustain Water Resour Manag 7(48):8. https://doi.org/10.1007/s40899-021-00525-9
10. Hamidi MD, Kissane S, Bogush AA, Karim AQ, Sagintayev J, Towers S, Greenwell HC (2023) Spatial estimation of groundwater quality, hydrogeochemical investigation, and health impacts of shallow groundwater in Kabul city, Afghanistan. Sustain Water Resour Manag 9:1–20. https://doi.org/10.1007/s40899-022-00808-9
11. Foster SSD (2001) The interdependence of groundwater and urbanization in rapidly developing cities. Urban Water 3:185–192. https://doi.org/10.1016/S1462-0758(01)00043-7
12. Houben G, Tünnermeier T, Himmelsbach T (2005) Hydrogeology of the Kabul Basin Part II: groundwater geochemistry and microbiology. BGR
13. Houben G, Tünnermeier T, Eqrar N, Himmelsbach T (2009) Hydrogeology of the Kabul Basin (Afghanistan), part II: groundwater geochemistry. Hydrogeol J 17:935–948. https://doi.org/10.1007/s10040-008-0375-1
14. Hussaini MS, Farahmand A, Shrestha S, Neupane S, Abrunhosa M (2022) Site selection for managed aquifer recharge in the city of Kabul, Afghanistan, using a multi-criteria decision analysis and geographic information system. Hydrogeol J 30:59–78. https://doi.org/10.1007/s10040-021-02408-x

15. Jawadi HA, Iqbal MW, Naseri M, Farahmand A, Azizi AH, Eqrar MN (2022) Nitrate contamination in groundwater of Kabul Province, Afghanistan: reasons behind and conceptual management framework discourse. J Mt Sci 19(5):1274–1291. https://doi.org/10.1007/s11629-021-7002-1
16. Jia X, O'Connor D, Hou D, Jin Y et al (2019) Groundwater depletion and contamination: spatial distribution of groundwater resources sustainability in China. Sci Total Environ 672:551–562. https://doi.org/10.1007/s10040-008-0332-z
17. Japan International Cooperation Agency (JICA) (2011) The study on groundwater resources potential in Kabul Basin, Kabul, Afghanistan
18. Kazemi SR (2018) Blue gold: the quest for household water in Kabul city. https://reliefweb.int/report/afghanistan/blue-gold-quest-household-water-kabul-city. Accessed Nov 2022
19. La Vigna F (2022) Review: Urban groundwater issues and resource management, and their roles in the resilience of cities. Hydrogeol J 30:1657–1683. https://doi.org/10.1007/s10040-022-02517-1
20. Landell Mills (2020) Project atlas, TA 8969. AFG: Kabul Managed Aquifer Recharge Project Preparation
21. Landell Mills (2020) Regional groundwater model, TA 8969. AFG: Kabul Managed Aquifer Recharge Project Preparation
22. Liu W, Chen W, Feng Q, Deo RC (2018) Situations, challenges and strategies of urban water management in Beijing under rapid urbanization effect. Water Supply 19:115–127. https://doi.org/10.2166/ws.2018.057
23. Mack, TJ, Akbari, MA, Ashoor, MH, Chornak, MP, Coplen, TB, Emerson, DG, Hubbard, BE, Litke, DW, Michel, RL, Plummer, LN, Rezai, MT, Senay, GB, Verdin, JP, and Verstraeten, IM. (2010) Conceptual model of water resources in the Kabul Basin, Afghanistan: U.S. Geological Survey Scientific Investigations Report 2009-5262. 240 pp. http://pubs.usgs.gov/sir/2009/5262
24. Mahaqi M, Mehiqi M, Moheghy MA, Moheghi MM, Hussainzadeh J (2021) Nitrate pollution in Kabul water supplies, Afghanistan; sources and chemical reactions: a review. Int J Environ Sci Technol. https://doi.org/10.1007/s13762-021-03551-4
25. Mahdawi Q, Sagin JM, Absametov M, Zaryab A (2022) Water recharge suitability in Kabul aquifer system within the Upper Indus Basin. Water 14:2390. https://doi.org/10.3390/w14152390
26. Mayer MA (2021) Global warming and Afghanistan: Drought, hunger, and thirst expected to worsen. https://www.afghanistan-analysts.org/en/reports/economy-development-environment/global-warming-and-afghanistan-drought-hunger-and-thirst-expected-to-worsen/. Accessed Nov 2022
27. Meldebekova G, Yu C, Li Z, Song C (2020) Quantifying ground subsidence associated with aquifer overexploitation using space-borne radar interferometry in Kabul, Afghanistan. Remote Sens 12(15):2461. https://doi.org/10.3390/rs12152461
28. Mohammaddost A, Mohammadi Z, Rezaei M, Pourghasemi HR, Farahmand A (2022) Assessment of groundwater vulnerability in an urban area: a comparative study based on DRASTIC, EBF, and LR models. Environ Sci Pollut Res 29:72908–72928. https://doi.org/10.1007/s11356-022-20767-0
29. Morris BL, Seddique AA, Ahmed KM (2003) Response of the DupiTila aquifer to intensive pumping in Dhaka, Bangladesh. Hydrogeol J 11:496–503. https://doi.org/10.1007/s10040-003-0274-4
30. National Statistic and Information Authority (NSIA) (2020) Estimated population of Afghanistan 2020–21. https://nsia.gov.af/library
31. Noori AR, Singh SK (2021) Status of groundwater resource potential and its quality at Kabul, Afghanistan: a review. Environ Earth Sci 80(18):1–13. https://doi.org/10.1007/s12665-021-09954-3
32. Noori AR, Singh SK (2021) Spatial and temporal trend analysis of groundwater levels and regional groundwater drought assessment of Kabul, Afghanistan. Environ Earth Sci 80:698. https://doi.org/10.1007/s12665-021-10005-0

33. Oiro S, Comte J-C, Soulsby C, MachDonald A, Mwakamba C (2020) Depletion of groundwater resources under rapid urbanization in Africa: recent and future trends in the Nairobi Aquifer System, Kenya. Hydrogeol J 28:2635–2656. https://doi.org/10.1007/s10040-020-02236-5
34. Paiman Z, Noori AR (2019) Evaluation of wastewater collection and disposal in Kabul city and its environmental impacts. Mod Environ Sci Engb 5(5):451–458. https://doi.org/10.15341/mese(2333-2581)/05.05.2019/012
35. Qureshi AS (2002) Water resources management in Afghanistan: the issues and options, working paper 49 IWMI, Pakistan country series no 14
36. Rasmussen SE (2015) Kabul-the fifth fastest growing city in the world-is bursting at the seams. The Guardian. https://www.theguardian.com/cities/2014/dec/11/kabul-afghanistan-fifth-fastest-growing-city-world-rapid-urbanisation. Accessed Sep 2022
37. Sarkar A, Ali S, Kumar S, Shekhar S, Rao SVN (2016) Groundwater environment in Delhi, India. In: Shrestha S, Pandey V, Thatikonda S, Shivakoti B (eds) Groundwater environment in Asian cities. Elsevier, pp 77–108. https://doi.org/10.1016/B978-0-12-803166-7.00005-2. ISBN: 978-0-12-803166-7
38. Saffi MH (2011) Groundwater natural resources and quality concern in Kabul Basin, Afghanistan, DACAAR, Kabul
39. Saffi MH (2019) National alarming on groundwater natural storage depletion and water quality deterioration of Kabul city and immediate response to the drinking water crises. DACAAR, Kabul
40. Shams AK, Muhammad NS (2021) Toward sustainable water resources management: critical assessment on the implementation of integrated water resources management and water–energy–food nexus in Afghanistan. Water Policy 24(1):1–18. https://doi.org/10.2166/wp.2021.07
41. Shroder J, Ahmadzai SJ (2016) Transboundary water resources in Afghanistan: climate change and land-use implications. Elsevier, Amsterdam
42. The World Bank (2021) Lack of water linked to 10 percent of the rise in global migration. https://www.worldbank.org/en/news/press-release/2021/08/23/lack-of-water-linked-to-10-percent-of-the-rise-in-global-migration#:~:text=The%20report%20finds%20that%20water,affect%20about%20700%20million%20people. Accessed Oct 2022
43. The Work Bank (2022) Afghanistan GDP 1960–2022. https://www.macrotrends.net/countries/AFG/afghanistan/gdp-gross-domestic-product. Accessed Aug 2022
44. United Nations (2021) Kabul, Afghanistan metro area population 1950–2021. https://www.macrotrends.net/cities/20002/kabul/population. Accessed Aug 2022
45. Wafa W, Hairan MH, Waizy H (2020) The impacts of urbanization on Kabul city's groundwater quality. Int J Adv Sci Technol 29(4):10796–10809
46. Wakode HB, Baier K, Jha R, Azzam R (2017) Impact of urbanization on groundwater recharge and urban water balance for the city of Hyderabad, India. Int Soil Water Int Soil Water Conserv Res 6(1):51–62. https://doi.org/10.1016/j.iswcr.2017.10.003
47. The Word Bank (2021) Afghanistan GDP 1960–2021. https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=AF. Accessed Nov 2022
48. Zaryab A, Noori AR, Wegerich K, Kløve B (2017) Assessment of water quality and quantity trends in Kabul aquifers with an outline for future drinking water supplies. CAJWR 3:3–11
49. Zaryab A, Nassery HR, Alijani F (2021) Identifying sources of groundwater salinity and major hydrogeochemical processes in the lower Kabul Basin aquifer, Afghanistan. Environ Sci Process Impacts 23:1589–1599. https://doi.org/10.1039/D1EM00262G
50. Zaryab A, Nassery HR, Alijani F (2022) The effects of urbanization on the groundwater system of the Kabul shallow aquifers, Afghanistan. Hydrogeol J 30:429–443. https://doi.org/10.1007/s10040-021-02445-6
51. Zaryab A (2022) Determination of the source of nitrate in Kabul aquifer using isotopic indicators and simulation of contaminant transport, PhD thesis, Shahid Beheshti University, Tehran
52. Zaryab A, Nassery HR, Knoeller K, Alijani F, Minet E (2022) Determining nitrate pollution sources in the Kabul Plain aquifer (Afghanistan) using stable isotopes and Bayesian stable isotope mixing model. Sci Total Environ 823:153749. https://doi.org/10.1016/j.scitotenv.2022.153749

53. Zhou Y, Wang L, Liu J, Li W, Zheng Y (2012) Options of sustainable groundwater development in Beijing Plain, China. Phys Chem Earth 47–48:99–113. https://doi.org/10.1016/j.pce.2011.09.001

Groundwater in the Nile Delta Aquifer, Egypt: Assessment, Modelling and Management with Climate Change in the Core

Asaad M. Armanuos, Sobhy R. Emara, Ahmed Shalby, Mohamed I. Metwally, Am Pris John, and Abdelazim Negm

Abstract Groundwater (GW) in the Nile Delta aquifer (NDA) is one of the most abundant freshwater sources of Egypt. Different activities such as agriculture, GW pumping, urbanization, industrial discharges and waste disposal significantly impact the quality of GW. Therefore, GW pollution has become a critical environmental issue in Egypt. The increasing use of fertilizers, pesticides, and the saltwater intrusion (SWI) into Mediterranean's coastal areas put the GW of the Nile Delta (ND) at a high risk of contamination. Furthermore, increasing pumping discharges and Sea Level Rise (SLR) further exacerbate the rate of SWI and deteriorate the GW quality of the ND. Understanding GW vulnerability is crucial for decision makers to manage GW resources and assess risks effectively. Moreover, GW modelling provides a comprehensive overview of water flow and contaminant transport through aquifers, aiding in assessment and GW resources management. This book chapter provides insights on the previous GW vulnerability studies, GW modelling, SWI modelling, and GW management studies in the NDA. The research can be applied to future

A. M. Armanuos (✉) · S. R. Emara · A. Shalby · M. I. Metwally
Faculty of Engineering, Tanta University, Tanta, Egypt
e-mail: asaad.matter@f-eng.tanta.edu.eg

S. R. Emara
e-mail: sobhy_emara39@f-eng.tanta.edu.eg

A. Shalby
e-mail: ahmed.shalby@f-eng.tanta.edu.eg

M. I. Metwally
e-mail: mohammedmetwally@f-eng.tanta.edu.eg

A. P. John
Department of Environmental Engineering (DIAm), University of Calabria, Via P. Bucci, 42B, 87036 Rende, Italy
e-mail: ampris.john@unical.it

A. Negm
Department of Water & Water Structures Engineering, Faculty of Engineering, Zigazig University, Zigazig, Egypt
e-mail: amnegm@zu.edu.eg

S. Ali and A. M. Armanuos (eds.), *Groundwater in Arid and Semi-Arid Areas*, Earth and Environmental Sciences Library, https://doi.org/10.1007/978-3-031-43348-1_11

resource management for GW in the Nile Delta (ND), freshwater protection, and risk management.

Keywords Groundwater · Saltwater intrusion · Nile Delta aquifer · Groundwater management · Groundwater pollution

1 Introduction

Coastal aquifers are an essential source of freshwater globally, particularly in arid and semi-arid regions with little rainfall and limited surface freshwater bodies. In arid and semi-arid regions, the development and urbanization of coastal zones are increasingly reliant on the groundwater supplies. Excessive pumping in coastal aquifers leads to a reduction in freshwater flux towards the sea and rainfall infiltration into the aquifer, resulting in saltwater intrusion extending inland, [9]. One of these coastal aquifers that is susceptible to saltwater intrusion from the Mediterranean Sea is the Nile Delta aquifer (NDA). The NDA has experienced intense GW pumping over the past 30 years. At present, there is a considerable dispersion zone between the freshwater in the aquifer and the saltwater intrusion from the Mediterranean Sea. Another significant fact is that climate change and sea level rise are accelerating the degree of seawater intrusion in the NDA. All in all, land usage, coastal erosion, potential impacts of sea level rise, seawater intrusion, and declining water quality are the top five concerns in the region of the Nile Delta. Therefore, this book chapter provides useful information on earlier studies regarding monitoring and data availability of NDA, groundwater vulnerability to pollution, groundwater flow modelling, seawater intrusion modelling, and groundwater management studies.

2 Monitoring of Groundwater in the Nile Delta and Data Availability

Understanding dynamic characteristics of a large aquifer system requires an inventory of its hydrologic, climatological, and geological attributes. Utilization and interpretation of observed data is closely related to other branches of earth sciences and necessitates a routine monitoring programme. Regarding the NDA, retrieving such a complete dataset is a key challenge. The majority of the observation data are inaccurate and limited in records [96]. Additionally, groundwater pumping data are not readily available and such data are treated as private and confidential [5]. Reports of hydrochemistry analysis habitually contain significant gaps and are occasionally questionable [23]. There is still a lack of data presenting heterogeneity in hydrogeological parameters despite the use of common interpolation and infilling methods [148]. According to [39, 65], there are consistent and undeservedly similar conditions in the aquifer's formations in the modelling study of NDA.

In order to overcome the scarcity of recent dataset, unconventional monitoring techniques (e.g., satellite-based data and geoelectric resistivity) are utilized. Data derived from the gravity recovery and climate experiment (GRACE) satellites mission are successfully operated to monitor variations in the entire aquifers' storage [104] or a portion of it [66, 105]. Geoelectrical resistivity are applied for imaging groundwater level, capturing the seawater-freshwater interfaces and delineating the lithology within the investigated parts of the aquifer [20, 97, 139, 168]. In the following sections, an investigation of the main characteristics of the aquifer system is presented which will be vital in outlining its hydrogeological environment.

2.1 Geometry and Geologic Setting

The NDA is bordered by clear hydraulic boundaries that delineate the system's extent geometry, as shown in (Fig. 1). The aquifer, which is oriented as a triangle, has its apex at the Cairo, the capital of Egypt. The aquifer is bounded to the north by the Mediterranean Sea, which creates its bottom. The El-Nubariya canal (a main irrigation canal) limits the aquifer to the west. The Suez Canal (a ship navigation saline canal) and the Ismailia canal (a main irrigation canal) are the eastern limiting boundaries. As a consequence, the aquifer covers an area of 30 million hectares [104]. The two Nile River branches (e.g., Damietta and Rosetta) represent a distinct feature of the aquifer GW system. Therefore, the aquifer is tapped by a complex irrigation and drainage networks [37]. A successive hydraulic structure including barrages, regulators and dams controls the water levels of these canals and drains. Furthermore, there is a substantial hydrogeological connection between the surface water and the aquifer reserve [117]. The entire NDA can be divided into three major sub-regions distinct in their geomorphology, hydrogeological and hydro-chemical features: the eastern fringe (area of 10 m Ha), the floodplain (area of 9 m Ha), and the western fringe (area of 11 m Ha).

Geologically, the Nile Delta aquifer is made up of a Quaternary stratum in which gravel and sand are overlaid by a Holocene aquitard. According to Sakr et al. [135], a clay cap of a depth varies from 5 to 20 m and hydraulic conductivity in the vertical direction equals to 0.67 mm/day. The thickness of aquifer decreases from 900 m in the north to 600 m in the middle and reach approximately 200 m in the south [37]. The primary water-bearing layer consists of sand and gravel deposits belonging to the Pleistocene and the Holocene, and this layer is intercalated by a thin clay lens [157]. More than this, the NDA is underpinned by a basal aquiclude of Pliocene, mainly composed of marine clay. It has its maximum depth in the ND center and extends to the outskirts with a average gradient of approximately 4 m/km [37].

As the aquifer's dimensions in the horizontal direction are equal to 100 times of its thickness, the flow is essentially supposed to be horizontal. The flow in vertical direction is generally unimportant except within the coastal margins [148]. However, the flow is essentially vertical within the upper aquitard and the horizontal flow is insignificant.

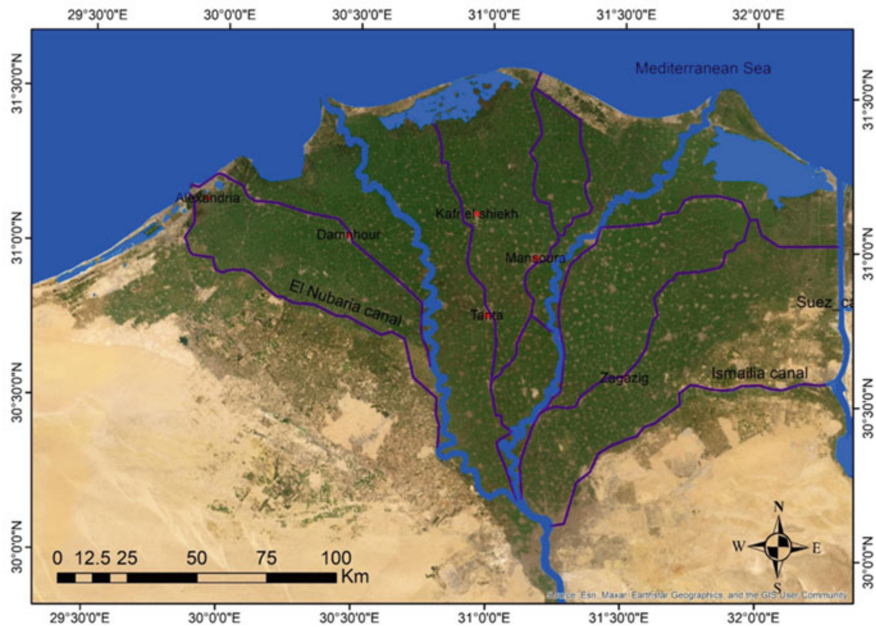


Fig. 1 A suggested plot representing the Nile Delta Aquifer (NDA)

2.2 Hydrogeological Characteristics

The surface irrigation network which utilizes the aquifer is essential for controlling groundwater flow [37]. The influent and effluent conditions vary spatially throughout the aquifer. When water levels of the streams lie below those of the aquifer, the surface water bodies can function like drainage systems. Relying on the depth and conductivity of the upper clay formation, the aquifer layer experiences either unconfined (over the southern parts) or semi-confined (over the northern parts) conditions. In general, the aquifer formation of ND is heterogeneous and anisotropic. The transmissivity ranges from 2000 to 3000 m^2/day in the southwestern portions and from 9000 to 15,000 m^2/day in the middle and southeastern portions [107]. High hydraulic conductivity values in the range of 70 to 100 m/day are observed within the aquifer [15]. As a sandy-gravel formation, the total porosity over the entire aquifer ranges between 25 and 40% while the effective porosity ranges between 12 and 19% [168]. The aquifer storativity is in the range of 0.01 to 0.001 in the southern areas, 0.1 to 0.01 in the southeastern and southwestern areas [145] and 0.0005 to 0.0009 in the northern area [37]. The longitudinal and lateral dispersivity is estimated as 100 m and 10 m, respectively [148].

2.3 *Recharge-Discharge Sources*

The Nile Delta aquifer (NDA) is consistently refilled through downward leakage of excess irrigation and direct seepage from the intensive irrigation network, making it a renewable storage source. See (Fig. 2). The infiltration rate varies between 0.25 and 0.80 mm/day in the floodplain areas where the basin irrigation is adopted [37]. Over the western and eastern desert fringes, a higher average leakage rate is reported reaching 2 mm/day [135].

Four components represent the groundwater discharge from the aquifer. These four components are (1) groundwater pumping throughout the aquifer, (2) outflow into the open drains, (3) direct surface water evaporation, and (4) flow between aquifers of GW. Outflow to the drainage scheme occurs mainly in the northern regions with a rate of 0.2 to 0.9 mm/day [107]. A small portion of water is naturally evaporated from low-lying areas (e.g., Wadi El-Natrun depression) and has a shallow groundwater table. The aquifer losses about 50 and 106 million m^3/year to the Moghra aquifer through Inter-aquifer flow [167]. Additionally, groundwater pumping is the primary discharge constituent derived out from NDA system. During the last 40 years, the rate of groundwater extraction has increased dramatically by 0.1 Bm^3/year [112]. Currently, the annual extraction rate from a total number of about 13,000 wells is estimated about 0.6, 2.0, and 0.9 Bm^3/year for the eastern, middle, and

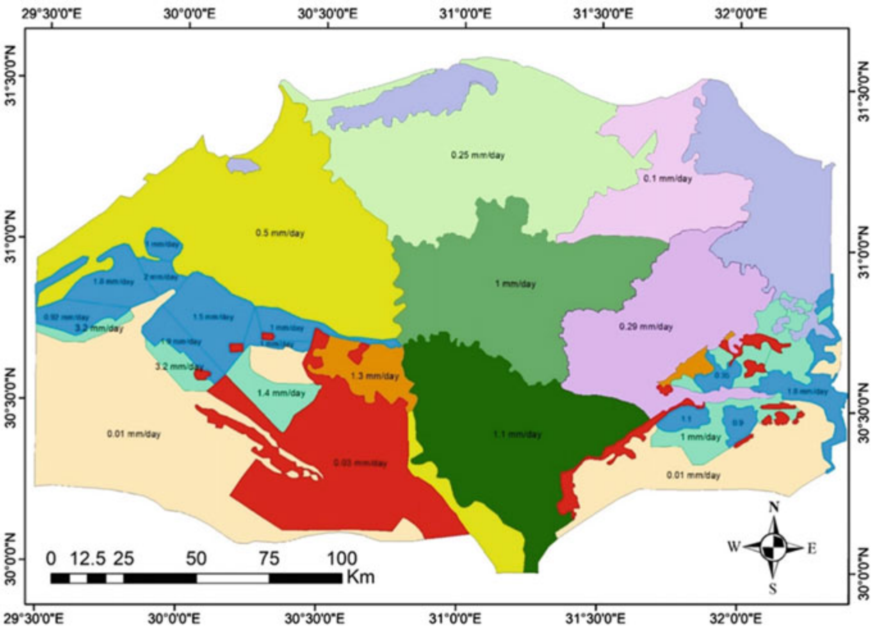


Fig. 2 A suggested plot representing the spatial distribution of recharge rate over the aquifer [107]

western Nile Delta regions, respectively [37]. The increasing groundwater pumping has resulted in a decrease in the piezometric surface and an increase in the salinity.

2.4 Hydro-geochemistry and Water Suitability

Agriculture and domestic effluents are the main contaminated source of the aquifer. The results of recent testing's for the groundwater samples revealed that the concentration of water quality parameters and heavy metals exceed the WHO's guidelines [98]. The extensive use of agricultural fertilizers has resulted in high concentrations of nitrate (NO_3), phosphate (PO_3) and potassium (K). A high concentration of trace elements (e.g., iron, and manganese) is attributed to industrial disposal into the open drains. Additionally, domestic sewages that are dumping directly into irrigation canals and drains in many villages of the Nile Delta have increased the biochemical oxygen demand (BOD) and ammonium concentration.

The majority of groundwater is still appropriate for irrigation [145]. Nevertheless, an increase in salinity is reported due to extensive abstraction in the middle delta, showing the contour line of 1,000 mg/L in the north [96]. In a contract, there is a decrease in salinity in the western and eastern fringes due to the recharge from the El-Nubaria and the Ismailia main canals.

Summing-Up

This heading presents a list of the aquifer system's information obtaining from various sources, including water levels, hydrochemistry analysis, water pumping, and recharge. However, sufficient data or limited sharing and accessibility make the conceptualization of the NDA incomplete or unconvincing. For these reasons, the authors understand the Egyptian water management agencies have limited under financial, technical, and human to carry out monitoring programs and maintain their updated databases. However, to set long-term goals for sustainable exploitation, it is recommended to improve a national geodata set, and also regular estimates of groundwater abstraction and automatic well control system.

3 Assessment of Groundwater Flow in the Nile Delta

Under two different scenarios, Dawoud et al. [52] constructed a GIS-based model for the Western Nile Delta's aquifer system, utilizing 60 observation wells from 1990 to 2002 to assess the potentiality of GW. In the first scenario, surface water flow decreased with 450×10^6 m^3 of yearly GW extraction when the irrigation network increased net recharge of the aquifer by 5.7%. In the second scenario, a new channel building increased the potential of the aquifer by an annual value of 23%.

Ismael [86] built a 3D GW flow model for Quaternary aquifer, based on data of 93 boreholes, mostly located in north of the Ismailia Canal. MODFLOW, finite difference model, was also used to simulate the distribution of GW head across the NDA system in both steady and transient states. The calibrated model was forcasted the future water level distribution for 20 years. According to the results, the GW head continued to increase and reached a peak of 2 m in the unconfined portion for the NDA. Nine scenarios demonstrated that more pumping was sufficient to control the increasing water table in confined aquifer and increasing seepage from the Ismailia canal and Damietta branch.

Ahmed et al. [22] used MODFLOW to simulate GW characteristics of the Wadi El Natrun's Pliocene aquifer, and the model was calibrated under transient and steady-state conditions, using the data of 14 observation wells. Four scenarios stimulated for GW depletion of 2025, 2030, 2040, and 2065. In the first scenario, 111 pumping wells were investigated with total discharge of 56,428 m^3/day. The second, third and fourth scenarios resulted in a 15, 25 and 50% increase in total discharge of 64,954 m^3/day, 70,602 m^3/day and Q4 = 84,723 m^3/day, indicating any increase in the pumping rate should not exceed 10% in the next 50 years (see Fig. 3).

Sobeih et al. [152] simulated three scenarios for the assessment of GW flow and GW budget for western ND region. The first scenario (enlarged recharge and canal construction) revealed that GW levels would increase, and flow direction would move towards the northeast, north, and northwest regions. A considerable amount of water logging would appear in Sadat City's southern, eastern, and western areas, as well as along the planned channel. However, the second and third scenarios (construction of new open drain and higher GW pumping) have resulted in a decline of GW levels and complete removal of water logging, particularly in the eastern part of Sadat City.

Depletion of GW levels in Wadi El Natrun was simulated by using GW Modelling System (GMS) calculated different extraction rates [60]. The excess of GW extraction

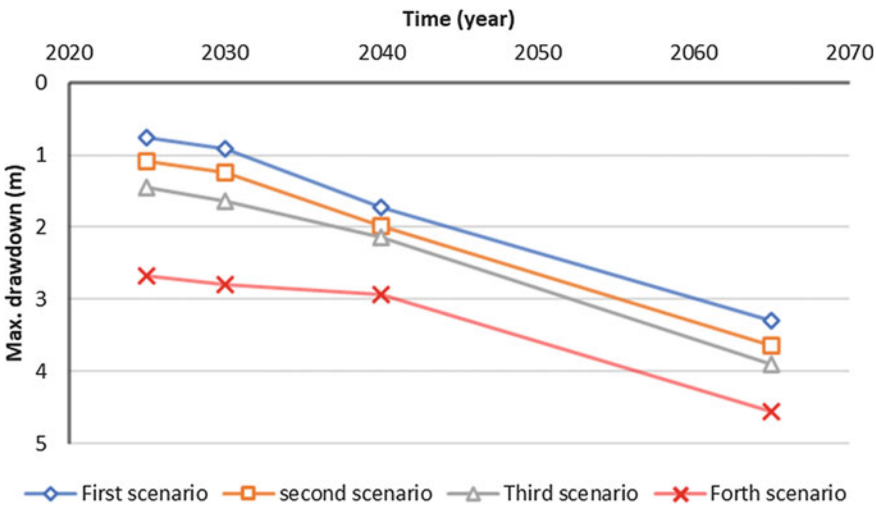


Fig. 3 Maximum drawdown for all scenarios after [22]

(approximately 105.84 × 10^6 m^3 per year) made GW head declined from 3 to 40 m in 2015 and 2050, correspondingly. Two scenarios were presented. The first scenario maintained the current abstraction rate as of 2013. The second scenario proposed drilling five wells in the western part of the study area, where the potential of the aquifer has lower level of TDS. In addition, the water abstraction rate in the central and southeastern parts of the aquifer would be reduced to half of the current rate. The optimal amount of water of 15,7000 m^3 per day) was found to be the best option for managing the groundwater resources without causing excessive depletion and the drawdown may drop by up to 4 m by the year 2050.

For GW sustainability and management in the Quaternary aquifer in the eastern part of the Nile Delta, Eltarabily et al. [68] used MODFLOW to assess several recharge and abstraction scenarios. The impact of land use and dam development in the upstream basin of the Nile River and short-term GW managing techniques were also investigated by three alternative scenarios. The results showed that there was an increase in pumped discharges of 15, 30 and 50% for agricultural extension and GW head of 20, 40, and 60 cm in Port Said Canal after operating GERD in 2017. When a 50% pumping stresses were imposed, GW head dropped 0.66 m and the reservoir could no longer maintain the aquifer capacity after 2020.

Another research group put an effort to examine the possible impact of increased pumping rates on GW levels in the NDA. For this purpose, [30] used MODFLOW to create a 3D GW model. As the basis case, the model was validated on the measurement of GW level. See (Fig. 4). Therefore, ten scenarios of ND discharges by 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100% were tested. The results of these scenarios revealed that increased pumping rates substantially influenced lowering the GW level in the middle and southern parts of NDA. The tenth scenario was termed the worst-case scenario because it doubled the extraction rate compared to other scenarios, in which GW levels were drawn down to 1.32, 1.59, and 2.41 m in the southern boundary, as shown in (Figs. 5 and 6).

Under four scenarios, Abd-Elaty et al. [1] investigated the relationship between irrigation channels and the NDA by using MODFLOW. Reduced channels discharged the four main diversion channels due to these reasons such as climate change, upper Nile diversions, irrigation channels lining, combination of usage of Photovoltaic (PV) Solar Panel and canal enclosure in closed conduits. Compared to the baseline, the first scenario reduced stream flow and GW levels where the aquifer recharge was ranging from 7.33 to 4.84 × 10^5 m^3/day. Furthermore, GW discharges from the aquifer to the four main channels extensively increased from 2.32 to 7.94*10^4 m^3/day. Channels leakage to the aquifer was calculated to be equal 1.47, 1.47, and 0.73*10^5 m^3/day, respectively. According to water budget estimates linked with channels lining second, third and fourth scenarios. Canal efficiencies were 29.3, 67.1, 75.3, and 91.8%, whereas 66, 20, 20, and 10% of aquifer recharge effectiveness represented for four scenarios. Therefore, it can be seen that based on these four scenarios, canal lining is probably the most effective way to manage the water resources in the ND.

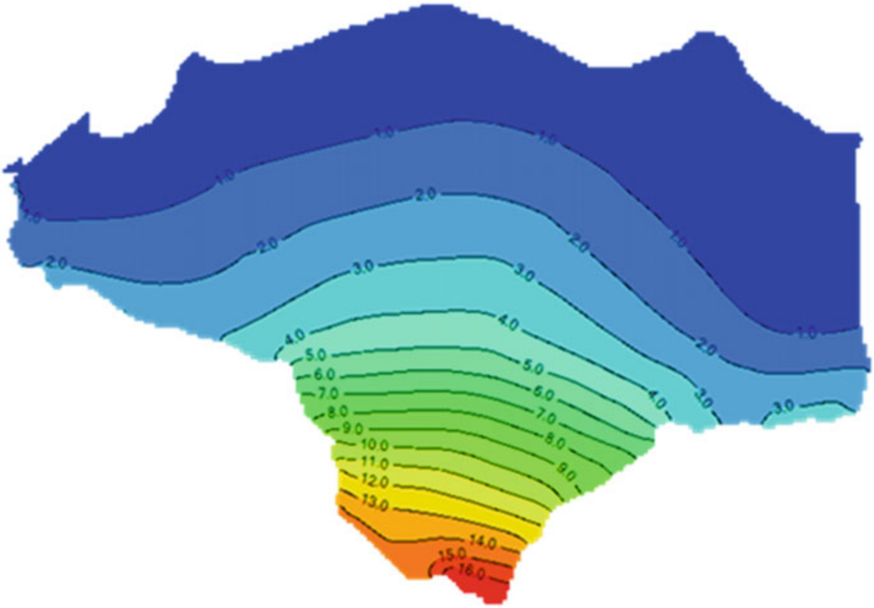


Fig. 4 Groundwater head in the Nile Delta aquifer, for the year 2008 [30]

4 Saltwater Intrusion Modelling Studies in the Nile Delta Aquifer, Egypt

Urbanization, excessive GW pumping, and sea level rise (SLR) all contribute to the environmental issue of SWI, which is rapidly increasing in coastal aquifers. An additional pressure is found in resources of GW through coastal aquifer system. Mitigation and controlling of SWI is essential in coastal GW aquifers that could be assessed by means of experimental tests and GW numerical modelling. It is imperative to control SWI to ensure the sustainability of water resources in the coastal aquifer for different purposes. In addition, it is also necessary to protect the freshwater volumes in coastal GW aquifers since many nations face limitation in their surface water availability.

The following paragraphs summarize the published studies covering the simulation of SWI in the NDA, the impact of GW pumping and SLR on freshwater-saltwater interface in the NDA.

Anon [27] used the electrical logging approach to investigate the acute interface between saltwater and freshwater in the NDA. The potentiometric contour, which was around 10 m above sea level, was the approximate point where the intrusion of seawater occurred. Farid [72] offered a novel approach modelling by changing AQUIFEM-1 in two dimensions as a moveable interface to address the problem of SWI in the NDA. To regulate the form and location of the saltwater interface and subsequently, the toe position in different extraction scenarios, the established model

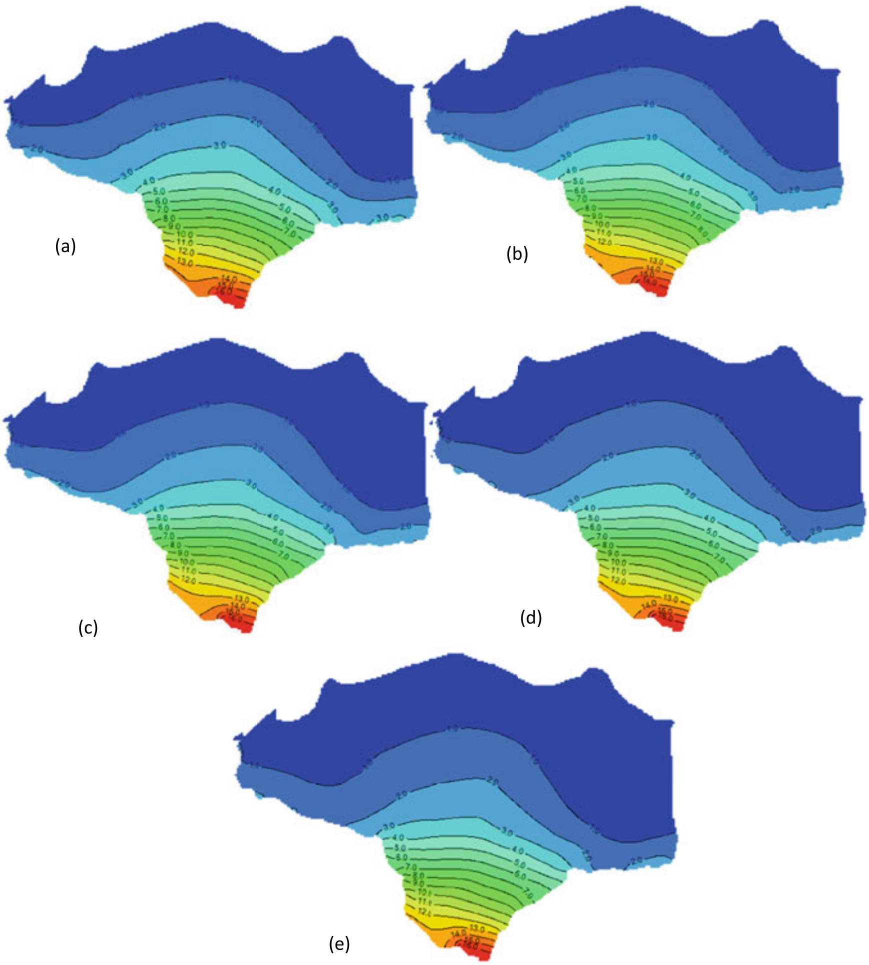


Fig. 5 Groundwater level distributions in the (NDA) for increasing pumping discharges by **a** 10%, and **b** 20%, **c** 30%, **d** 40%, and **e** 50% [30]

was applied to anticipate potential changes in the NDA's water abstraction, which could be doubled, tripled, or remain the same with the same recharge rate. More than that, Farid [72] showed that the northern region was highly saline because of the SWI and indicated a map of SWI distribution in the NDA where iso-salinity contour lines vary from 640 to 45,000 mg/l, as illustrated in (Fig. 7).

Serag El Din [144] stated that the GW upward flow from GW system in the ND to upper mud layer was about 3×10^3 m^3/year because of saltwater interruption and the GW recharge in the ND was almost 3 times greater than the upward loss. New technique for determination of the toe position of the SWI wedge across the NDA

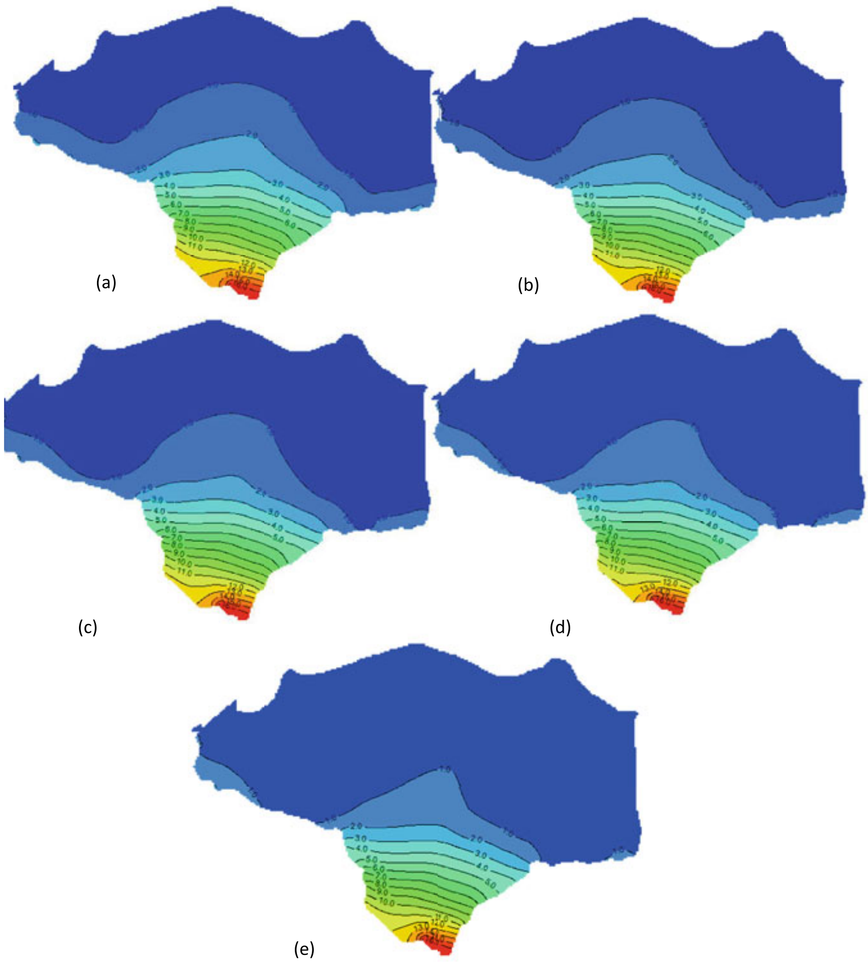


Fig. 6 GW level distributions in the (NDA) for increasing pumping discharges by **a** 60%, and **b** 70%, **c** 80%, **d** 90%, and **e** 100% [30]

and its extensions in the Eastern deserts and Western deserts was developed by [90]. The results suggested that NDA was impacted by saltwater that was present within a distance of 130 km from the Mediterranean Sea, or which was approximately near El-Bagour city. According to Kashef [90] and Anon [27], the NDA provided the water supply and industrial purposes with approximately 1.6 × 10^9 m^3 per year of consumption. An overview from the Ministry of Water Resources and Irrigation (MWRI) of Egypt showed that 0.82 km^3/hr of abstraction was due to the water system as a whole, and 2.42 km^3/hr was the absolute volume required to encounter the system's stresses for water supply and industry. For the theory of dispersion process in coastal aquifer systems, Sherif et al. [151] used a 2D Finite Element Method

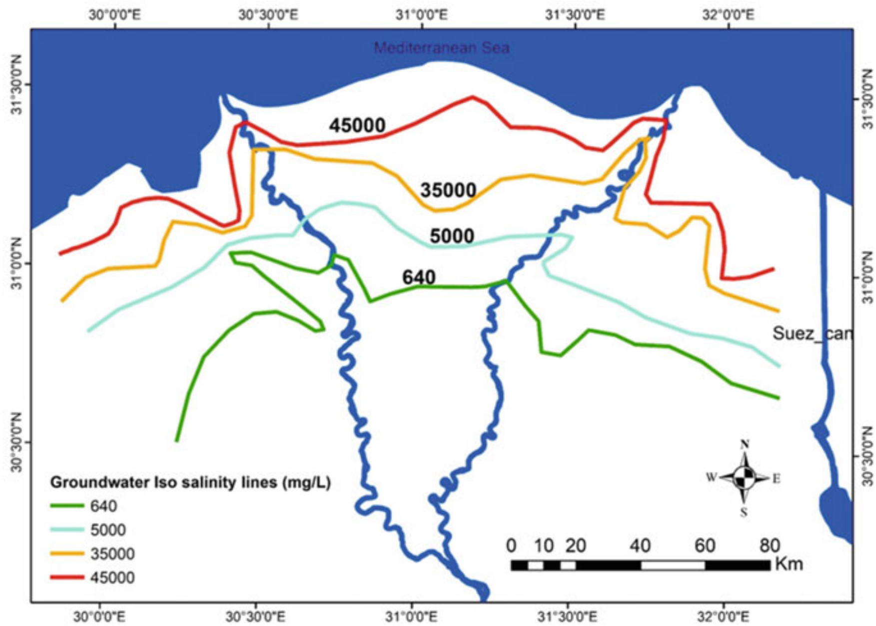


Fig. 7 Groundwater salinity distribution over the Nile Delta, [72]

(2D-FED) to predict the concentrations and subsurface flow. The equipotential line + 12.00 over the level of the Mediterranean Sea and the salinity contour level of 1,000 ppm were both in close proximity to the aquifer base at 106 km southern of Tanta City. According to RIGW/IWACO [130], SWI progressed to the aquifer system in Tanta city, and the interface between freshwater and seawater was effectively advanced inside into the NDA. Different researchers concluded that the NDA's GW flow and SWI have reached a stable state.

Soliman et al. [153] implemented a FEM to investigate the flow of GW and the transport of solutes in the porous medium. For simulating the SWI, the model was applied to the German town of Ruehen and the eastern portions of the NDA. The equi-concentration line (1,000 ppm) came to Isamila city. The extraction well data for the ND region for the years 1995, 1997, and 2002 was also provided by RIGW [128]. To determine the rate of extraction in 2008, data sheets were transferred and the annual abstraction rate in the ND region between 1992 and 2008 was broken down by governorate. For the years 1992 and 2008, the total withdrawal rate from the ND was 3.03 and 4.90 × 10^9 m^3/year, respectively [107], as shown in (Fig. 8). According to Dahab [51], the absolute annual abstraction rate from the GW in the ND increased to 2.123 × 10^9 m^3/year in 1993 due to water system and domestic requirements. Moreover, RIGW examined the ND governorates' pumping operations in Egypt. The overall rate volume of abstraction in 1992 was approximately 1.92 × 10^9 m^3/year, based on the inventory of abstraction wells. The governorates of El Gharbia

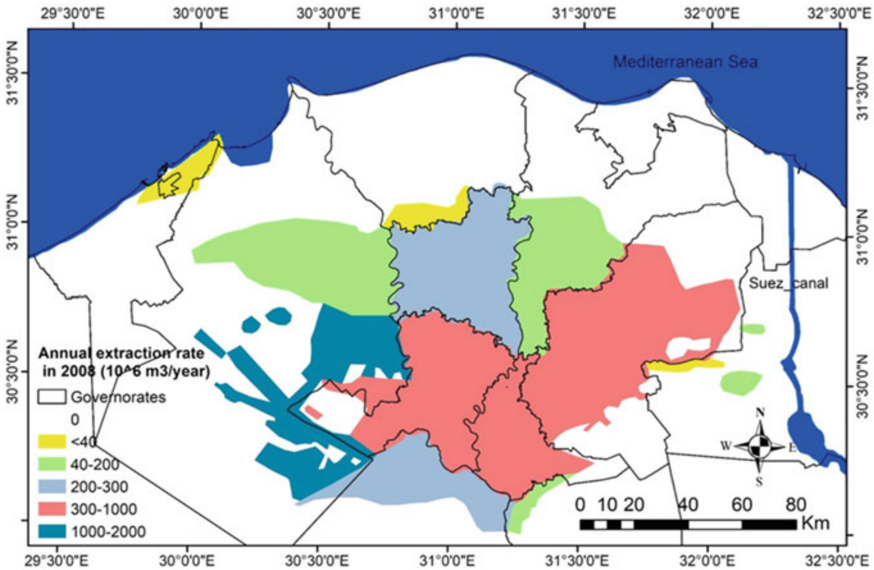


Fig. 8 The annual abstraction rate in the year of 2008 [107]

and Sharkia both registered extremely high numbers of abstraction wells, with El Gharbia having more than 3391 wells and Sharkia having 1719 wells, which were the highest numbers recorded.

Sherif and Singh [150] used the SUTRA code to simulate SWI in the NDA while accounting for the abstraction rates within every governorate. 1,000 ppm of equi-concentration progressed inland into the aquifer for a distance equals 41 km, and 35,000 ppm of equi-concentration intruded inland for a distance equals 84 km. In order to determine the ideal places for extraction in six various scenarios, Sherif [146] utilized the SUTRA GW model to observe the effects of pumping discharges in the NDA on the SWI. Based on pumping rates, the ND was separated into three areas: the central, eastern, and western regions. An extensive decrease in SWI was established in the middle ND when water abstraction rates from the eastern and western ND were comparable. With a noticeable decline on the eastern side, the SWI in the ND resulted the retreat from the middle Delta. The contour line of 35,000 mg/l progressed more into the NDA where an additional abstraction was expanded in the central Delta. Sherif and Singh [150] examined how climate change impacted SWI in two different coastal GW aquifers: the Madras aquifer in India and the NDA in Egypt. A numerical model was utilized to examine how 0.2- and 0.5-m of See Level Rise (SLR) would affect saltwater intrusion. The findings demonstrated that an increase of 0.5 m in the Mediterranean SLR will cause an additional 9.0 km of encroachment into the ND. On the other hand, if the Bay of Bengal increased a similar amount of SLR, the Madras Aquifer would result in an additional 0.4 km of SWI. The study suggested that the

NDA was at a higher risk of facing challenges compared to the Madras aquifer due to climate change and SLR.

Another study of Sherif [146] was based on the 2D-FED code to model the effects of SLR on the vertical SWI in the NDA, finding that the line of 1,000 ppm concentration forwarded marginally into the GW aquifer system due to the 0.2 m SLR in the Mediterranean Sea (MS) while the salinity concentration of 35,000 ppm advanced 2.5 km inland due to the constant piezometric head. When the SLR increased to 0.5 m, the lines of 35,000 ppm concentration and 1,000 ppm concentration encroached 1.5 and 9.0 km deeper 9.0 km into the aquifer. Using a 2D FEM by means of a density-dependent approach, Sherif and Al-Rashed [149] first proposed a vertical prediction of the SWI (2D-FED), which determined the NDA's seawater/freshwater dispersion zone and groundwater flow regime. According to base boundary estimates, it was observed that the concentration line of 35,000 ppm (saltwater line) encroached into the NDA up to a distance of 63 km, while the salinity concentration of 1,000 ppm (freshwater line) extended into the GW aquifer to a distance of 108.0 km. Furthermore, the research indicated a flux from the freshwater side to the seawater side over the semi-permeable layer with a depth of 22.0 km. For evaluating the impacts of various abstraction scenarios on the SWI mechanism, Sherif and Al-Rashed [149] employed the SUTRA code in order to stimulate SWI in the NDA with a horizontal orientation. It is suggested that might assist lessens the SWI movement could potentially be reduced by reorganizing abstraction wells and altering land use for agricultural activities in the ND. Besides, any additional abstraction should be ideally conducted in the center of the ND to minimize any negative consequences.

In the study of Sherif [147] based on the influences of variations of the land use on the SWI, additional rice-growing scenarios were tested in the northern and southern areas of the ND. The findings suggested that in all circumstances, any additional abstraction would be reduced in the eastern and western portions of the delta and practiced from its center. Given that the clay cap layer turned into increasingly permeable and thinner, rice cultivation should be extensively considered which would reduce the entry of seawater. The saline concentration maps illustrating contour lines from 1960 to 2000 was published by RIGW [129]. The contour maps used by RIGW showed how the development activities were affected the saline dispersion in the NDA. The salinity of the GW increased significantly between 1980 and 1990, and the southward-moving Iso-Salinity of 1,000 ppm indicated an increase in seawater intrusion. Morsy [107] analyzed the GW salinity in the NDA from 1992 to 2008, resulting in the fresh GW moved northward and displaced the saline GW. The analysis also revealed that the salinity level of 1,000 ppm penetrated further north in the central NDA (see Fig. 9).

In order to demonstrate the impact of GW recharge scenarios and increasing saltwater levels on the salinity of the GW in northern Egypt, Gossel et al. [79] constructed a 3D GW model of the Nubian Aquifer System using FEFLOW. The findings supported the hypothesis that the Qattara depression became salinized as a result of SWI. A 3D FEM for modelling variable density (FEFLOW) was used by Sherif et al. [148] to analyze the SWI in the NDA in horizontal display. A two-dimensional real simulation in the vertical direction was also utilized to focus on the

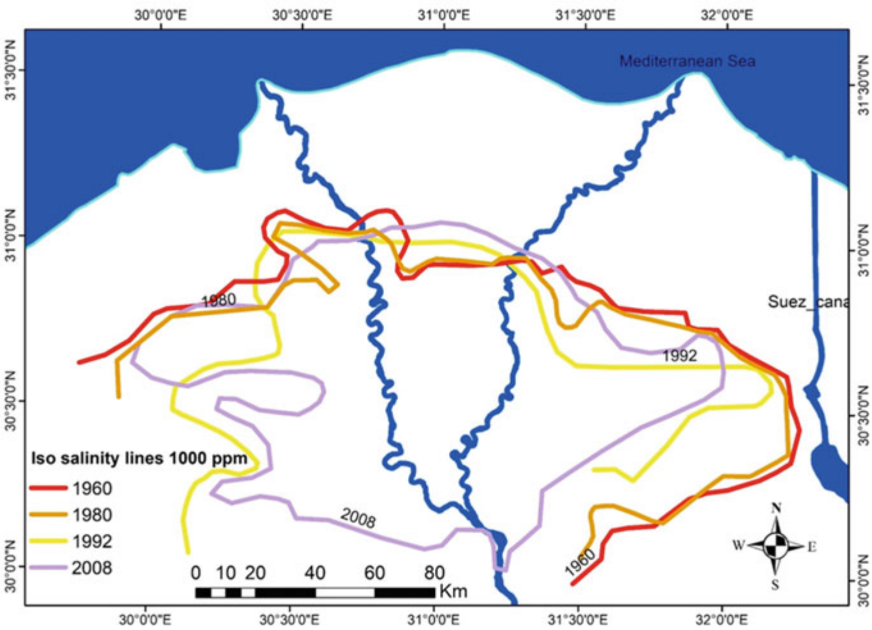


Fig. 9 The advancement of the contour line of 100 mg/l in the NDA, modified by [107]

concept of equivalent freshwater head. The study was executed in four horizontal sections at depths of 100, 200, 300, and 400 m were assigned a sufficient pressure head representing the depth of the respective segment. The outcomes indicated that seawater intruded several kilometers inland at a depth of 100 m while at 200 m, the transition zone shifted further into the aquifer to reach Tanta City. The seawater reached Mansoura at depths of 300 and 400 m, affecting the whole dynamic region of the studied domain, respectively.

For evaluating the impact of SLR due to global warming, Sherif et al. [148] utilized a 2D-FED in the vertical direction in the NDA. The researchers discovered that the line of 5,000 ppm concentration invaded 2.0 km inland for a 20 cm rise while the line of 35,000 ppm concentration moved to 4.5 km inland for a 50 cm rise in the Mediterranean Sea (MS) level. According to El Arabi [56], the GW in the NDA and its adjacent desert were recharged by the Nile River recharge through canal seepage and deep percolation from irrigation systems. The total extraction rate from the ND and its surroundings was approximately 4.6×10^9 m^3 and only 0.5×10^9 m^3 was specifically extracted from the desert aquifer and the coastline front districts. Projections for 2015 anticipated a significant increase in total annual GW pumping from the Nile Delta, reaching 11.4×10^9 m^3 due to the regional water resource management plans.

Utilizing the well-known GW Modeling System (GMS), which combines the MODFLOW, MT3DMS, and SEAWAT, Essawy [69] established a 3D GW flow model for the entire NDA for simulation of the SWI. The effects of SLR (three anticipated scenarios: 0.2, 0.5, and 1 m) in the years 2050 and 2100 were examined with regard to the saltwater/freshwater interface in the NDA. According to observations, the saltwater-freshwater interface will move an extra 1.0 to 4.5 km in 2050 and somewhere between 2.0 and 6.0 km in 2100 as a result of an increase in seal level of between 0.2 and 1.0 m. The general consensus is that the influences of SLR on the SWI in the NDA do not appear to be critical. A 3D model (SEAWAT) was used by Abd-Elaty [5] to evaluate the SWI in the NDA. In 2008, RIGW utilized the available data on the saline concentration in several wells. The results confirmed that the line 1,000 mg/L concentration encroached further inland into the GW aquifer system and reached 93.75 km from the coastal line of the MS. However, the line 35,000 ppm concentration progressed inland by 63.75 km from the coastal line in the cross section at the central of the delta.

Abd-Elaty [5] applied SEAWAT model to analyze how pumping operations affected SWI in the NDA. Three different growing abstraction rate scenarios were added to the model and changed by 25, 50, and 100%. The results displayed that the line of 35,000 ppm concentration at a vertical portion in the center of the Delta inland was forced to 63.75, 66.5, and 65.75 km, individually, by the increase of abstraction rates by 25, 50, and 100%. However, the salinity line of 1,000 mg/L concentration shifted further into the GW aquifer to different locations of 98.25, 101.25, and 107.75 km at a comparable cross section. Sefelnasr and Sherif [142] analyzed the potential impacts of SLR with different scenarios of well pumping on the SWI issue in the NDA utilizing FEFLOW. Six different scenarios were studied. The sixth scenario, with a 1.0 m SLR and increased abstraction volume, was assumed to be the most permissible option in which there was a reduction in the freshwater volume to approximately 513×10^9 km^3. The study predicted that vast areas of the Mediterranean coastal zone of the ND region would be flooded by saltwater and a shoreline in eastern and western of the ND would move to several kilometers inland.

Abdelaty et al. [6] updated the model for three different SLR scenarios at 0.25, 0.5, and 1.0 m by using SEAWAT code. The results of the study shows that if the SLR was 0.25 m, the concentration line of 35,000 mg/l in the middle of ND inland into the NDA would expand to 66.75 km. Likewise, with SLR at 0.5 and 1.0 m, the concentration line would rise to 67.0 km and 67.75 km. Nevertheless, the concentration line of 1,000 mg/l would be forced to travel inland to 97.75, 96.25, and 97.0 km, respectively due to the SLR by 0.25, 0.50, and 1.0 m at the similar cross section. Relying on the findings of site-specific vulnerability evaluations, Mazi [99] assumed that the NDA was at risk of the SWI. A total aquifer could break the NDA by 20% while a 10% fall in GW head will accelerate SWI by about a 5–8 acceleration of GW heard could result a reduction of GW head by 20%.

In order to analyze the SWI in the NDA concerning the climate change, Abd-Elhamid et al. [8] incorporated a coupled transient FEM (2D-FEST) which is applied for the process of the solute transport across both in the saturated and unsaturated zones. The findings demonstrated that the Iso-line 1 progressed inland by 112 km at a vertically cross section in the center of the ND region while the Iso-line 35 interrupted inland into the NDA by around 64 km from the coastal line. Another result pointed out that an extra 100 cm of SW occurred in the NDA which was about 8 km deep as a result of unsustainable GW pumping. Also, a further 15 km of SWI appeared due to a 100 cm sea level rise and a declined 100 cm piezometric head. Nofal et al. [115] stimulated the model regarding the piezometric head and the GW flow fluxes to understand the effect of SWI into the NDA.

The results of the study showed that three anticipated scenarios of 0.2, 0.5, and 1.0 m SLR on GW heads heightened by 0.0 to 0.5 m after 30 years. However, 7.0 km from the coastline shoreline was used to check the salinity of the GW system. Abd-Elhamid et al. [8] evaluated the SWI in the NDA, based on 2D-FEST. The result of the study revealed that an additional 10 km of seawater would seep into the NDA with a 100 cm rise in sea level. Wassef and Schüttrumpf [163] used FEFLOW programming to build a 3D FEM in the western ND to study SWI under several anticipated scenarios of the climate change. The outcomes exhibited that consistently by 2100, it is projected that the saltwater interface will extend a limit of approximately 43 km as predicted by RCP 2.6 scenarios whereas it is anticipated to advance at 57 km as predicted by RCP 8.5 scenarios. The overuse of GW will result in a rise in salinity content to approximately 5000 mg/l. Furthermore, Armanuos and Negm [39] implied the SEAWAT to simulate the SWI in the NDA while taking into account several scenarios of SLR and GW depletion. The findings indicated that there was a 25 km wide transition zone between the equi-line 1000 mg/L and the eqi-line 35,000 mg/L. As well, the freshwater line encroached to a distance of 105 km extended from the coastal shoreline while the saltwater line extended into the NDA to a distance of 56 km, as shown in (Fig. 10).

By the year of 2100, it is projected that both saltwater and freshwater lines will move further inland by a distance of 6.75 and 5.5 km, respectively, as a result of GW withdrawal reducing the south head by 1.0 m. Previous research by Armanuos [31] and Armanuos and Negm [39] has also indicated a 1.0 m sea level rise significantly

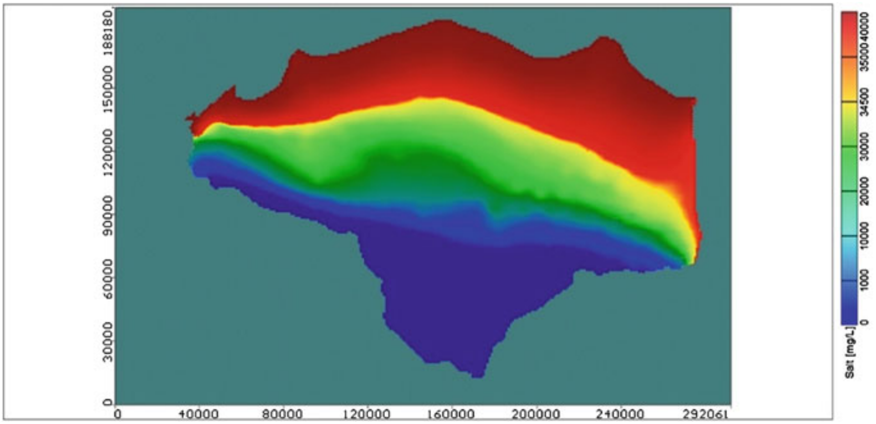


Fig. 10 Horizontal distribution of TDS in the Nile Delta aquifer for the base case (year 2008), [31, 39]

impacted SWI in the NDA with an increase of 8.2 km for SWI and 6.5 km for freshwater intrusion comparing with the base situation [31].

In six climate change scenarios that included rising pumping discharges and SLR, Mabrouk et al. [94] utilized SEAWAT to simulate the SWI in the NDA. The year 2010 served as the baseline scenario. The results of this study exhibited that GW abstraction had a larger effect on accelerating the process of SWI in the NDA and the NDA's freshwater capacity. Salem et al. [95] built three-dimensional model based on variable density GW flow model, indicating the SWI caused salinization of GW in the northern parts, the eastern parts and south-western parts of the NDA as a result of an excessive extraction rate and the breakdown of marine fractured limestone and shale.

The ND's Quaternary aquifer is one of the largest GW aquifers in the world according to Salman et al. [140]. The Mediterranean Sea (MS) substantially influences the aquifer across its north coast. Substantially, the GW quality in the northern regions of the ND has declined because of the extensive pumping over the last two decades. Salem et al. [136] aimed to manage the multi-tracing approach for the GW flow mechanism and SWI in the study area. The incorporation of GW chemistry and borehole temperatures was beneficial for achieving the study's objectives. Eight borehole temperatures and occasionally groundwater samples from both shallow and deep zones were monitored. The findings revealed that the Tala well in the south experienced a downward flux of 0.8 m/year. Fresh GW flowed through south Tanta City to south Kafr Elsheikh City, whereby the upward fluxes for the Kafelarab, Nawag, and Elkarada wells were estimated to be 0.1 to 0.5, 0.35, and 0.23 m/year. Additionally, the SWI significantly impacted the hydrochemistry of the GW in the region north of Kafr Elsheikh City. The observed temperature characteristics were consistent with discharge patterns and their premeditated upward fluxes were 0.6, 1.2, and 2.8 m per year for the Kafr Mesaaed, Elhadady, and Motobes wells, consistently.

Abd-Elaty et al. [2] examined the NDA various pumping and SLR scenarios and focused on four hypotheses to mitigate SWI. These four hypotheses are reducing aquifer pumping, increasing recharge by utilizing treated waste water, increasing brackish water extraction for the desalination process, and combining these approaches. The results showed that raising recharge rates could delay SWI by 19.5% more than reducing pumping (6.2%) or brackish water extraction (5.9%). With a retarded percentage of 21.3%, a combination approach pumping, recharge, and extraction was demonstrated to be most effective approach for managing SWI in coastal GW aquifers.

A recent study was conducted by Armanuos et al. [36] to model the effects of SLR and the irrigation canal network in the NDA. Three scenarios were proposed: (1) sea level rise, (2) changes in groundwater extraction rate, and (3) a combination of both. It was found that the third scenario was the worst with distances of 7.22, 7.73, 8.20, and 10.20 km, correspondingly. Yet, the length of SWI decreased by 4.0 km compared to previous studies even including all branches of the irrigation network. A research group of Zelenakova et al. [169] simulated the influences of climate change and SLR on Egypt's northern beaches and presented suitable adaptations using PLAXIS and 2D-FEST. The findings supported predictions that SLR would have an impact on several cities along Egypt's northern shores and the NDA. Moreover, using treated wastewater for recharge and reducing extraction from the NDA could help protect the area from potential SLR.

According to following tables, Table 1 provides a clear representation of the intrusion length for both freshwater and saltwater. At the same time, Table 2 describes a comprehensive summary of the various factors influencing the SWI within the NDA.

5 Modeling of Groundwater Contamination in the Nile Delta Aquifer

GW pollution in the Nile Delta Aquifer (NDA) threats fresh water source of Egypt. The following paragraphs provide a summary of the published studies and their findings in the ND area.

For simulating the GW flow and solute transport in the middle region of the ND, Ghoraba et al. [78] conducted MODFLOW and MT3DMS, specifically in the El-Gharbiya Governorate which is known for its high population and agricultural activities but inadequate public sewage infrastructure. For the model, water levels and variations in solute concentration were determined within the region at different times. The MODFLOW code was utilized to manage the characteristics of groundwater flow through the aquifer. A solute transport with datasets for MT3DMS that corresponded with MODFLOW was stimulated over time. Based on the results, the researchers suggested a groundwater remediation program involving the installation of abstraction wells in the Birma area, where ammonium contamination levels were found to be high, using multiple wells to extract polluted groundwater for treatment and subsequent reuse in irrigation activities.

Mohammed [106] applied a GW model using MODFLOW combined with a solute transport model to predict the movement and the pollution of heavy metals. The combination of industrial effluents and residential sewage was depleted into three-lined ozone ponds which were utilized for irrigation in the regions. Exceptionally, the oxidation ponds were contaminated with heavy metals, including Cr^{2+}, Ni^{2+}, Sr^{2+}, Fe^{2+} and Al^{2+}. The infiltration process from the oxidation ponds and the associated reclamation lands irrigated with wastewater indicated significant environmental concerns. Moreover, contamination plume will move 18, 21 and 23 km in the NE direction over fifty years for the parameters of Al, Fe and Sr pollutants separately. Based on these findings, it is strongly suggested that wastes produced by the oxidation pond should not be utilized in water system without proper treatment processes. Additionally, GW wells should be located away from contamination sources, and monitoring wells should be installed around oxidation ponds for regular observation.

Eltarabily et al. [67] examined the impact of utilizing nitrogen fertilizer on the pollution of GW in the middle of Southern region of the ND. The concentration of NO_3 inside shallow GW was evaluated depending on the dose of applied urea.

Table 1 The intrusion length for the saltwater and freshwater lines in the NDA

The Study	The studied year	The used code	The intrusion length for 35,000 mg/l	The intrusion length for 1,000 mg/l
Anon [27]	1980	–	–	The seawater interface reached a potentiometric contour of around +10.00 m
Farid [72]	1980	AQUIFEM-1	–	–
Kashef [90]	1980	–	–	The NDA is deeply invaded by saltwater
Sherif et al. [151]	1988	2D-FED	–	106 km
RIGW/IWACO [130]	1999	–	–	Reached Tanta City
Soliman et al. [153]	1991	–	–	Reached Ismailia city
Sherif and Singh [150]	1999	2D-FED	41	84
Sherif and Al-Rashed [149]	2001	2D-FED and SUTRA	63	108
RIGW [129]	2002	–	–	Intruded more southward in the NDA
Essawy [69]	2008	GMS (MODFLOW, MT3DMS, and SEAWAT)	–	–
Abdelaty et al. [6]	2008	SEAWAT	63.75	93.75
Sefelnasr and Sherif [142]	2008	FEFLOW	–	–
Abd-Elhamid et al. [8]	2008	2D-FEST	64	112
Wassef and Schüttrumpf [163]	2008	FEFLOW	–	–
Armanuos et al. [31], Armanuos [37], Armanuos and Negm [39]	2008	SEAWAT	56	105
Abd-Elhamid [10]	2008	SEAWAT	75.75 (Eastern)	90.25 (Eastern)

(continued)

Table 1 (continued)

The Study	The studied year	The used code	The intrusion length for 35,000 mg/l	The intrusion length for 1,000 mg/l
Abd-Elhamid et al. [12]	2008	SEAWAT	63.9	101.5
Mabrouk et al. [94]	2010	SEAWAT	–	–
Mabrouk et al. [95]	2010	PMWIN and SEAWAT	–	–

Normally, nitrogen fertilizer was being used. A MODFLOW and MT3D was utilized for modelling the GW flow and NO_3 movement forms in the Governorate of El-Menoufia, situated in the middle area of the ND spring. The observed GW level and NO_3 concentration were compared with the simulated results for model calibration for the year 2014. The outcomes emphasized the significant issue of groundwater (GW) contamination by NO_3 in certain regions, especially at shallow depths of around 40 m.

Hussein et al. [85] modelled for 10th Ramadan city, southeastern parts of the ND area. The samples were gathered from the GW wells and oxidation ponds distributed around the study region to examine the concentrations for contaminations in the GW system and the transport rate of contaminants to the GW system through a period of thirty years. The findings represented that the concentration of ions (Al^{3+}, Fe^{2+}, Sr^{2+}, Ni^{2+}, and Cr^{2+}) of all samples exceeded the World Health Organization (WHO) guidelines for drinking water. Furthermore, the groundwater samples were contaminated with Sr^{2+}, Al^{3+}, and Fe^{2+} ions.

In order to prevent groundwater pollution from drains in NDA, Abd-Elaty et al. [4] applied MODFLOW and MT3DMS software considered two water supply systems: GW and surface water. Total dissolved solids (TDS) pollution was firstly identified for a more effective defense method through the four scenarios. The first scenario focused on altering the head and concentration conditions at the polluted drain and canal boundary. The second scenario intended to locate for the polluted drain where there was a low permeability layer. The third scenario involved constructing a cut-off wall along the edges of the polluted drain. Lastly, the fourth scenario investigated the usage of lining material properties for polluted drain. As a result, confined aquifer pollutants were fewer than unconfined aquifer pollutants and there was a slight decrease of the salt variability by +19.01%. In the hypothetical example, the application of the cut-off wall resulted in a decrease in GW aquifer salt of +28.49% but no difference in the NDA when it came to contaminant control.

Furthermore, Abd-Elaty et al. [3] used MODFLOW for simulating GW flow and the pollutant transport into the Eastern NDA, Egypt. The study aimed to monitor the quality of GW due to the utilization of wastewater from drains for irrigation as freshwater was at high risk in the region. The stimulation revealed that the contamination level of the aquifer increased due to untreated wastewater usage, the population

Table 2 The impacts of sea level rise on saltwater intrusion in the Nile Delta aquifer

The study	The used code	Scenarios	The intrusion length for 35,000 mg/l or advancement	The intrusion length for 1,000 mg/l or advancement
Sherif and Singh [150]	–	0.20 and 0.5 m SLR scenarios	–	9.0 km advancement (0.5m scenarios)
Sherif [146]	2D-FED	0.2 and 0.5 m SLR scenarios	2.50 km advancement (0.20 m scenarios), and 9.0 km advancement (0.50 m scenarios)	1.50 km advancement (0.50 m scenarios)
Sherif et al. [148]	2D-FED	0.2 and 0.5 m SLR scenarios	4.50 km advancement (0.50 m scenarios)	2.00 km advancement (5,000 ppm) (0.20 m scenarios)
Nofal et al. [115]	MODFLOW and SEAWAT	0.20, 0.50, 1.0 m SLR scenarios	–	7.0 km extra advancement
Essawy [69]	MODFLOW, MT3DMS and SEAWAT	0.20, 0.50, and 1.0 m SLR scenarios	–	(1.0–4.50 km) for (0.2–1.00 m) scenarios and (2.0 to 6.0 km) for the same scenarios by the years 2050 and 2100 respectively
Abdelaty et al. [6]	SEAWAT	0.25, 0.50, and 1.0 m SLR scenarios	66.75 km, 67.0 km, and 67.75 km in the middle of ND for 0.25, 0.50, and 1.0m scenarios respectively	97.75 km, 96.25 km, and 97.00 km in the middle of ND for 0.25, 0.50, and 1.0m scenarios respectively
Sefelnasr and Sherif [142]	FEFLOW	0.5 m, and 1.0 sea level rise scenarios	–	The total freshwater volume decreased to 513 km^3 for 1.0 m SLR scenarios and multiple of abstraction
Abd-Elhamid et al. [8]	2D-FEST	100 cm SLR scenarios	–	10 km advancement for 1,000 ppm

(continued)

Table 2 (continued)

The study	The used code	Scenarios	The intrusion length for 35,000 mg/l or advancement	The intrusion length for 1,000 mg/l or advancement
Wassef and Schüttrumpf [163]	FEFLOW	RCP 2.6, and RCP 8.5	–	43 and 57 km intrusion length for RCP 2.6 and RCP 8.5 respectively
Armanuos et al. [31], Armanuos [37], Armanuos and Negm [39]	SEAWAT	100 cm SLR scenario	In the eastern, central, and western ND, correspondingly, there are 44.65, 60.25 and 82.20 km	In the eastern, central, and western portions of the ND, 68.84, 108.20 and 106.50 km, correspondingly

growth and the decrease in freshwater in the region, leading to higher average COD levels. To ensure sufficient freshwater, the study investigated how treated wastewater combined with freshwater affected the environment. It was found that there was a positive impact on water quality and local farming, making life secure.

6 Groundwater Vulnerability Modelling in the Nile Delta Aquifer (NDA)

GW vulnerability is an essential approach for GW resources management. The following paragraphs give insights on definition of GW vulnerability and summarize the vulnerability of GW studies in the area of the ND.

GW pollution is considered a dangerous environmental problem in Egypt and the globe. It is primarily founded on expanding of the human connection with GW environment [101]. Hence, there is a critical requirement for a method which accurately interprets GW information to monitor and facilitate data sharing between water resource managers and decision-makers. In such circumstances, GW vulnerability assessment is one of the most widely recognized tools for planning, protecting and managing of GW resources [81]. A number of studies related to vulnerability of GW for pollution was investigated, for example, DRASTIC [24], GOD [74], AVI [156], SINTACS [50], SEEPAGE [114], ISIS [113], EPIK [54], MINNESOTA [110], RISK [121], EPPNA [40] and SI [127] in [162]. Moreover, it is obvious that the remote sensing, the geographical information system (GIS) and the DRASTIC are useful methods for identifying areas that are at risk of groundwater [21, 22, 26, 47, 49, 76, 77, 122, 133, 134, 159, 160].

DRASTIC index consists of a set of seven hydrological factors: (D) is depth of groundwater, (R) is the net GW recharge, (A) is aquifer media, (S) is soil media,

(T) is topography, (I) is the effect of the vadose zone, and (C) is the hydraulic conductivity of the aquifer [24]. Modified DRASTIC index, Pesticide DRASTIC index, Pesticide DRASTIC-LU index and Susceptibility Index (SI) are created from the DRASTIC index. Consequently, the vulnerability DRASTIC model are changed (modified DRASTIC) in order to consider the land use effect especially in agricultural regions [59, 161]. Furthermore, the SI and Pesticide DRASTIC indices are proposed to evaluate the vulnerability of GW in agricultural regions [26]. In particular, the land use effects was included in the package of SI but the type of soil media, the vadose zone effect and the hydraulic conductivity were excluded [127]. Another approach, the Pesticide DRASTIC approach, was recommended for utilizing the same hydrological boundaries of DRASTIC with various assigned weights.

Mogren and Shehata [103] used WMCDSS and GIS to map the Quaternary aquifer's susceptibility to GW contamination located in an area northeast of ND. The outcomes of GW vulnerability demonstrated four classes from low to highly vulnerable to pollution. As per the map, the approving territories for GW utilization are situated in regions where low to extremely low vulnerable has been detected. These areas are allocated over the total area of 4080 km^2 and covers 53.68% of the investigated area and the zones having moderate to high GW sensitivity approximately 3520 km^2 showed that 46.32% of the study area were suffering GW quality deterioration. Therefore, Elewa et al. [64] assessed the GW vulnerability especially in the northeastern area of the ND, utilizing GIS and WMCDSS. The results from the study confirmed that about 53.69% of the studied area was categorized as extremely to low vulnerable to pollution, followed by 46.31% of the total studied area was characterized as high to mildly vulnerable to pollution. In addition, about 28.77% of the study region was limited as slightly susceptible to pollution. As the result of that, a specific management plan and practices are necessary for controlling and preventing the SWI in the south.

Gad et al. [75] evaluated the sensitivity of GW to pollution in the Quaternary aquifer of the Wadi El-Tumilat (QAWT), East ND, Egypt with useful tool (QAWT) that is based on PRAST, GOD, and DRASTIC vulnerability index models. The outcomes of GW maps of vulnerability from the three applied approaches indicated significant variations due to the differing criteria used for each index. The high observed category according to QAWT Vulnerability index was medium vulnerable to pollution, on the other hand, according to DRASTIC and PRAST indices about 31 and 35% were considered as highly vulnerable to pollution, respectively. Moreover, areas were highly susceptible to pollution are closely linked with areas that have low water levels, high soil values, and high permeability of the vadose zone, but the southern part of Wadi El Tumilat were regarded as the best region for land reclamation. Furthermore, Gemail et al. [76] used DRASTIC index and integrated electrical conductivity (IEC) model to evaluate the GW susceptibility to pollution in the ND to detect the vulnerable zones to GW contamination. The results from the two approaches were contrary. Yet, a positive coefficient was detected between DRASTIC and IEC modelling and its value was 0.82. Only 19.81% of the entire area of study was considered extremely highly vulnerable to pollution, followed by 41%

as highly vulnerable to pollution. Nevertheless, moderate vulnerable area and low vulnerable zone to pollution were 27 and 12%, individually.

Hence, Seleem et al. [143] used the DRASTIC method and ArcGIS to evaluate the unconfined aquifer's GW susceptibility for pollution within the region near the Ismailia canal situated in the eastern parts of the ND. The outcomes confirmed that the region with shallow depth to GW level near the Ismailia canal was considered highly vulnerable to pollution as a result of its highly population density and the industrial factories located in the study area. Additionally, the landfill, septic tanks, the municipal and agricultural drains existed around the area of Ismailia canal. The area around Ismailia canal was considered extremely sensitive to pollution; the area north to Ismailia canal is classified as having a high GW vulnerability to pollution, moderate and low vulnerable zones was located in western and eastern parts, and southern parts of the area of study.

To estimate the GW vulnerability to pollution in the Wadi El-Natrun Depression of Egypt, El Osta et al. [60] utilized the DRASTIC vulnerability model. The GW in the study region was considered polluted resulting from high level of abstraction and the return flow of the polluted water from the irrigation system. The results of GW vulnerability maps confirmed that middle and southeastern areas were highly vulnerable to pollution. The vulnerability map from modified DRASTIC model showed that high-danger zones were significant in the eastern portions of the region and were connected to the return flows from the polluted water.

Next to this, Khalifa et al. [91] implemented the DRASTIC approach to assess the significance of the DRASTIC hydrological parameters for the susceptibility of GW of the aquifer which is located in the central Delta in Gharbiya Governorate (Egypt). The results from vulnerability model were verified and validated using nitrate concentration of the GW data. About 24% of the region was categorized as low vulnerable to pollution, 30% as moderate susceptible, 35% and 11% as highly and very highly vulnerable to pollution, respectively. Armanuos et al. [33, 34] utilized five various vulnerability models to assess the sensitivity of GW to pollution in the western parts of the ND. The vulnerability indices of DRASTIC, Pesticide DRASTIC, modified DRASTIC, Pesticide DRASTIC-LU and Susceptibility Index (SI) indicated nitrate concentration in 108 GW wells. The concentration map distributed the western area of the ND. About 25% of the region area was ranked as very highly vulnerable to GW pollution according to DRASTIC, Pesticide DRASTIC-LU and SI models. The vadose zone was considered the most important factors compared with other parameters. Therefore, the results from different vulnerability maps confirmed consistency a significant technique for land use, GW resources management in the Western ND area and similar areas with the same conditions, as shown in (Fig. 11).

Salem et al. [138] revealed the GW vulnerable areas in the north western portions of the NDA using DRATSTIC method and GIS. According to the vulnerability map from generic DRASTIS model about 28.4, 58.9, 12.7% of the entire region are considered low, moderate, and very high vulnerable to pollution, respectively. On the other hand, the vulnerability pesticide DRASTIC models confirmed that 22.4, 61.4, and 16.2% of the entire study area was rated as extremely highly, very highly, and moderate vulnerable to GW pollution.

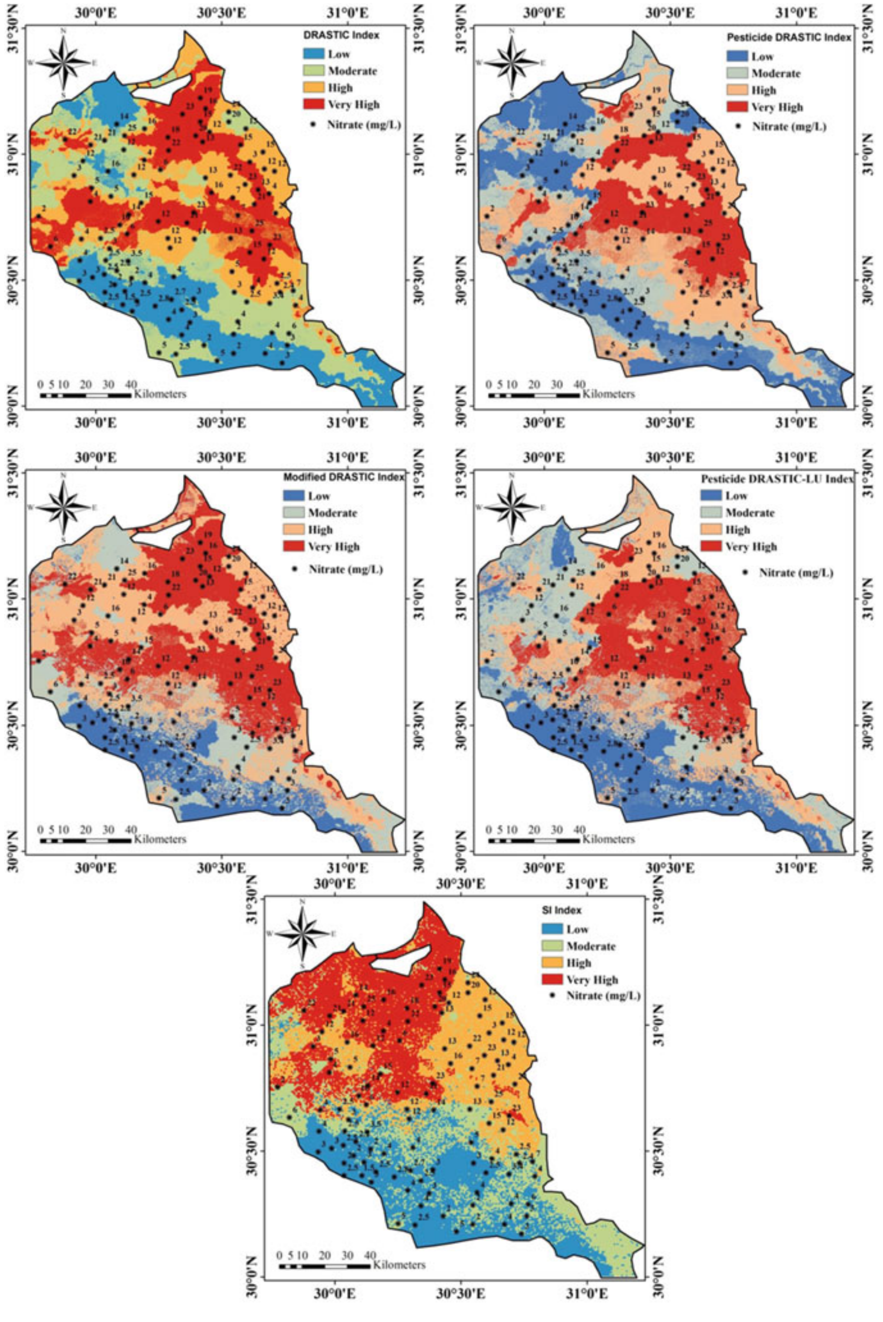


Fig. 11 Groundwater vulnerability in the central of the Nile Delta region for various vulnerability models [35, 38]

Abu-Bakr [19] studied the vulnerability of GW to contamination in western parts on the ND in the Wadi Al-Natrun to compare with Al-mina governorate which represents the Nile valley and El Gharga Oasis located in the western desert region. The surfer 12 and the AHP were used to produce the GW vulnerability maps in the three studied areas. The main finding showed that the vulnerability categorization for each study area were endorsed by the associated map of GW vulnerability. In the Wadi Al-Natrun region, nearly 67% of the aquifer was categorized as moderate vulnerable to pollution, followed by about 3.3% was considered as low to moderate vulnerable to pollution and about 28.7% was characterized as medium to high sensitive to pollution. Regarding to this result, Table 3 summarizes the GW vulnerability studies in the ND area.

Moreover, Metwally et al. [102] evaluated vulnerability areas in the central ND, Gharbia Governorate by using DRASTIC vulnerability models (Egypt). The DRASTIC maps were produced for the modified pesticide DRASTIC, the modified DRASTIC, and the pesticide DRASTIC. The ratings and weights of the vulnerability DRASTIC models input variables were improved after utilizing AHP. The collected analysis showed that the South of Zefta was characterized as an extremely high vulnerable region depending on all DRASTIC models. All DRASTIC models, with the exception of those for AHP-pesticide and AHP-modified pesticide, were classified the majority of the Qutur region as a moderately sensitive zone. Most of the Samanod region and the area to the north of Al-Mahalla Al-Kubra were considered to be within a very low vulnerability area, as shown in (Fig. 12).

A modified GIS-based DRASTIC-LU approach by [28] was used to quantify the GW vulnerability of the ND. Groundwater vulnerability levels to contamination were calculated by using two kinds of modified DRASTIC-LU systems, general and pesticide. The study region was highly and very highly exposed to pollution, with 42.69 and 53.91%, correspondingly, according to the generic DRASTIC-LU model output, with the exception of the northwest, which had a moderate susceptibility of 3.38%. On the other hand, the outcomes of the pesticide DRASTIC-LU approach clarified that a moderate sensitivity of 9.78%. Moreover, the majority of the ND was highly and very highly vulnerable with corresponding vulnerability values of 50.68 and 39.53% except the northern and southern regions. The output feature map demonstrated a high connection with the pesticide vulnerability system that was based on the nitrate data. Thus, the impact of depth to GW level and the net rate of recharge were established to be the most crucial aspects to take into account after evaluating the model sensitivity.

Salem and Hasan [137] evaluated GW vulnerability to SWI using the (GIS)-based GALDIT model and HFE diagram. According to the GALDIT approach, the coastal and central regions which covered 37.7% of the total area and their regions were categorized as highly susceptible to SWI. Nevertheless, the southern regions made up 62.3% of the overall area were exposed to intrusion hazards. The parameters of the updated vulnerability are aquifer hydraulic conductivity (K) and aquifer thickness (L). In addition, the new GALDIT map demonstrated that significant vulnerability percentages existed in the northern regions and increased by 15% when compared to the traditional GALDIT index. The HFE diagram showed that seawater intruded

Table 3 Groundwater vulnerability studies in the Nile Delta aquifer

No	Study	Vulnerability models and other tools used	Study area	Results	Recommendations
1	Mogren and Shehata [103]	Weighted Multi-Criteria Decision Support System model (WMCDSS) and GIS	Eastern ND	53.68% (moderate to high), 46.32% of the study area suffers from GW quality deterioration	Uncommon treatment and changing of crop patterns are recommended
2	Elewa et al. [64]	(WMCDSS) and (GIS)	Eastern ND	53.69% (very to low), followed by 46.31% (high to moderate) vulnerable to pollution	A specific management plan and practices to controlling and preventing the SWI and GW quality deterioration in the south
3	Gad et al. [75]	PRAST, GOD, and DRASTIC	Wadi El-Tumilat (QAWT), East Delta, Egypt	DRASTIC and PRAST indices about 31 and 35% (highly vulnerable)	The high suitable regions for novel reclamation of land were found in the southern area of Wadi El Tumilat particularly
4	Gemail et al. [76]	DRASTIC and integrated electrical conductivity (IEC)	Central ND	19.81% (very highly vulnerable), 41% (highly vulnerable), 27 and 12% (moderate vulnerable area and low vulnerable zone)	——-
5	Seleem et al. [143]	DRASTIC and ARCGIS	Ismailia canal, eastern regions of the ND	The area around Ismailia canal is categorized as (very highly vulnerable), north to Ismailia canal (highly vulnerable western and eastern parts, and southern parts (moderate and low vulnerable)	High-danger zones in the eastern parts of the study area are connected to the water flow from the polluted water from irrigation system

(continued)

Table 3 (continued)

No	Study	Vulnerability models and other tools used	Study area	Results	Recommendations
6	El Osta et al. [60]	DRASTIC	Wadi El-Natrun Depression of Egypt	High risk areas (eastern parts)	–
7	Khalifa et al. [91]	DRASTIC with (GIS)	The middle Delta in Gharbiya Governorate	24% (low vulnerable to pollution), 30% (medium vulnerable), 35% and 11% (highly and very highly vulnerable)	–
8	Armanuos et al. [32, 34]	DRASTIC, Pesticide DRASTIC, modified DRASTIC, Pesticide DRASTIC-LU and Susceptibility Index (SI)	Western ND	25% (very highly vulnerable) depends on DRASTIC, Pesticide DRASTIC-LU and SI models	Vulnerability maps confirmed its consistency as a significant approach for planning of land use and organizing of GW resources in the Western ND area and similar areas with the same conditions
9	Salem et al. [138]	DRATSTIC model and GIS	Western ND	22.4, 61.4, and 16.2% of the total study area (very highly), (highly), and (moderate)	–
10	Abu-Bakr [19]	Golden software surfer 12 and the (AHP)	Wadi Al-Natrun, Western ND	67% (medium), 3.3% (low to medium) and about 28.7% (high) vulnerable to pollution	–

the coastal area. The new GALDIT map demonstrated that the northern regions continued to rise, approximately 15% higher than the traditional GALDIT index. Likewise, the HFE diagram showed that the northern coastal zones were high risk of seawater leakage. These locations exist within the Na-Cl type field which reflects salinization of GW.

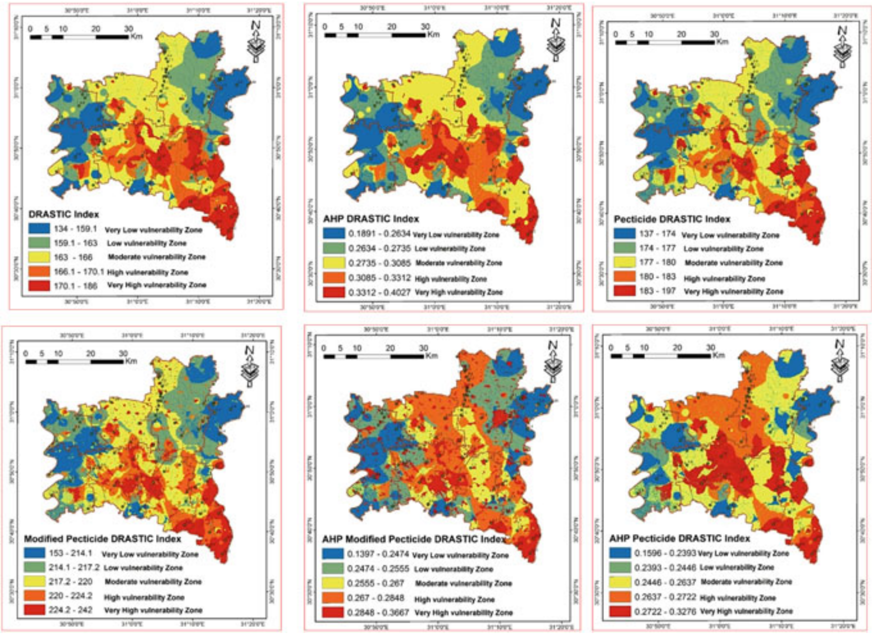


Fig. 12 Groundwater vulnerability in the central Nile Delta region for various vulnerability models, [102]

7 Modelling of Groundwater Management in the Nile Delta Region

The groundwater management modelling is a powerful method for water resources management. The efficiency of GW modelling mostly relies on both GW flow and contaminant transport mechanisms. This section introduces an overview of the GW management modelling in the NDA.

Soliman et al. [154] simulated the effects of different strategies for water management in western ND region and changes on GW level using MODFLOW code. The results confirmed that increasing the drawdown by 11.5 and 15 m and increasing canal leakage by 20 and 48% were considered as the worst-case scenarios. On the other hand, increasing the drawdown by 3.5 and 5 m and increasing canal leakage by 29 and 40% were considered as the best two scenarios. Regarding a GIS-based GW Western NDA system model, Dawoud et al. [52] established a model that provided valuable post-processing data associated with modelling of GW in the region.

The created model was modified under the steady state and transient conditions, based on the measured GW heads over the past 20 years. Two proposed scenarios were tested; one of them reduced surface water inflow while increasing yearly withdrawal from the GW system by around 450 × 10^6 m^3, resulting in a net GW recharge (approximately 5.7% increase) and aquifer vulnerability (about 91% decrease). The other scenario could increase the yearly potential of Western NDA by approximately 23%. In order to explore the real litho-stratigraphy and aquifer heterogeneity in the northern and center area of the ND, Nofal et al. [115] carried out the ongoing stratigraphy of the NDA system utilizing litho-logical information from the new well penetrations of varying depths. These wells have been planned and executed by RIGW under the National GW Quality Monitoring program. Moreover, it assessed hydrochemistry status in the NDA from various depths (25–650 m) of the National GW Quality Monitoring system. El Molla et al. [58] discussed how land reclamation projects and reduced canal flow have led to water shortages for surface irrigation in Western ND. The Ministry of Water Resources and Irrigation (MWRI) implemented a development plan to increase land reclamation by 625,000 feddan in the western ND by 2017. Using different water resources (surface water, GW, and wastewater reuse), different scenarios were considered to prevent the depletion of the GW aquifer system. The newly constructed and adjusted GW flow model was used to predict the effects of these scenarios on the GW aquifer system by 2017.

Owing to urbanization and an excess of GW extraction, the water quality degradation in the ND region has put immense pressure on the management of water resource. Therefore, the National Water Resources Plan for Egypt highlighted that the GW extraction rate from the NDA system exceeded the GW abstraction safe yield [111]. Nevertheless, accurate data regarding GW extraction levels in the ND region was lacking [62]. A detailed analysis of the increasing GW usage in the central area of the ND region by El-Agha et al. [62] provided some information on the impact of water irrigation systems and presented valuable data on well density variations across the study area, measurements of GW salinity and legalization on GW management.

Armanuos et al. [37] assessed the possible effect of Grand Ethiopian Renaissance Dam (GERD) and abstraction scenarios on the GW level in the NDA utilizing MODFLOW code. In this research, an incorporated 3-D GW model was implemented the complete irrigation system canals located in the ND area. The GW model was experienced for 3 different scenarios: (1) decrease of water canal depths, (2) increase of the abstraction rate from the NDA and (3) a combination of the two scenarios. According to the results, the impact of increasing abstraction rate on GW level in the ND was much more substantial than minimizing the water canals depth. Hence, the reality of the presence of the layer of upper clay cap decreased the measure of water entering and coming to the GW in the NDA. The previous scenario introduced the most pessimistic scenario as the mean value of GW level drawdown increased to 1.26 m, 1.7 m and 1.35 m in the western, middle and eastern areas of the ND, individually.

Ezzeldin et al. [70] compared the distinctions and similarities between the MODFLOW-USG and MODFLOW 2005 in simulating 3D GW flow model in the Quaternary aquifer of eastern ND region. In the study, the applied model was transferred to the stratigraphic model, enabling the automatic organization of the boundary condition data in arrays indistinguishable by the grid cells. The PC-based program called PEST joined MODFLOW 2005 and MODFLOW USG to align the aquifer's head of groundwater. GW levels observed in the year of 1991 were utilized for the steady state condition calibration and then as introductory conditions for the calibration of the transient case calibration between 1991 and 2004. The outcomes showed that MODFLOW-USG offered adaptability in the model grid design, allowing for the use of non-rectangular cell forms. Likewise, the simulation of MODFLOW-2005 took approximately 20 times longer to complete and it used six times more cells than the MODFLOW-USG.

For the sustainable strategy for managing of the GW system in the Quaternary aquifer eastern of the ND, Eltarabily et al. [68] evaluated different scenarios of recharge and extraction rates. The effects of land use and building dams upstream of the Nile River on GW management measures were investigated by MODFLOW model. The future transient simulation was run through three different scenarios. Growing abstraction rates by 15, 30, and 50% make agricultural activities increased and Nile water levels were estimated into 0, 0, and 0.6 m in the Port Said Canal, following the GERD which was expected to operate in 2017. In addition, the study indicated that the NDA remained stable at the present abstraction rate through 2023 and GW heads declined by 0.2 and 0.42 m in the southern area while a slight increase in the northern area. Therefore, GW storage could not be enhanced beyond 2020.

Another research group Nofal et al. [116] created a 3D model of the NDA for water management strategies. The implemented model was utilized to examine the impact of GW system heads and aquifer salinity on aquifer sensitivity to various pumping and recharge rates. The findings supported the idea that aquifer sensitivity to existing conditions differ according to location. Changes in pumping rates greatly impacted all strata of GW heads in the NDA. It was shown that a 100% increase in extraction rate substantially influenced GW heads. The NDA's center and southwestern borders showed signs of susceptibility to the rising abstraction rate. However, diminishing the abstraction rate by half demonstrated that aquifer system had recovered in certain areas, particularly those with high pumping rates (like South West edges). Other findings highlighted the necessity to appropriately manage the GW pumping rates in the ND. Changes in abstraction must be monitored and controlled by the government according to Nofal et al. [116]. Regarding the salinity's sensitivity, different abstraction rates had a much smaller effect on the aquifer beneath the ND than local abstraction areas close to the shore in which decreased abstraction rates had a negligible effect. It was found that the quantity in the ND was sensitive compared to the quality [116]. Nonetheless, in areas of a negligible upper clay layer, irrigation systems and crop patterns might be the only way to enhance groundwater levels [116].

Significantly, Egypt population has grown from 27.9×10^6 in 1960 to 88.8×10^6 in 2015 since the High Aswan Dam (HAD) was constructed although Egypt's annual share of the Nile Water has continued unceasing at 55.5 BCM/y. The HAD was created to manage water shortages and potential flooding through the rainy season, as well as to control the flow and preserve the Nile water [63]. The total water storage capacity of HAD is 121 BCM, out of which 90 BCM are used as "life storage" and 31×10^9 m^3 as "dead storage" [109]. All of the nations in the Nile basin have signed a number of international agreement showing how much each of them would receive the amount of water. As a result, Egypt and Sudan agreed to a deal for the use of the

Nile water that come into their respective territories. According to the deal, Egypt would receive 55.5×10^9 m^3/yr and Sudan would get 18.5×10^9 m^3/yr under the framework on which Sudan would build the Roseires Dam on the Blue Nile and Egypt would build the HAD on the main Nile [166].

The GERD construction on the Blue Nile at Guba, 60 km from the Sudanese border, began in Ethiopia in 2011. The storage capacity of the dam was 74×10^9 m^3 in which 60 BCM was regarded as actual live storage, and it was utilized to produce 6000 Megawatts of power [158]. The proposed project would cover an area of 1800 km^2, and when it was finished, it would have a height of about 140 m, building it the biggest hydropower dam in Africa. Though the dam intended to produce electricity (as stated by the Ethiopian government), a sizable amount of Nile water ($74 \times 10^9 m^3$) would be transported into its reservoir to increase storage. This would significantly impact the Nile River discharge in the downstream GERD countries, which extended into the Sudanese and Egyptian provinces. As a consequence, Egypt's water share ($55 .5 \times 10^9$ m^3) would be exaggerated. Nile water levels would decline. In addition, GW recharge rate in the NDA would decrease but not for additional SWI into the NDA.

Recently, a few research implemented to examine the potential influences of GERD construction on Egypt. By separating estimated and obtained data, Farrag [73] demonstrated the high correlation between GW levels and surface water levels. This suggests that the lack of surface water will impact both surface water and GW as a concern caused by the development of the GERD. To combat the undesirable consequences of the GERD development on Egypt, Ramadan et al. [123] proposed revising or altering the policies implemented by the MWRI, in any event, there would be multiple sorts of significant issues. The results were obtained by creating several GERD operation situations using a mathematical model. Wheeler et al. [165] discovered that the AHD would extend its base operational level for four years in a row, changing Egypt's water supplies while the GERD was conserved during the dry years.

Ramadan et al. [124] utilized MODSIM model to investigate the potential influences of GERD construction on the conditions of flow in the Nile River while taking into account three distinct situations of filling the GERD reservoir through a period of the years of 2, 3, and 6. According to the findings, the Nile River flow at HAD would decline by 37.263, 25.413, and 13.287 BCM, respectively. Due to this, the Nile River's water level and irrigation system would deteriorate and GW recharges the NDA would be decreased. As a result, the Mediterranean Sea's SWI into the NDA would occur much faster. The impacts of the GERD construction on Egypt's water supplies were mathematically studied by Abdelhaleem and Helal [7], who concluded that the country's water share should not decline by more than 5–15% in any projected scenario. The reservoir of GERD might be filled in four distinct ways during periods of the years of 2, 5, 10, and 20. The annual water volume required to fill the GERD reservoir up to its necessary level of 146 m were 39.5, 15.8, 7.9, and 3.95 BCM/y. According to Attalla [41], GERD was proving to be a significant issue of contention between Ethiopia and Egypt. Alternative strategies including reuse drainage water and reduction in surface water wastage were consequently suggested. Arby [29] studied the reasons why Egypt refused the GERD using qualitative approaches based on secondary data from sources such as articles, e-news, other digital books, and other scholarly sources. The findings indicated that a significant amount of Nile water would be lost, which would weaken the economy of Egypt. According to El-Nashar and Elyamany [65], the estimated stored water would be greater than the water of the dam, AHD and the GRED mentioned that 12.1×10^9 m^3 of water would be saved by using recommended methods.

Using the MODFLOW code, Armanuos et al. [37] evaluated the GERD's potential influence and extraction of different scenarios on the GW level in the NDA. This study used a 3D GW model that incorporates the entire network of irrigation canals in the ND region. The constructed model was put to the test under three different conditions: (1) decreasing water canal depths, (2) raising the rate which water was withdrawn from the NDA, and (3) combining the two conditions. As a result of the presence of the upper clay cap, the amount of water entering and coming to the GW in the NDA declined. Hence, increasing the abstraction rate had a much greater impact on GW level in the ND rather than reducing the depth of water canals.

According to Armanuos et al. [37], the average value of the drawdown increased to 1.26, 1.7, and 1.35 m in the western, middle, and eastern regions of the Nile Delta, correspondingly. It can be seen that the final scenarios were the worst case. For the assessment of Quaternary aquifer in the eastern side of the ND, Eltarabily et al. [68] evaluated three different scenarios of recharge and abstraction rates. The impacts of rerouting land use and building dams upstream of the Nile River on GW management measures were investigated using MODFLOW. The future transient simulation was tested through 2023. It indicated increasing abstraction rates by 15, 30, and 50% for agricultural activity and decreasing GW heads of the Port Said Canal by 0, 0, and 0.6 m in relation to GERD operated in 2017. The zone budget results for the study region exhibited that the aquifer was steady at the existing abstraction rate through 2023. For the first and second proposed scenarios separately, GW heads declined by 0.2 and 0.42 m in the southern area whereas a moderate rise was seen in the northern area. GW head decreased by 0.66 m at the point where additional abstraction stress was applied (a 50% increase). Nevertheless, GW storage was no longer sufficient to enhance the GW aquifer's capacity past the year 2020.

Abd-Elhamid et al. [12] experienced the Nile River's probable influence on the NDA system because of the construction of the GERD. Therefore, they suggested various remedial measures. To simulate GW flow and SWI while accounting for GERD operation, a 3D model of the NDA was created using the SEAWAT code. Two possibilities for filling the GERD reservoir over periods of 3 and 6 years were put into action. The results showed that under the first and second scenarios, the highest point in GW level will occur in the center region of the ND. Under the first and second scenarios, the saltwater line (35,000 ppm) would extend further inland the NDA for the distances of 110.2 and 108.25 km. On the other hand, the freshwater line (1000 ppm) would increase further inland the NDA for the distances of 70.85 and 67.3 km. The findings showed that the GW pumping rates from the aquifer system would need to be reduced by 60 and 40% respectively to enhance the freshwater volume in the NDA system while filling the GERD reservoir within 3 or 6 years.

Additionally, the expected consequences of the GERD construction on the Nile Delta, Egypt, were evaluated by [42]. These include the effects of altering distributed crop patterns at GW levels and lowering surface water levels and cultivating various crops that require less water on soil salinity. For these reasons, the ND region's eastern portions have been identified as a model region for the assessment. The findings demonstrated that the NDA's GW level was obviously inversely proportional to its surface water level. The GW level declined from 5.0 m to 2.0 m in the case study region in 2012 when the surface water level was reduced by 50%. After modification, the GWL was declined to 1.30 m by distributing crop patterns from rice to new crops. The findings also showed that there was a strong correlation between altered crop patterns and soil salinity. When non-rice crops like grapes were grown in the Nile Delta, the salt level of the soil raised. After ten years of model simulation, the salinity level increased from 0.45 S/m to 0.48 S/m. This assessment highlights the negative impacts of GERD development on the Egypt's water resources, the soil salinity, the crop yields, and the Egyptian national income.

Abd-Elhamid et al. [13] utilized MODFLOW to estimate land subsidence and the characteristics of the middle ND. This study considered three scenarios: a reduction in aquifer recharge, an increase in extraction, and a combination of both. In accordance with the findings, any plans to take more water from the NDA in the future were needed to consider the potential for the land to sink due to excessive pumping from the underground water source. Besides, the study showed that over pumping could happen land subsidence, especially in the dry regions.

Furthermore, the SEAWAT model was employed to the NDA near the mouth of the Nile Rosetta branch by El Shinawi et al. [61] to predict the GWH for the present condition and potential SLR situations. In 2020, 2040, and 2060, the GWH results would be between 0 and 0.40, 0 and 0.45, and 0 and 0.55 cm. Following that, high least squares linear regression analysis was applied to estimate future upward land subsidence using the GWH. With correlation coefficients ($r^2 = 0.87$), an inverse association between both the GWH and the upward land subsidence was discovered. In the years 2020, 2040, and 2060, the rates of upward land subsidence reduced the hydraulic head as a consequence of SLR. Additionally, it was found that the Rosetta Promontor revealed the maximum thickness and accumulation levels of the Holocene deposits.

Using the SEEP/W model to calculate variations in the GW table and moisture in the root zone, Abd-Elziz et al. [17] assessed the effects of ICR utilizing concrete on the soil and crop yields. Unlined, lined, and lined canals with a drainage pipe are the three case studies that have been modeled and contrasted. Several canals in the ND-Sero, Dafan, and New-Aslogy-are subjected to the approach. The findings revealed that the use of ICR has led to a reduction in water loss from canals. The lining method has shown a greater decline in losses compared to lining with a drainage pipe, achieved by minimizing losses from canals. Additionally, the water table beneath the embankment has decreased. While this could lead to improved crop yields and protection from logging, it may also result in less recharge of groundwater aquifers.

8 Methods for Adaptation and Mitigation of Saltwater Intrusion in the Nile Delta Aquifer, Egypt

The Nile Delta Aquifer (NDA) of Egypt is known globally as the greatest fresh GW reservoir, mainly replenished by the irrigation water. However, the NDA is subjected to an extreme SWI issue because of its location, geological and geometric conditions, restricted natural recharge, and extensive GW pumping. The northern areas of the ND cannot be fully utilized GW due to the risk of freshwater-saltwater interface. To accomplish the suitable GW management in the ND region, it is necessary to develop SWI advancements and the combination process between freshwater and saline groundwater.

To accurately model the movement of SWI and salinity distribution, the actual state of stratigraphy and heterogeneity of the NDA must be taken into consideration. The standard modeling idea of the NDA had assumed the aquifer to be a homogenous porous media made up of graded sand and gravel with a clay cap at the upper part. Different techniques have been proposed for controlling SWL and protecting GW resources, increasing fresh GW volume and reducing seawater volume [69]. Table 4 summarizes various methods proposed by many scholars. The examinations essentially focused on the process of salinization of the GW in different deltas around the globe (updated after [96]).

9 Conclusions

The following conclusions of this research can be summarized as follows:

Different tools of GW vulnerabilities have been applied to different parts of the ND region. DRASTIC, DRASTIC-LU, SI, Pesticide DRASTIC, PRAST, GOD, and modified DRASTIC (commonly GW vulnerabilities models) have been implemented by researchers to evaluate GW sensitivity to pollution in the ND. The published studies cover western Nile Delta, eastern ND and small parts on central ND regions. The nitrates concentration in available observation wells has been utilized to validate the outcomes from GW vulnerability approaches. However, no studies cover the whole area of the ND. Accessing available data is a major obstacle for researchers. All studies confirm that the NDA categorizes moderate to highly vulnerable to pollution. Significantly, the coastal areas are considered highly vulnerable to pollution due to saltwater intrusion.

Limited studies concerned on modelling the GW contamination in the ND region did not take into account the SWI which will be addressed in separate paragraphs. MODFLOW and MT3DMS have been used to model GW contamination in different regions of the Nile delta. It is noted that only one study covers the whole area of ND and simulates the nitrates pollution in the GW system. Other studies cover small parts in eastern, middle and eastern parts. One of the published studies was conducted specifically for areas near industrial cities to simulate the following contaminant

Table 4 Methods to control seawater intrusion in coastal aquifers (updated after [96])

No	Method	Source	Advantages	Disadvantages	Conclusion
1	Rice cultivation	[57, 92]	It has a considerable decrease in soil salinization	It depends on a huge volume of water That is at present a very rare resource	Uneconomic solution
2	Permitting 10 to 20% of the fresh water of irrigation to leach the soil	[18]	No salt aggregation, salt export will coordinate salt import and will in the long run prevent the infiltration of saltwater to GW system	This might be a risk-based approach as it could force the returning of salt process to the area of the root zone	Not recommended
3	Cultivation of salt tolerant crops	[71]	Cultivation of tolerant crops in northern parts can resist salt concentration	It is considered as a limited approach for specific types of plants can be cultivated	Highly recommended in the northern coast of Egypt
4	Establishing wetlands in salinized regions	[44]	Egypt has the following lakes (Maryut, Idku, Burullus, Manzala, and Bardawil) in the north of the Nile Delta which may be contemplated as natural process for adaption	This method can be applied only in low lying areas of the ND	Highly recommended in the northern lakes of Egypt
5	Abstraction of saline groundwater	[119, 120]	It is an effective method for disposing the saline water	Removal of disposal abstracted saline water might affect various environmental problems	Not recommended in coastal aquifers with shallow depths
6	Expanding in land reclamation	[119, 120]	It contributes to increase the volume of freshwater recharge	It depends on availability of lands and freshwater	Recommended in Egypt

(continued)

Table 4 (continued)

No	Method	Source	Advantages	Disadvantages	Conclusion
7	Artificial recharge	[32, 46, 93, 126]	This method increases the freshwater outflow to the aquifer. The efficiency of this approach depends on the rates of pumping and injection, wells depth, the properties of coastal aquifer and wells distances	It depends on a huge volume of water, that is at present a very rare resource	Recommended in areas where there is a plentiful supply of water
8	Physical barriers	[33, 34, 80, 87]	This method contributes to stabilization the coast and reduces the SWI. The barrier height has a very substantial parameter in the mechanism of retreating rates	This approach is considered to be the costliest strategy either utilizing sheet pile walls or clay trenches. In any case, it is only can be applied for the shallow aquifer considering its gigantic expense	Economic feasibility is the cornerstone
9	Compressed Air Injection	[55, 164]	This method decreases the The permeability of aquifer and minimizes the discharge short-term	Few studies discuss this method. Still in the experimental phase and not completely established	Additional experiments on large scale is essential

(continued)

Table 4 (continued)

No	Method	Source	Advantages	Disadvantages	Conclusion
10	Combination between barrier wall and freshwater injection	[38]	This method provides coast stabilization and decreases the seawater intrusion. The barrier depth and location, freshwater injection rate is important parameter to control the degree of efficiency	It needs a large volume of water. In addition, it is only available for the shallow aquifer duet to the high cost	It is recommended for availability of water in abundance and needed for construction of clay trenches or sheet pile wall
11	Pump and Treat (P&T)	[25, 100, 131]	Genetic algorithms are needed to find the optimal well position and extraction rate to decrease the cost of aquifer remediation and pumping and treating	This approach is considered to be the costliest approach, including cost of pumping, treating, remediation of aquifer, and maintenance	Not recommended
12	Recharge and Abstraction (R&A)	[45, 125, 155]	Application of this methods decreases seawater volume and increases freshwater volume that could support for controlling SWI. These methods provide better outcomes as compared to using individual methods	This method is considered to be high-cost, including cost of extraction saline water, and recharge freshwater	It is recommended in case of availability of water for recharging in abundance

(continued)

Table 4 (continued)

No	Method	Source	Advantages	Disadvantages	Conclusion
13	Abstraction, Desalination, and Recharge (ADR)	[14, 16]	ADR method gives best results rather than abstraction saline water or recharge saline water alone. It obtains repulsion of saltwater intrusion. It is low cost method compared to saline abstraction, resulting in low salt concentration in the aquifer	It is considered costly method which includes cost of abstraction, desalination, recharge to aquifer, construction of desalination plants, maintenance, and abstraction/ recharge wells. Also, the disposal from abstraction of very saline water and brackish water can be an environmental problem	It is recommended for Egypt and can be applied in the north area of Egypt. Distributed desalination projects can be constructed near to the coast. It seems to be an effective method to achieve repulsion of SWI compared with separately methods
14	Treatment, Recharge, Abstraction, and Desalination (TRAD)	[16, 88]	These approach combines saline wastewater abstraction, desalination process of abstracted saline water, and injection deeply the treated wastewater. It controls the SWI in coastal aquifers Low coast and least salinity could be attained over and done with the models of optimization	It is relatively cost method includes the cost of abstraction, desalination of abstracted water, desalination plants construction, maintenance, and cost of injection of treated water	It is recommended in the north of Egypt to reduce the SWI and increase the freshwater volume in aquifer. It is a type of GW remediation and environmentally friendly to reduce the risk for wastewater

(continued)

Table 4 (continued)

No	Method	Source	Advantages	Disadvantages	Conclusion
15	Coastal earth fill	[11]	Different coastal earth fill soil can be utilized to expand the shoreline towards the sea. It decreases the saltwater intrusion. It minimizes the expected risks of SWI and rise in sea level	It depends mainly on the availability of different types of earth fill soil, its cost includes the cost of soil, movement and transportation, soil fixation process and maintenance	It is recommended for Egypt to extent the shoreline of coastal area in the north of Egypt and decreases the future risks of SLR and minimizes the SWI
16	Aquifer Storage and Recovery (ASR)	[48, 53, 84]	It is an approach for water resource management in many countries worldwide. It provides alternated way to surface water storage (Reservoirs and dams). It is the injection deeply freshwater through ADR method resulted in increase the aquifer storage and continuous repulsion of SWI. It improves the quality of GW	The economic cost of the ADR includes the cost of recharging/ abstraction water, and maintenance. It depends in many factors to increase the efficiency of recovery of water storage	It is recommended for application in Egypt once the water is available for recharging and abstracted to reuse again after storage

(continued)

Table 4 (continued)

No	Method	Source	Advantages	Disadvantages	Conclusion
17	Abstraction, desalination, and recharge by treated wastewater (ADRTWW)	[82, 83, 88]	Combination between saltwater abstraction, desalination of abstracted water, recharging of retreats wastewater control the SWI and low coast and salinity distribution compared with alone methods	It is considered relatively coast method, which includes cost of saline water abstraction, desalination abstracted water, movement of treated abstracted water, maintenance of destination plants and drilled wells	In Egypt, this method is recommended to control and reduce the seawater intrusion. It achieves GW remediation from saline water, environment friendly methods as the wastewater will be treated and reused for other purposes. It provides a water source form treated the wastewater
18	Construction of recharge canals near to coast	[108]	Using the surface water recharge canal resulted in reduction of saltwater intrusion. The hydraulic gradient, location of recharge canal are very important parameters controls the degree of efficiency of this method. Construction of recharge canal near to the SWI wedge achieved higher repulsion ratio	It depends on availability of surface water for recharge canals, availability of area and path for canal construction, it costs includes canal construction, maintenance, water transportation or treatment to provide continuous appropriate water source	It is recommended for Egypt. The source of water can be provided from desalination of saltwater, treated drainage water and retreated wastewater. Application of the method could be more effective in the North of Egypt near to the coastal line of Mediterranean Sea

(continued)

Table 4 (continued)

No	Method	Source	Advantages	Disadvantages	Conclusion
19	Abstraction of Saline Water and Recharge Using Surface Ponds	[89]	Combination between saltwater extraction and then recharge GW through ponds give better results than abstraction of saline water alone	Removal of disposal extracted the saltwater could cause another environmental issue It depends on availability of lands and freshwater	It is recommended and can be utilized in Egypt in case of the freshwater is available. Treated wastewater, desalinated brackish water, treated drainage water can be a source for water ponds
20	Natural recharge	[43, 132]	It prevents the saltwater intrusion, minimizing runoff to the Mediterranean Sea, increasing the storage of groundwater	The efficiency of this method relies on the permeability of cap soil and it needs high permeable soil. The GW recharge may take time to arrive GW storage. It includes dam construction coat and maintenance	It is recommended in northern area of Egypt

(continued)

Table 4 (continued)

No	Method	Source	Advantages	Disadvantages	Conclusion
21	Reduction of pumping rates	[141, 170]	It decreases extraction rates and helps to increment the freshwater volume	It is considered as a short-term solution as it helps to reduce the SWI but cannot prevent the SWI. In the future, with increasing the population, growing stresses the SWI will not be prevented and controlled	It is not recommended in Egypt as it can only achieved from private sectors. Increasing the population growth in Egypt results a huge pressure in available surface water and GW. It can only be applied if the surface water is available in abundance. It is limited to apply in some areas and impossible to apply for whole Nile Delta
22	Reallocation of pumping wells	[118]	It decreases the upcoming of saltwater intrusion	It is considered to be high-cost method. It faces some obstacles such as building location and aquifer size. It is supposed as a temporary solution	It is not recommended. It will change the crop pattern based on water availability, decrease the water availability, and damage large area of lands. It is very difficult to apply for large areas like Nile Delta

parameters, including in the GW system Al^{3+}, Fe^{2+}, Sr^{2+}, Ni^{2+}, Cr^{2+}, NO_3, Cr^{2+}, Ni^{2+}, Sr^{2+}, and Al^{2+}. The modeling results confirmed that the city was contaminated with main contaminant parameters found in the oxidation ponds. The results of Nitrate simulation also validated that emphasized regions of contaminated GW with nitrate, particularly in the shallow depths of 40 m because of excessive use of nitrogen-based fertilizers and the flooded water from irrigation system.

Extensively, SWI in the NDA have been studied by different researchers over 30 years, using different codes of 2-D and 3-D model for the NDA. Previous studies revealed that the aquifer is homogenous without considering the heterogeneity of the aquifer. The following codes have been used to simulate the interface extended between the freshwater and the saltwater in the NDA: MODFLOW and SEAWAT, SUTRA, FEFLOW, 2D-FED, AQUIFEM-1, 2D-FEST, PMWIN and SEAWAT. It is obvious that MODFLOW and SEAWAT are common to use the extent of the SWI and distribution of salinity in the NDA system. Most of studies related to SWI in the ND confirmed that the sea level rise and increasing pumping discharge have been accelerating the degree of SWI and the additional seawater progression into the ND. As a result of that, the freshwater volume in the aquifer system decreased and degraded the GW quality. Hence, the freshwater–saltwater interface has intruded into the middle of the ND, ranging from 84 to 112 km from the coastal shoreline. The 35,000 mg/L saltwater line encroached into the GW aquifer to a distance of 41 to 63.9 km.

Several research studies have suggested different techniques for controlling SWI in the NDA. Yet, all of these studies remain at the stage of recommendations for future implementation. The research findings point out that the SWI can be managed by decreasing the abstraction rates, reallocating pumping discharges, recharging freshwater or retreated wastewater, desalinated water. The effectiveness of these approaches depends on increasing the freshwater volume in the aquifer and replenishing the GW level to enhance the flow from freshwater aquifer towards saltwater zone. Optimization algorithms models should be applied to determine the appropriate and controlled GW pumping or freshwater injection through wells. The mentioned method should also be integrated with cost–benefit analysis to discover proper applicable techniques. However, a lack of funds may present additional challenges to cover the costs of wastewater treatment, freshwater movement, desalination of saline water and treated water injection into the aquifer. Moreover, there is still limitation of withdrawal of saline water from the GW aquifer due to the environmental concerns, well depth limitations, the availability of treated wastewater or desalinated water. Suitable methods of construction such as cutoff and barrier walls may be effective but these methods are limited with the depth of the walls. Additional maintenance costs and availability of construction materials are hindrances on the applicability.

10 Recommendations for Future Studies

The use of vulnerability maps has been found to be a crucial tool in the planning land use and managing GW resources in the ND region and similar areas with the same conditions. It is recommended that future studies model the whole area of the ND for good visualization and representation of the GW vulnerability to pollution. In addition, it is important for decision makers to consider effective management of GW resources. Using different vulnerability models with various input parameters gives more attention about the aquifer parameters and its effect of the results of GW vulnerability maps. In the near future, temporal data on GW levels, GW recharge, and nitrate concentrations are necessary for modelling the spatial and temporal variations of GW vulnerability to pollution in the NDA.

The modelling of GW contamination can be integrated with GW monitoring to cover all areas of the ND region. Modelling of GW pollution is important for improved managing of GW resources in the ND, risk management and protection. Integrated modelling of GW contamination should be emphasized with continuous measuring of GW quality parameters in different layers to recognize the extent the pollution. Additionally, data on the rates of fertilizers and pesticides commonly used in agricultural lands should be collected. At the same time, continuous recording of GW levels in monitoring network to detect any changes in the whole area is essential.

Many researchers have predicted that a 1 m sea level rise expected by 2100 will occur with an additional 10 km intrusion length of the SWI line. Therefore, it is recommended to impose more restrictions on GW pumping in the future for proper management of GW management in the ND region, especially in the southern regions of the ND owing to the expansion of rice cultivation.

The upcoming investigation should be focused based on prolonged monitoring of GW levels, water levels fluctuations in canals, actual case of GW withdrawal, GW salinity, movement of shore line boundary in the coastal area, actual representations of freshwater and GW interaction, real state of salinity in northern lakes, heterogeneity of the NDA system and complexity.

Acknowledgements The authors would like to thank the STDF-Egypt for the financial support received under the framework of a project (ID#46278). This book chapter is part of a project titled "Optimal Exploitation Strategies for Sustainable Utilization of Fossil Groundwater Reserves in Egypt" funded by the Science and Technology Development Fund (STDF), Egypt.

References

1. Abd-Elaty I, Abd-Elmoneem SM, Abdelaal GM, Vrána J, Vranayová Z, Abd-Elhamid HF (2022) Groundwater quality modeling and mitigation from wastewater used in irrigation, a case study of the Nile Delta aquifer in Egypt. Int J Environ Res Public Health 19(22):14929. https://doi.org/10.3390/ijerph192214929
2. Abd-Elaty I, Javadi AA, Abd-Elhamid H (2021) Management of saltwater intrusion in coastal aquifers using different wells systems: a case study of the Nile Delta aquifer in Egypt. Hydrogeol J 29(5):1767–1783. https://doi.org/10.1007/s10040-021-02344-w
3. Abd-Elaty I, Pugliese L, Bali KM, Grismer ME, Eltarabily MG (2022) Modelling the impact of lining and covering irrigation canals on underlying groundwater stores in the Nile Delta, Egypt. Hydrol Process 36(1):e14466. https://doi.org/10.1002/hyp.14466
4. Abd-Elaty I, Zelenakova M, Straface S, Vranayová Z, Abu-hashim M (2019) Integrated modelling for groundwater contamination from polluted streams using new protection process techniques. Water 11(11):2321. https://doi.org/10.3390/w11112321
5. Abd-Elaty IM (2014) Numerical and experimental study for simulating climatic changes effects on Nile Delta aquifer [Ph.D. Thesis]. Ph.D. thesis, Faculty of Engineering, Zagazig University, Zagazig

6. Abdelaty IM, Abd-Elhamid HF, Fahmy MR, Abdelaal GM (2014) Investigation of some potential parameters and its impacts on saltwater intrusion in Nile Delta aquifer. JES. J Eng Sci 42(4):931–955
7. Abdelhaleem F, Helal E (2015) Impacts of grand Ethiopian renaissance dam on different water usages in upper Egypt. Br J Appl Sci Technol 8(5):461–483. https://doi.org/10.9734/BJAST/2015/17252
8. Abd-Elhamid H, Javadi A, Abdelaty I, Sherif M (2016) Simulation of seawater intrusion in the Nile Delta aquifer under the conditions of climate change. Hydrol Res 47(6):1198–1210. https://doi.org/10.2166/nh.2016.157
9. Abd-Elhamid HF (2010) A simulation-optimization model to study the control of seawater intrusion in coastal aquifers. University of Exeter
10. Abd-Elhamid HF (2016) Investigation and control of seawater intrusion in the Eastern Nile Delta aquifer considering climate change. Water Supply 17(2):311–323. https://doi.org/10.2166/ws.2016.129
11. Abd-Elhamid HF, Abd-Elaty I, Hussain MS (2020) Mitigation of seawater intrusion in coastal aquifers using coastal earth fill considering future sea level rise. Environ Sci Pollut Res 27(18):23234–23245. https://doi.org/10.1007/s11356-020-08891-1
12. Abd-Elhamid HF, Abd-Elaty I, Negm AM (2018) Control of saltwater intrusion in coastal aquifers. In: Negm AM (ed) Groundwater in the Nile Delta, vol 73. Springer International Publishing, pp 355–384. https://doi.org/10.1007/698_2017_138
13. Abd-Elhamid HF, Abd-Elkader BS, Wahed O, Zeleňáková M, Abd-Elaty I (2022) Assessment of changing the abstraction and recharge rates on the land subsidence in the Nile Delta, Egypt. Water 14(7):1096. https://doi.org/10.3390/w14071096
14. Abd-Elhamid HF, Javadi AA (2008) An investigation into control of saltwater intrusion considering the effects of climate change and sea level rise. 4
15. Abd-Elhamid HF, Javadi AA (2010) A simulation-optimization model to study the control of seawater intrusion in coastal aquifers using ADR methodology. In: Proceedings of the twenty-first salt water intrusion meeting (SWIM), Azores, Portugal, June, 21–26
16. Abd-Elhamid HF, Javadi AA (2011) A cost-effective method to control seawater intrusion in coastal aquifers. Water Resour Manage 25(11):2755–2780. https://doi.org/10.1007/s11269-011-9837-7
17. Abd-Elziz S, Zeleňáková M, Kršák B, Abd-Elhamid HF (2022) Spatial and temporal effects of irrigation canals rehabilitation on the land and crop yields, a case study: the Nile Delta, Egypt. Water 14(5):808. https://doi.org/10.3390/w14050808
18. Abrol IP, Yadav JSP, Massoud FI (1988) Salt-affected soils and their management. Food Agric Org
19. Abu-Bakr HAE-A (2020) Groundwater vulnerability assessment in different types of aquifers. Agric Water Manag 240:106275. https://doi.org/10.1016/j.agwat.2020.106275
20. Ageeb GW, Ali RR, El Semary MA, Essa EF (2017) Characterizing groundwater West of Nile Delta using electric resistivity
21. Ahirwar S, Shukla JP (2018). Assessment of groundwater vulnerability in upper Betwa river watershed using GIS based DRASTIC model. J Geol Soc India 91(3):334–340. https://doi.org/10.1007/s12594-018-0859-0
22. Ahmed AO, Khalaf S, Abdalla MG, El Masry AA, Author C (2015) Groundwater management in Wadi El Natrun Pliocene aquifer, Egypt. Int J Sci Eng Res 6(9):291–302
23. Al-Agha DE, Closas A, Molle F (2015) Survey of groundwater use in the central part of the Nile Delta. Water and Salt Management in the Nile Delta: Report
24. Aller L, Bennett T, Lehr J, Petty RJ, Hackett G (1987) DRASTIC: a standardized system for evaluating ground water pollution potential using hydrogeologic settings. US Environmental Protection Agency, Washington, DC, p 455
25. Aly AH, Peralta RC (1999) Optimal design of aquifer cleanup systems under uncertainty using a neural network and a genetic algorithm. Water Resour Res 35(8):2523–2532
26. Anane M, Abidi B, Lachaal F, Limam A, Jellali S (2013) GIS-based DRASTIC, pesticide DRASTIC and the Susceptibility Index (SI): comparative study for evaluation of pollution

potential in the Nabeul-Hammamet shallow aquifer, Tunisia. Hydrogeol J 21(3):715–731. https://doi.org/10.1007/s10040-013-0952-9
27. Anon (1980) Investigation project of sustained yield of aquifers, part 1. Groundwater Research Institute Cairo
28. Arafa NA, Salem ZE-S, Ghorab MA, Soliman SA, Abdeldayem AL, Moustafa YM, Ghazala HH (2022) Evaluation of groundwater sensitivity to pollution using GIS-based modified DRASTIC-LU model for sustainable development in the Nile Delta Region. Sustainability 14(22):14699. https://doi.org/10.3390/su142214699
29. Arby RS (2017) the rejection of Egypt toward grand Ethiopian renaissance Dam in Ethiopia (2011–2016). http://repository.umy.ac.id/handle/123456789/11418
30. Armanuos A, Ahmed K, Sanusi Shiru M, Jamei M (2021) Impact of increasing pumping discharge on groundwater level in the Nile Delta aquifer, Egypt. Knowl-Based Eng Sci 2(2):13–23. https://doi.org/10.51526/kbes.2021.2.2.13-23
31. Armanuos AM (2017) Experimental and numerical study of saltwater intrusion in the Nile delta aquifer, Egypt [PhD Thesis]. Egypt-Japan University of Science and Technology (E-JUST)
32. Armanuos AM, Al-Ansari N, Yaseen ZM (2020) Assessing the effectiveness of using recharge wells for controlling the saltwater intrusion in unconfined coastal aquifers with sloping beds: numerical study. Sustainability 12(7):2685. https://doi.org/10.3390/su12072685
33. Armanuos AM, Al-Ansari N, Yaseen ZM (2020) Underground barrier wall evaluation for controlling saltwater intrusion in sloping unconfined coastal aquifers. Water 12(9):2403. https://doi.org/10.3390/w12092403
34. Armanuos AM, Allam A, Negm AM (2019) Assessment of groundwater vulnerability to pollution in Western Nile delta aquifer, Egypt. In: Twenty-second international water technology conference, IWTC22
35. Armanuos AM, Allam A, Negm AM (2020) Assessment of groundwater vulnerability to pollution in Western Nile delta aquifer, Egypt. Int Water Technol J (IWTJ) 10
36. Armanuos AM, Eldin Ibrahim MG, Negm A, Takemura J, Yoshimura C, Mahmod WE (2022) Investigation of seawater intrusion in the Nile Delta aquifer, Egypt. J Eng Res 6(1):10–28
37. Armanuos AM, Ibrahim MG, Mahmod WE, Negm A, Yoshimura C, Takemura J, Zidan BA (2017) Evaluation of the potential impact of Grand Ethiopian Renaissance Dam and pumping scenarios on groundwater level in the Nile Delta aquifer. Water Supply 17(5):1356–1367. https://doi.org/10.2166/ws.2017.037
38. Armanuos AM, Ibrahim MG, Mahmod WE, Takemura J, Yoshimura C (2019) Analysing the combined effect of barrier wall and freshwater injection countermeasures on controlling saltwater intrusion in unconfined coastal aquifer systems. Water Resour Manage 33(4):1265–1280. https://doi.org/10.1007/s11269-019-2184-9
39. Armanuos AM, Negm A (2018) Integrated groundwater modeling for simulation of saltwater intrusion in the Nile Delta aquifer, Egypt. Groundwater Nile Delta. https://doi.org/10.1007/698_2017_184
40. Artuso E, Oliveira MM, Lobo-Ferreira JP (2002) Assessment of groundwater vulnerability to pollution using six different methods: AVI, GOD, DRASTIC, SI, EPPNA and SINTACS. Application to Evora Aquifer. LNEC-GIAS, Lisbon
41. Attalla RA (2015) Grand Ethiopian renaissance dam (GERD). Worcester Polytechnic Institute
42. Aziz SA, Zeleňáková M, Mésároš P, Purcz P, Abd-Elhamid H (2019) Assessing the potential impacts of the Grand Ethiopian renaissance dam on water resources and soil salinity in the Nile Delta, Egypt. Sustainability 11(24):7050
43. Bajjali W (2005) Model the effect of four artificial recharge dams on the quality of groundwater using geostatistical methods in GIS environment, Oman
44. Bates B, Kundzewicz Z, Wu S (2008) Climate change and water. Intergovernmental panel on climate change secretariat
45. Botero-Acosta A, Donado LD (2015) Laboratory scale simulation of hydraulic barriers to seawater intrusion in confined coastal aquifers considering the effects of stratification. Procedia Environ Sci 25:36–43. https://doi.org/10.1016/j.proenv.2015.04.006

46. Bray BS, Yeh WW-G (2008) Improving seawater barrier operation with simulation optimization in southern California. J Water Resour Plan Manag 134(2):171–180
47. Brindha K, Elango L (2015) Cross comparison of five popular groundwater pollution vulnerability index approaches. J Hydrol 524:597–613. https://doi.org/10.1016/j.jhydrol.2015.03.003
48. Cederstrom DJ (1947) Artificial recharge of a brackish water well. US Geological Survey
49. Chandoul IR, Bouaziz S, Dhia HB (2015) Groundwater vulnerability assessment using GIS-based DRASTIC models in shallow aquifer of Gabes North (South East Tunisia). Arab J Geosci 8(9):7619–7629. https://doi.org/10.1007/s12517-014-1702-6
50. Civita M (1994) Aquifer vulnerability maps to pollution. Pitagora Ed., Bologna
51. Dahab KA (1993) Hydrological evaluation of the Nile Delta after the high dam construction [Ph.D. Thesis]. PhD thesis. Faculty of Science. Monofia University, Egypt
52. Dawoud MA, Darwish MM, El-Kady MM (2005) GIS-based groundwater management model for Western Nile Delta. Water Resour Manage 19(5):585–604. https://doi.org/10.1007/s11269-005-5603-z
53. Dillon P (2005) Future management of aquifer recharge. Hydrogeol J 13(1):313–316. https://doi.org/10.1007/s10040-004-0413-6
54. Doerfliger N, Jeannin P-Y, Zwahlen F (1999) Water vulnerability assessment in karst environments: a new method of defining protection areas using a multi-attribute approach and GIS tools (EPIK method). Environ Geol 39(2):165–176
55. Dror I, Berkowitz B, Gorelick SM (2004). Effects of air injection on flow through porous media: observations and analyses of laboratory-scale processes. Water Resour Res 40(9). https://doi.org/10.1029/2003WR002960
56. El Arabi N (2012) Environmental management of groundwater in Egypt via artificial recharge extending the practice to soil aquifer treatment (SAT). Int J Environ Sustain 1(3). https://doi.org/10.24102/ijes.v1i3.91
57. El Guindy S, Risseeuw IA, Nijland HJ (1987) Research on water management of rice fields in the Nile Delta, Egypt. International Institute for Land Reclamation and Improvement (ILRI)
58. El Molla AM, Dawoud MA, Hassan MS, EWEA HA MR (2005). Integrated management of water resources in Western Nile Delta: 1-building and calibrating the groundwater model. In: ASCE 4th international symposium on environmental hydrology, Cairo, Egypt. Accessed 7–9
59. El Naqa A (2004) Aquifer vulnerability assessment using the DRASTIC model at Russeifa landfill, northeast Jordan. Environ Geol 47(1):51–62. https://doi.org/10.1007/s00254-004-1126-9
60. El Osta M, Hussein H, Tomas K (2018) Numerical simulation of groundwater flow and vulnerability in Wadi El-Natrun depression and vicinities, West Nile Delta, Egypt. J Geol Soc India 92(2):235–247. https://doi.org/10.1007/s12594-018-0986-7
61. El Shinawi A, Zeleňáková M, Nosair AM, Abd-Elaty I (2022) Geo-spatial mapping and simulation of the sea level rise influence on groundwater head and upward land subsidence at the Rosetta coastal zone, Nile delta, Egypt. J King Saud Univ Sci. https://doi.org/10.1016/j.jksus.2022.102145
62. El-Agha DE, Closas A, Molle F (2015) Dynamics of groundwater use in the central part of the Nile Delta. Dry Land Systems Report, IWMI, WMRI, Cairo
63. El-Atfy H (2007) Integrated national water resources plan in Egypt. Ministry of Water Resources and Irrigation Alexandria Governorate
64. Elewa HH, Shohaib RE, Qaddah AA, Nousir AM (2013). Determining groundwater protection zones for the Quaternary aquifer of northeastern Nile Delta using GIS-based vulnerability mapping. Environ Earth Sci 68(2):313–331. https://doi.org/10.1007/s12665-012-1740-x
65. El-Nashar WY, Elyamany AH (2018) Managing risks of the Grand Ethiopian renaissance dam on Egypt. Ain Shams Eng J 9(4):2383–2388. https://doi.org/10.1016/j.asej.2017.06.004
66. El-Sagheer AA, Amin MM, Refaat MM, Freeshah MA (2016) Groundwater storage changes detected from gravity recovery and climate experiment (GRACE) data in Nile Delta aquifer. https://www.researchgate.net/publication/305637364

67. Eltarabily MG, Negm AM, Yoshimura C, Saavedra OC (2017) Modeling the impact of nitrate fertilizers on groundwater quality in the southern part of the Nile Delta, Egypt. Water Sci Technol Water Supply 17(2):561–570
68. Eltarabily MG, Negm AM, Yoshimura C, Takemura J (2018) Groundwater modeling in agricultural watershed under different recharge and discharge scenarios for quaternary aquifer Eastern Nile Delta, Egypt. Environ Model Assess 23(3):289–308. https://doi.org/10.1007/s10666-017-9577-z
69. Essawy BTA (2013) Effect of climate change on sea water intrusion in the Nile Delta coastal aquifer (M.Sc. Thesis). Faculty of Engineering at Cairo University Giza, Egypt
70. Ezzeldin MM, El Alfy KS, Gawad HAA, Abd Elmaboud ME (2018) Comparison between structured and unstructured MODFLOW for simulating groundwater flow in three-dimensional multilayer quaternary aquifer of East Nile Delta, Egypt. Hydrol Curr Res 09(01). https://doi.org/10.4172/2157-7587.1000297
71. FAO (1985) Water quality for agriculture irrigation and drainage (paper no. 29, rev. 1)
72. Farid MS (1980) Nile Delta groundwater study. M.Sc. The-Sis, Faculty of Engineering, Cairo University, Cairo
73. Farrag AA (2005) The hydraulic and hydrochemical impacts of the Nile system on the groundwater in upper Egypt. Assute Univ Bull Environ Res 8(1):87–102
74. Foster SSD (1987) Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. Vulnerability of soil and groundwater to pollutants. International Conference (Noordwijk Aan Zee 1987-03-30)
75. Gad MI, El-Kammar MM, Ismail HMG (2015) Groundwater vulnerability assessment using different overlay and index methods for quaternary aquifer of Wadi El-Tumilat, East Delta, Egypt. Asian Rev Environ Earth Sci 2(1):9–22. http://www.asianonlinejournals.com/index.php/AREES
76. Gemail KS, Alfy ME, Ghoneim MF, Shishtawy AM, El-Bary MA (2017) Comparison of DRASTIC and DC resistivity modeling for assessing aquifer vulnerability in the central Nile Delta, Egypt. Environ Earth Sci 76(9):1–17. https://doi.org/10.1007/s12665-017-6688-4
77. Ghazavi R, Ebrahimi Z (2015) Assessing groundwater vulnerability to contamination in an arid environment using DRASTIC and GOD models. Int J Environ Sci Technol 12(9):2909–2918. https://doi.org/10.1007/s13762-015-0813-2
78. Ghoraba SM, Zyedan BA, Rashwan IMH (2013) Solute transport modeling of the groundwater for quaternary aquifer quality management in Middle Delta, Egypt. Alexandria Eng J 52(2):197–207. https://doi.org/10.1016/j.aej.2012.12.007
79. Gossel W, Sefelnasr A, Wycisk P (2010) Modelling of paleo-saltwater intrusion in the northern part of the Nubian aquifer system, Northeast Africa. Hydrogeol J 18(6):1447–1463. https://doi.org/10.1007/s10040-010-0597-x
80. Hasan Basri M (2001) Two new methods for optimal design of subsurface barrier to control seawater intrusion [Ph.D]. University of Manitoba
81. Huan H, Wang J, Teng Y (2012) Assessment and validation of groundwater vulnerability to nitrate based on a modified DRASTIC model: a case study in Jilin City of northeast China. Sci Total Environ 440:14–23. https://doi.org/10.1016/j.scitotenv.2012.08.037
82. Hussain MS (2015) Numerical simulation and effective management of saltwater intrusion in coastal aquifers [Ph.D]. University of Exeter
83. Hussain MS, Javadi AA, Sherif MM (2015) Three dimensional simulation of seawater intrusion in a regional coastal aquifer in UAE. Procedia Eng 119:1153–1160. https://doi.org/10.1016/j.proeng.2015.08.965
84. Hussain MS, Javadi AA, Sherif MM (2016) Artificial recharge of coastal aquifers using treated wastewater to control saltwater intrusion. Qual Quant 1:4
85. Hussein EE, Fouad M, Gad MI (2019) Prediction of the pollutants movements from the polluted industrial zone in 10th of Ramadan city to the Quaternary aquifer. Appl Water Sci 9(1):1–19. https://doi.org/10.1007/s13201-019-0897-9
86. Ismael A (2007) Applications of remote sensing, GIS, and groundwater flow modeling in evaluating groundwater resources: two case studies; East Nile Delta, Egypt and Gold Valley, California. ETD Collection for University of Texas, El Paso, USA

87. James G, Hiebert R, Warwood B, Cunningham A (2001) Subsurface biofilm for controlling saltwater intrusion. In: Proceeding of the 1st international conference and workshop on saltwater intrusion and coastal aquifers, monitoring, modelling, and management, Morocco.
88. Javadi A, Hussain M, Sherif M, Farmani R (2015) Multi-objective optimization of different management scenarios to control seawater intrusion in coastal aquifers. Water Resour Manage 29(6):1843–1857. https://doi.org/10.1007/s11269-015-0914-1
89. Javadi A, Hussain MS, Sherif MM (2013) Optimal control of seawater intrusion in coastal aquifers. In: International conference on computational mechanics (CM13). http://hdl.handle.net/10871/18648
90. Kashef A-AI (1983) Harmonizing Ghyben-Herzberg interface with rigorous solutions. Groundwater 21(2):153–159
91. Khalifa AA, Elshemy MM, Masoud AA, Rashwan IMH (2019). Assessment of aquifer vulnerability for pollution for middle delta in Egypt using geographic information system and DRASTIC technique. J Eng Res 3:132–139. https://doi.org/10.21608/erjeng.2019.125528
92. Kotb TH, Watanabe T, Ogino Y, Tanji KK (2000) Soil salinization in the Nile Delta and related policy issues in Egypt. Agric Water Manag 43(2):239–261
93. Luyun R, Momii K, Nakagawa K (2011) Effects of recharge wells and flow barriers on seawater intrusion. Ground Water 49(2):239–249. https://doi.org/10.1111/j.1745-6584.2010.00719.x
94. Mabrouk M, Jonoski A, Oude Essink GHP, Uhlenbrook S (2018) Impacts of sea level rise and groundwater extraction scenarios on fresh groundwater resources in the Nile Delta governorates, Egypt. Water, 10(11):1690. https://doi.org/10.3390/w10111690
95. Mabrouk M, Jonoski A, Oude Essink GH, Uhlenbrook S (2019) Assessing the fresh–saline groundwater distribution in the Nile delta aquifer using a 3D variable-density groundwater flow model. Water 11(9):1946. https://doi.org/10.3390/w11091946
96. Mabrouk MB, Jonoski A, Solomatine D, Uhlenbrook S (2013) A review of seawater intrusion in the Nile Delta groundwater system–the basis for assessing impacts due to climate changes and water resources development. Hydrol Earth Syst Sci Discuss 10(8):10873–10911
97. Mahmoud M, El-Shahat A (2005) Geoelectric resistivity contribution to the late quaternary geology of the north eastern corner of the Nile Delta, Egypt. In: The sixth annual U.A.E. University Research Conference
98. Masoud AA (2014) Groundwater quality assessment of the shallow aquifers west of the Nile Delta (Egypt) using multivariate statistical and geostatistical techniques. J Afr Earth Sc 95:123–137. https://doi.org/10.1016/j.jafrearsci.2014.03.006
99. Mazi A (2014) Seawater intrusion risks and controls for safe use of coastal groundwater under multiple change pressures [Ph.D. Thesis]. Department of Physical Geography and Quaternary Geology, Stockholm University
100. McKinney DC, Lin M-D (1994) Genetic algorithm solution of groundwater management models. Water Resour Res 30(6):1897–1906. https://doi.org/10.1029/94WR00554
101. Mendizabal I, Stuyfzand PJ (2011) Quantifying the vulnerability of well fields towards anthropogenic pollution: the Netherlands as an example. J Hydrol 398(3–4):260–276. https://doi.org/10.1016/j.jhydrol.2010.12.026
102. Metwally MI, Armanuos AM, Zeidan BA (2022) Comparative study for assessment of groundwater vulnerability to pollution using DRASTIC methods applied to central Nile Delta, Egypt. Int J Energy Water Resour. https://doi.org/10.1007/s42108-022-00198-w
103. Mogren S, Shehata M (2012) Groundwater vulnerability and risk mapping of the Quaternary aquifer system in the Northeastern part of the Nile Delta, Egypt. Int Res J Geol Mining (IRJGM)
104. Mohamed A (2020) Gravity applications to groundwater storage variations of the Nile Delta aquifer. J Appl Geophys 182:104177. https://doi.org/10.1016/j.jappgeo.2020.104177
105. Mohamed A, Ragaa Eldeen E, Abdelmalik K (2021) Gravity based assessment of spatio-temporal mass variations of the groundwater resources in the Eastern Desert, Egypt. Arab J Geosci 14(6):1–15. https://doi.org/10.1007/s12517-021-06885-y

106. Mohammed IG (2015) Modeling of contaminant transport in 10th of Ramadan City area, East Delta, Egypt. Int J Water Resour Environ Eng 7(10):139–152. https://doi.org/10.5897/IJWREE2014.0616
107. Morsy WS (2009) Environmental management to groundwater resources for Nile Delta region [Ph.D. Thesis]. Faculty of Engineering, Cairo University Cairo, Egypt
108. Motallebian M, Ahmadi H, Raoof A, Cartwright N (2019) An alternative approach to control saltwater intrusion in coastal aquifers using a freshwater surface recharge canal. J Contam Hydrol 222:56–64. https://doi.org/10.1016/j.jconhyd.2019.02.007
109. Moussa A, Soliman M, Aziz M (2001) Environmental evaluation for High Aswan Dam since its construction until present. In: Sixth international water technology conference, IWTC, Alexandria, Egypt
110. Murat V (2000) Étude comparative des méthodes d'évaluation de la vulnérabilité intrinsèque des aquifères à la pollution: Application aux aquifères granulaires du piémont laurentien. [Ph.D. Thesis]. Université du Québec, Institut national de la recherche scientifique
111. MWRI (2005) National water resources plan for Egypt 2017
112. MWRI (2013) Adaptation to climate change in the Nile Delta through integrated coastal zone management. Ministry of Water Resources and Irrigation Cairo, Egypt
113. Navalur KCS, Engel BA (1997) Predicting spatial distribution of vulnerability of Indiana State Aquifer system to nitrate leaching using a GIS. SANTA_FE_CDROM/Sf_papers/Navulur_kumar/My_paper.Html. http://ncgia.ucsb.edu/conf
114. Navulur KCS (1996) Groundwater vulnerability evaluation to nitrate pollution on a regional scale using GIS [Ph.D. Thesis]. Purdue University
115. Nofal ER, Amer MA, El-Didy SM, Fekry AM (2015). Sea water intrusion in Nile Delta in perspective of new configuration of the aquifer heterogeneity using the recent stratigraphy data. J Am Sci 11(6):281–292. http://www.jofamericanscience.org
116. Nofal ER, Fekry AM, Ahmed MH, El-Kharakany MM (2018). Groundwater: Extraction versus recharge; vulnerability assessment. Water Sci 32(2):287–300. https://doi.org/10.1016/j.wsj.2018.07.002
117. Nossair AM (2011) Climate changes and their impacts on groundwater occurrence in the northern part of east Nile Delta [Ph.D. Thesis]. M.Sc. thesis, Faculty of Science, Zagazig University, Egypt
118. Ofelia T, Marcela P, Monica D (2004). Salt water vertical upward intrusion due to intensive exploitation. Santa Fe. Argentina. In: Proceeding of the 18th Salt Water Intrusion Meeting, Cartagena (Spain)
119. Oude Essink GH (2001) Improving fresh groundwater supply—problems and solutions. Ocean Coastal Manage 44(5):429–449. https://doi.org/10.1016/S0964-5691(01)00057-6
120. Oude Essink GH (2001) Salt water intrusion in a three-dimensional groundwater system in the Netherlands: a numerical study. Transp Porous Media 43(1):137–158
121. Petelet-Giraud E, Dörfliger N, Crochet P (2000). RISKE: Méthode d'évaluation multicritère de la cartographie de la vulnérabilité des aquifères karstiques. Application aux systèmes des Fontanilles et Cent-Fonts (Hérault, Sud de la France). Hydrogéologie (Orléans) 4:71–88. http://pascal-francis.inist.fr/vibad/index.php?action=getRecordDetail&idt=14309961
122. Rahman A (2008) A GIS based DRASTIC model for assessing groundwater vulnerability in shallow aquifer in Aligarh, India. Appl Geogr 28(1):32–53. https://doi.org/10.1016/j.apgeog.2007.07.008
123. Ramadan SM, Negm AM, Smanny M, Helmy A (2013) Environmental impacts of Great Ethiopian Renaissance Dam on the Egyptian water resources management and security, Conference Paper
124. Ramadan SM, Negm AM, Smanny M, Helmy AHM (2015). Quantifying the impacts of impounding grand Ethiopian renaissance dam reservoir on Nasser lake active storage. In: Proceedings of eighteenth international water technology conference (IWTC 18), Sharm ElSheikh, pp 12–14
125. Rastogi AK, Choi GW, Ukarande SK (2004) Diffused interface model to prevent ingress of sea water in multi-layer coastal aquifers. J Spatial Hydrol 4(2)

126. Reichard EG, Johnson TA (2005) Assessment of regional management strategies for controlling seawater intrusion. J Water Resour Plan Manag 131(4):280–291
127. Ribeiro L (2000) SI: a new index of aquifer susceptibility to agricultural pollution. ERSHA/CVRM, Instituto Superior Técnico, Lisboa, Portugal
128. RIGW (1990) Hydrogeological map for the Nile Delta area, scale 1: 500000. Research Institute for Ground Water. El Kanter El Khairia Egypt
129. RIGW (2002) Nile Delta groundwater modeling report. Research Institute for Groundwater
130. RIGW/IWACO (1999) Environmental management of groundwater resources (EMGR). Final Technical Report TN/70.0067/WQM/97/20; Kanater El-Khairia, Egypt
131. Rogers LL, Dowla FU (1994) Optimization of groundwater remediation using artificial neural networks with parallel solute transport modeling. Water Resour Res 30(2):457–481
132. Ru Y, Jinno K, Hosokawa T, Nakagawa K (2001). Study on effect of subsurface dam in coastal seawater intrusion. In: First international conference on saltwater intrusion and coastal aquifers monitoring, modeling, and management. Essaouira, Morocco, pp 23–25
133. Saatsaz M, Sulaiman WNA, Eslamian S, Mohammadi K (2011) GIS DRASTIC model for groundwater vulnerability estimation of Astaneh-Kouchesfahan Plain, Northern Iran. Int J Water 6(1–2):1–14
134. Saha D, Alam F (2014) Groundwater vulnerability assessment using DRASTIC and Pesticide DRASTIC models in intense agriculture area of the Gangetic plains, India. Environ Monit Assess 186(12):8741–8763. https://doi.org/10.1007/s10661-014-4041-x
135. Sakr SA, Attia FA, Millette JA (2004) Vulnerability of the Nile Delta aquifer of Egypt to seawater intrusion. In: International conference on water resources of arid and semi-arid regions of Africa, issues and challenges, Gaborone, Botswana
136. Salem ZE, Gaame OM, Hassan TM (2018). Integrated subsurface thermal regime and hydrogeochemical data to delineate the groundwater flow system and seawater intrusion in the Middle Nile Delta, Egypt. Groundwater Nile Delta 461–486
137. Salem ZE, Hasan SS (2021) Use of GALDIT model and HFE-diagram to assess seawater intrusion vulnerability in West Nile Delta, Egypt. Arab J Geosci 14(14):1–15. https://doi.org/10.1007/s12517-021-07678-z
138. Salem ZE, Sefelnasr AM, Hasan SS (2019) Assessment of groundwater vulnerability for pollution using DRASTIC index, young alluvial plain, Western Nile Delta, Egypt. Arab J Geosci 12(23):727. https://doi.org/10.1007/s12517-019-4883-1
139. Salem ZE-S, Osman O (2019). Use of one-dimensional subsurface temperature profiles to characterize the groundwater flow system in the northwestern part of the Nile Delta, Egypt. In: Negm AM (ed) Groundwater in the Nile Delta. Springer International Publishing, pp 387–423. https://doi.org/10.1007/698_2018_248
140. Salman SA, Arauzo M, Elnazer AA (2019) Groundwater quality and vulnerability assessment in west Luxor Governorate, Egypt. Groundwater Sustain Develop 8:271–280. https://doi.org/10.1016/j.gsd.2018.11.009
141. Scholze O, Schneider W, Hillmer G (2003) Protection of the groundwater resources of Metropolis Cebu (Philippines) in consideration of saltwater intrusion into the coastal aquifer. Geochemical processes in soil and groundwater: measurement, modelling, upscaling. GeoProc2002 Conference, Bremen, Germany, 4–7 March 2002, pp 93–103
142. Sefelnasr A, Sherif M (2014) Impacts of seawater rise on seawater intrusion in the Nile Delta aquifer, Egypt. Groundwater 52(2):264–276. https://doi.org/10.1111/gwat.12058
143. Seleem AS, Kaiser MF, Athelib HS (2018) Data integration to assess aquifer vulnerability potential to pollution around Ismailia canal using remote sensing and GIS techniques. J Geol Geophys
144. Serag El Din HM (1989) Geological, hydrochemical and hydrological studies on the Nile Delta quaternary aquifer [Ph.D. Thesis]. Faculty of Science, Mansoura University Mansoura, Egypt
145. Sharaky AM, Atta SA, El Hassanein AS, Khallaf KMA (2007) Hydrogeochemistry of groundwater in the Western Nile Delta aquifers, Egypt. 2nd Int Conf Geol Tethys 19(21):1–23

146. Sherif M (1999) Nile delta aquifer in Egypt. In: Seawater intrusion in coastal aquifers—concepts, methods and practices. Springer, pp 559–590. https://doi.org/10.1007/978-94-017-2969-7_17
147. Sherif M (2003) Assessment, modeling and management of seawater intrusion in the Nile delta aquifer. Tecnología De La Intrusión De Agua De Mar En Acuíferos Costeros: PAÍSES MEDITERRÁNEOS\copyright IGME, Madrid
148. Sherif M, Sefelnasr A, Javadi A (2012) Incorporating the concept of equivalent freshwater head in successive horizontal simulations of seawater intrusion in the Nile Delta aquifer, Egypt. J Hydrol 464:186–198. https://doi.org/10.1016/j.jhydrol.2012.07.007
149. Sherif MM, Al-Rashed MF (2001) Vertical and horizontal simulation of seawater intrusion in the Nile Delta aquifer. In: First international conference on saltwater intrusion and coastal aquifers, monitoring, modeling, and management, Essaouira, Morocco, pp 23–25
150. Sherif MM, Singh VP (1999) Effect of climate change on sea water intrusion in coastal aquifers. Hydrol Process 13(8):1277–1287. https://doi.org/10.1002/(SICI)1099-1085(19990615)13:8%3C1277::AID-HYP765%3E3.0.CO;2-W
151. Sherif MM, Singh VP, Amer AM (1988) A two-dimensional finite element model for dispersion (2D-FED) in coastal aquifers. J Hydrol 103(1–2):11–36. https://doi.org/10.1016/0022-1694(88)90003-0
152. Sobeih MM, El-Arabi NE, Helal EEDY, Awad BS (2017) Management of water resources to control groundwater levels in the southern area of the western Nile delta, Egypt. Water Sci 31(2):137–150. https://doi.org/10.1016/j.wsj.2017.09.001
153. Soliman M, El-Mongy A, Talaat M, Hassan A, Maniak U (1991) Groundwater quality model with applications to various aquifers. Environ Geol Water Sci 17(3):201–208
154. Soliman SM, Fattah MK, Ahmed MG (2014) Sustainable development and management of water resources in west Nile delta, Egypt. Int J Sci Eng Res 5(11):1296–1310
155. Sriapai T, Walsri C, Phueakphum D, Fuenkajorn K (2012) Physical model simulations of seawater intrusion in unconfined aquifer. Songklanakarin J Sci Technol 34(6)
156. Stempvoort DV, Ewert L, Wassenaar L (1993) Aquifer vulnerability index: a GIS-compatible method for groundwater vulnerability mapping. Can Water Resour J 18(1):25–37. https://doi.org/10.4296/cwrj1801025
157. Taha AA, El-Mahmoudi AS, El-Haddad IM (2004) Pollution sources and related environmental impacts in the new communities southeast Nile Delta, Egypt. Emirates J Eng Res 9(1):35–49
158. Tesfa B (2013) Benefit of grand Ethiopian renaissance dam project (GERDP) for Sudan and Egypt. EIPSA Commun Article: Energy, Water, Environ Econ
159. Thirumalaivasan D, Karmegam M, Venugopal K (2003) AHP-DRASTIC: Software for specific aquifer vulnerability assessment using DRASTIC model and GIS. Environm Model Softw 18(7):645–656. https://doi.org/10.1016/S1364-8152(03)00051-3
160. Trent VP (1991) "Drastic" mapping to determine the vulnerability of ground-water to pollution. In: Proceedings of the 1991 Georgia water resources conference, Held March 19 and 20, 1991, At the University of Georgia
161. Umar R, Ahmed I, Alam F (2009) Mapping groundwater vulnerable zones using modified DRASTIC approach of an alluvial aquifer in parts of Central Ganga Plain, Western Uttar Pradesh. J Geol Soc India 73(2):193–201. https://doi.org/10.1007/s12594-009-0075-z
162. van Beynen PE, Niedzielski MA, Bialkowska-Jelinska E, Alsharif K, Matusick J (2012) Comparative study of specific groundwater vulnerability of a karst aquifer in central Florida. Appl Geogr 32(2):868–877. https://doi.org/10.1016/j.apgeog.2011.09.005
163. Wassef R, Schüttrumpf H (2016) Impact of sea-level rise on groundwater salinity at the development area western delta, Egypt. Groundwater Sustain Dev 2–3:85–103
164. Werner AD, Ward JD, Morgan LK, Simmons CT, Robinson NI, Teubner MD (2012) Vulnerability indicators of sea water intrusion. Ground Water 50(1):48–58. https://doi.org/10.1111/j.1745-6584.2011.00817.x
165. Wheeler KG, Basheer M, Mekonnen ZT, Eltoum SO, Mersha A, Abdo GM, Zagona EA, Hall JW, Dadson SJ (2016) Cooperative filling approaches for the grand Ethiopian renaissance dam. Water Int 41(4):611–634. https://doi.org/10.1111/j.1745-6584.2011.00817.x

166. Whittington D, Waterbury J, Jeuland M (2014) The Grand Renaissance Dam and prospects for cooperation on the Eastern Nile. Water Policy 16(4):595–608. https://research.manchester.ac.uk/en/publications/the-grand-renaissance-dam-and-prospects-for-cooperation-on-the-ea
167. Zaid SM (2006) Geo-environmental study of eastern Nile Delta, Egypt [Ph.D. Thesis]. Faculty of Science, Zagazig University, Egypt, p 339
168. Zarif FM, Elshenawy AM, Barseem MS, Al-Abaseiry AA, Sayed ANE (2022) Evidence of geoelectrical resistivity values on groundwater conditions in Wadi El Natrun and its vicinities, West Delta, Egypt (cases studies). Sci Rep 12(1):1–16. https://doi.org/10.1038/s41598-022-12644-0
169. Zelenakova M, Abd-Elhamid H, Barańczuk K, Barańczuk J (2022) Assessment and adaptation to climate change and sea level rise impacts on Egypt's northern coasts. IOP Conf Ser Mater Sci Eng 1252(1):012009. https://doi.org/10.1088/1757-899X/1252/1/012009
170. Zhou Y, Rowe RK (2005) Modeling of clay liner desiccation. Int J Geomech 5(1):1–9. https://doi.org/10.1061/~ASCE!1532-3641~2005!5:1~1!

Groundwater Contamination by Fluoride and Mitigation Measures for Sustainable Management of Groundwater in the Indo-Gangetic Plains of India

Mohammed Aasif Sulaiman, Divya, Mohammad Masroor Zafar, Saima Anjum, and Anupma Kumari

Abstract Groundwater contamination has escalated due to pressures from domestic activities, industrial operations, agricultural practices, and improper management in many parts of the world. This calls for a thorough investigation of the causes, effects, and explores the multifaceted nature of contamination pathways followed by implicating the available mitigation options for the groundwater conservation. The chapter reviewed the spatial disparity in the fluoride (F^-) concentration, it's controlling factors and, the associated health impacts studied in the groundwater of the Indo-Gangetic Plain. The Indo-Gangetic Plain of India, with a population size of more than 700 million people extracts nearly 25% of the global groundwater to meet its domestic, agricultural, and other demands. Various contaminants like F^-, As, and NO_3^- are reported mainly from some areas of the Indo-Gangetic Plain, with associated non-carcinogenic health cost. The geological deposit of Quaternary alluvial sediment, was found primarily contributes to F^- in the groundwater of Indo-Gangetic Plains, with substantial input from anthropogenic activities. Moreover, the severity of F^- toxicity is more pronounced in the Northern, and lower regions of Indo-Gangetic Plains. Na–HCO_3 water type, alkaline pH, water depth, increased evaporation process are some major controlling factors in the dissolution process of F^-. Further, the study will be helpful for young researchers to investigate F^- contamination in groundwater of the Indo-Gangetic Plains, in order to conserve resources and reduce pollution burden.

Keywords Fluoride · Groundwater pollution · Indo-gangetic plains · Non-carcinogenic · Fluorosis

M. A. Sulaiman · Divya · M. M. Zafar · S. Anjum · A. Kumari (✉)
Department of Zoology, Environmental Biology Laboratory, Patna University, Patna, India
e-mail: anupmakumari10@yahoo.com

S. Ali and A. M. Armanuos (eds.), *Groundwater in Arid and Semi-Arid Areas*, Earth and Environmental Sciences Library, https://doi.org/10.1007/978-3-031-43348-1_12

1 Introduction

Among various groundwater contaminants, fluoride (F^-) is classified as the twelfth most hazardous pollutant by US Agency for Toxic Substances and Disease Registry (ATSDR) because of its high reactivity, and toxicity potential to cause serious health risks [136]. Elevated fluoride levels have a significant impact on more than 25 countries [37] and possess a global health concern to more than 261 million people [11, 10, 14, 52, 67, 93, 96, 186]. Kut et al. [92] reported various degree of fluorosis symptoms in more than 80 million East African Rift Valley people. The elevated level of fluoride in North American countries like Mexico (2.39 mg/L) and Canada (10.9 mg/L) have been documented by Rentería-Villalobos et al. [139], and [31] respectively. Ireland, Sweden, and Estonia are some European countries that have experienced high fluoride levels in their groundwater [26, 65, 117, 148]. Bangladesh, China, India, Indonesia, Iran, Iraq, Jordan, Korea, Pakistan, Palestine, Saudi Arabia, Sri Lanka, Syria, Thailand, Turkey, and Yemen are among the Asian nations with the highest levels of fluoride in their groundwater, ranging from as low as <0.02 to 40.8 mg/L [9, 14, 77].

Fluoride's essentiality and toxic effects are differentiated via a narrow margin [77]. A major portion of the fluoride ingested by the body is stored in the bones or teeth (around 80–90% in newborns and 60% in adults), and the remainder being eliminated in the urine [22]. Although, fluoride in drinking water is good for developing bones and teeth in the range of 0.6–1.2 mg/L [32, 41, 105, 178]. It is hazardous when it exceeds 1.5 mg/L and causes tooth cavities, dental, skeletal, and crippling fluorosis, and deformation of bone structures [28, 63, 112, 114, 187].

India is home to over 12 million of the 85 million tonnes of fluoride deposits on the earth's crust of the world [171], explaining the possible source of fluoride enrichment in the groundwater through bedrock interaction. The Indo-Gangetic Plains of India, alone covers a vast northern area with 11 states, having 43% of the total Indian population. The non-judicial overuse of groundwater for drinking, household, agricultural, and other reasons has contributed to deteriorate the water quality in many parts of the Ganga River basin [163, 194]. Fluoride is one of the major contaminants in the Indo-Gangetic Plains, that has gained special attention because of its continuous rise and detrimental health impacts in the recent past. The consumption of fluoride-contaminated water, has affected more than 66 million people with dental and skeletal fluorosis, where 6 million children below the age of 14 [36, 146]. This increased fluoride concentration has reported in the groundwater of Mahendergarh, Bhiwani, Hisar, Patiala of Trans Gangetic Plains, Unnao, Ghaziabad, Agra, Raebareli of Upper Gangetic Plains Pratapgarh, Varanasi, Jamui, Gaya and Nawada districts of Middle Gangetic plains and Birbhum, Bankura, Dinapur, and Purulia of Lower Gangetic Plains [33]. More than 50% of the population of Uttar Pradesh having evidence of fluorosis, with Unnao and Pratapgarh being the worst affected districts, whereas, certain location in the West Bengal have even exceeded beyond 18 mg/L of fluoride level [172].

Thus, this chapter aims to compile the existing knowledge on fluoride in groundwater conducted in various parts of the Indo-Gangetic Plains. The brief detailing of the factor responsible for fluoride enrichment, it's dissolution process, health impacts and mitigation measures carried out in the past and present scenarios will help the authorities and inhabitants to understand the sources and controlling mechanism of fluoride in the groundwater of Indo-Gangetic Plains of India.

2 Sources

The sources of fluoride contamination could be anthropogenic, such as the usage of pesticides and industrial waste, as well as geogenic (natural), like the existence of fluorine-bearing minerals in rocks and sediments.

2.1 Natural Sources

Fluoride-containing minerals found in rocks, soils, and sediments are the principal causes of groundwater contamination. According to Rao [134], few widely occurring fluoride-bearing minerals include biotite, muscovite, lepidolite, tourmaline, and the hornblende series minerals glucophane, riebeckite, and asbestos (chrysotile, actinolite, anthophyllite). Only topaz, fluorite, villiaunite, and cryolite have fluorine as a necessary component in their chemical compositions out of the 416 fluoride-bearing rock minerals [72]. The constitution of these minerals contains an adequate amount of fluorine [72]. Granitic rocks contain high concentration of fluoride minerals, ranging from 500 to 1400 mg/kg. Volcanic and gneissic rocks might also be an originating source [80]. These are the geogenic sources of fluoride found in the Gangetic plain so far.

2.2 Anthropogenic Sources

Industrialization and agricultural operations are the most significant anthropogenic sources. Fluoride concentrations have been reported to be high in adjacent areas of coal combustion and brick kilns. Agricultural fertilizers, particularly rock phosphate fertilizers, contain extremely high levels of fluoride and are the most significant anthropogenic sources of fluoride pollution in water [48, 91]. Fluoride is also released into the environment by aluminum melting, glass, phosphate fertilizer, brick manufacturing, and coal-fired thermal power plants [124]. The use of superphosphate fertilizers in agricultural land is estimated to contribute up to 0.34 mg/L of fluoride [135]. Fluoride is also introduced into groundwater through irrigation with fluoride-enriched water [123]. These are the anthropogenic sources of fluoride from the Gangetic plain.

2.3 Health Effects

Elevated fluoride levels in drinking water has dangerous effects on humans; dental and skeletal fluorosis, long-term exposure to high levels of fluoride has been reported to causes genetic damage, premature aging, mental retardation, nervousness, depression, cancer, renal disease, hypertension, a neurotoxicological complication in children, spontaneous abortion, severe soft tissue damage, and other health problems across the globe (Table 1, McLaren [100]) [59, 75, 76, 166, 179, 188].

3 Status of Fluoride Contamination in the Groundwater of Indo-Gangetic Plains

The Indo-Gangetic Plain (IGP), covers about 850,000 sq km area, and expands over the vast plains of River Ganga and Brahmaputra. The Indo-Gangetic Plain basin is formed as a result of orogenic uplift, which has a depression even greater than 2000 m at places in the Middle Gangetic Plains of Uttar Pradesh and Bihar [145]. It is characterized by the thick deposition of recent alluvial sediment of Tertiary and Quaternary period, derived from the Himalaya and partly from the Peninsular India [165, 180]. The subtropical climate, with hot summer and cold winter, and high rainfall (>1000 mm), mainly controls the aquifer's recharge mechanism [164]. Due to the underlain thick piles of unconsolidated to semi-unconsolidated rock and heavy precipitation, the groundwater aquifer of the Indo-Gangetic Plains is recharged annually. The spatial variation in the ionic composition of the groundwater of the Indo-Gangetic Plains is noted because of the differential intensity and volume of rainfall a particular region receives, its residence time in the aquifer, irrigation return flow, canal leakage, river inundation and on the abstraction of groundwater. The section

Table 1 Fluoride level in groundwater with their respective health impacts

Fluoride concentration (mg/L)	Health impacts
<0.5	Promotes dental decay
0.5–1.5	Optimal range for bone and tooth health
1.5–4.0	Dental fluorosis in children
4.0–10	Dental and skeletal fluorosis, arthritis, hypertension, infertility, neurological disorders
>10	Promotes crippling fluorosis, cancer

Source Dissanayake [47], Kimambo et al. [77], Ali et al. [14], Duvva et al. [51]

will detail the findings of work done on the spatial–temporal variation of fluoride contamination, source identification, and factors responsible for fluoride enrichment in the groundwater of the Ganga River Basin by various researchers. Descriptive details of various research articles on fluoride contamination were extracted and illustrated in sub-groups as States name, range of fluoride values, locations, and their respective references in Table 1.

Figure 1 shows the spatial variation of the fluoride concentration in the Indo-Gangetic Plains of India recorded in the year from 2010 to 2020. The maximum value of fluoride was observed at Bhiwani, Haryana (18.5 mg/L; [13] in the Trans Gangetic Plain. Gupta and Misra [58] observed high fluoride content in nearly 60–70% of the groundwater samples of Jhajjar district, Haryana, whereas, [120] reported fluoride contamination in the 98% of the groundwater samples at Patiala, Punjab. Lucknow, Kanpur and Unnao (Uttar Pradesh) in the Upper Gangetic Plains was noted with the maximum fluoride value of 6.85 mg/L, 6.5 mg/L and 6.0 mg/L respectively. Misra et al. [103] worked on fluoride contamination in the shallow and deep aquifer of Mathura Tahsil in the Upper Gangetic Plains to address the problems posed by fluoride. The study observed a value of 0.1–2.5 mg/L of fluoride in the groundwater of the concerned villages, which can cause dental and skeletal fluorosis among the inhabitants. The fluoride concentration in groundwater was observed up to 17.20 mg/L in the Raebareli region of Uttar Pradesh [142]. Agra was reported to be the most affected district, where 60.27% of villages have exceeded the permissible WHO standards of 1.5 mg/L of fluoride in the groundwater samples of Uttar Pradesh [12]. A study by Mridha et al. [112] in Gaya and Nawada district of Bihar, in the Middle Gangetic Plains, noted that 48.1% and 91% of groundwater samples have crossed the safe limit of fluoride in drinking water. The study has noted a very high value of fluoride (8.56 mg/L) in the Gaya district, which is 5.7 times higher than the standard prescribed limits. 37% districts in the Lower Gangetic plains are reportedly under fluoride contamination zone [190]. Biswas et al. [30] working in the Lower Gangetic Plains of India, observed a slightly higher value of fluoride in the wet season than in the dry season in the coastal regions. Birbhum, Bankura and Purulia districts are observed to be the most fluoride affected areas in the Lower Gangetic Plains of India with maximum fluoride concentration of 18.25 mg/L, 12.2 mg/L and 10.75 mg/L respectively.

4 Factors Affecting Fluoride Enrichment in the Indo-Gangetic Plains

The high concentration of fluoride in the groundwater is mainly attributed to geogenic sources and marginally due to anthropogenic factors. Geogenic contributors to fluoride in the groundwater of Indo-Gangetic plain have been reported by several studies [7, 30, 34, 89, 97, 142, 155, 181]. Hydro-geochemical investigations by Sahu et al. [142] observed that the high fluoride concentration level in the groundwater samples

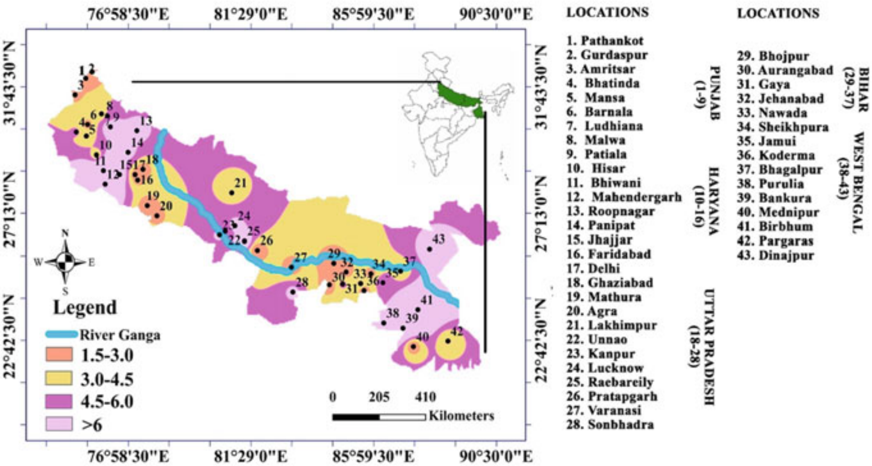


Fig. 1 Spatial distribution of fluoride in the Indo-Gangetic Plains of India from 2010 to 2020

was exclusively due to the weathering of fluoride-bearing minerals. According to Shukla et al. [155], the main causes of elevated fluoride levels in the groundwater were rock-water interaction and the dissolution of fluoride-bearing minerals such as muscovite, fluorspar, fluorite, fluorapatite, biotite, cryolite, hydroxyapatite, and amphibole. Kumar et al. [88] investigated Jamui region of Bihar and found the preferential hydro-geochemical facies for fluoride enrichment in the groundwater aquifer. The study noted that the Ca^{2+} –HCO_3^- type water has low fluoride concentration (1 mg/L) and Na^+–HCO_3^- and Mg^{2+} –HCO_3^- facies is associated with higher fluoride content (>1 mg/L). Samal et al. [145] observed a significant role of high evapotranspiration and low rainfall in the fluoride enrichment of groundwater in arid to semi-arid climatic conditions. High bicarbonate ions in the groundwater thermodynamically favours the dissolution of fluoride rich minerals ($CaF_2 + 2HCO_3 = 2F^- + CaCO_3 + H_2O = CO_2$). Nijesh et al. [119] have studied the hydro-geochemical characteristic in the 23 districts of Upper Gangetic plains, and observed similar results to that of Ali et al. [13], Adimalla et al. [2], Kumar et al. [89], Maurya et al. [97], and Shukla and Saxena [153], that alkaline conditions rich in sodium and bicarbonate facilitate the release of fluoride from their respective minerals. Samal et al. [145] uses d-excess ($= \delta D - 8 \times \delta^{18}O$) value to decipher the contribution of evaporation in fluoride enrichment of groundwater and noted a lower d-excess value from the states of West Bengal, Bihar and Uttar Pradesh is correlated with high fluoride content. It has been discovered that microorganisms aid in mineral weathering and fluoride release [62, 185]. According to Zhou et al. [195], the availability of fluoride in the environment is greatly influenced by the breakdown of fluorapatite by *Pseudomonas fluorescens* P35 for nutrient acquisition. The depth of bore wells also plays an important role in controlling fluoride contamination. Several researchers have reported that the majority of the samples that don't comply with the drinking water standards come from shallow depth aquifers and suggested a depth greater than 90 m is comparatively safer from fluoride pollution [40, 50, 103, 121, 161]. Interestingly, Nizam et al. [120] found that deeper aquifers are more prone to fluoride contaminated than shallow ones, probably due to subsurface pollutant leaching. pH has a differential influence on the dissolution of different fluoride bearing minerals. Sivasankar et al. (2016) reported the dissolution of fluorite and cryolite is favoured at alkaline pH, while dissolution of apatite, mica and amphiboles is favored at acidic pH. Raj and Shaji [129], Kumar et al. [89], Adimalla [2], Shukla and Saxena [153], Devi et al. [46], and Sahu et al. [143] have agreed to the discussion of a positive correlation of alkaline pH with fluoride dissolution in the aquifer. Alkaline pH having high OH ion with ionic radii 1.40 Å replaces exchangeable F^- (1.33 Å) from fluoride bearing minerals due to similar ionic radii [61]. Therefore, the occurrence of fluoride in groundwater aquifers is a collaborative influence of geogenic and paleoclimatic factors. In addition, fluoride concentration in groundwater is determined by soil porosity, temperature, residence time, microbial activities, aquifer leakage, clay used in brick kilns, and other anthropogenic factors [51, 68, 145, 169, 174].

5 Health-Hazard of Fluoride Toxicity in the Indo Gangetic Plains

Numerous drinking wells in the Indo-Gangetic Plain are in an alarming situation regarding deteriorating groundwater quality and its impact on human health upon exposure to fluoride-contaminated water. According to studies conducted in various regions of Indo- Gangetic plain, drinking water with a high fluoride content has been linked to both chronic and emerging pandemic disorders in humans [30, 50, 51, 89, 144, 155, 181]. Fluoride concentration in different exposure values has distinct effects on human health (Table 1). A dose greater than 100 mg/L hampers normal growth and development and direct exposure of 2.5 to 5 g of fluoride can even lead to even death [160]. As per the latest report of the Ministry of Jalshakti, Lokshabha presented in 2020, 5485 habitations across 17 states are affected by fluoride-contaminated drinking water [122]. Kumar et al. [82] and Dutta et al. [50] have reported the risk of adverse health effect due to high fluoride content in drinking water observed in 5.47% of population at Chinhat, Lucknow, and 95% of the groundwater samples at Fatehpur, Uttar Pradesh, respectively. A similar case of dental and skeletal fluorosis due to high concentration of fluoride in the groundwater has also been reported at Fatehpur [50], Jamui, Bihar [89], Pratapgarh, Uttar Pradesh [97], Raebareli, Uttar Pradesh [155]. A non-carcinogenic health risk assessment study in the Indo-Gangetic Plains of India by Maurya et al. [97] marked differences in the case of fluorosis to different age groups. The study revealed infants are at higher risk (89.19%), followed by children and adults (83.78%). Mridha et al. [112] noted the similar vulnerability of fluoride toxicity to the children of Bankey Bazar, Gaya and Rajauli, Nawada in comparison to teenagers and adults. Nizam et al. [120] investigated the severity of fluoride toxicity between humans, females, and children. The study conducted in the Northern parts of Indo-Gangetic Plains has agreed with the findings made by previous studies and noted the detrimental effects of fluoride-rich water consumption are more prevalent in children ($HQ_{avg} = 3.1$) followed by males ($HQ_{avg} = 2.9$) and females ($HQ_{avg} = 2.5$). Shukla and Saxena [153, 154] studied a seasonal disparity in fluoride related health hazards for children and adults in the central parts of Indo Gangetic alluvial Plains. The $HQ_{fluoride}$ varies between 0.17–10.93 and 0.13–8.53 in pre-monsoon, 0.21–10.05 and 0.16–7.84 in post-monsoon for children and adults, respectively. The study observed a 12.51% (adults) and 11.10% (children) rise in the HQ value from post-monsoon to pre-monsoon and debated the possible role of anthropogenic factors in this spatial variability (Table 2).

6 Mitigation Strategies

The government of India took early measures in 1980s against fluoride contamination by launching "The Technology Mission on safe drinking water" in 1986 by the Prime Minister Rajiv Gandhi. A fluorosis control cell was also established at All India Institute of Medical Science, Delhi (1987–1997) to co-ordinate between the state health departments of all fluoride affected states [122]. The centre was later expanded as the global consultation centre in 1997. A total of 13 districts in India were reported as fluoride affected in the earlier studies but the number rose to 17 in 2000, including some Indo-Gangetic Plain states. Another major program, NPPCF (National Programme for Prevention and Control of Fluorosis), was launched by the Indian government in 2008–09 which covered 100 districts in 17 states in a phase wise manner [141]. Central Ground Water Board did data collection and compilation in two volumes [33, 34] which revealed that each state and Union territory lying in the Indo-Gangetic Plain exceeds the permissible limit of 1.5 mg/L for fluoride as prescribed by Bureau of Indian Standards [20]. The program was brought under National Health Mission (NHM) in 2014–15 where the number of districts were increased to 195. The mission helped the districts financially to purchase equipment, set up laboratories, increasing man power, training, awareness and treatment to affected individuals in the area [116]. The private sector has also provided notable contributions in the Indo-Gangetic Plains. Environmental Quality Monitoring Group (EQMG) conducted extensive survey in Sonbhadra district of Uttar Pradesh in 2004 and accordingly planned mitigation strategy for 21 villages combining community and individual rainwater harvesting, handpumps attached with fluoride kits with a final cost of Rs. 632 per individual [122]. State government, research institutions, and NGOs have also made significant impacts. Recently, Integrated Fluorosis Mitigation (IFM) program was launched in selected villages of Nawada district in Bihar with collaboration of Government of Bihar, AN College Patna, CSIR NEERI Nagpur, NIRTH Jabalpur, PHED and UNICEF, Patna. CSIR- NEERI supplied adsorbent based defluoridation units that could be attached to handpumps for rapid removal of fluoride from groundwater [18]. Awareness programs were frequently organised and

Table 2 Descriptive details of various research work on fluoride contamination in the groundwater of Indo-Gangetic Plains

	S. no.	State	Range (mg/l)	Location	References
Upper Gangetic plain	1	Uttar Pradesh	0.42–6.85	Lucknow	[82]
	2		0.15–2.50	Agra	[15, 16]
	3		1.0–6.5	Kanpur	[106]
	4		0.9–1.4	Mathura	[125]
	5		0.19–4.33	Unnao	[71]
	6		BDL-6.0	Unnao	[118]
	7		0.98–3.42	Lakhimpur	[182]
	8		0.12–8.3	Raebarli	[153]
	9		0.01–1.83	Unnao	[17]
	10		0.0–1.5	Ghaziabad	[6]
	11		2.21–2.29	Raebareli	[142]
	12		0.9–4.12	Agra	[189]
	13		0.14–4.88	Agra	[12]
	14		0.32–3.5	Banda	[156]
	15		0.01–4.10	Bundelkhand	[19]
	16		0.09–10.9	Ghaziabad	[158]
	17		0.80–13.9	Unnao	[70]
	18		1.05–13.9	Unnao	[74]
	19		0.14–5.34	Kanpur	[146]
	20		0.1–2.5	Mathura	[102]
	21		0.11–12.80	Agra	[57]
	22		0.1–2.5	Mathura	[103]
Middle Gangetic plain	23	Uttar Pradesh	0.20–1.20	Pratapgarh	[54]
	24		0.29–2.1	Varanasi	[38]
	25		0.2–21.1	Pratapgarh	[97]
	26		0.82–7.15	Fatehpur	[44]
	27		0.41–3.99	Pratapgarh	[172]
	28		0.08–6.7	Sonbhadra	[130]
	29		0.10–6.70	Sonbhadra	[131]
	30		0.483–6.7	Sonbhadra	[132]
	31		0.07–2.80	Varanasi	[130]
	32	Bihar	0.12–1.15	Bhojpur	[90]
	33		0.37–2.32	Sheikhpura	[90]
	34		BDL-2.1	Arwal and Jehanabad	[27]
	35		0.38–8.56	Gaya & Nawada	[112]
	36		4.8–4.9	Nawada	[140]

(continued)

Table 2 (continued)

	S. no.	State	Range (mg/l)	Location	References
	37		1.44–7.51	Nawada	[159]
	38		1.13–3.59	Nawada	[87]
	39		0.2–5.0	Gaya	[78]
	40		0.01–5.80	Jamui	[90]
	41		0.30–1.63	Koderma	[145]
	42		0.6–7.2	Gaya	[133]
	43		3.6–5.8	Jamui	[88]
	44		1.6–1.7	Jamui	[64]
	45		1.93–2.98	Bhagalpur	[55]
	46		0.00–1.34	Bhagalpur	[181]
	47		0.68–1.98	Bhagalpur	[162]
	48		0.05–1.73	Aurangabad	[5]
	49		0.19–14.4	Gaya	[193]
	50		0.07–1	Bhojpur	[149]
	51		0.10–2.50	Rohtas	[137]
Lower Gangetic plain	52	West Bengal	0.58–1.724	Mednipur and Parganas	[30]
	53		0.01–19	Birbhum	[23]
	54		1.51–2.9	Pargaras	[45]
	55		1.30–7.0	Purulia	[39]
	56		0.3–17.6	Birbhum	[60]
	57		0.3–18.25	Birbhum	[115]
	58		0.1–12.2	Bankura	[108]
	59		0.33–18.08	Birbhum	[109]
	60		0.39–7.2	Dinajpur	[147]
	61		0.01–1.6	Bankura	[145]
	62		0.006–1.95	Birbhum	[57]
	63		0.30–13.60	Birbhum	[107]
	64		1.24	Nadia	[44]
	65		1.75	Parganas	[44]
	66		1.61	Burdwan	[44]
	67		1.38	Midnapore	[44]
	68		1.08	Midnapore	[44]
	69		1.06	Purulia	[44]
	70		0.12–8.16	Purulia	[24]
	71		0.41–1.01	Malda	[126]

(continued)

Table 2 (continued)

	S. no.	State	Range (mg/l)	Location	References
	72		1.50–10.8	Bankura	[35]
	73		0.125–10.75	Purulia	[29]
	74		0.1–1.362	Nadia	[99]
	75		0.01–1.18	Hooghly	[91]
	76		0.1–1.362	Rajapur	[127, 128]
Trains Gangetic plain	77	Delhi	0.14–3.15	Older Alluvial Plains of Delhi	[15, 16]
	78		0.0–1.9	Southwest Delhi	[1]
	79		0.20–51.2	Delhi	[42]
	81		0.02–4.13	Delhi	[85]
	82		0.10–16.5	Delhi	[43]
	83	Haryana	0.23–2.35	Faridabad, Gurgaon	[168]
	84		0.2–6.9	Panipat	[76]
	85		0.3–16.0	Mahendergarh	[191]
	86		0.3–18.5	Bhiwani	[13]
	87		0.5–2.98	Hisar	[86]
	88		0.3–9.0	Jhajjar	[58]
	89		BDL-7.14	Roopnagar	[152]
	90		1.00–1.90	Sirsa City	[110]
	91		0.95–2.42	Gurgaon	[157]
	92		1.90–5.20	Gurgaon	[157]
	93		1.65–1.90	Gurgaon	[157]
	94		0.03–16.6	Hisar	[139]
	95		0.30–6.90	Jind	[101]
	96	Punjab	0.51–2.7	Mansa	[150]
	97		0.05–1.38	SBS Nagar	[104
	98		0.29–4.79	Bhatinda	[84]
	99		0.37–2.3	Barnala	[84]
	100		0.08–2.75	Ludhiana	[84]
	101		0.8–2.5	Amritsar	[151]
	102		0.5–1.8	Gurdaspur	[151]
	103		0.6–1.5	Pathankot	[151]
	104		0.60–5.07	Malwa	[4]
	105		0.06–0.66	Patiala	[83]
	106		0.02–1.61	Muktsar	[83]
	107		1.5–9.2	Patiala	[120]

Table 3 Mitigation techniques used in the Indo-Gangetic Plains for fluoride contaminated groundwater

Technique	Advantage	Limitation	References
1. Coagulation and Precipitation	• Cost efficient • Easy to design, use and maintain • Chemicals are easily available	• Sludge disposal is a major issue • Increased risk of Al^{3+} contamination • Water becomes unpleasant after treatment • Correct dosage of chemicals changes hence require periodic analysis	[66, 113]
2. Adsorption	• Low cost • Easy to use • The regeneration percentage of adsorbent is high • Various adsorbents are available	• Sulphate, Carbonate, and Phosphate can compete with F^- ion • Safe disposal of sludge is a concern • After regeneration, the efficiency of the adsorbent is reduced • pH should be maintained between 5–6	[8, 184]
3. Membrane Technology	• Higher efficiency for F-removal • The process is mostly automatic and reliable • Micro-organisms as well as suspended solids can be simultaneously removed	• Removes all ions present in water; requires remineralization • Require pH correction after treatment • Large volume of water is wasted as brine • Brine disposal is a major issue • Expensive than other techniques	[3, 56, 173]

best nutritional supplements were provided in the IFM approach. The government also plans to increase the number of Reverse Osmosis units at community level that can supply water to entire villages at a subsidized rate [21]. Rainwater harvesting as an alternate water source is also being promoted by the Central and State Government [167]. At present, Coagulation and Precipitation, Adsorption and Reverse Osmosis techniques are used in the IGP (Table 3).

6.1 Coagulation and Precipitation

Coagulation and precipitation are common processes used to remove a wide range of impurities from water, including colloids, Dissolved Organic Matter, and are also applied to defluoridation [8, 73]. Specific chemicals known as coagulants are used in raw water, which forms solid flocculants or flakes after combining with fluoride ions. The precipitate is then filtered out, lowering the fluoride considerably. Therefore, the process is collectively referred to as 'Coagulation and Precipitation'. Various coagulants have been used for the removal of fluoride from water, such as lime, alum, zeolite, bauxite, ferric chloride, sodium silicate, sodium aluminate and silica gel [8, 73, 79, 184]. However, the best results are obtained by combined alum and lime [183]. This method is also known as the Nalgonda technique, which was developed by National Environmental Engineering Research Institute (NEERI) in 1975 and was frequently used in villages around Nalgonda in Andhra Pradesh, India [191]. The technique is nowadays widely used throughout Asia as its removal accuracy is nearly 70%. The removal of fluoride is affected by the pH of the water, therefore, the concentration of alum is determined based on fluoride level and pH in the study area [183].

6.2 Adsorption

Adsorption is a term given to the adhesion of an ion onto a surface [66] which is one of the traditional methods widely used for defluoridation. Several substances have been investigated in need of a cheap and suitable adsorbent to lower the fluoride level in the water. Activated alumina is the most common adsorbent and several reports of large-scale installations are available [92, 94, 138]. Activated alumina possesses a unique characteristic that enables it to maintain its structural stability in water with a high surface-to-weight ratio that increases the number of active sites to facilitate adsorption. Yadav et al. [191] explained the mechanism involved, which includes three basic steps. In the beginning, fluoride ions are transferred to the alumina surface from the solution, followed by their adsorption on the particle surface. In the last step, adsorbed ions are shuttled to the inner surfaces of the porous alumina. Alumina has proven to be an efficient adsorbent, but due to health risks associated with its use, several other substances have been tested by researchers worldwide. These include activated red mud [175], Geothite [170], Brushite [111], Aluminum hydroxide coated rice husk ash [53], synthetic siderite [95], and granular ferric hydroxide [81]. Different factors play a crucial role in deciding the best adsorbent, such as pH of water, adsorption capacity, time duration required, regeneration time and stability of the adsorbent [69].

6.3 Membrane Technology (MT)

Membrane technology (MT) has emerged as another process that can be applied for defluoridation. Reverse Osmosis and Nanofiltration are two major techniques used under MT where contaminated water is passed through a semipermeable membrane. Reverse Osmosis uses simple hydraulic pressure to pass water from one side of the tank to another by crossing a semipermeable membrane [8, 98]. The pressure ensures that salts and ions cannot pass the membrane although water and some impurities can easily cross the membrane [49]. The performance of reverse osmosis greatly depends upon pH and temperature, which need to be maintained for better results [191]. Different commercial nano-filters have also been used for defluoridation such as NF-90, NF-270, BW30, and NF-400. The research carried out by Bejaoui et al. [25] revealed that NF-90 was very efficient in lowering the fluoride level from 20 mg/L to below 0.5 mg/L while NF-270 was able to decrease the load of fluoride ions from 10 mg/L to 0.5 mg/L [8]. NF-400 was most suitable for a lower level of fluoride whereas BW30 can be used to treat extremely high fluoride contaminated water [192]. A comparison of all the methods discussed with their advantages and limitations has been presented in Table 3. Moreover, the states of Indo-Gangetic Plains should telecast a commercial based on the negative outcomes of fluorosis, and can also include this as a chapter in the class 10th curriculum to increase awareness among the children towards groundwater contamination, and associated health hazards. A low-cost water testing kit should be prepared and distributed at Panchayat level to increase the contribution of local people. IGP experiences exceptionally good rainfall during the monsoon season and therefore rainwater harvesting techniques should be promoted. Reverse Osmosis technique for defluoridation should be implemented at community level and proper subsidy must be provided by the state governments and other NGOs.

7 Conclusion

This chapter gives a comprehensive account of fluoride status, major health implications, and mitigation strategies in the Indo-Gangetic plains of India. Non-judicial abstraction of groundwater has reportedly caused severe groundwater quality deterioration, and has differentially impacted the health of the inhabitants, especially in the Indo-Gangetic plains of North India. Fluoride levels in the studied region have been substantially increased by anthropogenic processes such as fertilizers, brick kilns, and industrial run-off, with major contribution from natural processes. Health impacts associated with fluoride depend upon concentration and duration of exposure which may vary from gastroenteritis, anorexia, stiffness, and dental fluorosis to skeletal fluorosis. The rise in fluoride associated health risk since 2010, in the studied stretch portrays an alarming state for fluoride toxicity to the inhabitants of Indo Gangetic Plains. Several defluoridation techniques have been developed, including Coagulation, Adsorption, Electrocoagulation, Reverse osmosis and Nanofiltration, to bring the fluoride level under desirable BIS limits. Each of these techniques has some advantages over others, but none are highly effective and economical at the same time. Therefore, these methods should be customized and combined to target specific areas so that they can provide low fluoride level groundwater at the most economical prices in the long run. Research focusing on bioremediation and other cost effective and viable techniques should be promoted. Proper monitoring of groundwater and implementation of updated policies should be done by the government to manage fluoride levels in groundwater.

8 Recommendations

The review article provides sufficient evidence regarding the current aggravated fluoride levels in the groundwater of the Indo-Gangetic Plain (IGP), and the associated health risks. The authors recommend that researchers, NGOs, and relevant government authorities continuously monitor fluctuations in fluoride concentration and report any new regions showing fluoride levels above the desirable limits of 1 mg/L set by the Bureau of Indian Standards (BIS) in 2012. Furthermore, they should propose organizing awareness campaigns to emphasize the importance of conserving groundwater resources and the health hazards associated with consuming fluoride-rich water. To address this issue effectively, research institutes should collaborate with local state governments to develop cost-effective mitigation strategies for fluoride removal. While techniques such as reverse osmosis, and nanofiltration are known to be effective, they can be expensive. This can be overcomed by installing large-scale plants at the city level to reduce the cost per person. Additionally, these plants can be customized according to the specific fluoride contamination levels in different areas. Therefore, it is essential to promote research that focuses on devising more effective and economical techniques for fluoride removal.

In summary, the review article highlights the concerning fluoride levels in the groundwater of the Indo-Gangetic Plains (IGP), and the associated health risks. It urges continuous monitoring, reporting of new affected regions, awareness campaigns, and collaboration between research institutes and local governments to develop affordable mitigation strategies. It emphasizes the need for large-scale plants and encourages research on more effective and economical techniques for fluoride removal.

Acknowledgements The Authors are thankful to Dr. Shakir Ali Khan, for giving us the opportunity to contribute a book chapter to the book series. The authors express their sincere gratitude to all the members of Environmental Biology Laboratory of Patna University, Patna for their contributions.

References

1. Acharya, S, Sharma, S, Khandegar, V. (2018) Assessment of groundwater quality by water quality indices for irrigation and drinking in South West Delhi, India. Data Brief 18:2019–2028. https://doi.org/10.1016/j.dib.2018.04.120
2. Adimalla N (2020) Assessment and mechanism of fluoride enrichment in groundwater from the hard rock terrain: a multivariate statistical approach. Geochem Int 58(4):456–471. https://doi.org/10.1134/S0016702920040060

3. Agyeman I, Reinwald M, Jeihanipour A, Schäfer AI (2019) Removal of fluoride and natural organic matter from natural tropical brackish waters by nanofiltration/reverse osmosis with varying water chemistry. Chemosphere 217:47–58. https://doi.org/10.1016/j.chemosphere.2018.10.135
4. Ahada CP, Suthar S (2019) Assessment of human health risk associated with high groundwater fluoride intake in southern districts of Punjab, India. Expo Health 11:267–275. https://doi.org/10.1007/s12403-017-0268-4
5. Aher KR, Salve PL, Gaikwad SG (2020) Assessing nitrate and fluoride contamination in drinking water and their health risk assessment in drought prone area of gv-35 watershed of Aurangabad district, central India. J Appl Geochem 22(3):232–250. https://www.indianjournals.com/ijor.aspx?target=ijor:jag&volume=22&issue=3&article=006
6. Ahmad S, Khurshid S (2019) Hydrogeochemical assessment of groundwater quality in parts of the Hindon River basin, Ghaziabad, India: implications for domestic and irrigation purposes. SN Appl Sci 1:1–12. https://doi.org/10.1007/s42452-019-0161-9
7. Ahmad S, Mazhar SN (2020) Hydrochemical characteristics, groundwater quality and sources of solute in the Ramganga Aquifer, Central Ganga Plain, Bareilly District, Uttar Pradesh. J Geol Soc India 95(6):616–625. https://doi.org/10.1007/s12594-020-1488-y
8. Ahmad S, Singh R, Arfin T, Neeti K (2022) Fluoride contamination, consequences and removal techniques in water: a review. Environ Sci: Adv 1:620–661. https://doi.org/10.1039/d1va00039j
9. Alabdulaaly AI, Al-Zarah AI, Khan MA (2013) Occurrence of fluoride in ground waters of Saudi Arabia. Appl Water Sci 3:589–595. https://doi.org/10.1007/s13201-013-0105-2
10. Alarcon-Herrera MT, Bundschuh J (2020) Co-occurrence, possible origin, and health-risk assessment of arsenic and fluoride in drinking water sources in Mexico: Geographical data visualization. Sci Total Environ 698:134–168. https://doi.org/10.1016/j.scitotenv.2019.134168
11. Alarcon-Herrera MT, Bundschuh J, Nath B, Nicolli HB, Guutierrez M, Reyes-Gomez VM, Nunez D, Martin-Dominguez I, Sracek O (2013) Co-occurrence of arsenic and fluoride in groundwater of semi-arid regions in Latin America: Genesis, mobility and remediation. J Hazard Mater 262:960–969. https://doi.org/10.1016/j.jhazmat.2012.08.005
12. Ali S, Kumari M, Gupta SK, Sinha A, Mishra BK (2017) Investigation and mapping of fluoride-endemic areas and associated health risk—a case study of Agra, Uttar Pradesh, India. Hum Ecol Risk Assess Int J 23(3):590–604. https://doi.org/10.1080/10807039.2016.1255139
13. Ali S, Shekhar S, Bhattacharya P, Verma G, Chandrasekhar T, Chandrashekhar AK (2018) Elevated fluoride in groundwater of Siwani Block, Western Haryana, India: a potential concern for sustainable water supplies for drinking and irrigation. Groundw Sustain Dev 7:410–420. https://doi.org/10.1016/j.gsd.2018.05.008
14. Ali S, Thakur SK, Sarkar A, Shekhar S (2016) Worldwide contamination of water by fluoride. Environ Chem Lett 14:291–315. https://doi.org/10.1007/s10311-016-0563-5
15. Ali, S, Khan, SU, Gupta, SK, Sinha, A, Gupta, MK, Abbasnia, A, Mohammadi, AA. (2021a) Health risk assessment due to fluoride exposure from groundwater in rural areas of Agra, India: Monte Carlo simulation. Int J Environ Sci Technol 18:3665–3676. https://link.springer.com/article/https://doi.org/10.1007/s13762-020-03084-2
16. Ali S, Shekhar S, Chandrasekhar T, Yadav AK, Arora NK, Kashyap CA, Chandrasekharam D (2021b) Influence of the water–sediment interaction on the major ions chemistry and fluoride pollution in groundwater of the Older Alluvial Plains of Delhi, India. J Earth Syst Sci 130(98). https://link.springer.com/article, https://doi.org/10.1007/s12040-021-01585-3
17. Ansari JA, Umar R (2019) Evaluation of hydrogeochemical characteristics and groundwater quality in the quaternary aquifers of Unnao District, Uttar Pradesh, India. Hydro Res 1:36–47. https://doi.org/10.1016/j.hydres.2019.01.001
18. Avisek M, Yashoda R, Manjunath P (2021) Fluorosis mitigation programmes and its impact on health—the Indian scenario. RGUHS J Dent Sci 13(2)

19. Avtar R, Kumar P, Singh CK, Sahu N, Verma RL, Thakur JK, Mukherjee S (2013) Hydrogeochemical assessment of groundwater quality of Bundelkhand, India using statistical approach. Water Qual Expo Health 5:105–115. https://link.springer.com/article/10.1007/s12403-013-0094-2
20. BIS (Bureau of Indian Standards) 10500 (2012) Indian standard drinking water specification
21. Bajpai S, Alam N, Biswas P (2019) Present and potential water-quality challenges in India. Separation Science and Technology 11:85–112. https://doi.org/10.1016/B978-0-12-815730-5.00004-1
22. Barbier O, Arreola-Mendoza L, Del Razo LM (2010) Molecular mechanisms of fluoride toxicity. Chem.-Biol. Interact. 188(2):319–333. https://doi.org/10.1016/j.cbi.2010.07.011
23. Batabyal AK, Gupta S (2017) Fluoride-contaminated groundwater of Birbhum district, West Bengal, India: interpretation of drinking and irrigation suitability and major geochemical processes using principal component analysis. Environ Monit Assess 189(8):1–24. https://doi.org/10.1007/s10661-017-6041-0
24. Behera B, Kumar N, Moharana M (2014) Assessment of ground water pollution due to fluoride pollution and water quality in and around Purulia district, West Bengal, India. J Chem Pharmaceut Res 6:384–392
25. Bejaoui I, Mnif A, Hamrouni B (2014) Performance of reverse osmosis and Nanofiltration in the removal of fluoride from model water and metal packaging industrial effluent. Sep Sci Technol 49(8):1135–1145. https://doi.org/10.1080/01496395.2013.878956
26. Berger T (2016) Fluoride in surface water and groundwater in Southeast Sweden—sources, controls and risk aspects. Linnaeus University Dissertations. https://www.diva-portal.org/smash/record.jsf?dswid=3340&pid=diva2%3A929470
27. Bhatt AG, Kumar A, Trivedi PR (2021) Integration of multivariate statistics and water quality indices to evaluate groundwater quality and its suitability in middle Gangetic floodplain Bihar. SN Appl Sci 3:426. https://doi.org/10.1007/s42452-021-04394-x
28. Bhattacharya P, Adhikari S, Samal AC, Das R, Dey D, Deb A, Ahmed S, Hussein J, De A, Das A, Joardar M, Panigrahi AK, Roychowdhury T, Santra SC (2020) Health risk assessment of Co-occurrence of toxic fluoride and Arsenic in groundwater of Dharmanagar region, North Tripura (India). Groundwater Sust Dev 11:100430. https://doi.org/10.1016/j.gsd.2020.100430
29. Bhattacharya HN, Chakrabarti S (2011) Incidence of fluoride in the groundwater of Purulia district, West Bengal: A geo-environmental appraisal. Curr Sci 101(2):152–155
30. Biswas T, Pal SC, Saha A (2023) Hydro-chemical assessment of coastal groundwater aquifers for human health risk from elevated arsenic and fluoride in West Bengal, India. Mar Pollut Bull 186114440. https://doi.org/10.1016/j.marpolbul.2022.114440
31. Boyle DR, Chagnon M (1995) An incidence of skeletal fluorosis associated with groundwaters of the Maritime Carboniferous Basin, Gaspé Region, Quebec, Canada. Environ Geochem Health 17(1):5–12. https://link.springer.com/article, https://doi.org/10.1007/BF00188625
32. Brindha K, Elango L (2011) Fluoride in groundwater: causes, implications and mitigation measures. In: Monroy SD (Ed) Fluoride properties, applications and environmental management, pp 111–136. https://www.novapublishers.com/catalog/product_info.php?products_id=15895
33. CGWB (2010) Groundwater quality in shallow aquifers of India. Central Ground Water Board, Faridabad, India
34. CGWB (2014) Concept note on geogenic contamination of ground water in India with a special note on Nitrate. Central Ground Water Board, MoWR, RD&GR, Govt of India. http://www.cgwb.gov.in/WQ/Geogenic%20Final.pdf
35. Chakrabarti S, Bhattacharya HN (2013) Inferring the hydro-geochemistry of fluoride contamination in Bankura district, West Bengal: a case study. J Geol Soc India 82(4):379–391. https://doi.org/10.1007/s12594-013-0165-9
36. Chakraborti D, Rahman MM, Chatterjee A, Das D, Das B, Nayak B, Pal A, Chowdhury UK, Ahmed S, Biswas BK, Sengupta MK, Lodh D, Samanta G, Chakraborty S, Roy MM, Dutta RN, Saha KC, Mukherjee SC, Pati S, Kar PB (2016) Fate of over 480 million inhabitants living in arsenic and fluoride endemic Indian districts: Magnitude, health, socio-economic

effects and mitigation approaches. J Trace Elem Medivine Biol 38:33–45. https://doi.org/10.1016/j.jtemb.2016.05.001
37. Chaudhary V, Prasad S (2015) Rapid removal of fluoride from aqueous media using activated dolomite. Anal Methods 7(19):8304–8314. https://doi.org/10.1039/C5AY01044F
38. Chaurasia AK, Pandey HK, Tiwari SK, Pandey P, Ram A (2021) Groundwater vulnerability assessment using water quality index (WQI) under geographic information system (GIS) framework in parts of Uttar Pradesh India. Sustain Water Resour Manag 7(3):1–15. https://doi.org/10.1007/s40899-021-00513-z
39. Chowdhury, P, Mukhopadhyay, BP, Nayak, S, Bera, A. (2021) Hydro-chemical characterization of groundwater and evaluation of health risk assessment for fluoride contamination areas in the eastern blocks of Purulia district, India. Environ, Dev Sustain, 1–28. https://doi.org/10.1007/s10668-021-01911-1
40. Chuah CJ, Lye HR, Ziegler AD, Wood SH, Kongpun C, Rajchagool S (2016) Fluoride: a naturally-occurring health hazard in drinking-water resources of Northern Thailand. Sci Total Environ 545:266–279. https://doi.org/10.1016/j.scitotenv.2015.12.069
41. Commins, BT, World Health Organization (1985) Controlling fluoride levels; a literature survey, World Health Organization
42. Dash JP, Sarangi A, Singh DK (2010) Spatial variability of groundwater depth and quality parameters in the National Capital Territory of Delhi. Environ Manage 45:640–650. https://doi.org/10.1007/s00267-010-9436-z
43. Datta PS, Deb DL, Tyagi SK (1996) Stable isotope (18O) investigations on the processes controlling fluoride contamination of groundwater. J Contam Hydrol 24(1):85–96
44. Datta AS, Chakrabortty A, De Dalal SS, Lahiri SC (2014) Fluoride contamination of underground water in West Bengal, India. Fluoride 47(3):241–248
45. De A, Mridha D, Joardar M, Das A, Chowdhury NR, Roychowdhury T (2022) Distribution, prevalence and health risk assessment of fluoride and arsenic in groundwater from lower Gangetic plain in West Bengal, India. Groundwater Sustain Dev 16:100722. https://doi.org/10.1016/j.gsd.2021.100722
46. Devi G, Goswami L, Kushwaha A, Sathe SS, Sen B, Sarma HP (2021) Fluoride distribution and groundwater hydrogeochemistry for drinking, domestic and irrigation in an area interfaced near Brahmaputra floodplain of North-Eastern India. Environ Nanotechnol Monitor Manage 16:100500. https://doi.org/10.1016/j.enmm.2021.100500
47. Dissanayake CB (1991) The fluoride problem in the ground water of Sri Lanka—environmental management and health. Int J Environ Stud 38(2–3):137–155
48. Divya, Sulaiman MA, Zafar MM, Kumari A (2023) Assesing the fluoride toxicity, and the source contributors to the major ionic constituents in the groundwater aquifer of Middle Ganga River Basin, Rohtas, India. Int J Energy Water Resour. https://doi.org/10.1007/s42108-023-00245-0
49. Dubey S, Agarwal M, Gupta AB (2018) Recent developments in defluoridation of drinking water in India. Environ Pollut 77:345–356. https://doi.org/10.1007/978-981-10-5792-2_28
50. Dutta V, Fatima N, Kumar N (2019) Excessive fluoride in groundwater of Central Ganga Alluvial Plain: a case study of Fatehpur, North India. Int J Environ Sci Technol 16(12):7791–7798. https://doi.org/10.1007/s13762-018-2145-5
51. Duvva LK, Panga KK, Dhakate R, Himabindu V (2022) Health risk assessment of nitrate and fluoride toxicity in groundwater contamination in the semi-arid area of Medchal, South India. Appl Water Sci 12(1):11
52. Edmunds WM, Smedley PL (2013) Fluoride in natural waters, In: Selinus O, Alloway B, Centeno JA, Finkelman RB, Fuge R, Lindh U, Smedley PL(eds) Essentials of medical geology, vol 2. Springer, pp 311–336. https://doi.org/10.1007/978-94-007-4375-5_13
53. Ganvir V, Das K (2011) Removal of fluoride from drinking water using aluminum hydroxide coated rice husk ash. J Hazard Mater 185(2–3):1287–1294. https://doi.org/10.1016/j.jhazmat.2010.10.044
54. Gautam VK, Kothari M, Singh PK, Bhakar SR, Yadav KK (2022) Spatial mapping of groundwater quality using GIS for Jakham River basin of Southern Rajasthan. Environ Conserv J 23:234–243. https://doi.org/10.36953/ECJ.021936-2175

55. Gouri K, Choudhary SK (2017) Fluoride Contamination in groundwater sources of Bhagalpur Municipal Corporation Area, Bhagalpur, Bihar. IOSR J Environ Sci Toxicol Food Technol 11(1):45–49
56. Grzegorzek M (2021) Nanofiltration usage for fluoride removal in the sodium chloride presence. Arch Environ Prot 47:98–108. https://doi.org/10.24425/aep.2021.139506
57. Gupta S, Banerjee S, Saha R, Datta JK, Mondal N (2006) Fluoride geochemistry of groundwater in Nalhati-1 block of the Birbhum district, West Bengal India. Fluoride 39(4):318–320
58. Gupta R, Misra AK (2018) Groundwater quality analysis of quaternary aquifers in Jhajjar District, Haryana, India: Focus on groundwater fluoride and health implications. Alex Eng J 57(1):375–381. https://doi.org/10.1016/j.aej.2016.08.031
59. Hillier S, Inskip H, Coggon D, Copper C (1996) Water fluoridation and osteoporotic fracture. Community Dent Health 13(20):63–68
60. Hossain M, Patra PK, Ghosh B, Khatun A, Nayek S (2021) Sensitive assessment of groundwater-associated, multi-exposure health hazards in a fluoride-enriched region of West Bengal India. Environ Geochem Health 43(11):4515–4532. https://doi.org/10.1007/s10653-021-00942-x
61. Hu S, Luo T, Jing C (2013) Principal component analysis of fluoride geochemistry of groundwater in Shanxi and Inner Mongolia, China. J Geochem Explor 135:124–129. https://doi.org/10.1016/j.gexplo.2012.08.013
62. Hutchens E, Valsami-Jones E, Harouiya N, Chaïrat C, Oelkers EH, McEldoney S (2006) An experimental investigation of the effect of Bacillus megaterium on apatite dissolution. Geomicrobiol J 23(3-4):177–182. https://doi.org/10.1080/01490450600599239
63. Iheozor-Ejiofor Z, Worthington HV, Walsh T, O'Malley L, Clarkson JE, Macey R, Alam R, Tugwell P, Welch V, Glenny AM (2015) Water fluoridation for the prevention of dental caries (Review). Cochrane Database Syst Rev. https://doi.org/10.1002/14651858.CD010856.pub2
64. Inaniyan M, Raychoudhury T (2019) Application of activated carbon–metal composite for fluoride removal from contaminated groundwater in India. Int J Environ Sci Technol 16:7545–7554. https://doi.org/10.1007/s13762-018-2097-9
65. Indermitte E (2010) Exposure to fluorides in drinking water and dental fluorosis risk among the population of Estonia. Dissertationes Geographicae Universitatis Tartuensis, p 41
66. Ingle NA, Dubey HV, Kaur N, Sharma I (2014) Defluoridation techniques: which one to choose. J Health Res Rev 1(1):1–4
67. Islam ARMT, Pal SC, Chowdhuri I, Islam RSMS, Rahman MM, Zahid A, Idris AM (2021) Application of novel framework approach for prediction of nitrate concentration susceptibility in coastal multi-aquifers Bangladesh. Sci Total Environ 801:149811. https://doi.org/10.1016/j.scitotenv.2021.149811
68. Jacks G, Bhattacharya P, Chaudhary V, Singh KP (2005) Controls on the genesis of some high-fluoride groundwaters in India. Appl Geochem 20(2):221–228. https://doi.org/10.1016/j.apgeochem.2004.07.002
69. Jadhav SV, Bringas E, Yadav GD, Rathod VK, Ortiz I, Marathe KV (2015) Arsenic and fluoride contaminated groundwaters: a review of current technologies for contaminants removal. J Environ Manage 162:306–325. https://doi.org/10.1016/j.jenvman.2015.07.020
70. Jha SK, Nayak AK, Sharma YK (2010) Potential fluoride contamination in the drinking water of Marks Nagar, Unnao district, Uttar Pradesh India. Environ Geochem Health 32(3):217–226. https://doi.org/10.1007/s10653-009-9277-y
71. Jha SK, Sharma YK, Nayak AK, Mishra VK, Damodaran T (2020) Groundwater quality with special reference to fluoride in Unnao District, Uttar Pradesh, India: a hydro-geochemical and multivariate statistical approach. Fluoride 53(4):582–594
72. Jha SK, Singh RK, Damodaran T, Mishra VK, Sharma DK, Rai D (2013) Fluoride in groundwater: toxicological exposure and remedies. J Toxicol Environ Health, Part B 16(1):52–66. https://doi.org/10.1080/10937404.2013.769420
73. Jha PK, Tripathi P (2021) Arsenic and fluoride contamination in groundwater: a review of global scenarios with special reference to India. Groundw Sustain Dev 13:100576. https://doi.org/10.1016/j.gsd.2021.100576

74. Jha SK, Nayak AK, Sharma YK (2009) Fluoride occurrence and assessment of exposure dose of fluoride in shallow aquifers of Makur, Unnao district Uttar Pradesh India. Environ Monit Assess 156(1):561–566. https://doi.org/10.1007/s10661-008-0505-1
75. Jiang H, Li X, Tian L, Wang T, Wang Q, Niu P, Chen P, Luo X (2019) Defluoridation investigation of Yttrium by laminated Y-Zr-Al tri-metal nanocomposite and analysis of the fluoride sorption mechanism. Sci Total Environ 648:839–1672. https://doi.org/10.1016/j.scitotenv.2018.08.258
76. Kaur L, Rishi MS, Siddiqui AU (2020) Deterministic and probabilistic health risk assessment techniques to evaluate non-carcinogenic human health risk (NHHR) due to fluoride and nitrate in groundwater of Panipat, Haryana India. Environmental Pollution 259:113711. https://doi.org/10.1016/j.envpol.2019.113711
77. Kimambo V, Bhattacharya P, Mtalo F, Mtamba J, Ahmad A (2019) Fluoride occurrence in groundwater systems at global scale and status of defluoridation-state of the Art. Groundw Sustain Dev 9:100223. https://doi.org/10.1016/j.gsd.2019.100223
78. Krishan A, Mishra RK (2020) Study on groundwater quality and status of Amas Block in Gaya District of Bihar with special reference to fluoride contamination. Algerian J Environ Sci Technol 6(4)
79. Kromah V, Powoe SPB, Asumana C (2022) Groundwater defluoridation with composite oxyhydroxide mineral ores—the case with bauxite, a systematic review. Water 14(18):2829. https://doi.org/10.3390/w14182829
80. Kumar SPJ (2017) Fluoride in groundwater-sources, geochemical mobilization and treatment options. Int J Environ Sci & Nat Resour 1(4):106–108
81. Kumar E, Bhatnagar A, Ji M, Jung W, Lee SH, Kim SJ, Lee G, Song H, Choi JY, Yang JS, Jeon BH (2009) Defluoridation from aqueous solutions by granular ferric hydroxide (GFH). Water Res 43(2):490–498. https://doi.org/10.1016/j.watres.2008.10.031
82. Kumar D, Kishor RK, Sharma U, Mishra S, Yadav AK, Kumar N (2021) Geoclassification of fluoride-affected areas of Lucknow, Uttar Pradesh India. Environ Qual Manag 31(3):283–290. https://doi.org/10.1002/tqem.21779
83. Kumar M, Kumari K, Ramanathan AL, Saxena R (2007) A comparative evaluation of groundwater suitability for irrigation and drinking purposes in two intensively cultivated districts of Punjab India. Environ Geol 53(3):553–574. https://doi.org/10.1007/s00254-007-0672-3
84. Kumar R, Mittal S, Sahoo PK, Sahoo SK (2020) Source apportionment, chemometric pattern recognition and health risk assessment of groundwater from southwestern Punjab, India. Environ Geochem Health 43:733–755. https://doi.org/10.1007/s10653-020-00518-1
85. Kumar M, Ramanathan AL, Rao MS, Kumar B (2006) Identification and evaluation of hydrogeochemical processes in the groundwater environment of Delhi India. Environ Geol 50(7):1025–1039. https://doi.org/10.1007/s00254-006-0275-4
86. Kumar S, Sharma SK (2017) Groundwater quality of Hisar city of Haryana state, India—status of fluoride content. Int J Chem Sci 15(4):1–10
87. Kumar P, Singh AK (2021) Study of fluorosis problems in Hardia Sector D (Jajpur Village) of Rajauli Block of Nawada District Bihar. Biospectra 16(1):37–40
88. Kumar S, Venkatesh AS, Singh R, Udayabhanu G, Saha D (2018) Geochemical signatures and isotopic systematics constraining dynamics of fluoride contamination in groundwater across Jamui district, Indo-Gangetic alluvial plains, India. Chemosphere 205:493–505. https://doi.org/10.1016/j.chemosphere.2018.04.116
89. Kumar D, Singh A, Jha RK, Sahoo SK, Jha V (2019) A variance decomposition approach for risk assessment of groundwater quality. Expo Health 11:139–151. https://doi.org/10.1007/s12403-018-00293-6
90. Kumar R, Singh S, Kumar R, Sharma P (2022) Groundwater quality characterization for safe drinking water supply in sheikhpura district of Bihar, India: a geospatial approach. Front Water 4:848018. https://doi.org/10.3389/frwa.2022.848018
91. Kundu MC, Mandal B (2009) Assessment of potential hazards of fluoride contamination in drinking groundwater of an intensively cultivated district in West Bengal India. Environ Monit Assess 152(1):97–103. https://doi.org/10.1007/s10661-008-0299-1

92. Kut KMK, Sarswat A, Srivastava A, Pittman CU Jr, Mohan D (2016) A review of fluoride in African groundwater and local remediation methods. Groundw Sustain Dev 2:190–212. https://doi.org/10.1016/j.gsd.2016.09.001
93. Lacson CFZ, Ming-Chun L, Yao-Hi H (2021) Fluoride-containing water: A global prespective and a pursuit to sustainable water defluoridation management-an overview. J Clean Prod 280:124236. https://doi.org/10.1016/j.jclepro.2020.124236
94. Lee JI, Hong SH, Lee CG, Park SJ (2021) Fluoride removal by thermally treated egg shells with high adsorption capacity, low cost, and easy acquisition. Environ Sci Pollut Res 28(27):35887–35901. https://doi.org/10.1007/s11356-021-13284-z
95. Liu Q, Guo H, Shan Y (2010) Adsorption of fluoride on synthetic siderite from aqueous solution. J Fluorine Chem 131(5):635–641. https://doi.org/10.1016/j.jfluchem.2010.02.006
96. Malago J, Makoba E, Muzka AN (2017) Fluoride levels in surface and groundwater in Africa: a review. Am J Water Sci Eng 3(1):1–17. https://doi.org/10.11648/j.ajwse.20170301.11
97. Maurya, J, Pradhan, SN, Seema, Ghosh, AK. (2020) Evaluation of ground water quality and health risk assessment due to nitrate and fluoride in the Middle Indo-Gangetic plains of India. Hum Ecol Risk Assess: Int J 27(5):1349–1365. https://doi.org/10.1080/10807039.2020.1844559
98. Mazighi A, Lounici H, Drouiche N, Leenaerts R, Abdi N, Grib H, Mameri N (2015) Economic study of groundwater defluoridation of the North African Sahara. Desalin Water Treat 54(10):2681–2691. https://doi.org/10.1080/19443994.2014.906327
99. Mazumder DNG, Ghosh A, Majumdar KK, Ghosh N, Saha C, Mazumder RNG (2010) Arsenic contamination of ground water and its health impact on population of district of Nadia, West Bengal, India. Indian J Community Med: Official Publ Indian Assoc Prev Soc Med 35(2):331. https://doi.org/10.4103/0970-0218.66897
100. McLaren JR (1976) Possible effects of fluorides on the thyroid. Fluoride (United States) 9(2)
101. Meenakshi V, Garg K, Renuka K, Malik A (2004) Groundwater quality in some villages of Haryana, India: focus on fluoride and fluorosis. J Hazard Mater 106(1):85–97. https://doi.org/10.1016/j.jhazmat.2003.09.007
102. Misra AK, Mishra A (2007) Study of quaternary aquifers in Ganga Plain, India: focus on groundwater salinity, fluoride and fluorosis. J Hazard Mater 144(1–2):438–448. https://doi.org/10.1016/j.jhazmat.2006.10.057
103. Misra, AK, Mishra, A, Premraj (2006) Escalation of groundwater fluoride in the Ganga alluvial plain of India. Fluoride 39:35–38
104. Mittal S, Kumar R, Sahoo PK, Sahoo SK (2021) Geochemical assessment of groundwater contaminants and associated health risks in the Shivalik region of Punjab, India. Toxin Rev 40(4):928–944. https://doi.org/10.1080/15569543.2020.1802597
105. Mohapatra M, Singh P (2009) Review of fluoride removal from drinking water. J Environ Manage 91(1):67–77. https://doi.org/10.1016/j.jenvman.2009.08.015
106. Mohapatra AK, Sujathan S, Ekamparam AS, Singh A (2021) The role of manganese carbonate precipitation in controlling fluoride and uranium mobilization in groundwater. ACS Earth Space Chem 5(10):2700–2714. https://doi.org/10.1021/acsearthspacechem.1c00133
107. Mondal D, Gupta S, Reddy DV, Nagabhushanam P (2014) Geochemical controls on fluoride concentrations in groundwater from alluvial aquifers of the Birbhum district, West Bengal, India. J Geochem Explor 145:190–206. https://doi.org/10.1016/j.gexplo.2014.06.005
108. Mondal S, Kumar S (2017) Investigation of fluoride contamination and its mobility in groundwater of Simlapal block of Bankura district, West Bengal India. Environ Earth Sci 76(22):1–9. https://doi.org/10.1007/s12665-017-7122-7
109. Mondal D, Dutta G, Gupta S (2016) Inferring the fluoride hydrogeochemistry and effect of consuming fluoride-contaminated drinking water on human health in some endemic areas of Birbhum district West Bengal. Environ Geochem Health 38(2):557–576. https://doi.org/10.1007/s10653-015-9743-7
110. Mor S, Singh S, Yadav P, Rani V, Rani P, Sheoran M, Ravindra (2009) Appraisal of salinity and fluoride in a semi-arid region of India using statistical and multivariate techniques. Environ Geochem Health 31(6):643–655. https://doi.org/10.1007/s10653-008-9222-5

111. Mourabet M, El Rhilassi A, El Boujaady H, Bennani-Ziatni M, Taitai A (2017) Use of response surface methodology for optimization of fluoride adsorption in an aqueous solution by Brushite. Arab J Chem 10:S3292–S3302. https://doi.org/10.1016/j.arabjc.2013.12.028
112. Mridha D, Priyadarshni P, Bhaskar K, Gaurav A, De A, Das A, Roychowdhury T (2021) Fluoride exposure and its potential health risk assessment in drinking water and staple food in the population from fluoride endemic regions of Bihar India. Groundw Sustain Dev 13:100558. https://doi.org/10.1016/j.gsd.2021.100558
113. Mukherjee S, Sahu P, Halder G (2018) Comparative assessment of the fluoride removal capability of immobilized and dead cells of Staphylococcus lentus (KX941098) isolated from contaminated groundwater. Environ Prog Sustain Energy 37(5):1573–1586. https://doi.org/10.1002/ep.12853
114. Mukherjee I, Singh UK (2017) Groundwater fluoride contamination, probable release, and containment mechansms: a review on Indian context. Environ Geochem Health. https://doi.org/10.1007/s10653-018-0096-x
115. Mukherjee I, Singh UK, Patra PK (2019) Exploring a multi-exposure-pathway approach to assess human health risk associated with groundwater fluoride exposure in the semi-arid region of east India. Chemosphere 233:164–173. https://doi.org/10.1016/j.chemosphere.2019.05.278
116. Mumtaz N, Pandey G (2017) A Study on integrated fluorosis mitigation plan for endemic fluorosis region-an Indian perspective. Int J Civil Eng Technol 8(4):84–91
117. Neal C, Neal M, Davies H, Smith J (2003) Fluoride in UK rivers. Sci Total Environ 314:209–231
118. Nigam N, Srivastava SK (2020) Groundwater quality of shallow aquifer in Uttar Pradesh. Int J Res Eng Sci Manag 3(7):207–209. https://journal.ijresm.com/index.php/ijresm/article/view/53
119. Nijesh P, Akpataku KV, Patel A, Rai P, Rai SP (2021) Spatial variability of hydrochemical characteristics and appraisal of water quality in stressed phreatic aquifer of Upper Ganga Plain, Uttar Pradesh, India. Environ Earth Sci 80:1–15. https://doi.org/10.1007/s12665-021-09410-2
120. Nizam S, Virk HS, Sen IS (2022) High levels of fluoride in groundwater from Northern parts of Indo-Gangetic plains reveals detrimental fluorosis health risks. Environ Adv 8:100200. https://doi.org/10.1016/j.envadv.2022.100200
121. Patel KS, Sahu BL, Dahariya NS, Bhatia A, Patel RK, Matini L, Bhattacharya P (2017) Groundwater arsenic and fluoride in Rajnandgaon District, Chhattisgarh, northeastern India. Appl Water Sci 7:1817–1826. https://doi.org/10.1007/s13201-015-0355-2
122. Pavithra R, Madan Kumar PD (2020) Integrated fluorosis mitigation-an-Indian perspective. J Sci Dent 5(1):30–35
123. Pettenati M, Perrin J, Pauwels H, Ahmed S (2013) Simulating fluoride evolution in groundwater using a reactive multicomponent transient transport model: application to a crystalline aquifer of Southern India. Appl Geochem 29:102–116. https://doi.org/10.1016/j.apgeochem.2012.11.001
124. Pickering WF (1985) The mobility of soluble fluoride in soils. Environ Pollut Ser B, Chem Phys 9(4):281–308. https://doi.org/10.1016/0143-148X(85)90004-7
125. Qureshi A, Armo CS (2021) Evaluation of groundwater quality in Raya Block, Mathura District (Uttar Pradesh) using water quality index. Int J Geogr, Geol Environ 4(1):49–53
126. Rahaman S, Sinha AC, Pati R, Mukhopadhyay D (2013) Arsenic contamination: a potential hazard to the affected areas of West Bengal, India. Environ Geochem Health 35:119–132. https://doi.org/10.1007/s10653-012-9460-4
127. Rahman MM, Sengupta MK, Ahamed S, Chowdhury UK, Hossain MA, Das, Chakraborti D (2005) The magnitude of arsenic contamination in groundwater and its health effects to the inhabitants of the Jalangi—one of the 85 arsenic affected blocks in West Bengal, India. Sci Total Environ 338(3):189–200. https://doi.org/10.1016/j.scitotenv.2004.06.022
128. Rahman MM, Sengupta MK, Ahamed S, Chowdhury UK, Lodh D, Hossain A, Chakraborti D (2005) Arsenic contamination of groundwater and its health impact on residents in a village in West Bengal, India. Bull World Health Organ 83(1):49–57

129. Raj D, Shaji E (2017) Fluoride contamination in groundwater resources of Alleppey southern India. Geosci Front 8(1):117–124. https://doi.org/10.1016/j.gsf.2016.01.002
130. Raju NJ, Dey S, Das K (2009) Fluoride contamination in groundwaters of Sonbhadra district, Uttar Pradesh, India. Curr Sci, 979–985.
131. Raju NJ, Dey S, Gossel W, Wycisk P (2012) Fluoride hazard and assessment of groundwater quality in the semi-arid Upper Panda River basin, Sonbhadra district, Uttar Pradesh India. Hydrol Sci J 57(7):1433–1452
132. Raju NJ, Ram P, Dey S (2009) Groundwater quality in the lower Varuna river basin, Varanasi district, Uttar Pradesh. J Geol Soc India 73(2):178–192. https://doi.org/10.1007/s12594-009-0074-0
133. Ranjan S, Yasmin S (2019) Geological source of fluoride in fluoride endemic region of Gaya district, Bihar, India. Biosci Biotechnol Res Commun 12(4):1165–1172. https://doi.org/10.21786/bbrc/12.4/41
134. Rao NCR (2003) Fluoride and environment-a review.In: Proceedings of the third international conference on environment and health, Chennai, India, pp 386–399
135. Rao NS, Rao PS, Dinakar A, Rao PVN, Marghade D (2015) Fluoride occurrence in the groundwater in a coastal region of Andhra Pradesh, India. Appl Water Sci. https://doi.org/10.1007/s13201-015-0338-3
136. Rashid A, Farooqi A, Gao X, Zahir S, Noor S, Khattak JA (2020) Geochemical modeling, source apportionment, health risk exposure and control of higher fluoride in groundwater of sub-district Dargai Pakistan. Chemosphere 243:125409. https://doi.org/10.1016/j.chemosphere.2019.125409
137. Ray D, Ravindar Rao R, Bhoi AV, Biswas AK, Ganguly AK, Sanyal PB (2000) Physico-chemical quality of drinking water in Rohtas district of Bihar. Environ Monit Assess 61(3):387–398. https://doi.org/10.1023/A:1006165615097
138. Ray C, Roy PK, Majumder A, Roy MB (2020) Performance analysis of some low-cost and locally available adsorbents that remove excess fluoride ion from raw water to develop a filter for the rural population. J Inst Eng (India): Ser E 101(2):149–160. https://doi.org/10.1007/s40034-020-00168-z
139. Rentería-Villalobos M, Covarrubias-Muños A, Pinedo-Álvarez A, Manjon-Collado G (2017) Hydrochemistry and 222Rn concentrations in spring waters in the arid zone El Granero, Chihuahua Mexico. Geosciences 7(1):12
140. Ruhela M, Singh VK, Ahamad F (2021) Assessment of groundwater quality of two selected villages of Nawada district of Bihar using water quality index. Environ Conserv J 22(3):387–394. https://doi.org/10.36953/ECJ.2021.22344
141. Saha D, Ray RK (2019) Groundwater resources of India: potential, challenges and management. In: Groundwater development and management: issues and challenges in South Asia, pp 19–42
142. Sahu P, Kisku GC, Singh PK, Kumar V, Kumar P, Shukla N (2018) Multivariate statistical interpretation on seasonal variations of fluoride-contaminated groundwater quality of Lalganj Tehsil, Raebareli District (UP) India. Environ Earth Sci 77(13):1–11. https://doi.org/10.1007/s12665-018-7658-1
143. Sahu S, Gogoi U, Nayak NC (2021) Groundwater solute chemistry, hydrogeochemical processes and fluoride contamination in phreatic aquifer of Odisha, India. Geosci Front 12(3):101093. https://doi.org/10.1016/j.gsf.2020.10.001
144. Salve PR, Maurya A, Kumbhare PS, Ramteke DS, Wate SR (2008) Assessment of groundwater quality with respect to fluoride. Bull Environ Contam Toxicol 81:289–293
145. Samal AK, Mishra PK, Biswas A (2020) Assessment of origin and distribution of fluoride contamination in groundwater using an isotopic signature from a part of the Indo-Gangetic Plain (IGP), India. Hydro Res 3:75–84. https://doi.org/10.1016/j.hydres.2020.05.001
146. Sankararamakrishnan N, Shaarma AK, Iyengar L (2008) Contamination of nitrate and fluoride in ground water along the Ganges Alluvial Plain of Kanpur district, Uttar Pradesh India. Environ Monit Assess 146(1–3):375–382. https://doi.org/10.1007/s10661-007-0085-5

147. Sarkar H, Das S, Ray SS (2015) Scope for development of river bed sub-surface aquifer in fluoride affected blocks of south dinajpur district, West Bengal as sustainable mitigation measures. In: Proc. Int. Sem. challenges to ground water management: vision 2050, pp 423–440
148. Schuler, P, Campanyà, J, Moe, H, Doherty, D, Williams, NH, & McCormack, T. (2022) Mapping the groundwater memory across Ireland: A step towards a groundwater drought susceptibility assessment. J Hydrol.https://doi.org/10.1016/j.jhydrol.2022.128277
149. Shahnawaz MD, Singh KM, Shekhar H (2009) Physico-chemical parameters in groundwater of Bhojpur district in middle Gangetic plain. Proc Indian Natl Sci Acad 75(4):167–172
150. Sharma T, Litoria PK, Bajwa BS, Kaur I (2021) Appraisal of groundwater quality and associated risks in Mansa district (Punjab, India). Environ Monit Assess 193:1–21. https://doi.org/10.1007/s10661-021-08892-8
151. Sharma T, Sharma A, Kaur I, Mahajan RK, Litoria PK, Sahoo SK, Bajwa BS (2019) Uranium distribution in groundwater and assessment of age dependent radiation dose in Amritsar, Gurdaspur and Pathankot districts of Punjab, India. Chemosphere 219:607–616. https://doi.org/10.1016/j.chemosphere.2018.12.039
152. Shekhar S, Sarkar A (2013) Hydrogeological characterization and assessment of groundwater quality in shallow aquifers in vicinity of Najafgarh drain of NCT Delhi. J Earth Syst Sci 122(1):43–54. https://doi.org/10.1007/s12040-012-0256-9
153. Shukla S, Saxena A (2020) Groundwater quality and associated human health risk assessment in parts of Raebareli district, Uttar Pradesh India. Groundw Sustain Dev 10:100366. https://doi.org/10.1016/j.gsd.2020.100366
154. Shukla S, Saxena A (2020) Water quality index assessment of groundwater in the Central Ganga Plain with reference to Raebareli district, Uttar Pradesh India. Curr Sci 119(8):1308–1315
155. Shukla S, Saxena A, Khan R, Li P (2021) Spatial analysis of groundwater quality and human health risk assessment in parts of Raebareli district, India. Environ Earth Sci 80(24):800. https://doi.org/10.1007/s12665-021-10109-7
156. Singh S (2016) Fluoride Contamination in Groundwater in Some Villages of Banda District, Uttar Pradesh, India. Int J Innov Res Sci Technol 3(06):2349–6010
157. Singh B, Gaur S, Garg VK (2007) Fluoride in drinking water and human urine in Southern Haryana India. J Hazard Mater 144(1–2):147–151. https://doi.org/10.1016/j.jhazmat.2006.10.010
158. Singh KP, Gupta S, Mohan D (2014) Evaluating influences of seasonal variations and anthropogenic activities on alluvial groundwater hydrochemistry using ensemble learning approaches. J Hydrol 511:254–266. https://doi.org/10.1016/j.jhydrol.2014.01.004
159. Singh AK, Kumar P, Patel V (2021) Groundwater fluoride contamination in Bhaunr Village of Rajauli Block of Nawada District Bihar. Biospectra 16(2):25–28
160. Singh G, Rishi MS, Herojeet R, Kaur L, Sharma K (2020) Evaluation of groundwater quality and human health risks from fluoride and nitrate in semi-arid region of northern India. Environ Geochem Health 42:1833–1862. https://doi.org/10.1007/s10653-019-00449-6
161. Singh KP, Malik A, Mohan D, Singh VK, Sinha S (2006) Evaluation of groundwater quality in northern Indo-Gangetic alluvium region. Environ Monitor Assess 112:211–230. https://doi.org/10.1007/s10661-006-0357-5
162. Sinha AK, Sarthi PP (2016) Study on iron and fluoride distribution in five districts of Bihar, 2–3. https://doi.org/10.13140/RG.2.2.24488.78087
163. Sulaiman MA, Zafar MM, Divya, Prabhakar R, Kumari A (2023a) Evaluation of ionic composition and hydrogeochemical processes of the groundwater in Muzaffarpur, district, Bihar, India. Ind J Environ Protect 43(3):263–269. https://www.e-ijep.co.in/43-3-263-269/
164. Sulaiman MA, Zafar MM, Afshan N, Kumari A (2021) Impact of Lockdown on Air Pollutants during COVID-19 at Patna, India. Asian J Atmos Environ 15(4):62–77. https://asianjae.org/_common/do.php?a=html&b=22
165. Sulaiman MA, Zafar MM, Prabhakar R, Kumar R, Sinha Rk, Kumari A (2023b) A multivariate statistical approach to evaluate the hydro-geochemistry of groundwater quality in the middle

Ganga river basin, Patna, India. Acta Geophys, 1–14. https://doi.org/10.1007/s11600-023-01071-y
166. Sun L, Gao Y, Liu H, Zhang W, Ding Y, Li B (2013) An assessment of the relationship between excess fluoride intake from drinking water and essential hypertension in adults residing in fluoride endemic areas. Sci Total Environ 443:864–869. https://doi.org/10.1016/j.scitotenv.2012.11.021
167. Susheela AK (2017) Fluoride and fluorosis mitigation: Indian contributions and its impact. In: Water and sanitation in the new millennium, pp 97–105
168. Swain S, Sahoo S, Taloor AK (2022) Groundwater quality assessment using geospatial and statistical approaches over Faridabad and Gurgaon districts of National Capital Region India. Appl Water Sci 12(4):75. https://doi.org/10.1007/s13201-022-01604-8
169. Talpur SA, Noonari TM, Rashid A, Ahmed A, Jat Baloch MY, Talpur HA, Soomro MH (2020) Hydrogeochemical signatures and suitability assessment of groundwater with elevated fluoride in unconfined aquifers Badin district, Sindh, Pakistan. SN Appl Sci 2:1–15
170. Tang Y, Wang J, Gao N (2010) Characteristics and model studies for fluoride and arsenic adsorption on goethite. J Environ Sci 22(11):1689–1694. https://doi.org/10.1016/S1001-0742(09)60307-7
171. Teotia, SP, Teotia, M. (1994) Endemic fluorosis in India: A challenging national health problem. J Assoc Physicians India 32:347–352. https://europepmc.org/article/med/6746548
172. Tiwari AK, Singh AK, Mahato MK (2017) GIS based evaluation of fluoride contamination and assessment of fluoride exposure dose in groundwater of a district in Uttar Pradesh, India. Hum Ecol Risk Assess Int J 23(1):56–66. https://doi.org/10.1080/10807039.2016.1220824
173. Tolkou AK, Meez E, Kyzas GZ, Torretta V, Collivignarelli MC, Caccamo FM, Katsoyiannis IA (2021) A mini review of recent findings in cellulose-, polymer-and graphene-based membranes for fluoride removal from drinking water. C 7(4):74. https://doi.org/10.3390/c7040074
174. Toolabi A, Bonyadi Z, Paydar M, Najafpoor AA, Ramavandi B (2021) Spatial distribution, occurrence, and health risk assessment of nitrate, fluoride, and arsenic in Bam groundwater resource, Iran. Groundwater Sustain Dev 12:100543. https://doi.org/10.1016/j.gsd.2020.100543
175. Tor A, Danaoglu N, Arslan G, Cengeloglu Y (2009) Removal of fluoride from water by using granular red mud: batch and column studies. J Hazard Mater 164(1):271–278. https://doi.org/10.1016/j.jhazmat.2008.08.011
176. US EPA (1985) Drinking water criteria document on fluoride. Washington DC, US Environmental Protection Agency, Office of Drinking Water, (TR-823–5)
177. US EPA (2004). Risk assessment guidance for superfund volume 1: human health evaluation manual (Part E, Supplemental Guidance for Dermal Risk Assessment) final. EPA/540/R/99/005 OSWER 9285.7-02EP PB99-963312 July 2004, Office of Superfund Remediation and Technology Innovation U.S. Environmental Protection Agency Washington, DC.
178. US EPA (2010). Fluoride: exposure and relative source contribution analysis. Health and Ecological Criterioa Division, Office of Science and Technology, Office of Water, Washington, DC, EPA 820-R-10-015
179. Valdez-Jimenez L, Soria Fregozo C, Miranda Beltran ML, Gutierrez Coronado O, Perez Vega MI (2011) Effects of the fluoride on the central nervous system. Neurologia (Barcelona, Spain) 26(50):297–300. https://doi.org/10.1016/S2173-5808(11)70062-1
180. Valdiya KS (2016) Tertiary basins: along coasts and offshore. In: The making of India. Society of earth scientists series. Springer, Cham. https://doi.org/10.1007/978-3-319-25029-8_20
181. Verma DK, Bhunia GS, Shit PK, Kumar S, Mandal J, Padbhushan R (2017) Spatial variability of groundwater quality of Sabour block, Bhagalpur district (Bihar, India). Appl Water Sci 7(4):1997–2008. https://doi.org/10.1007/s13201-016-0380-9
182. Verma KK, Kumar A, Singh M, Verma CL (2020) Developing a model for urinary fluoride levels in relation to the fluoride content of drinking water and foodstuffs in a rural population in Lakhimpur (Kheri), Uttar Pradesh, India. India Fluoride 53(4):595–610
183. Vithanage M, Bhattacharya P (2015) Fluoride in drinking water: health effects and remediation. CO_2 Sequestration, Biofuels Depollution 5:105–151, Springer, Cham. https://doi.org/10.1007/978-3-319-11906-9_4

184. Wan, K, Huang, L, Yan, J, Ma, B, Huang, X, Luo, Z, Zhang, H, Xiao, T. (2021) Removal of fluoride from industrial wastewater by using different adsorbents: a review. Sci Total Environ, 773.https://doi.org/10.1016/j.scitotenv.2021.145535
185. Welch SA, Taunton AE, Banfield JF (2002) Effect of microorganisms and microbial metabolites on apatite dissolution. Geomicrobiol J 19(3):343–367. https://doi.org/10.1080/01490450290098414
186. Wen D, Zhang F, Zhang E, Wang C, Han S, Zheng Y (2013) Arsenic, fluoride and iodine in groundwater of China. J Geochem Explor 135:1–21. https://doi.org/10.1016/j.gexplo.2013.10.012
187. World Health Organization (2011) 'Guidelines for Drinking-water Quality. https://apps.Who.int/iris/bitstream/handle/10665/44584/9789241548151_eng.pdf
188. Xiong X, Liu J, He W, Xia T, He P, Chen X, Yang K, Wang A (2007) Dose-effect relationship between drinking water fluoride levels and damage to liver and kidney functions in children. Environ Res 103(1):112–116. https://doi.org/10.1016/j.envres.2006.05.008
189. Yadav KK, Gupta N, Kumar V, Choudhary P, Khan SA (2018) GIS-based evaluation of groundwater geochemistry and statistical determination of the fate of contaminants in shallow aquifers from different functional areas of Agra city, India: levels and spatial distributions. RSC Adv 8(29):15876–15889. https://doi.org/10.1039/C8RA00577J
190. Yadav KK, Kumar V, Gupta N, Kumar S, Rezania S, Singh N (2019) Human health risk assessment: study of a population exposed to fluoride through groundwater of Agra city, India. Regul Toxicol Pharmacol 106:68–80. https://doi.org/10.1016/j.yrtph.2019.04.013
191. Yadav KK, Kumar S, Pham QB, Gupta N, Rezania S, Kamyab H, Yadav S, Vymazal J, Kumar V, Tri DQ, Talaiekhozani A (2019) Fluoride contamination, health problems and remediation methods in Asian groundwater: a comprehensive review. Ecotoxicol Environ Saf 182.https://doi.org/10.1016/j.ecoenv.2019.06.045
192. Yadav M, Singh G, Jadeja RN (2021) Fluoride contamination in groundwater, impacts, and their potential remediation techniques. groundwater geochemistry: pollution and remediation methods, 22–41. https://doi.org/10.1002/9781119709732.ch2
193. Yasmin S, Monterio S, Ligimol PA, D'Souza D (2011) Fluoride contamination and fluorosis in Gaya Region of Bihar India. Current Biotica 5(2):232–236
194. Zafar MM, Sulaiman MA, Prabhakar R, Kumari A (2022) Evaluation of the suitability of groundwater for irrigational purposes using irrigation water quality indices and geographical information systems (GIS) at Patna (Bihar), India. Int J Energy Water Resour, 1–14.https://doi.org/10.1007/s42108-022-00193-1
195. Zhou J, Wang H, Cravotta III C A, Dong Q, Xiang X (2017) Dissolution of fluorapatite by Pseudomonas fluorescens P35 resulting in fluorine release. Geomicrobiol J 34(5):421–433. https://doi.org/10.1080/01490451.2016.1204376

Groundwater Quality in Shallow Aquifers of the Sedimentary Plain in Iraq: A Potential Concern for Drinking and Irrigation

Alhassan H. Ismail

Abstract Iraq is considered as one of the arid or semi-arid territories presently facing a water scarcity challenge along with quality, especially in the sedimentary plain area of Iraq. Recently, groundwater was used as an alternative source for different uses due to decline in level of surface water. Therefore, many random shallow wells have been drilled in Iraq. In the present chapter, an attempt has been made to document the groundwater management and quality of shallow groundwater in the sedimentary plain of Iraq. The major drivers affecting groundwater quantity and quality in the study area are high evaporation rate, low rainfall and rapid population growth. Moreover, a case study was presented to evaluate the hydrochemistry in Tooz area of Iraq based on Bascaron Water Quality Index (BWQI). The results revealed that the groundwater is highly saline and mainly belongs to Na–Cl, Ca–Cl, and mixed Ca–Mg–Cl water types. Furthermore, it was found that the groundwater was generally unsuitable for drinking and irrigation in most of the sedimentary plain area. Thus, the results of this study will be helpful to governing authorities in planning any management schemes in Iraq.

Keywords Hydrochemistry · Groundwater quality · Iraq water · Water quality index · Tooz water quality

1 Introduction

Iraq, also known as Mesopotamia, is exposed to many environmental challenges due to its geographical location within the arid and semi-arid regions and the economic, political, and security crises. The pressures resulting from the high demand on water resources, and the continued decline in their rates, have led to significant changes in Iraq's hydrological situation during the past 30 years. Iraq relies heavily on the surface water for water supply, irrigation, and industrial uses [19]. The decrease in

A. H. Ismail (✉)
Institute of Technology-Baghdad, Middle Technical University, Baghdad, Iraq
e-mail: alhassan_hayder@mtu.edu.iq

S. Ali and A. M. Armanuos (eds.), *Groundwater in Arid and Semi-Arid Areas*, Earth and Environmental Sciences Library, https://doi.org/10.1007/978-3-031-43348-1_13

surface water levels and precipitation during the past few years reflects the decline in water levels of reservoirs, lakes, and rivers. The water level of the Tigris and Euphrates rivers, the country's primary water source, has fallen to less than a third of its levels [34]. Consequently, the storage capacity has significantly reduced, and the governing authorities estimated that its water reserves are declining at a faster and dangerous rate. The main reason for the decline in Tigris and Euphrates river levels is the Southeastern Anatolia Project (GAP), which launched in the 1970's. GAP is a mega Turkish project consisting of 22 dams and 19 hydroelectric power plants that use large amounts of the Tigris and Euphrates rivers water [24]. The GAP project has affected Iraq's water share and led to surface water quality problems like an increase in water salinity [1]. In addition, increased water demand, domestic wastewater discharge, and climate change, the mismanagement of water resources in conjunction with Iraq's political instability leads to various challenges in the country [16].

On the other hand, water shortage negatively affected the agricultural sector, to the extent that Iraq transformed from a major wheat exporter to the world's largest importer [15]. Traditional and unbalanced irrigation and drainage methods have led to a great waste of water resources, pointing to the fact that more than 90% of Iraq's total water is consumed in the agricultural sector, which provides only a small percentage of the country's food needs [22, 45]. Moreover, climate change is another reason responsible for water quantity losses and quality deterioration. Further, high temperature in Iraq led to increased evaporation rate, therefore, water salinity has increased mainly due to GAP project and climate change [16, 20].

Groundwater quality has been extensively studied by several researchers at the local and global levels in Iraq [3, 5, 6, 17, 20–22, 24, 38, 44]. In the present study, a case study was introduced to assess the groundwater quality and its chemistry in the Tooz area of Iraq. Tooz is a district in the north-eastern part of Saladin Governorate. Its main settlement is the city of Tuz Khurmatu. Other towns include Sulaiman Bek, Yankjah, and Amirli. The study area is located in a semi-arid climate zone [11]. The primary water resources in the region include rainfall, groundwater, and surface water. Groundwater is being recharged mainly by the 100-km-long Awaspi stream. However, in the case of suitability sites for groundwater recharge, the Tooz area ranges from poor to moderate [35]. People use groundwater for drinking and domestic purposes through pumped and dug wells.

The importance of this area is emerged due to the lands of the sedimentary plain being characterized by their high suitability for agriculture (arable land). Therefore, providing knowledge of the suitability of groundwater for drinking and irrigation along with hydrochemistry status is necessary for the management of groundwater resource in Iraq. Figure 1 shows governorates and districts of Iraq in the sedimentary plain area. The current chapter documented the groundwater quality and hydrochemistry status in Iraq's sedimentary plain and investigated the Tooz area of Iraq based on Bascaron Water Quality Index (BWQI). Few studies were conducted to explore the hydrochemistry of groundwater in the sedimentary plain area of Iraq. The present chapter reviews the previous studies regarding groundwater quality in the studied area and explores the hydrochemistry of groundwater in the Tooz area which has been the first time examined.

2 Sedimentary Plain in Iraq

Iraqi land is amalgamation of mountains, foothills, Jazeera, desert, and sedimentary plain (Mesopotamian plain) (Fig. 2). Nearly, 75% of the population of Iraq is concentrated in the sedimentary plain, although it covers only 24% of the total area of Iraq and extends from the northwest towards the southeast. This is due to their fertile soil which resulted from the accumulation of sediments deposited by Tigris and Euphrates Rivers, which feed this region with water. The region contains potential amount of groundwater and large quantities of oil.

The Iraqi land is covered mostly by sedimentary rocks and sediments of Quaternary age. The sedimentary rocks consist mainly of clastic, carbonates, and subordinate gypsum, shale, and marl [4]. The Quaternary sediments comes from Mesopotamian land and covers large area of Iraq, especially in the central part. They are expressed by alluvial sediments of the Tigris and Euphrates Rivers flood plains. Tigris and Euphrates rivers are Iraq's main rivers, as shown in Fig. 3. The sediments are dominantly composed of silt, clay, and sand with subordinate gravels. Furthermore, gypcrete and sand dunes also exist in some areas of Iraq. Mesopotamia Plain is sedimentary plain and wide lowland. It is bordered by the low folded zone from the north and east, the western desert and Al-Jazira area from the western side, and from the south to the Arabian Gulf [43]. The geological map of Iraq is shown in Fig. 3.

3 Drivers

3.1 Climate Change

The sedimentary plain area is characterized by low annual rainfall and high evaporation due to hot climate. The annual rainfall rates ranges from 75 to 10 mm (the rainy season is specifically between October and April), and the temperatures ranges from 15 to 20 °C in winter, while 35–45 °C during summer. The average annual total depth of evaporation from the water surfaces is 1300 mm in the north, 2000 mm in the middle, 2400 mm in the south of Iraq (it may reach 300 mm monthly during July and August) [30]. Table 1 shows the average annual rainfall (mm) from 1970 to 2011 in different areas of Iraq [30]. Clearly, the cities in the sedimentary plain are characterized by low annual rainfall.

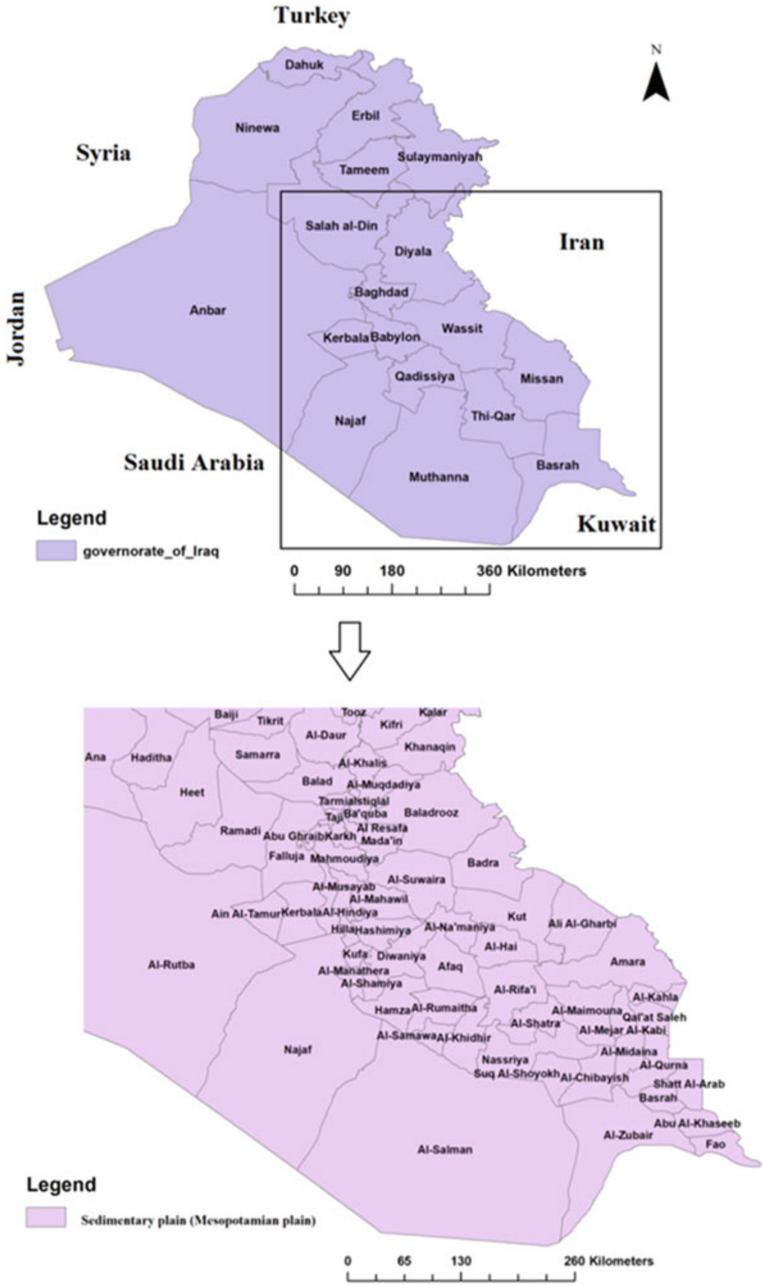


Fig. 1 Governorate of Iraq along with district of Iraq in the sedimentary plain zone

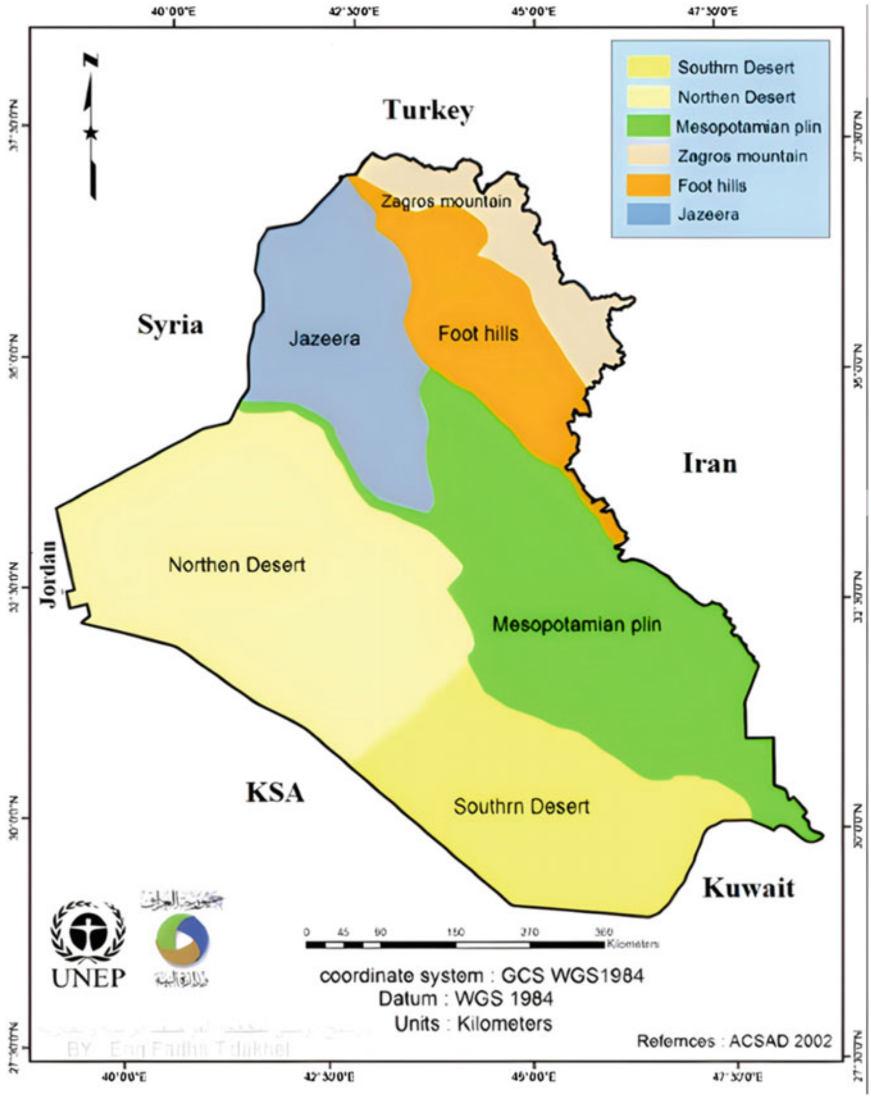


Fig. 2 Major geomorphic classification of Iraqi land [30]

3.2 Population Growth

As already mentioned, sedimentary plain covers only 24% of the total area of Iraq. However, 75% of the population of Iraq lives in this area. On the other hand, Iraq's population has rapidly increased during past few decades. Iraq's estimated population was 3.38 million in 1934 and reached 24 million in 1997 [10]. Further, it is expected to cross 50 million in 2030. The increase in population led to an increase in water

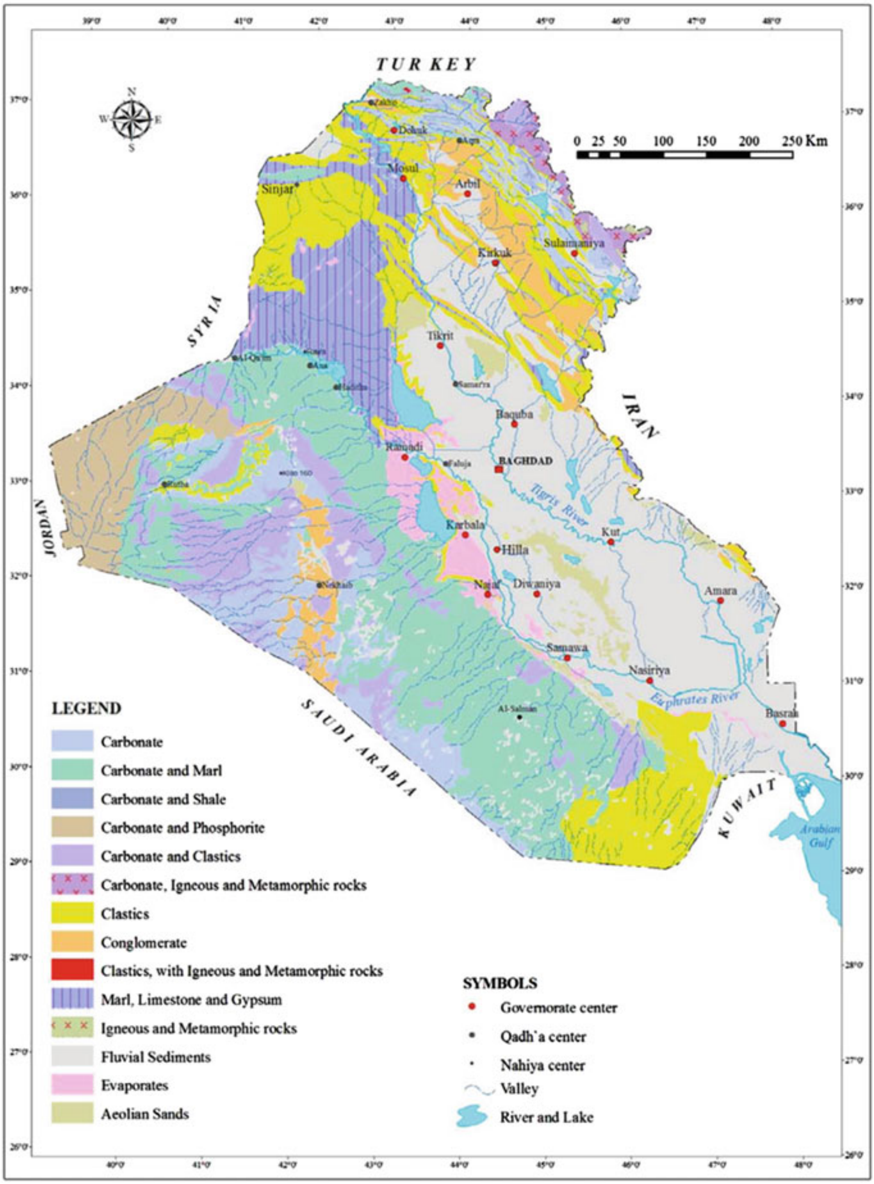


Fig. 3 Geological map of Iraq (adopted from Sissakian and Fouad [37])

Table 1 Annual rate of rainfall from 1970 to 2011 in different areas of Iraq [30]

Seq.	Station/city	Annual rate (mm)	Seq.	Station/city	Annual rate (mm)
1	Zakho	560.7	11	Tooz[a]	239.8
2	Erbil	389.5	12	Baghdad[a]	120.6
3	Salah-Aldin[a]	576.7	13	Hillah[a]	99.5
4	Mosul	354.0	14	Kut[a]	131.2
5	Baiji	196.9	15	Samarra[a]	160.2
6	Haditha	130.6	16	Karbala[a]	91.9
7	Ar-Rutbah	117.2	17	Samawah[a]	89.7
8	Sinjar	355.1	18	Amarah[a]	169.7
9	Tikrit[a]	170.3	19	Hit[a]	94.3
10	Najaf[a]	79.6	20	Khalis	246.7

[a] Cities located in the sedimentary plain

demand along with the deterioration of the water quality of the Tigris and Euphrates rivers including groundwater. Therefore, groundwater exploitation in Iraq as an alternative irrigation source has increased exponentially. Thus, numerous random shallow wells were drilled in Iraq for irrigation [20].

3.3 Urbanization

The urban area has been expanded exponentially in Iraq during the past two decades. The migration from rural to urban areas is the most significant form of internal migration in Iraq. Internal migration from rural to urban was frequent from the end of the twentieth century in Iraq. The main reason for internal migration was the difference in economic and social conditions, job prospects and better life style [10].

Agriculture was a source of livelihood for more than 60% of people in the 1950s. This rate decreased to 28.5% in the 1990s [10]. Lack of water is one of the important reasons for people's reluctance to farm. Large-scale urbanization has led to a decline in the amount of fertile land. Besides, the economic activity in urban areas has limited agriculture and animal farming [45].

4 Groundwater Quality in the Sedimentary Plain

Groundwater was found to be highly deteriorated in Iraq, especially, in its sedimentary plain. Table 2 shows the maximum values reported for the major ions in different areas of sedimentary plains, namely the urban area of Baghdad, Ali al-Garbi Area in Misaan, Tarmiah district, Balad district in Salah Al-Din Governorate, Wasit Governorate, and Babylon Governorate. The Table 2 shows the study areas are characterized relatively by high TDS and EC. The highest maximum value was recorded in the urban area of Baghdad, the capital of Iraq, while the lowest value was recorded from the Ali Al-Garbi area in Misaan governorate (south of Iraq). Generally, TDS and EC in the groundwater of sedimentary plains in Iraq are high, making groundwater unsuitable for drinking and irrigation. Ismail et al. [24] stated that anthropogenic activities have highly affected groundwater quality. However, they found that the evaporation process plays an important role in controlling the groundwater in Baghdad. Furthermore, available studies on some important water quality parameters in the groundwater of Iraq, such as fluorides and some potentially toxic heavy metals, have a significant impact on humans, plants, and soils when used for drinking and irrigation [7, 27, 41]. Therefore, future studies should focus on exploring the concentrations of fluorides and some potentially toxic elements in groundwater and their compatibility with local and international standards [7, 9].

Table 3 shows the hydrochemistry of groundwater in different areas of sedimentary plain in Iraq. From Table 3, Piper plot [33] showed that water types in all areas in the sedimentary plain of Iraq are of Na–Cl, Ca–Cl, and Mixed Ca–Mg–Cl types indicating high-salinity water (Fig. 4). These types of water suggest that the evaporation process is the primary factor controlling groundwater quality in the area. Besides, mixing high-salinity water caused by surface contamination sources, and domestic wastewater, with existing water followed by ion exchange reactions [20, 22, 23].

Gibbs ratio is proposed by Gibbs [18] which is calculated by the formulas: (Na + K)/(Na + K + Ca) and Cl/(Cl + HCO_3), both are plotted with TDS. The Gibbs ratio gives an indication of the mechanism controlling groundwater chemistry. It can be seen from Table 3 that the groundwater in the sedimentary plain of Iraq was fallen in the evaporation dominance zone. This observation suggests that the evaporation process mainly controls groundwater chemistry in Iraq's sedimentary plain.

The chloro-alkaline indices (CAI1 and CAI2) calculated using the formulas $CAI1 = Cl^- - (Na^+ + K^+)/Cl^-$ and $AI2 = Cl^- - (Na^+ + K^+)/SO_4{}^{2-} + HCO_3{}^- + CO_3{}^{2-} + NO_3{}^-$ [36]. If the values of these indices are positive, it means that Na^+ and K^+ ions are exchanged with Mg^{2+} and Ca^{2+} ions in water and negative values refer that an exchange of Mg^{2+} and Ca^{2+} ions with Na^+ and K^+ from rocks. Most of the previous studies conducted in the sedimentary plain of Iraq indicate the majority of a chloro-alkaline disequilibrium with a minor effect of a direct base (cation–anion) exchange reaction (Table 3).

5 Water Suitability for Drinking and Irrigation

The suitability of groundwater for drinking in the sedimentary plain of Iraq is usually estimated by comparing the analytical results of chemical composition with drinking water standards (Table 2). It is obvious that the groundwater is unsuitable for drinking in different areas of the sedimentary plain in Iraq (Table 4). Irrigation suitability of groundwater usually being evaluated using hydrogeochemical parameters such as

Table 2 Maximum values of major ions in different area of sedimentary plain in Iraq

Area studied/year	pH	EC (µs/cm)	TDS (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Cl (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	NO_3 (mg/L)	References
Urban area of Baghdad/2014	8.8	29400	19020	1093	1902	6320	61	8590	3075	486	16.5	[24]
Ali al-Garbi Area in Misaan/2015–2016	6.9	6299	4850	1030	500	1187.5	41	1276	2950	220	28.8	[17]
Tarmiah district/2015	7.72	7420	11710	721	198	721	115	990	1557	539	10.1	[20]
Balad district, Salah Al-Din Governorate/2015	7.83	6870	4760	2280	540	780	98	809	1584	817	9	[22]
Wasit province/2013	7.91	14830	12460	906	543	1200	170	2280	3265	1098	12	[16]
Babylon Province/2015	7.91	24500	17900	1099	391	2332	198	3749	2875	2013	8.9	[28]
Drinking water standard	6.5–8.5	–	500	75	100	200	10	250	400	–	50	[42]

Table 3 Hydrochemistry of groundwater in different area of sedimentary plain in Iraq

Area studied/year	Piper diagram Water type	Gibbs ratio	Ion exchange process	References
Urban area of Baghdad/2014	NaCl and CaCl	Evaporation dominance zone	Chloro-alkaline disequilibrium	[24]
Ali al-Garbi Area in Misaan/ 2015–2016	NA	NA	NA	[17]
Tarmiah district/ 2015	Mixed CaMgCl and CaCl	Evaporation dominance zone	Chloro-alkaline disequilibrium	[20]
Balad district, Salah Al-Din Governorate/2015	Mixed CaMgCl and CaCl	Evaporation dominance zone	chloro-alkaline disequilibrium and direct base (cation–anion) exchange reaction	[22]
Wasit province/ 2013	Mixed CaMgCl and CaCl	Evaporation dominance zone	NA	[16]
Babylon Province/ 2015	NA	Evaporation dominance zone	Chloro-alkaline disequilibrium and direct base (cation–anion) exchange reaction	[28]

sodium adsorption ratio (SAR), residual sodium carbonate (RSC), sodium percentage (%Na), EC, US salinity diagram, and magnesium hazards (MH; Ali et al. [8]).

The following formulas were used for calculate these parameters for suitability of groundwater for irrigation:

$$\mathrm{SAR} = \frac{Na^{+}}{\sqrt{\frac{\mathrm{Ca}^{2+}+\mathrm{Mg}^{2+}}{2}}} \tag{1}$$

$$\mathrm{RSC} = (\mathrm{HCO_3}^{-} + \mathrm{CO_3}^{2-}) - (\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}) \tag{2}$$

$$\mathrm{Na\%} = \left[\frac{\mathrm{Na}^{+} + \mathrm{K}^{+}}{\mathrm{Na}^{+} + \mathrm{K}^{+} + \mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}}\right] \times 100 \tag{3}$$

$$\mathrm{MH} = \left[\frac{\mathrm{Mg}^{2+}}{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}}\right] \times 100 \tag{4}$$

where all the concentrations are expressed in meq/L.

It can be seen from Table 4 that based on SAR and RSC, the groundwater in the sedimentary plain of Iraq is suitable for irrigation. However, other parameters such as %Na and MH are suitable for irrigation in Balad district, Wasit, and Babylon. Whereas, based on EC and USSL plot the groundwater is very poor and unsuitable for

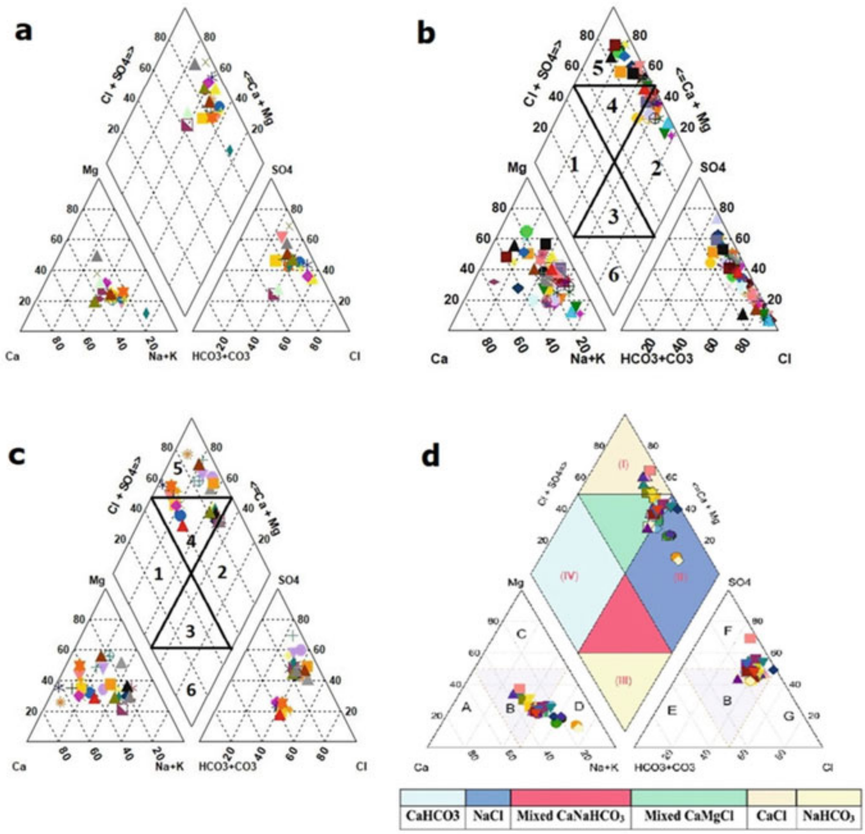


Fig. 4 Piper plots, **a** Tarmiah district [20], **b** Urban area of Baghdad [24], **c** Balad [22], **d** Wasit province [16]

irrigation for most areas of sedimentary plain (Table 4). Therefore, the groundwater in the sedimentary plain cannot be used for irrigation purposes.

6 Case Study

In this study, groundwater quality of Tooz area, Salah Al-Din Governorate, was evaluated and the suitability of groundwater for drinking and irrigation was investigated. For this work, groundwater samples from eleven sites were collected and analyzed for pH, TDS, EC and major ions. The American Public Health Association [12] recommended the methods used for the chemical analyses. Figure 5 shows the map of the study area along with the locations of sampling. It lies between latitude 33°10′0″ and 34°20′0″ North and longitudes 44°10′0″ and 44°50′0″ East. Tooz district is located

Table 4 Suitability of groundwater for drinking and irrigation in different area of sedimentary plain in Iraq

Area studied/year	Irrigation suitability						Drinking suitability	References
	SAR	RSC	%Na	MH	EC	USSL plot		
Urban area of Baghdad/2014	Excellent for most water samples	Safe	Permissible for most water samples	Unsuitable for irrigation	Unsuitable	Very poor	Unsuitable	[24]
Tarmiah district/2015	Excellent for most water samples	Safe	Doubtful to unsuitable for most water samples	Suitable for irrigation	Permissible to unsuitable	Moderate to very poor	Unsuitable	[20]
Balad district, Salah Al-Din Governorate/ 2015	Excellent	Safe	Excellent to permissible	Suitable for irrigation for most water samples	Permissible to unsuitable	Moderate to very poor	Unsuitable	[22]
Wasit province/2013	Excellent for most water samples	NA	Good to doubtful	Suitable for irrigation	Unsuitable	Very poor	Unsuitable	[16]
Babylon Province/ 2015	Excellent to Good	Safe	Excellent for most water samples	NA	Doubtful to unsuitable	Very poor	Unsuitable	[28]

in the north-eastern part of Saladin Governorate, Iraq (in the northern part of the sedimentary plain of Iraq).

The results of the chemical composition of groundwater in the study area are presented as descriptive statistics (minimum, maximum, mean, and standard deviation) in Table 5. pH values ranged from 7.11 to 7.21. pH was slightly alkaline in all groundwater samples. EC and TDS values in the groundwater of the Tooz area ranged from 5680 to 2005 μS/cm, and 1498 to 3985 mg/L with an average of 3446.82 and 2476 mg/L, respectively. The concentrations of cations, (i.e. Ca, Mg, Na and K ions) varied from 131 to 390, 51 to 212, 81 to 521 and 2 to 8 mg/L, with

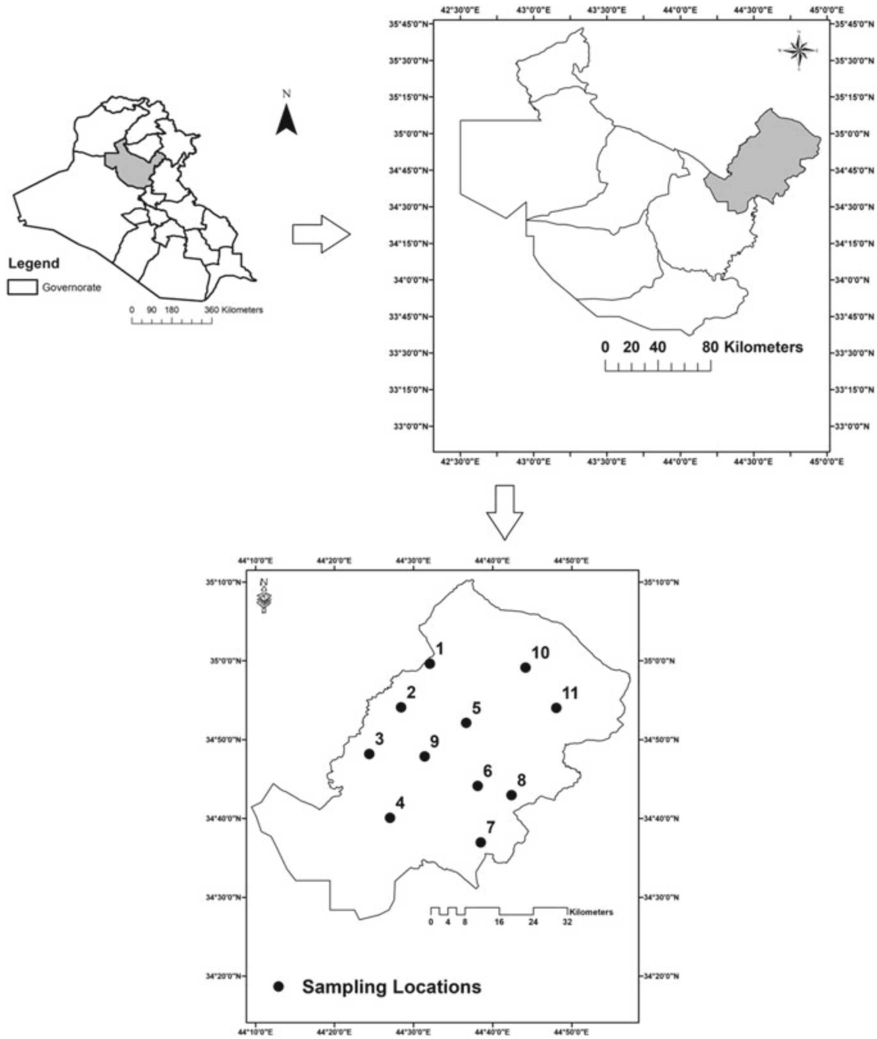


Fig. 5 Map of the study area

Table 5 Descriptive statistic of the chemical composition of the groundwater in the study area, $n = 11$

Parameter	Minimum	Maximum	Mean	Std. deviation
pH	7.11	7.71	7.31	0.22
EC (μs/cm)	2005	5680	3446.82	1134.54
TDS (mg/L)	1498	3985	2476.00	758.63
K^+ (mg/L)	2	8	4.59	2.00
Na^+ (mg/L)	81	521	310.64	113.60
Mg^{2+} (mg/L)	51	211	106.00	42.86
Ca^{2+} (mg/L)	131	390	220.09	75.47
Cl^- (mg/L)	282	884	470.82	183.19
SO_4^{2-} (mg/L)	293	1064	697.09	231.54
HCO_3^- (mg/L)	142	667	325.64	149.11
NO_3^- (mg/L)	2	11.6	4.91	3.38

average values of 220.09, 106.00, 310.64 and 4.59 mg/L in the groundwater samples, respectively. Among the anions, i.e. Cl, SO_4, HCO_3 and NO_3 ions varied from 282 to 884, 293 to 1064, 142 to 667and 2 to 11.6 mg/L, with average values of 470.82, 697.09, 325.64and 4.91 mg/L in the groundwater samples, respectively. The spatial variations of the groundwater samples in the study area are shown in Fig. 6.

6.1 Piper Plot

Hydrochemical classification of the groundwater in the Tooz area was examined using the Piper plot (Piper [33]; Fig. 7). The plot suggests that the groundwater samples are mainly belongs to 2 water types (Mixed Ca–Mg–Cl and Ca–Cl). The output of the Piper diagram was compatible with earlier studies conducted in Iraq by Ghalib et al. [17] (Misaan governorate), Ismail et al. [20] (Tarmiah district), and Ismail et al. [22] (Balad district).

6.2 Gibbs Plot

Gibbs ratio gives an expression to explore the functional sources of dissolved chemical constituents, such as precipitation dominance, rock–water interaction, and evaporation dominance. Gibbs plot for the groundwater of the Tooz area is shown in Fig. 8. It is obvious that all groundwater samples were fallen in the evaporation-dominance zone. This observation suggests that the evaporation process primarily controls the chemistry of groundwater in the Tooz area. The results were compatible

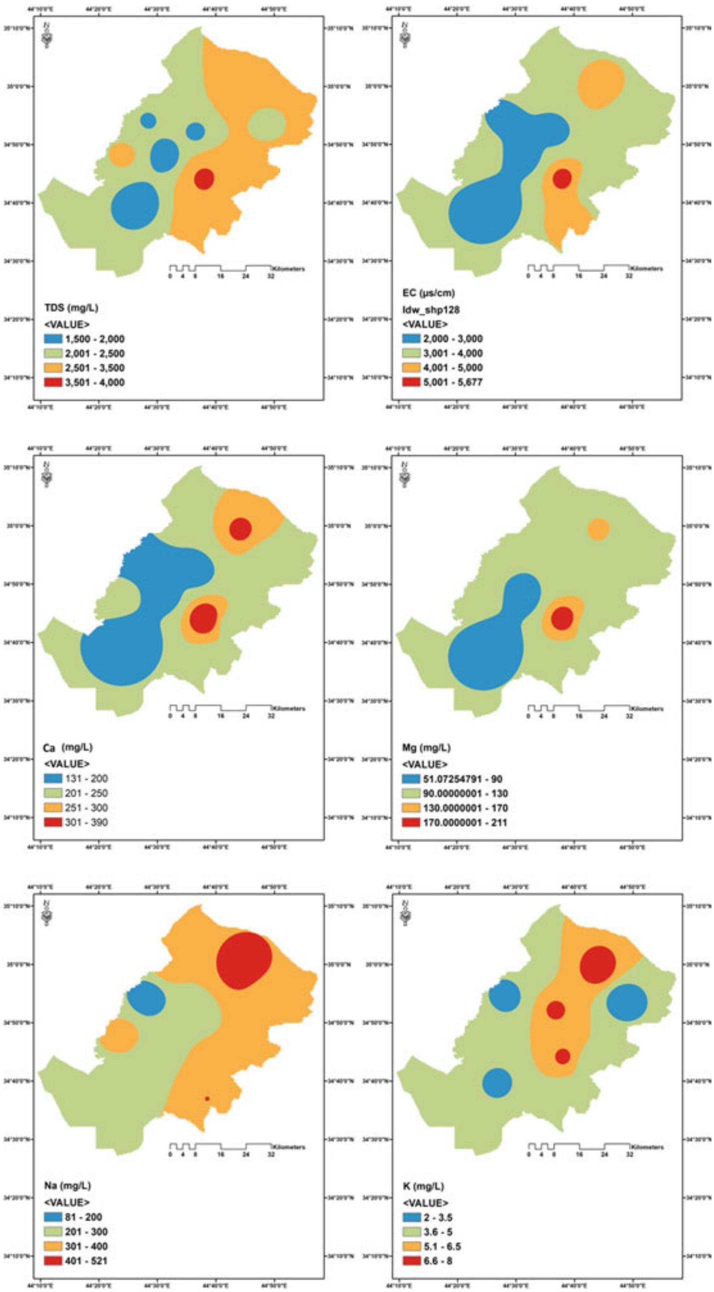


Fig. 6 Spatial variation of the groundwater samples in the study area

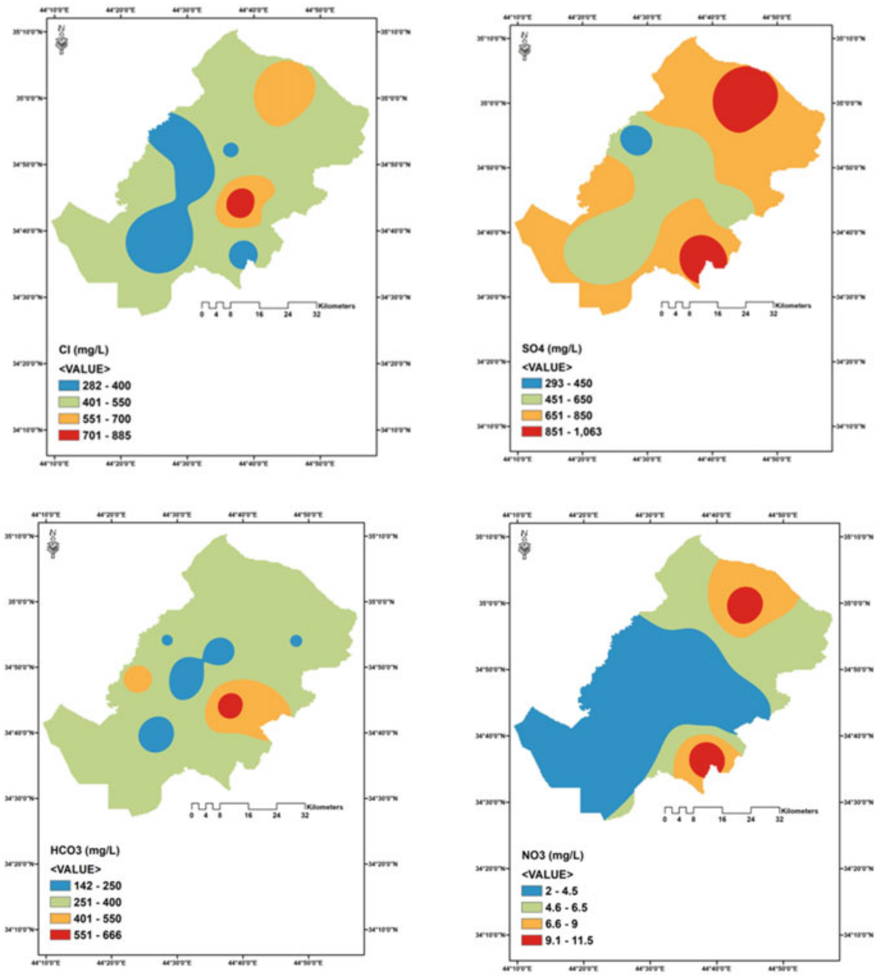


Fig. 6 (continued)

with all previous studies conducted in different areas of sedimentary plain in Iraq, as mentioned in Table 3.

6.3 Suitability of Groundwater for Drinking

The suitability of groundwater for drinking was examined using the Water Quality Index (WQI) technique [2, 31]. Numerous WQI models were developed previously by various authors refers to Lumb et al. [26] and Sutadian et al. [39]. In the present study, the selected index i.e., Bascaron Water Quality Index (BWQI) was used to investigate

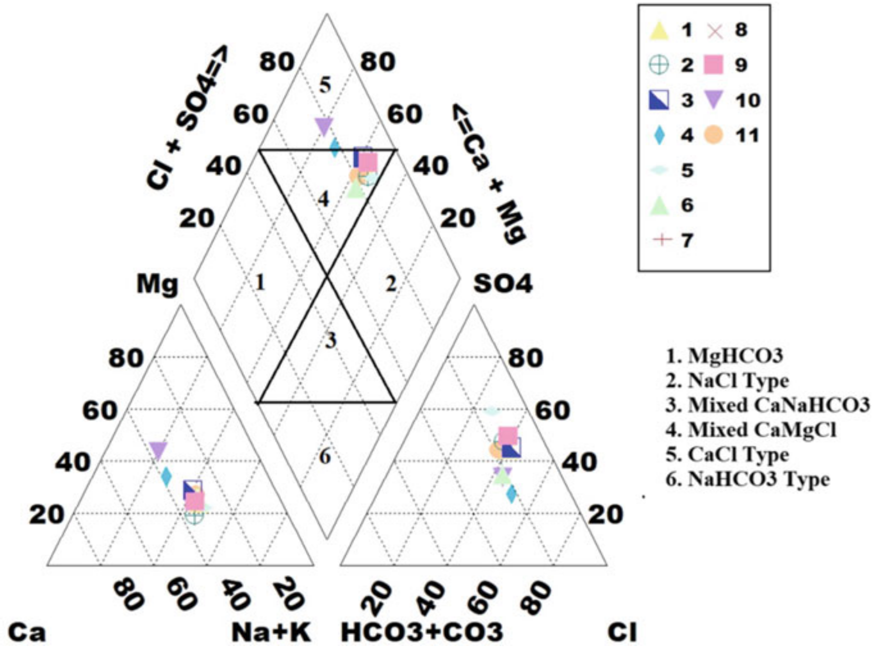


Fig. 7 Piper plot

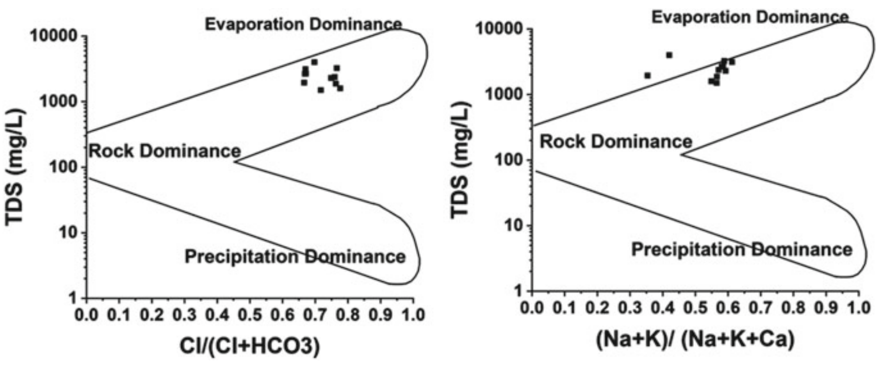


Fig. 8 Gibbs plot for the groundwater of the Tooz area

the groundwater quality [13]. This WQI was widely applied in the literature [14, 23, 25]. Moreover, BWQI has an advantage to include many water quality parameters for implementing the necessary calculation of the general index after specifying the normalization factors in addition to their weights. It can be calculated mathematically as

$$\mathrm{WQI} = \frac{\sum_{i=1}^{n} C_i P_i}{\sum_{i=1}^{n} P_i} \quad (5)$$

where:

n = The sum of variables.

C_i = value of the factor i after the appropriate normalization.

Pi = proportional weight associated with each factor which has the range of 1–4 depending to its impact on water usability.

Major ions along with physico-chemical parameters of groundwater is summarized in Table 5 which are normalized and weighted in previous research [25, 29, 32]. Eight water quality factors were evaluated in this work, that is, NO_3, SO_4, Cl, Mg, Ca, TDS, EC, and pH. HCO_3, Na, and K were excluded in the above calculations because they have no normalized and weighted parameters. The normalization parameters as well as their relative participation listed in Table 6 were utilized for the chosen factors to get the final BWQI.

The following categories were adopted in order to classify water quality:

- Excellent: 90–100
- Good: 71–90
- Average: 51–70
- poor: 26–50
- Very poor: 0–25.

Table 7 described the calculated sub-indices as well as the final values and categories of the studied water usability, which were found to be ranged from “Average” to “Poor”. Figure 9 illustrates the spatial variation of the studied BWQI. The result reveals that groundwater is unsuitable for drinking in the study area.

6.4 Suitability of Groundwater for Irrigation

The suitability of groundwater for irrigation in the study area was evaluated using different geochemical parameters such as SAR, Na%, EC, MH, and USSL diagram (see Sect. 5; Ali et al. [8]).

According to SAR and MH, the groundwater was suitable for irrigation in the study area, whereas the suitability of groundwater for irrigation ranged from good to permissible in the study area based on %Na (Fig. 10). EC denotes the total soluble salts in water and a very critical parameter for deciding the suitability of water for irrigation. The groundwater suitability based on EC was found to be unsuitable in majority of the study area (Fig. 10).

Lastly, US salinity diagram is shown in Fig. 11 [40]. It was observed that the groundwater samples were grouped with 2 zones (C4S1 and C4S2) indicating very poor water quality for irrigation use.

Table 6 Water suability factors which was normalized and weighted previously

Variables	Units	Relative weight (*Pi*)	Normalization factor (*Ci*)										
			100	90	80	70	60	50	40	30	20	10	0
pH	–	1	7	7–8	7–8.5	7–9	6.5–7	6–9.5	5–10	4–11	2–12	2–13	1–14
EC	μS/cm	1	<750	<1000	<1250	<1500	<2000	<2500	<3000	<5000	<8000	<=12,000	>12,000
TDS	mg/L	2	<100	<500	<750	<1000	<1500	<2000	<3000	<5000	<10,000	<=20,000	>20,000
Ca	mg/L	1	<10	<50	<100	<150	<200	<300	<400	<500	<600	<=1000	>1000
Mg	mg/L	1	<10	<25	<50	<75	<100	<150	<200	<250	<300	<=500	>500
Cl^-	mg/L	1	<25	<50	<100	<150	<200	<300	<500	<700	<1000	<=1500	>1500
SO_4	mg/L	2	<25	<50	<75	<100	<150	<250	<400	<600	<1000	<=1500	>1500
NO_3	mg/L	2	<0.5	<2	<4	<6	<8	<10	<15	<20	<50	<=100	>100

Table 7 The sub-index values along with relative weight, WQI and categorization values of BWQI index

Well no.	Sub-index values (C_i)								BWQI	Categorization
	pH	EC	TDS	Mg	Ca	Cl	SO_4	NO_3		
1	90	30	40	50	50	30	20	60	44.54	Poor
2	90	50	50	60	70	50	40	80	60	Average
3	90	30	40	50	50	30	20	80	48.18	Poor
4	90	50	60	70	60	40	30	80	59.09	Average
5	90	40	50	60	60	40	30	80	55.45	Average
6	90	20	30	30	40	20	20	80	41.81	Poor
7	90	30	30	60	50	40	10	40	39.09	Poor
8	90	30	40	50	50	30	30	80	50	Poor
9	90	50	50	70	60	50	30	80	58.18	Average
10	90	30	30	50	40	30	10	40	36.36	Poor
11	90	30	40	60	50	40	20	70	48.18	Poor
Relative weight (P_i)	1	1	2	1	1	1	2	2	$\sum P_i = 11$	

7 Conclusions

The groundwater in the sedimentary plain of Iraq is an important source for drinking and agriculture. However, the area's rapid population growth and climate change significantly affect the groundwater quality and quantity. It was observed that rock-water interaction has a low impact on the groundwater chemistry in the area. For the suitability of groundwater, it was found that most water quality parameters are exceeding the prescribed limits of WHO and may pose risks to the health of millions of people. The geochemical plots reveal that groundwater in the sedimentary plain area is unsuitable for irrigation. Further investigation of hydrochemistry and groundwater quality in the Tooz area showed that groundwater is not suitable for drinking (average to poor based on BWQI), and irrigation (based on EC and USSL plot). The hydrochemistry of Tooz area relatively have the same characteristics as other areas located in the sedimentary plain area of Iraq.

8 Recommendation

This study reveals that major potential toxic pollutants like fluoride and toxic heavy metals in the sedimentary plain of Iraq should be studied in details. Therefore, the governing authorities in Iraq need to provide appropriate solutions to treat groundwater for drinking and irrigation. In addition, the quality and quantity of two major

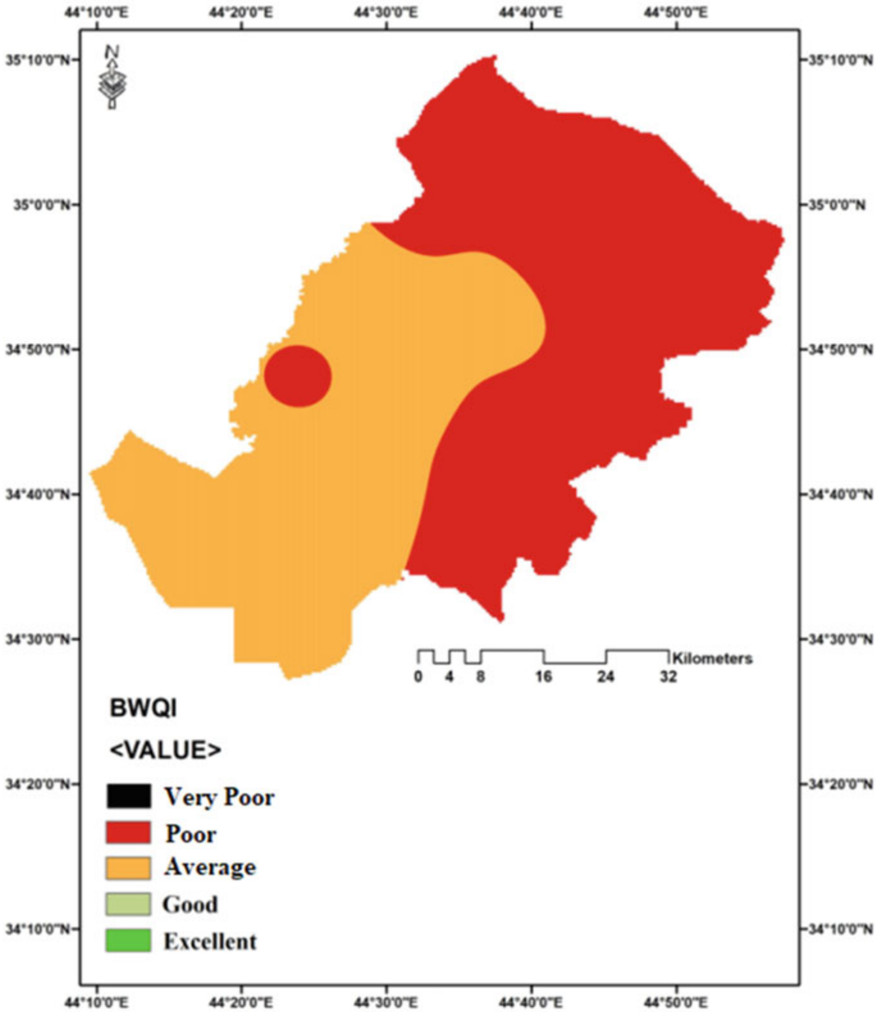


Fig. 9 The spatial variation of BWQI in the Tooz area

rivers i.e., Tigris and Euphrates should be maintained as these rivers are back bone of the country.

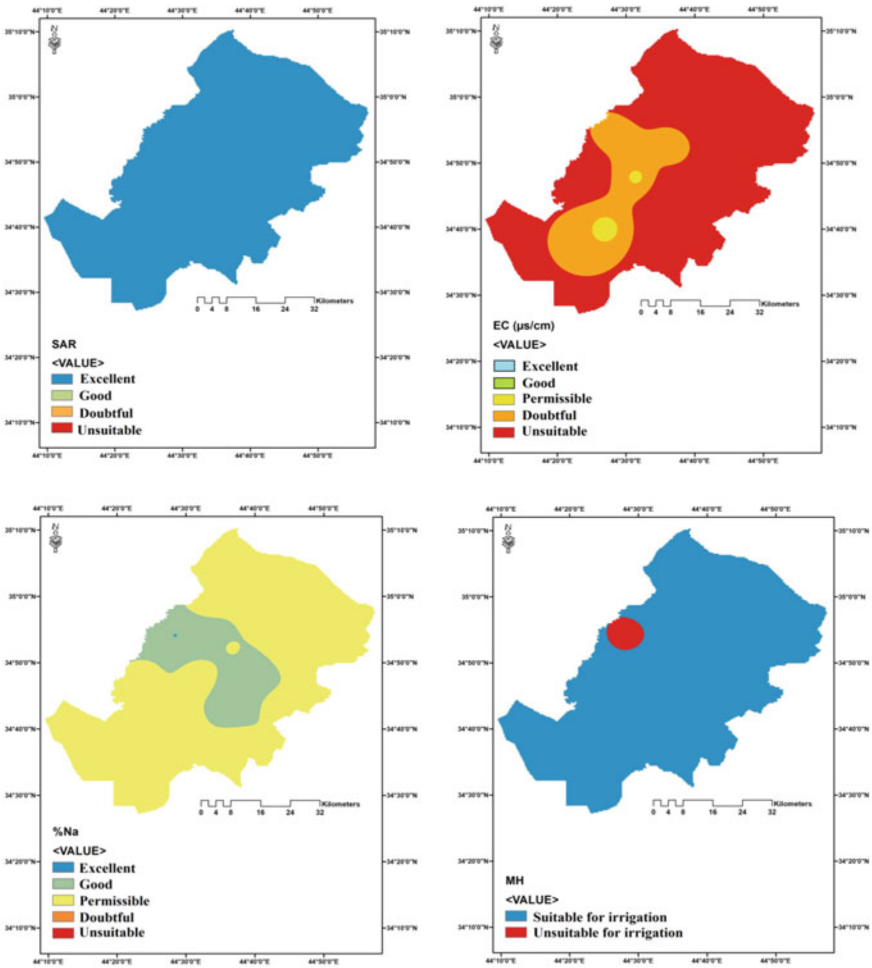


Fig. 10 Irrigation suitability

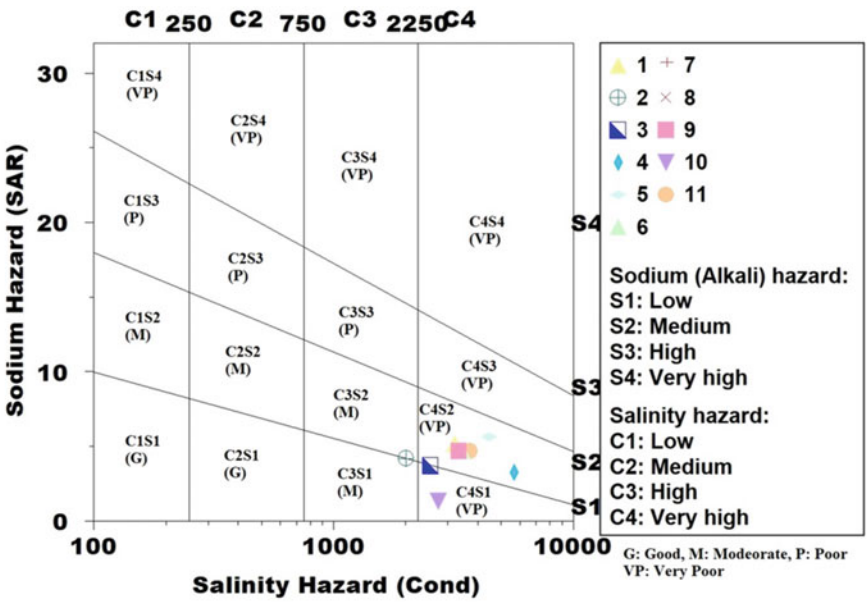


Fig. 11 USSL plot

Acknowledgements The author would like to thank the General Commission for Groundwater for conducting the analyses in their laboratories and supplying the groundwater data used in this study. It is also duly acknowledged that the editors have greatly supported during the preparation of this draft.

References

1. Abed B, Farhan AR, Ismail A, Al Aani S (2022) Water quality index toward a reliable assessment for water supply uses: a novel approach. Int J Environ Sci Technol 19:2885–2898. https://doi.org/10.1007/s13762-021-03338-7
2. Adimalla N, Li P, Venkatayogi S (2018) Hydrogeochemical evaluation of groundwater quality for drinking and irrigation purposes and integrated interpretation with water quality index studies. Environ Process 5(2):363–383
3. Al-Abadi AM, Fryar AE, Rasheed AA, Pradhan P (2021) Assessment of groundwater potential in terms of the availability and quality of the resource: a case study from Iraq. Environ Earth Sci 80:426. https://doi.org/10.1007/s12665-021-09725-0
4. Al-Aoufi HK, Al-Jaberi MH, Al-Saad HA (2021) Mineralogical properties of the Quaternary deposits in the Iraqihighway, east of Al Warka city-Southern Iraq. In: IOP conference series: earth and environmental science, vol 779, p 012064. https://doi.org/10.1088/1755-1315/779/1/012064
5. Al-Azawi AAO, Ward FA (2016) Groundwater use and policy options for sustainable management in Southern Iraq. Int J Water Resour Dev. https://doi.org/10.1080/07900627.2016.1213705

6. Al–Basrawi NH, Awad JH, Hussain TA (2015) Evaluation of the ground water in Baghdad governorate/Iraq. Iraqi J Sci 56(2C):1708–1718
7. Ali S, Fakhri Y, Golbini M, Thakur SK, Alinejad A, Parseh I, Shekhar S, Bhattacharya P (2019) Concentration of fluoride in groundwater of India: a systematic review, meta-analysis and risk assessment. Groundw Sustain Dev 9:100224. https://doi.org/10.1016/j.gsd.2019.100224
8. Ali S, Shekhar S, Bhattacharya P, Verma G, Chandrasekhar T, Chandrashekhar AK (2018) Elevated fluoride in groundwater of Siwani Block, Western Haryana, India: a potential concern for sustainable water supplies for drinking and irrigation. Groundw Sustain Dev 7:410–420. https://doi.org/10.1016/j.gsd.2018.05.008
9. Ali S, Shekhar S, Chandrasekhar T, Yadav AK, Arora NK, Kashyap CA, Bhattacharya P, Rai SP, Pande P, Chandrasekharam D (2021) Influence of the water–sediment interaction on the major ions chemistry and fluoride pollution in groundwater of the Older Alluvial Plains of Delhi. J Earth Syst Sci 130:98. https://doi.org/10.1007/s12040-021-01585-3
10. Alkhoja G, Neman R, Hariz S (2016) Social safety nets in Iraq: reform in a time of fragility, conflict, and violence. MENA knowledge and learning quick notes series; no 161. World Bank, Washington, DC
11. Al-Saady Y, Al-Suhail Q, Al-Tawash B, Othman A (2016) Drainage network extraction and morphometric analysis using remote sensing and GIS mapping techniques (Lesser Zab River Basin, Iraq and Iran). Environ Earth Sci 75:1243
12. APHA (2005) Standard methods for the examination of water and waste water, 21st edn. American Public Health Association, Washington DC
13. Bascaron M (1979) Establishment of a methodology for the determination of water quality. BolInf Medio Ambient 9:30–51
14. Debels P, Figueroa R, Urrutia R, Barra R, Niell X (2005) Evaluation of water quality in the Chillan river (Central Chile), using physical and chemical parameters and a modified water quality index. Environ Monit Assess 110(1–3):301–322
15. Ewaid SH, Abed SA, Al-Ansari N (2019) Water footprint of wheat in Iraq. Water 11:535. https://doi.org/10.3390/w11030535
16. Ghalib HB (2017) Groundwater chemistry evaluation for drinking and irrigation utilities in east Wasit province, Central Iraq. Appl Water Sci 7:3447–3467. https://doi.org/10.1007/s13201-017-0575-8
17. Ghalib H, Yaqub M, Al-Abadi A (2019) Hydrogeochemical modeling and isotopic assessment of the quaternary aquifer at Ali al-Garbi area in Misaan governorate, South of Iraq. In: Chaminé H, Barbieri M, Kisi O, Chen M, Merkel B (eds) Advances in sustainable and environmental hydrology, hydrogeology, hydrochemistry and water resources. CAJG 2018. Advances in science, technology & innovation. Springer, Cham. https://doi.org/10.1007/978-3-030-01572-5_30
18. Gibbs RJ (1970) Mechanisms controlling world's water chemistry, volt. Science 170:1088–1090
19. Ismail AH, Abed BS, Abdul-Qader S (2014) Application of multivariate statistical techniques in the surface water quality assessment of Tigris River at Baghdad stretch, Iraq. J Babylon Univ Eng Sci 22(2):450–463
20. Ismail AH, Hassan G, Sarhan A (2020) Hydrochemistry of shallow groundwater and its assessment for drinking and irrigation purposes in Tarmiah district, Baghdad governorate, Iraq. Groundw Sustain Dev, 10
21. Ismail AH, Muntasir AH, Channo RJ (2015) Groundwater quality assessment in urban area of Baghdad, Iraq, using multivariate statistical techniques. Eng Technol J 33 Part (A)(2):463–476.
22. Ismail AH, Muntasir AS, Mahmood W (2018) Hydrochemical characterization of groundwater in Balad district, Salah Al-Din Governorate, Iraq. Eng & Technol J 6(4):306–322
23. Ismail AH, Robescu D (2019) Assessment of water quality of the Danube river using water quality indices technique. Environ Eng Manag J 18(8):1727–1737
24. Ismail AH, Shareef MA, Alatar FM (2019) Hydrochemistry of groundwater and its suitability for drinking and irrigation in Baghdad, Iraq. Environ Process 6:543–560. https://doi.org/10.1007/s40710-019-00374-x

25. Kannel P, Lee S, Lee Y, Kanel S, Khan SP (2007) Application of water quality indices and dissolved oxygen as indicators for river water classification and urban impact assessment. Environ Monit Assess 132(1–3):93–110
26. Lumb A, Sharma TC, Bibeault JF (2011) A review of genesis and evolution of water quality index (WQI) and some future directions. Water Qual Expo Health 3(1):11–24
27. Mahammad S, Islam A, Shit PK (2022) Geospatial assessment of groundwater quality using entropy-based irrigation water quality index and heavy metal pollution indices. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-022-20665-5
28. Makki ZF, Zuhaira AA, Al-Jubouri SM, Al-Hamd R, Cunningham LS (2021) GIS-based assessment of groundwater quality for drinking and irrigation purposes in central Iraq. Environ Monit Assess 193:107. https://doi.org/10.1007/s10661-021-08858-w
29. Massoud MA (2012) Assessment of water quality along a recreational section of the Damour River in Lebanon using the water quality index. Environ Monit Assess 184:4151–4160
30. MOE (2019) Ministry of environment in Iraq, national action program to combat desertification (2015–2020). https://moen.gov.iq/Portals/0/National%20Action%20Program%20to%20Combat%20Desertification%20in%20Iraq.pdf
31. Nagaraju A, Thejaswi A, Sun L (2016) Statistical analysis of high fluoride groundwater hydrochemistry in Southern India: quality assessment and implications for source of fluoride. Environ Eng Sci J 33:1–7
32. Pesce SF, Wunderlin DA (2000) Use of water quality indices to verify the impact of Cordoba city (Argentina) on Suquia River. Water Res 34(11):2915–2926
33. Piper AM (1944) A graphical procedure in the geochemical interpretation of water. Trans Am Geophys Union 25:914–928
34. Rahi KA, Halihan T (2010) Changes in the salinity of the Euphrates River system in Iraq. Reg Environ Change 10:27–35. https://doi.org/10.1007/s10113-009-0083-y
35. Salar SG, Othman AA, Hasan SE (2018) Identification of suitable sites for groundwater recharge in Awaspi watershed using GIS and remote sensing techniques. Environ Earth Sci 77:701. https://doi.org/10.1007/s12665-018-7887-3
36. Schoeller H (1965) Qualitative evaluation of groundwater resources. In: Methods and techniques of groundwater investigations and developments. UNESCO, pp 54–83
37. Sissakian VK, Fouad SFA (2015) Geological map of Iraq, scale 1: 1000 000, 2012. Iraqi Bull Geol Min 11(1):9–16. 4th edition
38. Stevanovic Z, Iurkiewicz A (2009) Groundwater management in northern Iraq. Hydrogeol J 17:367–378. https://doi.org/10.1007/s10040-008-0331-0
39. Sutadian AD, Muttil N, Yilmaz AG, Perera BJC (2016) Development of river water quality indices—a review. Environ Monit Assess 188:58
40. USSL US Salinity Laboratory Staff (1954) Diagnosis and improvements of saline and alkali soils. US Department of Agriculture Handbook No 60, USDA, p 160
41. Vetrimurugan E, Brindha K, Elango L, Ndwandwe OM (2017) Human exposure risk to heavy metals through groundwater used for drinking in an intensively irrigated river delta. Appl Water Sci 7:3267–3280. https://doi.org/10.1007/s13201-016-0472-6
42. WHO (2011) Guidelines for drinking-water quality. World Health Organ 216:303–304
43. Yacoub SY (2011) Geomorphology of mesopotamia plain. Iraqi Bull Geol Min 4(Special Issue):7–32
44. Yahiaoui S, Meddi M, Razack M, Boufekane A, Bekkoussa BS (2023) Hydrogeochemical and isotopic assessment for characterizing groundwater quality in the Mitidja plain (northern Algeria). Environ Sci Pollut Res. https://doi.org/10.1007/s11356-023-27952-9
45. Zowain A, Ismail AH (2015) Management of salinity issues in Iraq's agricultural sector–a SWOT analysis. Eng Technol J 33 Part (A)(3):644–658

Investigating and Improving Natural Treatment Processes by Riverbank Filtration in Egypt

Ismail Abd-Elaty, Osama K. Saleh, Hala M. Ghanayem, Am Pris John, and Salvatore Straface

Abstract Water is a fundamental element for sustaining life. Water resources in arid regions are limited and subjected to various pollution through agriculture, domestic and industrial facilities which adversely affect human health. These regions are over-stressed by increasing water demands due to rapid population growth and climate change. Additionally, water treatment necessitates utilizing costly technologies on a global scale. In this perspective, Riverbank Filtration (RBF) is a green water filtration method that uses materials of the earth as a natural filter. RBF intimates immense potential in heavily stressed and polluted areas as a pre-treatment phase for drinking water production. Moreover, it is a water treatment technique that can effectively filter contaminated surface water. This chapter investigates the improvement of the RBF technique and its impact on drinking water requirements. Furthermore, the impact of climate change was considered in the current study in its evaluation of the proportion of bank filtration in the pumped water. While, safeguarding public health and enhancing national economic development, the research findings hold significant implications for policymakers and design engineers seeking to optimize RBF implementation. Finally, the study revealed that RBF is a viable and cost-effective technique for purifying polluted surface water into a safe water supply.

Keywords Riverbank filtration · Water treatment · Green water filtration · Climate change · Population

I. Abd-Elaty (✉) · O. K. Saleh · H. M. Ghanayem
Water and Water Structures Engineering Department, Faculty of Engineering, Zagazig University, Zagazig 44519, Egypt
e-mail: Eng_abdelaty2006@yahoo.com

H. M. Ghanayem
e-mail: osamaks@hotmail.com; hala_ghanayem2000@yahoo.com

A. P. John · S. Straface
Department of Environmental Engineering, University of Calabria, Ponte P. Bucci, 87036 Rende, Italy
e-mail: ampris.john@unical.it

S. Straface
e-mail: salvatore.straface@unical.it

S. Ali and A. M. Armanuos (eds.), *Groundwater in Arid and Semi-Arid Areas*, Earth and Environmental Sciences Library, https://doi.org/10.1007/978-3-031-43348-1_14

1 Introduction

Water is the key component in all life, essential not only for human consumption, but also for energy, industry, agriculture, and livestock, promoting advancements in living standards. However, the rapid population growth increases water demands in many countries, accompanied by a large increase in water consumption over the last century, which has led to a significant gap between the demand side and supply side. According to the United Nations Children's Fund (UNICEF), nearly 4.2 billion individuals lack adequate sanitation facilities while more than 2 billion ones lack access to potable water supplies [39, 48].

The global water demand is projected to increase by 55% in 2050, causing severe water stress in regions such as North and South Africa [82]. Developing countries have been facing the challenge of providing portable water of adequate quality to meet the needs of rapidly growing population. Additionally, water treatment cost is one of the main factors due to insufficient funding. For example, Egypt is currently experiencing a water shortage of approximately 13.5 Billion Cubic Meters per year [BCM/year], which is expected to continuously increase up to 26 BCM $year^{-1}$ by 2025 [61].

The Nile River (see Fig. 1) and its tributaries contribute about 80% of the drinking water supply in Egypt, however, the water is severely polluted as a consequence of domestic and industrial wastewater, reuse of agricultural drainage water, and flash floods resulting from heavy rainfall into the river. On the other hand, groundwater is considered as the second source of drinking water in Egypt, providing 20% of the total supply. However, excessive use of fertilizers and pesticides has resulted in high levels of chemicals in both drinking and irrigation wells remarkably. Many wells used for drinking water supply have been widely contaminated with iron, manganese, nitrate, and fecal coliform bacteria [2, 5, 8, 11]. For these reasons, Riverbank Filtration (RBF) is assumed as a affordable water treatment method that can significantly enhance surface water quality.

Several studies have reported the effectiveness of RBF in purifying Nile water and overcoming water quality matters [43, 45], and highlighted the importance of considering relevant settings when utilizing RBF as an economical method to provide high-quality drinking water.

According to the Intergovernmental Panel on Climate Change [50, 68] climate change will profoundly decrease surface water and groundwater in dry subtropical zones, leading to increased droughts by the end of the century. In another major study, climatic change has affected the hydrology of the River Nile basin where the average annual precipitation is expected to decrease in Egypt [21, 42]. Kwadijk [56] identified that a 10% increase in total rainfall in the river basin could enhance in a 40% increase in river flow, indicating the impact of precipitation on river flow. Besides, there will be an increase in precipitation between 2010 and 2039 (period I), followed by a decrease in the periods from 2040 to 2069 (period II) and 2070 to 2099 (period III), based on IPCC climate scenarios in 2007 [25, 52].

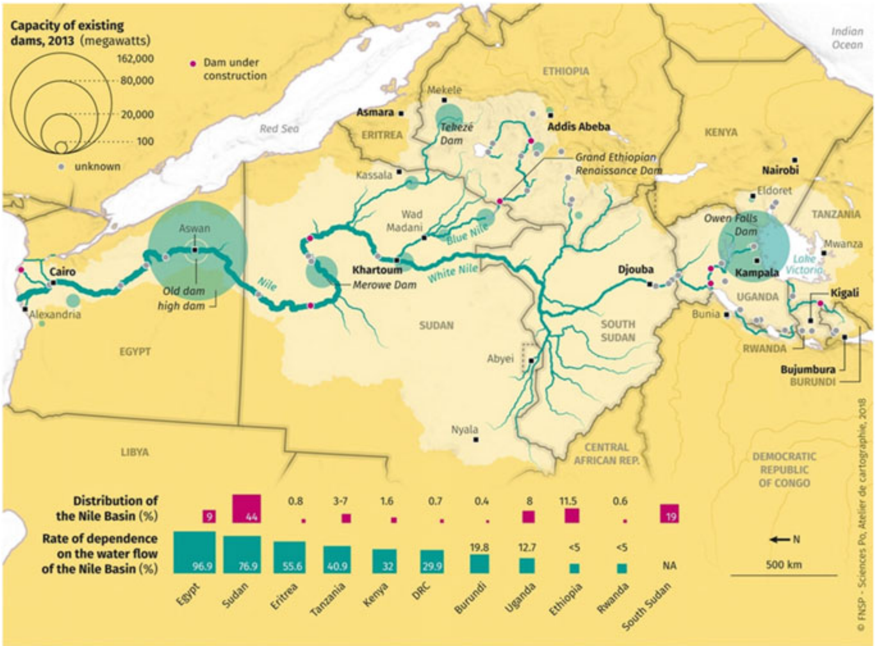


Fig. 1 The Nile River basin Sources: HydroSHEDS; FAO, AQUASTAT; PNUD, Water Stress in the Nile Basin, 2013; Nile Basin Initiative, 2012 (https://espace-mondial-atlas.sciencespo.fr/en/topic-resources/map-5C11-EN-nile-river-basin.html)

2 Water Resources Pollution in Egypt

Previous findings reveal that surface and groundwater pollution affects public health and the economic factors associated with the quality of water and the natural resources of reusable water. As per a report by Abdel-Shafy and Aly [20] showed that some hindrances of the existed regulations for the protection irrigation water are not effective. Low water quality and ineffectiveness of traditional water treatment methods such as boiling, filtration and sedimentation are necessary to improve with this constant nowadays.

2.1 River Pollution

Nile River is exposed to pollution from various sources. Industrial wastewater, oil pollution, native water and agricultural runoff contribute heavy metals, pesticides, herbicides, and microbes into water. Additionally, [36] claimed that excessive nutrient levels due to the blooming of blue-green algae produce cyanotoxins. These algae can danger the health of aquatic organisms and may poison humans.

Fig. 2 The Nile which is a vital water source has been becoming disease-inducing polluted waterway (Zaher [88])

2.2 Industry Pollutants

Egypt could be considered as the most industrialized country, but it is experiencing increasing deterioration of its surface and groundwater on account of the increasing uncontrolled discharge of pollutants from domestic and industrial wastes. It was estimated that annually, over 600 million cubic meters (MCM) of water are utilized for industrial purposes in the country, with 85% of it being expelled in drainage system which ends in the river of Nile [18, 83] (see Fig. 2). Moreover, it is worth noting that the total amount of Biochemical Oxygen Demand (BOD) to the Nile River from industries can contribute roughly 270 tons per day, equivalent to the untreated sewage generated from more than six million individuals. These untreated sewages were mainly discharged from industrial activities in Greater Cairo and Delta regions which produce a daily average of 0.75 and 0.50 tons [83].

2.3 Domestic Pollution

The rapid population growth has led to a greater accessibility to water networks that are incompatible with proper sanitation facilities as a result of inadequate infrastructures [36, 74]. Pathogens, parasites, nutrients, oxygen-requiring chemicals, and suspended particles are all concerns in local and municipal wastewater. Harmful compounds, including both heavy metals and micro-organic pollutants, are discharged into agriculture drains landing up the Nile River without proper treatment for domestic, industrial and commercial activities. Furthermore, sewage is directly discharged into small canals in several areas that has prompted the Ministry of Water

Resources and Irrigation (MWRI) to introduce Law 48 in 1982 to prevent such transgressions and maintain the purity of water resources [33].

2.4 Agriculture Pollutants

El-Sheekh [37] found that the construction of the Aswan High Dam (AHD) in 1968 caused a remarkable decrease in silt deposits on the Nile floodplains from over 20 million tons per year to less than 3 million tons per year. This resulted in an increase in the use of pesticides and chemical fertilizers in the last decade with a peak in the mid-70s.

The discharge of wastewater from channels to the Nile River is the main source of pollution, with an estimated volume of 16.91 BCM year^{-1}. In other words, it was approximately 20.9% of total water resources of Egypt. However, only 10% of the agriculture drains meet Egyptian standards for wastewater quality in the Nile Irrigation System [58]. These wastewater discharged into the Nile from drains contains various material such as dissolved salts from agricultural land, pesticide residues, and fertilizers, negatively impacting Nile water quality [19, 76].

2.5 Oil Pollution

The Nile River serves as a major transportation and communication route between the cities. Significantly, it is utilized for transporting petroleum products and deploying numerous cruise ships from Cairo to Aswan. However, there were several incidents of oil leaks into the Nile River.

In July 2008, the main pipeline of oil from the Helwan Cement Company resulted in the leakage of large quantities of mazut into the Nile, causing three water filters to suspend operations and significant water pollution. Another incident occurred in September 2010. This was nearly 100 tons of gasoline leaked into the Nile near Aswan due to a sinking deck barge.

In October 2012, a leak from the waste pipe of Naj Hammadi sugar factory resulted in a massive spill of oil that travelled downstream, covering about 176 m^2 and causing several water plants to shut down from Assiut to Qena [3, 10, 35, 40]. In April 2015, a barge carrying 500 tons of phosphate capsized in Qena had lead to a spill, causing the city's potable water station to shut down temporarily. The recorded incidents of oil leaks have indicated the disruption of water treatment plants and the implementation of solid regulations and preventive measures to ensure the safety and protection of the Nile River [23] (see Fig. 3).

Fig. 3 Overview of oil spill causing coating the surface of the water in the Nile River, Luxor, Egypt [23]

3 Groundwater Pollution

Groundwater quality is considered as one of the essential aspects in developing and managing water resources, particularly given increasing global water demand and intensity of water utilization. As a result, water quality issues have emerged as a major factor in the development and management of water resources locally and globally.

The deterioration of the surface and groundwater quality can lead to the pollution of aquifers [1, 6, 7, 9, 15, 34].

Groundwater pollution is mainly attributed to several sources, as discussed by Abd-Elaty et al. [10, 12, 16, 17], see in Fig. 4.

(i) Environmental factors**:** These sources include geological characteristics of the subsurface environment, including carbonate rocks, seawater intrusion, and invasion by brackish water from the adjacent aquifer.
(ii) Domestic factors**:** Domestic pollution in groundwater is primarily caused various sources such as the accidental breakage of sewers, percolation from septic tanks, rainwater infiltrating through sanitary landfills, and acid rains cause groundwater contamination. Additionally, artificial recharge using treated sewage water can also contribute to biological contaminants such as bacteria and viruses in groundwater [38].
(iii) Industrial factors: Industrial activities contribute to groundwater pollution through sewage disposals which contain heavy metals, non-deteriorating compounds, and radioactive materials.
(iv) Agriculture factors: agricultural pollution occurs when irrigation and rainwater dissolve and carry chemicals such as fertilizers, salts, herbicides, pesticides

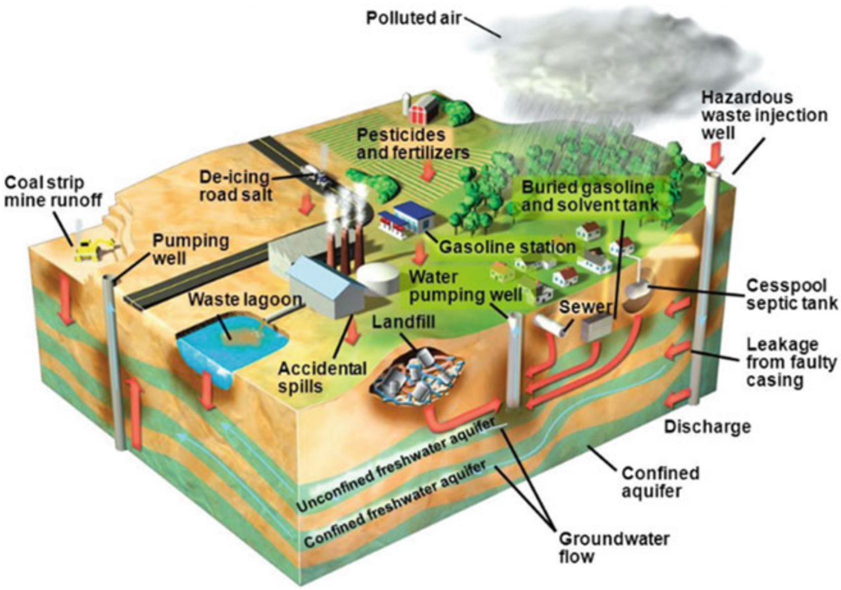


Fig. 4 Sources of groundwater contamination. *Source* (https://u.osu.edu/waterpollution2367/freshwater-pollution/)

and other contaminants into groundwater as they infiltrate through the ground surface and recharge the aquifer [8].

4 Traditional Drinking Water Purification Plants

A variety of water purifying techniques are currently being employed with its own unique benefits and drawbacks. In the long-term, reverse osmosis is considered to be the most effective method. Nevertheless, filtering remains the optimal method for basic tasks such as removing sediments and chlorine [69].

4.1 Boiling

The cheapest and safest way to purify water is boiling water. Water safety, a crucial aspect of human life, can be affected by water sources and/or delivery methods [46]. They mentioned that one effective method for ensuring clean water is heating it to a rolling boil and maintaining it there for one to three minutes for the purpose of killing parasites and bacteria that can pose a significant threat to human health. Another recommendation of these research groups is that residents living in high altitutes should take extra precautions when boiling and filtering their water. Boiling for a longer period of time and allowing chemical to settle before filtering are two main steps of reducing waterborne illness and increasing in purity of water.

4.2 Filtration

Filtration is considered one of the most effective methods of purifying water, especially when using the right multimedia filters [77]. This method uses chemical and physical processes to remove both large compounds and small, dangerous contaminants that can cause diseases. Unlike other water purification methods, filitration does not deplete all mineral salts that is necessary for human body. Using filtration systematically gives healthier drinking water through a chemical absorption process that effectively removes unwanted compounds from water. Here, we discover two examples of biological and physical approaches used in water purification. One approach is slow sand filters which are implied by using 1–2 m deep tubes filled with sand toretain the impurities present in the filtered water. Another one is activated carbon (charcoal), a microporous substance with high surface area and enhanced adsorption properties.

4.3 Distillation

It is a water purification method that utilizes heat to collect pure water in the form of vapour. This method exploits the scientific fact that water has a lower boiling point than other contaminants and disease-causing elements found in water. Firstly, water is heated to its boiling point, left to vaporize, and then directed into a condenser to cool, resulting in finally clean and safe drinking water. Distillation method effectively removes bacteria, germs, salts and other heavy metals such as lead, mercury and arsenic, making it ideal for people who have access to raw, untreated water. Nevetheless, this method has some disadvantages, such as being a slow and energy-intensive process of water purification. In addition, it requires a heat source for the purification and remains a costly process for large scale, commercial or industrial purification. We perceive that it is best suited for small quantities of water.

4.4 Water Purification Using Chlorination

Chlorination is a common method in water supply treatment, and it is used to eliminate microbes and prevent the spreading of waterborne diseases. Water can be purified using chlorine tablets or liquid chlorine which are readily available and cost-effective. However, caution should be taken when using chlorine liquid or tablets, especially for individuals suffering from thyroid problems, who should consult a medical practitioner before using this product. Additionally, take a note that using chlorine tablets in heated water is important as they dissolve better in water that is at 21 degree Celsius or higher.

4.5 Electromagnetic Light for Water Disinfection

Electromagnetic light, especially in the ultraviolet range, is often used in water decontamination. It can be seen that it is highly effective in killing microorganisms, making water clean and safe for consumption. Despite its effectiveness, one major limitation is its high cost, which can be a barrier to implementation on a larger scale. However, this method does not remove other contaminants such as heavy metals, salts, and chemicals. Therefore, combining with other water purification methods for maximum effectiveness would be effective.

5 Riverbank Filtration (RBF) Technique

In this chapter, we provide an overview of the concept of Riverbank Filtration (RBF), its usage in various countries across the globe, the mechanism of RBF, highlighting its advantages and disadvantages, as well as the challenges associated with RBF implementation. Additionally, for sustainable water treatment, we discuss the importance of sharing knowledge and experience related to RBF to improve the effectiveness of this technology.

5.1 Concept of Riverbank Filtration

Riverbank Filtration (RBF) is a well-established water treatment technique that has been used in Europe over a century to provide high-quality drinking water. As the water percolates through the ground, it undergoes naturally physical, chemical and biological processes including filtration, adsorption and biodegradation in the ground before being pumped up for consumptions, see in Fig. 5.

5.2 Usage of RBF in Countries Worldwide

RBF has been used extensively in Europe over decades, particularly in Germany where the first RBF system was implemented to provide drinking water to the city of Düsseldorf from the Rhine River [47]. In the United States, RBF systems have paid

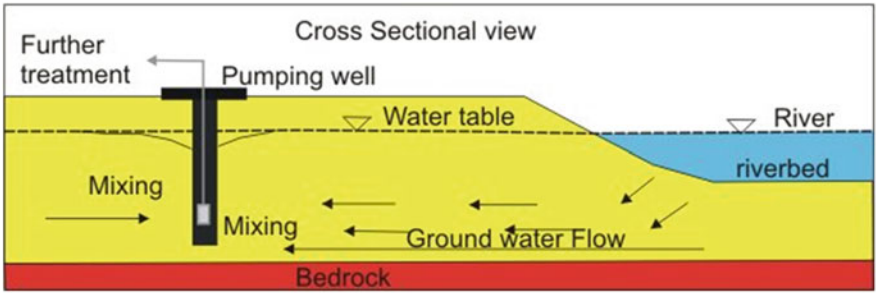


Fig. 5 Riverbank filtration: a simple overview of implementation and potential (*source* Mustafa et al. [63])

attention for over 50 years provide water to both the municipalities and industries [71] and [87]. These systems used in several midwestern cities in the US, such as Lincoln, Nebraska (on the Platte River), Des Moines, Iowa (on the Raccoon River) and Cedar Rapids, Iowa (on the Cedar River), were successfully implemented to mitigate the negative effects of agricultural runoff.

The usage of RBF in some countries was reported by many researchers [29, 71], and [54]. It was found that Egypt had the lowest rate of RBF usage at 0.1%. Germany had a moderate rate of 16%, while Hungary and the Slovak Republic had notably higher rates of 45% and 50%, respectively. Fact is that France and the Slovak Republic had the same usage rate of 50%. The Netherlands had a rate of 70%, while Switzerland had the highest rate at 80% among these countries, see in Fig. 6.

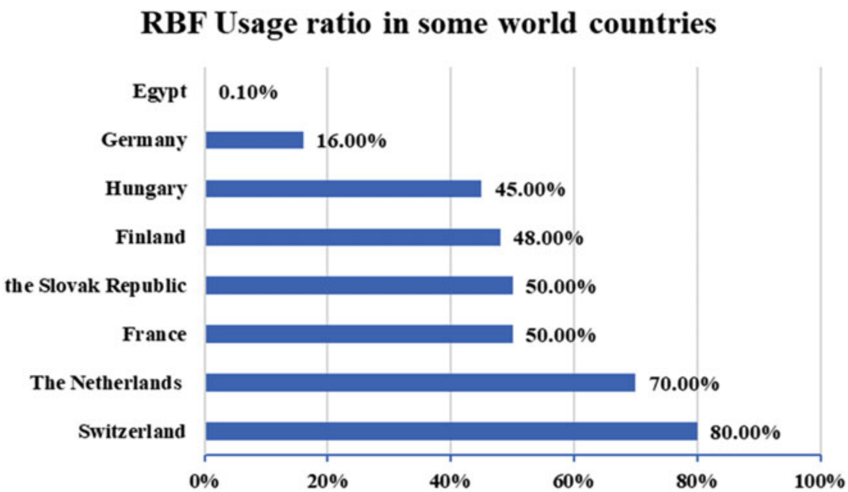


Fig. 6 Comparison of the percentage of riverbank filtration (RBF) usage in selected countries worldwide (*source* Doussan et al. [31])

Recently, an increasing number of countries worldwide, including some developing nations such as India, South Korea, Jordan and China, have begun to evaluate potential of RBF as a viable water treatment solution. In Thailand, this RBF system is accepted as an additional water source for municipal and industrial consumption [66]. Along the Ganges of India, RBF is mainly used for removing turbidity, organic compounds and bacteria [27].

Oberleitner et al. [64] organized a field investigation of two RBF well locations to examine the impact of water travel distance on micropollutant removal efficiency (a critical issue in water treatment). Covatti and Grischek [26] found that the most common source of ammonium in RBF is the mineralization of organic nitrogen occurring in the riverbed, which is also relevant for Egypt.

5.3 Mechanism of RBF

Riverbank Filtration (RBF) is a sort of filtration using existing geologic formations near rivers, lakes or ponds. As shown in Fig. 7, water is drawn from extraction wells that are closely located to the water bodies and allowed to flow through the sediment layers in the surrounding formations of inlets. This process removes contaminants, resulting in drinkable water, or further treated water for purification. The water extracted from RBF is much higher quality than the raw surface water [70].

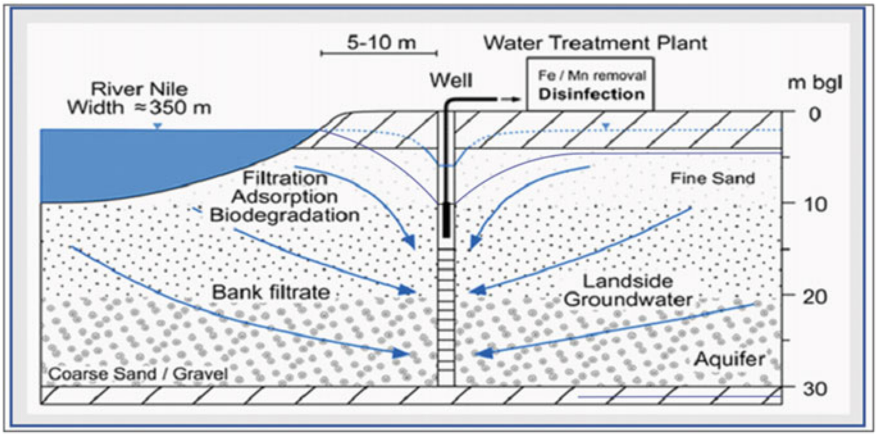


Fig. 7 A general RBF mechanism showing relationship between sediment permeability and contaminant removal efficiency (*source* Wahaab et al. [84])

5.4 Advantages of RBF

RBF systems can provide several advantages in water treatment and can effectively attenuate concentration or temperature peaks and protect against shock loads. Compared to traditional water treatment plants, it is more realiable for improving the removal capacity, especially for the concentrations of disinfection by-products and also reducing the total cost. Because of improving the quality of the treated water, RBF become a promising and cost-effective method that has been adopted in various countries worldwide.

5.5 Disadvantages of RBF

One of the common disadvantages of RBF is the potential for clogging of the riverbed, which can result in reduced flow rates and decreased efficiency of the filtration system. In addition, water losses due to mixing with saline groundwater can affect the quality of the treated water. The natural reactions occurring between the water and the porous medium could raise the concentrations of some undesired elements, for instance, Iron (Fe), Arsenic (As), Fluorine (F), Manganese (Mn), Ammonium (NH_4), Calcium (Ca), and Dissolved organic carbon (DOC) [59, 79]. As a result, post-treatment must be taken into account.

5.6 RBF Sharing

The numerical model of Multispecies Transport Model in 3-Dimensions (MT3D) was used together with the efficiency of riverbank filtration share (RBFS) equation. By utilizing this RBFS equation, one can evaluate the riverbank filtration system's efficiency in removing dissolved solids from the groundwater and compare it with the quality of surface water in the associated river or stream [28].

$$\mathrm{RBFS} = \frac{\mathrm{(TDS)GW} - \mathrm{(TDS)RBF}}{\mathrm{(TDS)GW} - \mathrm{(TDS)River}} \times 100\% \tag{1}$$

where,

RBFS: Riverbank Filtration System.

(TDS)GW: the total dissolved solids concentration in the groundwater,

(TDS)RBF: the total dissolved solids concentration in the water extracted through RBF, (TDS)River: the total dissolved solids concentration in the surface water of the river or stream

6 Investigation of RBF

Two approaches were used to investigate riverbank filtration (RBF): field investigation (collecting data on the hydrogeological characteristics of the site) and numerical simulation (application of certain principles for better understanding of groundwater flow dynamics, the physical and chemical properties of the aquifer, and the filtration efficiency of the riverbank).

6.1 Field Investigation

Due to the change of the geology of the site substantially from one location to another, the activities occurring in the vicinity of the RBF wells and climatic conditions can have an impact on performance of RBF [3, 22, 75].

In 2015, the Holding Company for Water and Wastewater (HCWW) drilled six Pumping Wells [PW] at the current case study of the RBF site at Embaba, Nile delta, Egypt close to the river Nile. The scheme [PW] depth ≈54 m in, 450 mm in diameter with a discharge of 150 m^3/h for each well, and total capacity ranges from 14,000 to 21,000 m^3/day. The distance between the wells and the river bank ranges between 10 and 15 m. Moreover, four test wells at a depth of 64 m with a maximum diameter of 216 mm were drilled to identify the lithology. Besides, two test wells at 30 m were installed: one at the side of the river and the other at the land with a diameter of 100 mm. Multiple samples were taken from all wells by the HCWW laboratory [43, 44]. The location was valid for RBF which the Nile naturally recharges the aquifer. The results revealed relevant values of Total Dissolved Solids (TDS), and NH_4 compatible with the Egyptian drinking water standards.

Lee et al. [57] collected water samples that were taken infrequently over a period of 1.5 years. Some parameters were sampled daily but at least quarterly for specific parameters. Continuous operation and regular monitoring of the RBF wells was not possible, resulting in low analyses for some parameters.

Water quality parameters were analyzed in the central laboratory of the Giza Water and Wastewater Company and the main reference laboratory of the Holding Company for Water and Wastewater [HCWW]. Unfiltered water samples for mineral analysis Water quality analyzes included turbidity, total dissolved solids [TDS], sulfate [$SO_4{}^{-2}$], alkalinity, chloride [Cl^-], ammonium [NH^{+4}], nitrate [NO^{-3}], total iron [phytate], manganese [Mn], total organic carbon [TOC], total colon [TC]. Analysis of water extracted from RBF wells is shown in Table 1.

Table 1 Water quality of the Nile River, RBF wells and landside well at Embaba site (*source* Ghodeif et al. [44])

parameter	Unit	Nile River [2015–2016]				All RBF wells [2015–2016]			
		N	Median	Min	Max	N	Median	Min	Max
pH		8	8.2	7.4	8.4	7	7.4	7.3	7.5
EC	µS/cm	8	392	321	456	106	477	398	572
TDS	mg/l	8	260	214	301	117	315	257	378
DO	°C	8	8.0	7.2	9.6	5	0.0	0.0	3.7
Temperature	NTU	8	26.4	17.0	30.2	5	24.1	24	24.5
Turbidity	mg/l	8	11.2	5.5	19.7	118	1.7	0.3	4.5
Alkalinity	mg/l	8	147	130	157	7	202	186	216
CI	mg/l	8	23	16	38	7	25	21	30
SO_4	mg/l	8	24	11	36	7	20	15	31
NO_3	mg/l	8	0.41	0.02	1.3	7	0.6	0.3	3.8
NH_4	mg/l	8	0.15	0.04	0.26	118	1.9	0.5	6.3
Fe_{tot}	mg/l	8	0.21	0.13	0.72	119	0.5	0.1	0.8
Mn	mg/l	8	0.05	0.03	0.06	119	0.8	0.4	1.1
Ca	mg/l	7	30	29	34	4	45	41	46
Mg	mg/l	7	11	9	12	4	15	13	17
Na	mg/l	7	26	24	30	4	28	27	31
K	mg/l	7	5.2	4.5	5.4	4	5.1	4.6	5.5

6.2 *Numerical Models for RBF Simulation*

With the advancement of simulation and modelling software, it is feasible to visualize the system [13, 14]. Rossetto et al. [72] used an interdisciplinary approach involving hydrodynamics, hydrochemistry and numerical modelling methods to assess changes in recharge from the river to the aquifer due to the construction of RBF infrastructure along the Serchio river in Lucca, Italy. Pholkern et al. [66], Jaramillo et al. [51] evaluated an RBF system by using a numerical and experimental model to simulate pesticide removal. Hence, Kazak and Pozdniakov [53] conducted a series of field investigations and numerical simulations in Voronezh, Russian Federation to reveal the potential source of iron in groundwater which was pumped through riverbank wells.

According to Lee et al. [59], numerical simulation and pumping tests were used to determine the impact of well structure and pumping rates on the extraction efficiency of the riverbank filtration process for the region of Daesan-Myeon located at the northwestern border of Changwon City, Korea near Nakdong River. The findings for that region indicated that the volume of filtered river water was determined the distance between the collector well and the river, and groundwater flow rate entering the horizontal arm of a radial collector was not uniform along the arm of a radial collector.

6.2.1 Groundwater Flow Model

Visual MODFLOW 2010.1 is a software tool used to model groundwater flow and contaminant transport. This tool integrates a range of models including MODFLOW-2000, SEAWAT, MODPATH, MT3DMS, MT3D99, RT3D, VMOD 3D-Explorer, Win PEST, Stream routing package, zone Budget, MGO, SAMG, and PHT3D. Some purposes of this tool are well head capture zone delineation, pumping well optimization, aquifer storage and recovery, groundwater remediation design, simulating natural attenuation, and saltwater intrusion [73]. The main component of governing groundwater flow equation is the combination of the law of mass balance and Darcy's law [55].

This visual MODFLOW 2010.1 was used for our stimulation of groundwater flow.

6.2.2 Darcy's Law

Darcy studied the flow of water through sand on an experimental basis and published his results in 1856. Behold that the negative sign indicates that the direction of flow is the direction of decreasing water level [81].

$$v = -K \times \left[\frac{\partial h}{\partial L} \right] \tag{2}$$

$$V = \frac{v}{n_{\mathrm{e}}} = \left[\frac{Q}{A \times n_{\mathrm{e}}} \right] \tag{3}$$

where, $\boldsymbol{Q}$: is the volume of water flowing through the cylinder per unit of time [LT^{-3}], $[\boldsymbol{\Delta h/\Delta L}]$: is the hydraulic gradient i over the cylinder, $\boldsymbol{K}$: is hydraulic conductivity [LT^{-1}], and $\boldsymbol{A}$: is area cross-section [L^2], $\boldsymbol{n_e}$: is the effective porosity, $\boldsymbol{v}$: is the Darcy-velocity [LT^{-1}], and $\boldsymbol{V}$: is the seepage velocity [or linear or pore velocity] of groundwater flow. It is also not the true velocity with which particles move in a porous medium [LT^{-1}].

6.2.3 General Form of Groundwater Flow Equation

The groundwater flow equation through a porous medium depends upon an equation that captures the essence of the physics of the flow. The conservation of fluid mass statement is given below [81]. The partial-differential equation of groundwater flow is used in VISUAL MODFLOW [60].

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+q=S_s\times\frac{\partial h}{\partial t} \tag{4}$$

where:

$\boldsymbol{K_{xx}}$, $\boldsymbol{K_{yy}}$, and $\boldsymbol{K_{zz}}$: are values of hydraulic conductivity along the x, y, and z coordinate axes, [LT^{-1}].

h: is the potentiometric head [L]. $\boldsymbol{S_s}$: is specific storage of the porous material [L^{-1}]. ***t***: is time [T].

q: is volumetric flux per unit volume representing source/sink terms; with $q < 0.0$ for flow out of the groundwater system, and $q > 0.0$ for flow in [T^{-1}].

6.3 Groundwater Solute Transport Model

A groundwater solute transport model is a mathematical model used to simulate the movement of solutes (such as contaminants) in groundwater and to evaluate the transport and fate of contaminants in aquifers.

6.3.1 Concepts of Solute Transport and Physical Transport Processes

The solute transport processes of groundwater include advection, dispersion, adsorption, biodegradation and chemical reactions [30]. Here, three main processes are described for the purposes of RBF.

7 (i) Advection

Advection is the movement of groundwater under a hydraulic or pressure gradient. Advective transport is the movement of dissolved solutes is carried along with flowing groundwater. The direction and rate of advective transport coincide with that of the groundwater flow [30]. The rate of solute transported by advection can be written as.

$$F_{\text{Advection}} = V_{\text{a}} \times n_{\text{e}} \times C \tag{5}$$

where, $\boldsymbol{V_a}$: is pore velocity or seepage velocity of water movement [LT^{-1}], $\boldsymbol{n_e}$: is effective porosity [dimension-less], and **C**: is concentration [PPM].

(ii) Dispersion

The process of mechanical mixing takes place in porous media as a result of the movement of fluids through the pore space. As water and solutes migrate through the subsurface via advection, they will tend to spread out, parallel to and normal to the flow path. The result will be dilution of the solute by a process known as dispersion. The mixing known along the fluid flow streamline is called longitudinal dispersion. Dispersion which occurs normal to the pathway is called lateral [or transverse] dispersion [86].

(iii) Diffusion

Molecular diffusion is the process that describes the spread of particles through random motion from regions of higher concentration to regions of lower porous media. Diffusion can occur when no hydraulic gradient drives flow and the pore water is static. The diffusion coefficient in a porous medium is less than that in pure liquids because of collisions with the pore walls so diffusion in groundwater systems is a very slow process. The diffusion coefficient depends on the materials, temperature, electrical fields, etc. It can be easily measured in the laboratory.

Molecular diffusion is expressed for a simple aqueous nonporous medium by Fick's law. Diffusion coefficient in porous media is smaller than in pure liquids primarily because a collision with the solids of the medium hinders diffusion. For a bulk diffusion coefficient, the effective diffusion coefficient in the porous medium (Dm) to account for the effects of tortuosity [solute move through porous media], the rate of solute transported by diffusion can be written below. The molecular diffusion coefficient values are in the range of 1.E−8 to 1.E−10 [$L^2\ T^{-1}$] at 25 °C [81].

$$F_{\text{Diffusion}} = D_{\text{m}} \times n_{\text{e}} \times \frac{\partial c}{\partial x}, \quad D_{\text{m}} = \xi \times D_{\text{mo}} \tag{6}$$

where, $\boldsymbol{D_{\mathbf{m}}}$: is the effective diffusion coefficient in the porous medium [$L^2\ T^{-1}$], $\boldsymbol{n_{\mathbf{e}}}$: is the effective porosity [–], $\frac{\partial C}{\partial x}$: is concentration gradient [p p mL^{-1}], $\boldsymbol{\zeta}$: tortuosity of the porous medium [dimension-less], and $\boldsymbol{D_{\mathbf{mo}}}$: is the free solution diffusion coefficient in aqueous solution [$L^2\ T^{-1}$].

7.1 Governing Equation for Solute Transport

Numerical models of groundwater have a powerful tool to simulate groundwater in both flow and solute transport systems. This gives ideal support in planning, design and management of groundwater resources and provides the decision maker with a database about the case study. This study used two numerical models to simulate groundwater flow and solute transport in the Nile delta aquifer as mentioned below.

Derivation of the advection–dispersion equation [ADE] is based on the law of conservation of mass. The derivation is based on those of [65] and is presented in [41]. It was assumed that the porous medium was homogeneous, isotropic and saturated. The flow was steady state and Darcy's law was applied. The flow was described by the average linear velocity or seepage velocity, which transported the dissolved mass by advection. Hydrodynamic dispersion was used to account for the additional spreading caused by fluctuations in the velocity field [24]. The solute transport equation as formulated in Eq. 7 was used.

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left[D_{ij}\frac{\partial C}{\partial x_i}\right] - \frac{\partial}{\partial x_i}(v_i * C) - \left[\frac{q_s}{n_e}C_s\right] + \sum_{K=1}^{N} R_K \tag{7}$$

where:

$\frac{\partial C}{\partial t}$: concentration with time [p p MT^{-1}], $\frac{\partial C}{\partial x_i}$: concentration gradient in i direction [p p mL^{-1}], $\mathbf{D_{ij}}$: the hydrodynamic dispersion coefficient [L^2 T^{-1}], **C**: is solute concentration [p p m], $\mathbf{n_e}$: is the effective porosity [–], $\mathbf{C_s}$: solute concentration of water entering from sources or sinks [M L^{-3}], $\mathbf{R_k}$: solute production rate or decay in reaction k of N different reactions [k = 1, …, N] [M L^{-3} T^{-1}]. $\boldsymbol{q_s}$*:* volumetric flow rate per unit volume of aquifer for sources and sinks [T^{-1}], and ***t:*** is time [T].

8 RBF Improvement

This section aims to improve the efficiency of the RBF system by developing a filter pack using numerical simulation in order to improve the RBF system before applying it to the field. The emplacement of gravel pack filter is installed in both vertical and horizontal directions to maximize the benefits of the RBF system and study the main parameters that affect the design of the gravel filter. The depth, width, length, thickness and hydraulic conductivity were studied using Visual MODFLOW. Five scenarios were applied to obtain the optimum dimensions of the gravel pack filter considering the Riverbank Filtration System (RBFS) [10, 12, 16, 17].

8.1 River Conditions

In this section, we describe two stages: river stage and removal of bed closing.

8.1.1 River Stage

The results indicated that rising the river water levels caused an decrease of TDS concentration around the RRBF system which resulted in an increase in (RBFS) meanwhile the travel time of river particles decreased.

8.1.2 Removal of Bed Closing

It is worth mentioning that maintaining high riverbed seepage by removing mud from the riverbed in front of the wells would ensure high productivity of the abstraction wells, as removing mud from the riverbed increases the permeability of the soil, which leads to an increase in efficiency of RBF sharing. Moreover, [44] indicated that the Nile is constantly exposed to these sediments which can reduce the hydraulic conductivity of the riverbed and limit the exchange of water between the river and the adjacent groundwater aquifer. Therefore, to tackle this issue, silt is dredged twice annually with the aid of appropriate equipment, which has been demonstrated to improve the hydraulic connection between the river and the main underground water reservoir.

8.2 Aquifer Conditions

To determine the quantity and quality of groundwater resources, three important aquifer conditions are the thickness of the clay cap, the hydraulic conductivity of the aquifer, and the rate of abstraction. It is well noted that the thickness of the clay cap can affect the groundwater recharge into the aquifer. The hydraulic conductivity determines the rate at which groundwater can flow through the aquifer while the abstraction rate mentioned to the rate at which groundwater is withdrawn from the aquifer.

8.2.1 Clay Cap Thickness

Increasing the clay cap thickness decreased the RBFS while the travel times increased.

8.2.2 Aquifer Hydraulic Conductivity

The results highlighted that the travel times decreased at higher values of aquifer hydraulic conductivity and higher pumping rates as expected. Therefore, it can be assumed that a major site selection criterion for RBF systems is the aquifer hydraulic conductivity, which matches with the hydraulic conductivities criteria presented by [49] in the range of 1×10^{-2} to 7.5×10^{-5} m/s along the Elbe River in Germany.

8.2.3 Aquifer Abstraction Rates

According to the stimulation result, increasing the abstraction rates from the aquifer had the most significant effect on RBFS.

8.3 RBF Conditions

There are several key factors related to the riverbank conditions. Some key factors will be discussed as below based on the findings.

8.3.1 RBF Well Discharge

According to the results obtained from the study, increased pumping rates led to a corresponding increase in riverbank filtration share (RBFS) while decreased travel time resulted in decreased RBFS values. Utilizing higher pumping rates in the model can facilitate the creation of a robust cone of depression [10]. Yet, achieving the same result with a larger number of wells having lower pumping rates might not be feasible option. Therefore, one viable alternative to achieve the same effect would be to use a horizontal collector well, but using a horizontal collector well may be achieved.

8.3.2 RBF Well Depths

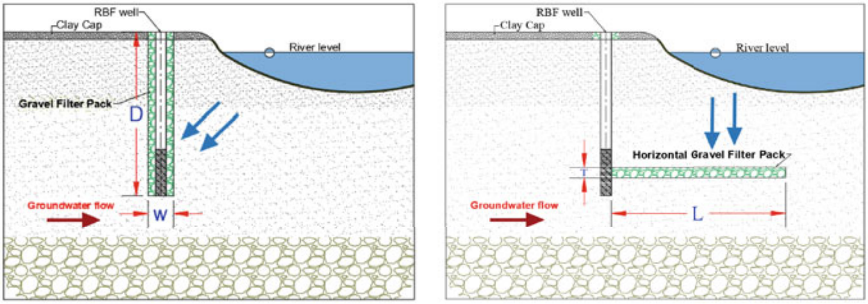
The inverstigation indicated that using increasing in well depths had a compariatively smaller impact on the range of RBFS values. However, an increase in travel times led to a decrease in RBFS values.

8.3.3 RBF Well Screen Lengths

The findings of this study indicate that there was no significant changes in RBFS values, but it was observed that travel times decreased as the screen lengths were altered. The screen length plays an important role in determining the entrance flow velocities and the lifespan of the wells. Notably, increasing the RBF well depth and screen length was comparatively less affected on RBFS than on travel times [32].

8.3.4 RBF Well Distances

The increase of the distance between the RBF wells and the river bank decreased RBFS while travel times increased due to the greater portion of groundwater. That huge amount of groundwater is present further away from the riverbank, so installing RBF wells close to the river bank is more effective in terms of increasing the RBF portion [89].



a. Vertical Gravel Filter b. Horizontal Gravel Filter

Fig. 8 Gravel pack filter in RBF in which the orientation of the filer depends on the specific geologic conditions

8.4 Emplacement of Vertical Filter Pack for RBF Wells

A filter pack surrounding the screen of pumping wells offers a critical advantage in reducting losses and increasing the hydraulic efficiency of the well. The filter zone is developed for well construction to remove fine particles, creating a zone of turbulent flow around the well screen. This optimization results in improved efficiency, specific capacity, and safe yield of the pumping well. The gravel pack filter [GPF] surrounding the well screen may be provided in two ways [17].

The first is a naturally developed filter which is produced by removing the fine sand and silt from the aquifer material, bringing these fines through the well screen openings by surging and bailing.

The second is the artificial pack type, in which an envelope of materials with a coarser uniform grain size than the aquifer is mechanically placed around the screen to filter the finer formation particles (see Fig. 8).

Smith [78] and Walton [85] described the design criteria for either type based on the effective size, uniformity coefficient, and other grain-size distribution considerations determined from mechanical analysis of the aquifer material.

Numbers of methods have been suggested to determine the gravel pack grain sizes. All these methods are based initially on sieve analysis of the aquifer. The designed filter is based on [80] following formula.

$$\frac{D15_{filter}}{D85_{aquifer}} < 4 < \frac{D15_{filter}}{D85_{aquifer}} \tag{8}$$

A common consensus is that a gravel pack will typically function effectively if the uniformity coefficient based on the grain size distribution curves of the filter pack and the aquifer material is similar to that of the aquifer. The grain size of the aquifer material should be multiplied by a constant of approximately with average value (4) Eq. (8) to create an envelope defining the filter grading.

Horizontal aggregation wells were used to develop infiltration water supplies that arose in the 1930s after oil engineer Liu Rani found that lower oil prices made the directly drilled horizontal wells less cost-effective. He modified his method from drilling horizontal wells in oil-bearing rock formations to a hydraulic lifting process in which perforated pipes are installed in underground water layer formations not covered by sand and gravel. For both oil and water, his theory suggests that in a horizontal configuration, installing the wells, whether they are open or sorting wells, could potentially result in increased returns compared to using a single vertical well. The reasoning behind this theory is that a horizontal well configuration reveals a larger area, leading to higher returns for each individual well.

By 1953, a technique had been developed in Germany wherein an artificial gravel-pack filter was installed around the well screens of laterals in a horizontal collector well to accommodate finer-grained formations. This technique also involves a solid pipe that is projected full-length into the formation. A special well screen is inserted into the pipe, and gravel materials are pumped into the annulus between the projection pipe and the screen while the pipe is retracted. The use of an artificial gravel-pack filter provides a transition between fine-grained formation deposits and more efficient screen openings [4, 6, 7, 9, 62].

Ghodeif et al. [44] showed the results of grain size analysis and estimation of the hydraulic conductivity of the aquifer around the pumping wells showed the artificial gravel pack is required due to:

- First condition
  Uniformity Coefficient [Cu]= $D_{60}/D_{10} < 3$.
- Second condition
  $D_{10} < 0.25$ mm

9 Climate Change and RBF

At present, we see that climate change has a huge impact on RBF. The Intergovernmental Panel on Climate Change [68] has mentioned that climate change is expected to result in both reduced surface water and groundwater resources in the driest subtropical zones where droughts are likely to increase in dry areas by the end of twenty-first century. However, water resources are expected to increase in high latitudes. It can be seen that climatic change has been affecting the River Nile basin with decreasing annual average precipitation in Egypt [21, 42].

According to Kwadijk [56], increasing river flow by 40% was happened to increasing in the total rainfall over the river basin by 10%. This condition confirms that the river flow is sensitive to basin precipitation. Moreover, based on climate scenarios of IPCC in 2007, the climate models have predicted that the precipitation will increase during the period [I] from 2010 to 2039, followed by a decrease in the subsequent periods [II] from 2014 to 2069 and [III] from 2070 to 2090 respectively [25, 52].

Two factors of climate change (higher temperature and reduced precipitation) result in decreased river flows, lower groundwater recharge rates, and increased polluted concentration in water resources. Therefore, it is found that these changes can significantly impact RBF systems [3, 17]. In other words, adaptation measures such as improving water use efficiency and monitoring water quality and quantity regularly are needed to consider for the sustainable RBF system.

10 Conclusion

The need for clean and safe drinking water is the most important fact for today. One technology, Riverbank Filtration (RBF), involves using natural filtration process to purify water. It is undeniable that this method is an alternative to traditional water treatment systems. Therefore, many countries are now following and using this RBF as a natural treatment process.

This study aimed to evaluate the RBF technique, its impact on drinking water requirements and improvement of natural water treatment process. The investigation of RBF included both field and model stimulations. Some points of this study are as follows:

- A decrease in hydraulic conductivity, river stage and riverbed permeability and abstraction rates resulted in lower portions of bank filtrate and longer in travel times.
- It is recommended that the abstraction wells would be shallow in depth, high productivity, and close proximity to the river bank to prevent high manganese concentrations in the pumped bank filtrate and achieve shorter travel times.
- Simulations for various scenarios using the effectiveness of Riverbank Filtration Share (RFBS) indicated that four parmeters (filter width, thickness in the river direction, length, and permeability) corresponded to an increase in RFBS. On the contrary, elevating filter depths, widths, and thickness in both river and groundwater directions created an initial increase in RFBS at a certain depth, followed by a decline as a consequence of the aquifer groundwater.

11 Recommendations

As a conclusion, this study proposes some key measures of sustainable Riverbank Filtration (RBF). It is essential to ensure continued operation of both RBF pumping wells and groundwater abstraction wells. Installation of RBF wells near the shoreline is highly recommended. Another considerable fact is that horizontal gravel pack filters should be utilized in future RBF sites with high permeability, especially near the riverbank. Finally, before construction of the plant of RBF to ensure the most effective and sustainable outcome, it should be more investigated for consistent experiment and numerical studies.

Acknowledgements The authors are thankful to the Department of Water and Water Structures Engineering, Faculty of Engineering, Zagazig University, Egypt, for constant support during the study.

References

1. Abd-Elaty I, Abdoulhalik A, Ahmed A (2023) The impact of future hydrology stresses and climate change on submarine groundwater discharge in arid regions: a case study of the Nile Delta aquifer, Egypt. J Hydrol: RegNal Stud 47:101395. https://doi.org/10.1016/j.ejrh.2023.101395
2. Abd-Elaty I, Eldeeb H, Vranayova Z, Zelenakova M (2019) Stability of irrigation canal slopes considering the sea level rise and dynamic changes: case study El-Salam Canal Egypt. Water 11(ASTMD5447-17):1046
3. Abd-Elaty I, Ghanayem HM, Zeleňáková M, Mésároš P, Saleh OK (2021) Numerical investigation for riverbank filtration sustainability considering climatic changes in arid and semi-arid regions; case study of RBF Site at Embaba, Nile Delta Egypt. Sustainability 13(4):1897
4. Abd-Elaty I, Kuriqi A, Ganayem HM, Ahmed A, Saleh OK and Garrote L (2023) Assessment of riverbank filtration performance for climatic change and a growing population. Front. Environ. Sci. 11:1136313. https://doi.org/10.3389/fenvs.2023.1136313
5. Abd-Elaty I, Kuriqi A, Pugliese L, Zelenakova M, Shinawi El A (2023) Mitigation of urban waterlogging from flash floods hazards in vulnerable watersheds. J Hydrol: RegNal Stud 47:101429, ISSN 2214-5818.https://doi.org/10.1016/j.ejrh.2023.101429
6. Abd-Elaty I, Kushwaha NL, Grismer ME, Elbeltagi A, Kuriqi A (2022) Cost-effective management measures for coastal aquifers affected by saltwater intrusion and climate change. Sci Total Environ 836:155656. https://doi.org/10.1016/j.scitotenv.2022.155656
7. Abd-Elaty I, Pugliese L, Straface S (2022) Inclined physical subsurface barriers for saltwater intrusion management in coastal aquifers. Water Resour Manage 36:2973–2987. https://doi.org/10.1007/s11269-022-03156-7
8. Abd-Elaty I, Pugliese L, Zelenakova M, Mesaros P, Shinawi AE (2020) Simulation-based solutions reducing soil and groundwater contamination from fertilizers in arid and semi-arid regions: case study the Eastern Nile Delta Egypt. Int J Environ Res Public Health 17(24):9373
9. Abd-Elaty I, Saleh OK, Ghanayem HM, Zeleňáková M, Kuriqi A (2022) Numerical assessment of riverbank filtration using gravel pack filter to improve water quality in arid regions. Front Earth Sci 10:1006930. https://doi.org/10.3389/feart.2022.1006930
10. Abd-Elaty I, Saleh OK, Ghanayem HM, Grischek T, Zelenakova M (2021) Assessment of hydrological, geohydraulic and operational conditions at a riverbank filtration site at Embaba, Cairo using flow and transport modeling. J Hydrol: Reg Stud 37:100900. https://doi.org/10.1016/j.ejrh.2021.100900
11. Abd-Elaty I, Sallam GA, Strafacec S, Scozzari A (2019b) Effects of climate change on the design of subsurface drainage systems in coastal aquifers in arid/semi-arid regions: case study of the Nile delta. Sci Total Environ J (672) (Ghodeif, Grischek et al. 2016), 283–295. https://doi.org/10.1016/j.scitotenv.2019.03.483
12. Abd-Elaty I, Shahawy AEL, Santoro S, Curcio E, Straface S (2021) Effects of groundwater abstraction and desalination brine deep injection on a coastal aquifer. Sci Total Environ, 148928, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2021.148928
13. Abdalla F, Shamrukh M (2010) Riverbank filtration as an alternative treatment technology: AbuTieg Case Study, Egypt. 103:255–268
14. Abdalla F, Shamrukh M (2016) Quantification of River Nile/Quaternary aquifer exchanges via riverbank filtration by hydrochemical and biological indicators, Assiut Egypt. J Earth Syst Sci 125(8):1697–1711

15. Abd-Elaty I, Straface S (2022) Mathematical models ensuring freshwater of coastal zones in arid and semiarid regions. In: Furze JN, Eslamian S, Raafat SM, Swing K (eds) Earth systems protection and sustainability. Springer, Cham. https://doi.org/10.1007/978-3-030-98584-4_3
16. Abd-Elaty I, Straface S, Kuriqi A (2021) Sustainable saltwater intrusion management in coastal aquifers under climatic changes for humid and hyper-arid regions. Ecol Eng (171). https://doi.org/10.1016/j.ecoleng.2021.106382
17. Abd-Elaty I, Zelenakova M, Straface S, Vranayová Z, Abu-hashim M (2019) Integrated modelling for groundwater contamination from polluted streams using new protection process techniques. Water 11(11):2321
18. Abdallah MAM (2021) Chemo speciation of metals in surficial sediments of Nile delta coastal zone ecosystem Egypt. Mar Syst Ocean Technol 16(1):43–53
19. Abdel-Dayem S, Abdel-Gawad S, Fahmy H (2007) Drainage in Egypt: a story of determination, continuity, and success. Irrig Drain: J Int Comm Irrig Drain 56(S1):S101–S111
20. Abdel-Shafy HI, Aly RO (2002) Water issue in Egypt: resources, pollution and protection endeavors. Cent Eur J Occup Environ Med 8(1):3–21
21. Agrawala S, Moehner A, El Raey M, Conway D, Van Aalst M, Hagenstad M, Smith J (2004) Development and climate change in Egypt: focus on coastal resources and the Nile. Organisation for Economic Co-operation and Development
22. Ahmed AKA, Marhaba TF (2017) Review on river bank filtration as an in situ water treatment process. Clean Technol Environ Policy 19:349–359
23. Ahram ol (2015) Sunken phosphate barge removed from Nile: Egyptian minister. 1. Retrieved 28–9, 2021, from http://english.ahram.org.eg/News/128942.aspx.
24. Alexander WR, Smith PA, McKinley IG (2003) Modelling radionuclide transport in the geological environment: a case study from the field of radioactive waste disposal. Radioact Environ 4:109–145
25. Beyene T, Lettenmaier DP, Kabat P (2010) Hydrologic impacts of climate change on the Nile River Basin: implications of the 2007 IPCC scenarios. Clim Change 100(3–4):433–461
26. Covatti G, Grischek T (2020) Sources and behavior of ammonium during riverbank filtration. Water Res:116788
27. Dash RR, Prakash EB, Kumar P, Mehrotra I, Sandhu C, Grischek T (2010) River bank filtration in Haridwar, India: removal of turbidity, organics and bacteria. Hydrogeol J 18(4):973–983
28. Dawoud MA, Darwish MM, El-Kady MM (2005) GIS-based groundwater management model for Western Nile Delta. Water Resour Manage 19(5):585–604
29. Dillon P, Stuyfzand P, Grischek T, Lluria M, Pyne R, Jain R, Bear J, Schwarz J, Wang W, Fernandez E (2018) Sixty years of global progress in managed aquifer recharge
30. Domenico PA, Schwartz FW (1998) Physical and chemical hydrogeology. Wiley, New York
31. Doussan C, Poitevin G, Ledoux E, Detay M (1997) River bank filtration: modelling of the changes in water chemistry with emphasis on nitrogen species. J Contam Hydrol 25(1–2):129–156
32. Dragon K, Drozdzynski D, Gorski J, Kruc R (2019) The migration of pesticide residues in groundwater at a bank filtration site (Krajkowo well field, Poland). Environ Earth Sci 78:1–11
33. El-Bedawy R (2014) Water resources management: alarming crisis for Egypt. J Mgmt Sustain 4:108
34. El-Hamid H, Hegazy T (2017) Evaluation of water quality pollution indices for groundwater resources of New Damietta Egypt. MOJ Ecol Environ Sci 2(6):00045
35. El-MasryAl-Youm. (2013) Al-Masry Al-Youm." from https://www.almasryalyoum.com/news/details/205158.
36. El-Sheekh M (2009) River nile pollutants and their effect on life forms and water quality. In: Dumont HJ (ed) The nile: origin, environments, limnology and human use. Dordrecht, Springer, Netherlands, pp 395–405
37. El-Sheekh MM (2016) Impact of water quality on ecosystems of the Nile River. The Nile River:357–385
38. El Arabi N (2012) Environmental management of groundwater in Egypt via artificial recharge extending the practice to soil aquifer treatment (SAT). Int J Environ Sustain 1(3)

39. Elkamhawy E, Zelenakova M, Abd-Elaty I (2021) Numerical canal seepage loss evaluation for different lining and crack techniques in arid and semi-arid regions: a case study of the River Nile Egypt. Water 13:3135. https://doi.org/10.3390/w13213135
40. Ewida A (2014) Oil spills: impact on water quality and microbial community on the Nile River Egypt. Int J Environ 3(4):192–198
41. Freeze R, Cherry J (1979) Groundwater. Prentice-hall
42. Gado TA, El-Agha DE (2021) Climate change impacts on water balance in Egypt and opportunities for adaptations. In: Agro-environmental sustainability in MENA Regions, Springer, pp 13–47
43. Ghodeif K, Grischek T, Bartak R, Wahaab R, Herlitzius J (2016) Potential of river bank filtration (RBF) in Egypt. Environ Earth Sci 75(8):671
44. Ghodeif K, Paufler S, Grischek T, Wahaab R, Souaya E, Bakr M, Abogabal A (2018) Riverbank filtration in Cairo, Egypt—part I: installation of a new riverbank filtration site and first monitoring results. Environ Earth Sci 77(7):270
45. Ghodeif KO (2011) Removal of iron and manganese within the aquifer using enhanced riverbank filtration technique under arid conditions. Riverbank filtration for water security in desert countries. Springer, pp 235–253
46. Gopalakrishnan L, Doriya K, Kumar DS (2016) Moringa oleifera: a review on nutritive importance and its medicinal application. Food Sci Human Wellness 5(2):49–56
47. Grischek T, Schoenhein D, Eckert P, Ray C (2010) Sustainability of river bank filtration. In: XXXVIII IAH congress: groundwater quality sustainability. University of Silesia Press, Krakow
48. Haarstrick A, Bahadir M (2022) Water and its global meaning. In: Water and Wastewater Management. Springer, pp 3–14
49. Hiscock KM, Grischek T (2002) Attenuation of groundwater pollution by bank filtration. J Hydrol 266(3–4):139–144
50. IPCC (2014) Climate Change 2014 ,Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer [eds.]]. IPCC, Geneva, Switzerland, 151 pp
51. Jaramillo M, Grischek T, Boernick H, Velez JI (2019) Evaluation of riverbank filtration in the removal of pesticides: an approximation using column experiments and contaminant transport modeling. Clean Technol Environ Policy 21(1):179–199
52. Jungudo MM (2022) The Impact of Climate Change in Egypt
53. Kazak ES, Pozdniakov SP (2021) Field study and reactive simulation of iron migration in groundwater during the riverbank filtration. Appl Geochem 124:104817
54. Kondor AC, Jakab G, Vancsik A, Filep T, Szeberényi J, Szabó L, Maász G, Ferincz Á, Dobosy P, Szalai Z (2020) Occurrence of pharmaceuticals in the Danube and drinking water wells: efficiency of riverbank filtration. Environ Pollut 265:114893
55. Kumar C (2002) Groundwater flow models. Scientist 'E1'National Institute of Hydrology Roorkee–247667 (Uttaranchal) publication
56. Kwadijk J (2007) Climate scenarios for the Nile basin and some consequences for its water management. WL| Delft Hydraulics Report Q 4119
57. Lee E, Hyun Y, Lee K-K, Shin J (2012) Hydraulic analysis of a radial collector well for riverbank filtration near Nakdong River South Korea. Hydrogeol J 20(3):575–589
58. MWRI, Ministry of Water Resources and Irrigation (2013) Proposed climate change adaptation strategy for the Ministry of Water Resources and Irrigation (MWRI) in Egypt, tech. report, Ministry of Water Resources and Irrigation, Egypt
59. Matusiak M, Dragon K, Gorski J, Kruc-Fijałkowska R, Przybylek J (2021) Surface water and groundwater interaction at long-term exploited riverbank filtration site based on groundwater flow modelling (Mosina-Krajkowo, Poland). J Hydrol: Reg Stud 37:100882
60. McDonald MG, Harbaugh AW (1988) A modular three-dimensional finite-difference groundwater flow model. US Geological Survey Reston, VA

61. Mohie El Din MO, Moussa AM (2016) Water management in Egypt for facing the future challenges. J Adv Res 7(3):403–412
62. Murshed M, Kamaruzaman A, Ab Aziz N, Kamal NM (2020) Influence of grain size distribution towards improvements of turbidity, colour and suspended particles in a riverbank filtration process-a column study. In: IOP conference series: materials science and engineering. IOP Publishing
63. Mustafa S, Bahar A, Aziz ZA, Suratman S (2014) Review of the role of analytical modelling methods in riverbank filtration system. J Teknol 71(1)
64. Oberleitner D, Schulz W, Bergmann A, Achten C (2020) Impact of seasonality, redox conditions, travel distances and initial concentrations on micropollutant removal during riverbank filtration at four sites. Chemosphere 250:126255
65. Ogata A (1970) Theory of dispersion in a granular medium. US Government Printing Office
66. Pholkern K, Srisuk K, Grischek T, Soares M, Schäfer S, Archwichai L, Saraphirom P, Pavelic P, Wirojanagud W (2015) Riverbed clogging experiments at potential river bank filtration sites along the Ping River, Chiang Mai Thailand. Environ Earth Sci 73(12):7699–7709
67. Pollock D (1998) Documentation of Computer Programs to compute and display pathlines using results from U.S. Geological Survey modular three-dimensional finite difference groundwater flow model, vol 89–381. U. S. Geological Survey, 188 pp.
68. Pörtner H-O, Roberts DC, Adams H, Adler C, Aldunce P, Ali E, Begum RA, Betts R, Kerr RB, Biesbroek R (2022) Climate change 2022: Impacts, adaptation and vulnerability. IPCC Geneva, Switzerland
69. Raghuram P, Rambabu T, Niharika K, Reddy M, Raju P (2000) Quality of panchayat/municipal treated water and reverse osmosis treated water in the villages of Western Delta of West Godavari District, Andhra Pradesh, India. Appl Hydrol, 87
70. Ray C (2011) Riverbank filtration concepts and applicability to desert environments. Riverbank filtration for water security in desert countries. Springer, pp 1–4
71. Ray C, Melin G, Linsky RB (2003) Riverbank filtration: improving source-water quality. Springer Science & Business Media.
72. Rossetto R, Barbagli A, De Filippis G, Marchina C, Vienken T, Mazzanti G (2020) Importance of the induced recharge term in Riverbank filtration: hydrodynamics, hydrochemical, and numerical modelling investigations. Hydrology 7(4):96
73. SWS (2010) Schlumberger water services. User's Manual. 460 Phillip Street—Suite 101 Waterloo, Ontario, CANADA. N2L 5J2
74. Sabry S (2010) How poverty is underestimated in Greater Cairo, Egypt. Environ Urban 22(2):523–541
75. Sahu RL, Dash RR, Pradhan PK, Das P (2019) Effect of hydrogeological factors on removal of turbidity during river bank filtration: laboratory and field studies. Groundw Sustain Dev 9:100229
76. Shamrukh M, Abdel-Wahab A (2011) Water pollution and riverbank filtration for water supply along river Nile, Egypt. In: Riverbank filtration for water security in desert countries. Springer, pp 5–28
77. Shannon MA, Bohn PW, Elimelech M, Georgiadis JG, Marinas BJ, Mayes AM (2008) Science and technology for water purification in the coming decades. Nature 452(7185):301–310
78. Smith HF (1954) Gravel packing water wells. Circular no. 044
79. Stuyfzand PJ, Juhàsz-Holterman MHA, de Lange WJ (2006) Riverbank filtration in the Netherlands: well fields. Clogging and Geochemical Reactions, Dordrecht, Springer Netherlands
80. Terzaghi K (1943) Theoretical Soil Mechanics. Wiley & Sons, New York, pp 11–15
81. Vandenbohede A, Lebbe L (2003) Simultaneous interpretation of drawdown and. Calibration and Reliability in Groundwater Modelling: A Few Steps Closer to Reality: Proceedings of the ModelCARE 2002 Conference: Held in Prague, Czech Republic, 17–20 June, 2002, International Assn of Hydrological Sciences.
82. WWAP (2018) United Nations World Water Assessment Programme/UN-Water. The United Nations World Water Development Report 2018: Nature-Based Solutions for Water. UN-Water. Paris, UNESCO., The United Nations World Water Development Report 2018.

83. Wahaab RA, Badawy MI (2004) Water quality assessment of the River Nile system: an overview. Biomed Environ Sci 17(1):87–100
84. Wahaab RA, Salah A, Grischek T (2019) Water quality changes during the initial operating phase of riverbank filtration sites in upper Egypt. Water 11(6):1258
85. Walton WC (1962) Selected analytical methods for well and aquifer evaluation. Bulletin (Illinois State Water Survey) no. 49
86. Warrick AW (2001) Soil physics companion. CRC Press
87. Weiss WJ, Bouwer EJ, Ball WP, O'Melia CR, Lechevallier MW, Arora H, Speth TF (2003) Riverbank filtration—fate of DBP precursors and selected microorganisms. J Am Water Works Ass 95(10):68–81
88. Zaher HA (2015) The Nile, a vital source of water, turns into source of disease. The Arab Weekly
89. Zhu Y, Zhai Y, Teng Y, Wang G, Du Q, Wang J, Yang G (2020) Water supply safety of riverbank filtration wells under the impact of surface water-groundwater interaction: Evidence from long-term field pumping tests. Sci Total Environ 711:135141