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REVIEW ARTICLE

A review: saltwater intrusion in North Africa's coastal areas—current state and future challenges

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Abstract

North Africa coastline extends on 8955 km from Mauritania to Egypt. These areas continue to experience population and economic growth. North Africa coastal aquifers were exposed to an increase in groundwater salinity and seawater intrusion, which may contribute to economic crisis as a result of freshwater resources crisis. This work aims to explore the status and a holistic comprehending review of saltwater intrusion extent in the region and future challenges. Results on seawater intrusion in North Africa, from published papers and grey literature, show a several efforts have been made in understanding this phenomenon and developing management strategies in Egypt, Libya, Tunisia, Algeria, Morocco, and Mauritania. The most method used is geochemical data and statistical analysis. Some studies linked geochemical data with geophysical techniques, geographical information system (GIS), and GALDIT index. Seawater intrusion varies from one country to another according to the aquifer hydrogeological settings, abstraction rates and aquifer morphology, climate change, urban expansion, and economic development. North Africa countries, such as Libya and Mauritania, need, for instance, more expertise and experience on the part of local researchers. The challenge of inadequate data and a need for a more robust data inventory was stressed. This paper recommends developing and building scientific capabilities in regional and international partnerships, and adopting rational water governance for sustainable development.

Keywords Groundwater · Coastal aquifer · Saltwater intrusion · Salinity · North Africa

Introduction

Countries of North Africa are facing a major crisis that threatens freshwater resources in coastal areas. More than 60% of the population is housed in the coastal zones in northern Africa (Hussain et al. 2019) inducing an increasing demand for fresh water resources to meet the needs for growth economic development (Khater 2019; Chen and Al-Maktoumi 2018). Freshwater availability per capita in North African countries is below 500 m^3/year (Khater 2019; Chen and Al-Maktoumi 2018). In arid coastal areas, such as North Africa, groundwater is a primary source of freshwater and is continuously subjected to over-abstraction as well as salinization due to seawater intrusion into aquifers. Studies undertaken in North Africa from Mauritania to Egypt (Toupet 1983; Steyl and Dennis 2010; Mohamed et al. 2017; Kraus 2013; Kouzana et al. 2009; Agoubi et al. 2013; Abdalla et al. 2010; Alfarrah and Walraevens 2018; Bindra et al. 2013; Brika 2018; Sefelnasr and Sherif 2014; Eissa et al. 2018) show that most coastal aquifers are subject to heavy urbanization and are exposed to marine intrusion.

Seawater intrusion is a substantial problem in coastal aquifers around the world. The problem is exacerbated where a highly permeable aquifer extends offshore and in contact with the sea (Bennett et al. 2002). This ecosystem imbalance results in an often significant degradation of the freshwater resource, which is noticeable as soon as seawater reaches 2% in aquifer (Custodio 1985). Under initial conditions, i.e., before urbanization, continental groundwater flows towards the coast thus representing the natural flow in coastal aquifer. The hydraulic head, sufficiently important in the coastal

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aquifer, maintains the seawater-freshwater interface in a stable configuration. The transition between freshwater-saltwater takes place relatively abruptly and not exceeding a few meters. The saltwater and freshwater are thus separated by a zone which is often assimilated to an abrupt interface limiting a wedge of saltwater whose slope is inclined towards the continent (Bonnet et al. 1974; Albitar 2007). The spatiotemporal evolution of the transition zone depends on both the following hydrodynamic and aquifer geometric factors (Bear and Verruijt 1987). Reilly and Goodman (1985) have indicated that the interface hypothesis is acceptable if the thickness of the transition area is less than one third the height of the freshwater zone. Nevertheless, in many aquifers, there is no straightforward interface that separate freshwater from seawater, but there is a large transition zone; its thickness depends on the geological and hydrodynamic characteristics of the aquifer characteristics such as permeability, diffusivity, and freshwater flow system (Cooper et al. 1964; Custodio 1985). Thus, in coastal aquifers with low hydraulic gradient, the transition zone can extend for several kilometers (Cooper et al. 1964). The thickness of the transition area tends to increase under the influence of external factors which modify the balance between the freshwater and the seawater such as tidal effects, over-abstraction, barometric pressure (Idowu and Lasisi 2020), aquifer recharge, climate change, and sea level rise (Bear and Cheng 2010).

Several approaches have been used to highlight saltwater intrusion (Idowu and Lasisi 2020) and include several methods such as geochemistry, groundwater hydrodynamic, piezometric level, against the sea level rise, and stable isotopes (Bear and Cheng 2010; Oiro et al. 2018). Other methods include the use of geophysical techniques (Oloruntola et al. 2019), numerical modeling (Van Camp et al. 2014; Idowu 2017), and geochemical methods (Agoubi et al. 2013; Liu et al. 2017). However, other authors have used several methods to highlight the salwater intrusion in the same area (Idowu 2017; George et al. 2015; Kazakis et al. 2016).

In North Africa, marine intrusion has grown in recent decades because of the long drought associated with over-abstraction and uncontrolled groundwater pumping. Today, due to over-exploitation of coastal aquifers, the North African coasts, which extend over 8955 km, were threatened by saltwater intrusion (Chen and Al-Maktoumi 2018).

Considering the environmental facts about seawater intrusion at the national and regional scale and the risks they pose to coastal water resources, especially in arid regions, it is necessary to assess seawater leakage studies in North Africa, which is among the regions most affected by drought and climate change. Therefore, this paper aims to conduct a comprehensive review and critical evaluation of seawater intrusion studies in the North African region. This paper also provides recommendations on future prospects in light of the challenges that await this region in facing future challenges.

Geographic extent

The North Africa region, defined in this study according to African Union (Fig. 1), comprises 6 countries (Mauritania, Morocco, Algeria, Tunisia, Libya, and Egypt). This region covers a total surface of over 7,065,441 km^2 (Table 1). North Africa countries are home to over than 200 million people (WBG 2020). They total a coastline of 8955 km (Table 1) that stretches over the Atlantic Ocean (Mauritania and Morocco), the Mediterranean (Morocco, Algeria, Libya, and Egypt), and the Red Sea for Egypt.

In North Africa, the coastal areas are the most populated. It is the relative availability of water that determines this distribution and the density of the population (Khater 2019). North Africa countries were under development. Their economy is based on oil (Algeria, Libya), and mineral wealth such as Mauritania, Morocco, and Tunisia (Fig. 2). However, the economy of Egypt is based on natural gas, tourism, and agriculture. In northern Africa, agriculture is well developed, especially in coastal areas, to ensure food security while the industry is still quite moderate.

Geology and hydrogeology overview

The surface water resources available in North Africa are limited under Saharan conditions, but a legacy of groundwater resources remaining from wetter conditions during the late Quaternary (Pleistocene/Holocene) is a significant asset (Hamed et al. 2018). Its climate is Saharan desert influenced by the Mediterranean to the north and the Atlantic to the west. The rains are rare and variable in time and space. Rains are more important in the extreme north (200 to 500 mm/year) and become weaker in the Saharan zone in the south (50 mm/year) (Hamed et al. 2018).

In North Africa, several transboundary aquifers have been identified (Altchenko and Villholth 2013). These aquifers represent large groundwater reserves shared between countries. Among them, the most important were the northern Saharan Aquifer System (NSAS), located north of the Sahara and shared between Algeria, Tunisia, and Libya over a million km^2 (OSS 2006). Then, the Nubian aquifer system that spans an over 2,000,000 km^2 is shared between Libya, Egypt, Tchad, and Sudan. In smaller size with an area of 450,000 km^2, the Mourzouk aquifer system is shared between Libya, Algeria, Tchad, and Niger. Then, the Jeffara coastal aquifer, with a surface area of 200,000 km^2, stretches over 500 km from the coast north of Gabès in Tunisia to Kohms (Libya)

Table 1 Geographic characteristics and resources in North African countries (WBG 2020)

Country	Area (km^2)	Coastline (km)	Population (WBG 2020) × 10^3	Population growth	Annual renewable water resource (km^3)	Availability, (m^3/year per capita)		
						1950	2000	2025
Mauritania	1,030,700	754	4526	2.7	11.4	--	4270	2391
Morocco	710,850	1835	36,472	1.2	29.8	3328	1051	771
Algeria	2,381,741	998	43,053	1.5	13.9	1588	442	298
Tunisia	165,150	1148	11,695	1	3.9	1105	407	304
Libya	1,775,000	1770	6777	1.9	0.8	777	143	93
Egypt	1,002,000	2450	100,388	1.8	68.5	3137	1000	716
Total	7,065,441	8955	202,911					

(OSS 2006). In the following, an overview of the geology and hydrogeology of each country was presented (Fig. 3).

Mauritania comprises five geological provinces: Rgueibat Dorsal, the Taoudeni Basin, Tindouf Basin, the Mauritanides chain, and coastal sedimentary basin (Mohamed et al. 2017). The coastal basin of Mauritania, set up following the opening of the Atlantic Ocean, forms a highly developed continental shelf affected by strong subsidence controlled by normal faults bordering the Atlantic basin, on which a stratigraphic succession was deposited ranging from the Triassic to the Quaternary. The climate is dependent on latitudinal variability and the influence of the Ocean. It is of the Saharan type in the north and Sahelian in the south and generally hot and dry. Maximum temperatures exceed 44°C in May–June, while the minimum can reach 10°C in January–February.

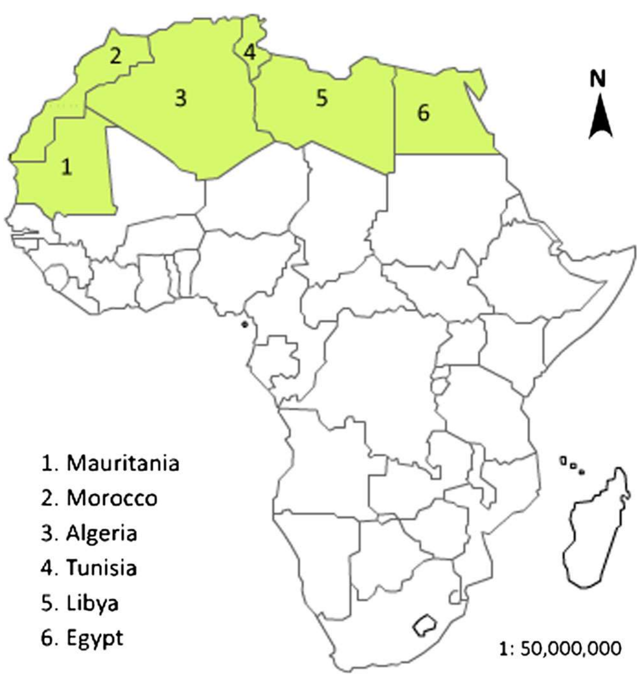

Fig. 1 Location map of North African countries according to African Union (SWAC 2017)

The main Mauritanian coastal aquifers were Continental Terminal (CT), Boulanouar, Benichab, Trarza, Aleg and Kaédi, and Alluvium aquifer of the Senegal River Valley. The exploitable water reserves in these coastal aquifers are of 953 × 10^6 m^3 with a salinity ranging from 256 to 1423 mg/l. Morocco has two sea fronts of 3500 km (500 km on the Mediterranean and 3000 km on the Atlantic). The coastal area is important due to its size and strategic role in economic development. It is characterized by dense population in addition to multiple economic activities.

Geologically, Algeria is located in the northwestern Africa on the Mediterranean Sea. This country is divided into two major tectonic units, separated by the South Atlas fault, which has been strongly affected by alpine tectonic. The Saharan platform in the south of Algeria (Saharan domain) is relatively stable and tectonic impact is less pronounced.

Coastline represents 4% of the territory limits in Algeria. It is made up of a coastal area and over a length of 1200 km and a string of Tellian Mountains which contain various basins and rich interior plains. This set has 2.5 million hectares of the national useful agricultural area. More than 60% of the total Algerian population currently lives in the northern coastal area.

The complex tectonic has segmented the major geological units from the Mesozoic to the Cenozoic, resulting in significant number limited compartmentalized aquifer units. The main coastal shallow aquifers are hosted in recent and quaternary unconsolidated Cenozoic sedimentary aquifers in the coastal plain. The high aquifer permeability's may be the origin of groundwater vulnerability and induce saline water intrusion. Much of the aquifer recharge comes from direct infiltration of precipitation.

Tunisia shows five structural zones which translate its position of transition between the geological units from the Alpine Origen in the North and African craton in the South. Hydrogeologically, Tunisia is characterized by deep aquifers in the south shared with Algeria and Libya. As for the north, surface water (dams and rivers) is the main source of fresh

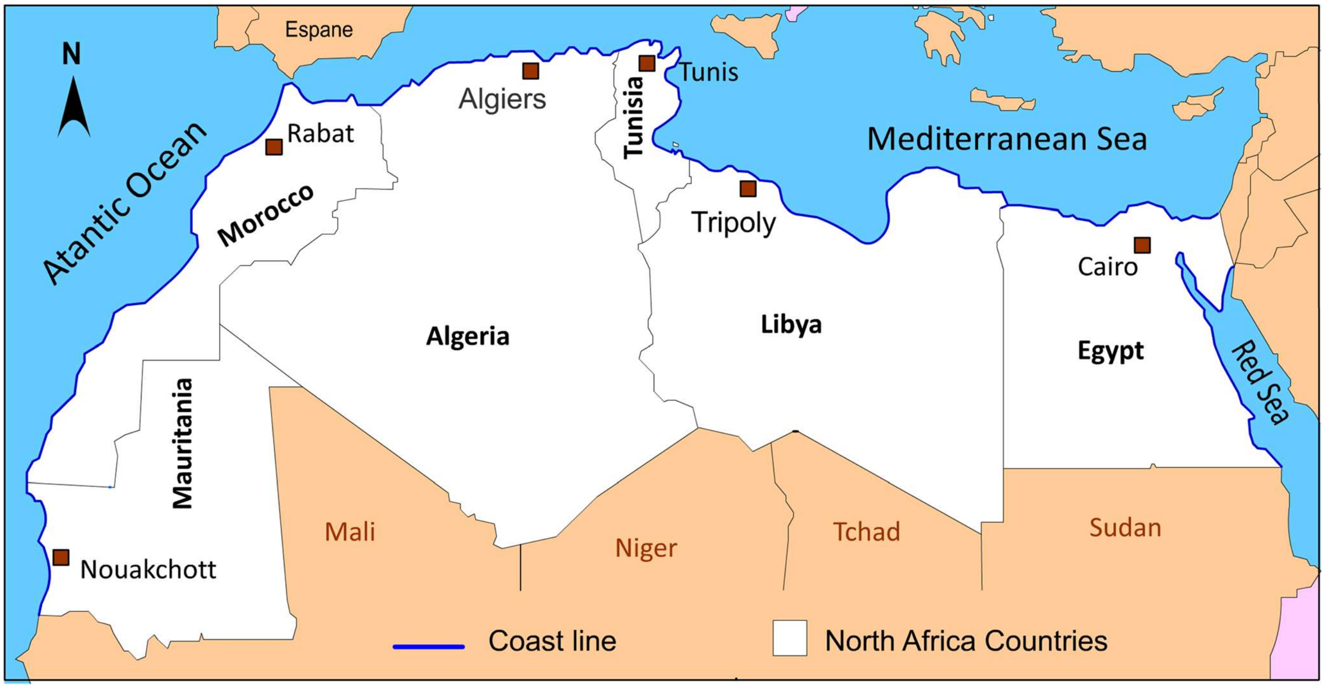

Fig. 2 Geographical extent of North African countries

water. Coastal areas in Tunisia are the most populated in Tunisia. Agricultural, tourist, and industrial activities are potential consumers of groundwater. It has a coastline stretching over 1148 km containing significant aquifers which are threatened by saltwater intrusion. Tunisia is characterized by a semi-arid climate over most of its territory and has limited water resources with variable recharge depending on the year and uneven spatial distribution. The main coastal aquifers in Tunisia are the Jeffara coastal aquifer; it extends from the Tunisian-Libyan border to the south of Sfax, the Sahel aquifer, Cap Bon aquifer, Grombalia aquifer, Bizerte, and Jandouba aquifers in the north.

Libya has two main geographic areas, the Mediterranean coastal area and Saharian province. The Libyan coastline stretches for 1750 km. The fertile lands are the coastal areas such as Jeffara plain, Misrata, Gulf of Sirte, and Ben Ghazi. The climate of Libya is semi-arid in the north and arid, dry, and hot aver all territory. Libyan coastal aquifers are the most used to meet the needs of the population, 90% of which are installed on the Mediterranean coast, and of economic development, which leads to a deterioration in the quality of groundwater and causes the marine intrusion of coastal aquifers.

However, the territory of Egypt consists mainly of desert. Only 3.5% of the country's surface is cultivated and inhabited permanently. Most of the Egyptian territory is located within the wide African desert strip. Of course, Egypt is subdivided into four major natural regions, the Nile Valley and the Nile Delta; the Western Desert west of the Nile; the Eastern Desert on east of the Nile River; and the Sinai Peninsula to the northeast.

Nile Valley and Nile Delta are the most important regions, being the only cultivable regions (with the exception of a few scattered oases) and comprising 99% of the population. The Nile Valley stretches for approximately 800 km between Aswan and Cairo.

Saltwater intrusion in north Africa coastals areas

The climate change impacts, such as decreased precipitation and sea level rise, could amplify salinization of coastal aquifers. Moreover, anthropogenic activities (excessive abstraction) could lead to a negative impact on coastal fresh groundwater. Coastal aquifers provide important quantities of freshwater. Their overuse affects the quality and quantity of groundwater. This induces the dropdown in piezometric levels and the saltwater intrusion (Niazi 2002). The salinization of coastal aquifers is a major hydrogeological risk affecting coastal regions, which are often densely populated and highly dependent on groundwater (Cheng 2003 in Niazi 2002). The coastal areas of the Mediterranean basin are particularly sensitive to this phenomenon. North Africa costal aquifers, from Mauritania to Egypt, will be the subject as following.

Seawater intrusion in Mauritanian Atlantic coastal area

Mauritania has a large coastal area extending from the Nouadhibou in the north to Rosso on the Senegalese borders

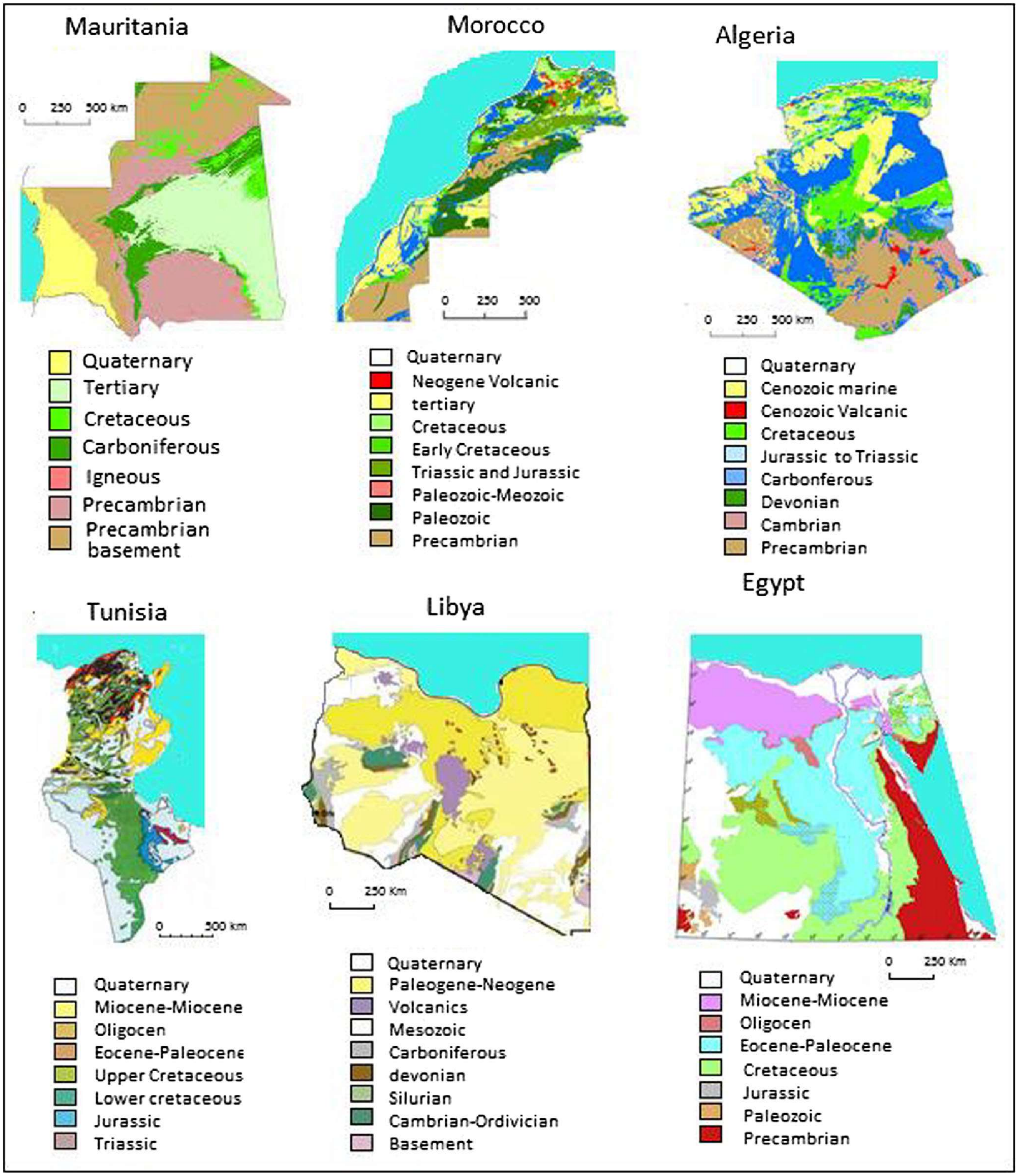

Fig. 3 Geologic maps of northern Africa countries (after Schlüter 2006, modified)

to the south. Coastal area is the most densely populated in the country. It includes the main cities such as the capital Nouakchott (holds over 27.1% of the country's population) (Friedel and Finn 2008) and the Nouamghar, Nouadhibou, and Rosso. The Mauritanian coastal basin forms a highly developed continental shelf on which a series of sedimentary layers have been deposited (Fall et al. 2017) and characterized by a desert climate under the influence of the Atlantic Ocean. This plain is experienced a growing population and socio-economic development.

The coastal Mauritanian part has been the subject of several works that have raised saltwater intrusion issue (Friedel and Finn 2008**;** Mohamed et al. 2017; Littaye and Ould Ahmed 2018; Mohamed et al. 2020). Mohamed et al. (2017) undertook works on the impact of climate change and eutrophication of groundwater in Nouakchott. Littaye and Ould Ahmed (2018) have focused on costal dynamics in Mauritania. They highlighted that Mauritanian coastal areas were threatened by sea level rise. Other studies such as El-Raey 2010 have shown that coastal water resources in the Nouakchott region are today influenced by climate change and anthropogenic effects, thus causing a quantitative and qualitative deterioration of groundwater resources. This issue is highlighted in the Benichab coastal aquifer by Mohamed et al. (2020). They have highlighted that groundwater salinization is due to over-abstraction and seawater mixing with a mean value of 8.42% and groundwater is dominated by NaCl.

Several methods of saltwater intrusion investigation have been used in coastal Mauritanian coastal areas. Most works undertaken in Mauritian coastal areas have based on water table measurements (Friedel and Finn 2008; Mohamed et al. 2017; Littaye and Ould Ahmed 2018), chemical indicators (major ions, bromide, ^{18}O, ^{2}H) (Mohamed et al. 2017), and sea level rise monitoring (Littaye and Ould Ahmed 2018).

On the basic of these findings, coastal freshwater resources in coastal basin of Mauritania are affected by saltwater. Several factors have controlling groundwater salinity; among them are natural factors such as drought and sea level rising by 1 to 2 m over the last 40 years (Mohamed et al. 2017), in addition to the excessive pumping as result of population growth. The topography of coastal basin shows a geomorphological depression which runs parallel to the coastline. Nouakchott has an elevation ranging from 1 m below sea level (−1 m) to 1 m above sea level (+1 m) (Mohamed et al. 2017). This situation further complicates the situation and favors the contamination of fresh water in the coastal basin.

Figure 4 shows that the coastal zone is entirely contaminated by saline waters with variable extensions sometimes exceeding a few tens of kilometers, especially in the region located between the aquifers of Benichab and Trarza.

Morocco: saltwater intrusion state

Morocco has two sides of coastal areas, the Mediterranean Sea in the north and Atlantic Ocean in the west. The Moroccan coasts have a rich environmental and ecological heritage both in terms of its intrinsic value and its demographic and socio-economic interest. It is home to a rich and varied environmental heritage which provides the freshwater resources at the base of various economic activities. This explains the human and urban concentration, more and more diffuse, sustained, and dense in these spaces. El Stitou Messari et al. 2003have indicated that, in Morocco coastal areas, high abstraction rates and low recharge have led to an imbalance in the freshwater/seawater equilibrium. This imbalance has produced a fall in the hydrostatic level, an inversion in the direction of groundwater flow, and, finally, marine intrusion (El Stitou Messari et al. 2003; Zouhri et al. 2010).

Studies carried out in Morocco such as Lakfifi et al. (2004), Bouya et al. (2011), Bzioui (2004), Hilali et al. (2003), EL Mokhtar et al. (2018), and Zouhri et al. (2010) have highlighted that coastal areas of Morocco was threatened by saltwater intrusion both in Atlantic side and Mediterranean coastal areas. Authors have concluded that the increase in water demand, together with the impact of the long drought over the last years, has given rise to high levels of abstraction from coastal aquifers, such as those of Sous, Haouz (Rochdane et al. 2015), the Rhiss-Nekor aquifer of Nador area (Baite et al. 2018), around Tetouan (Martil-Alila and Smir aquifers) (Hilali et al. 2003), Rabat (Temara aquifer), and Casablanca (Rharb aquifer) (Zouhri et al. 2010), Foum El Oued (El Mokhtar et al. 2018); Chaouia coastal aquifer (Lakfifi et al. 2004); Mnasra plain (Bouya et al. 2011); Jadida et Oualidia (Haddani 2010). The Atlantic oceanic side of Morocco comprises a large area in the west part of the country. The advances of the Meseta divide the coastal area into a series of sedimentary basins and coastal plains that comprise 20% of the total surface area of the country (El Stitou Messari et al. 2003).

Most of Morocco's coastal aquifers, located on the Atlantic coast, are in high demand to meet the needs of the population and agricultural activities, which leads to a lowering of the water table. El Mokhtar et al. (2018) indicated that these aquifers undergo remarkable piezometric fluctuations in some boreholes. In addition, these aquifers show a salinity which increases towards the coast line.

Through studies of marine water leakage in the coasts of Morocco, it can be observed that the methods widely adopted in the vast majority of studies are geochemical and stable methods. The results showed that the surface water is highly concentrated and characterized by NaCl water. Some studies such as Zouhri et al. (2010), El Alami et al. (2017), and Himi et al. (2017) have also adopted the geophysical method using electrical resistance, analytical methods, and GIS applications. In spite of the important results reached by the researchers, increased scrutiny of the data on coastal tables remains a necessity to increase knowledge and diagnosis of the reality of the coastal tables in Morocco, especially in the Atlantic coast, which is more vulnerable to seawater intrusion.

Saltwater intrusion problem in Algeria

In Algeria, seawater intrusion is a serious problem that threatens coastal aquifers (Morsli et al. 2017). A groundwater salinization of the coastal aquifers such as Annaba and Oran was detected (Saaidia et al. 2017; Djabri et al. 2013;

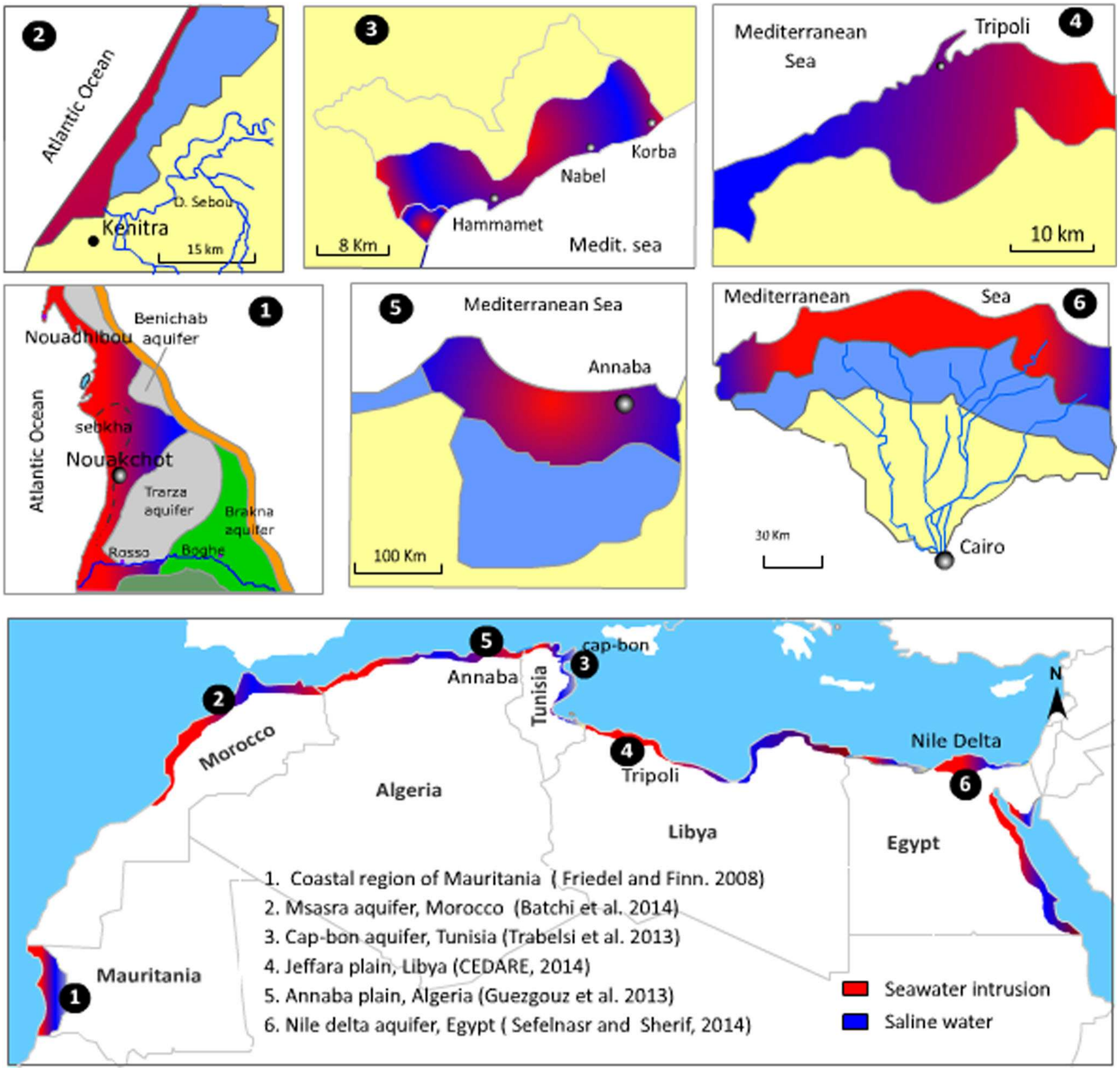

Fig. 4 Seawater intrusion map in North African coastal area

Bouderbala et al. 2016). This phenomenon has become more pronounced with climate change, population growth, and especially the increase in the density of populations near the Algerian coasts. This problem of salinization of coastal aquifers is of great importance for any coastal zone such as Algeria, which opens widely to the Mediterranean Sea (1200 km of coast) and whose coastal areas constitute large food regions.

As a result of excessive exploitation, the coastal aquifers could thus be affected by the phenomenon of saltwater intrusion. Works undertaken in the Algerian coastal areas was initiated at the end of the twentieth century (Imerzoukene et al. 1994). Their objectives were to understand the effect of urbanization and climate change on water resources using various geochemical, geophysical, and stable isotope approaches to demonstrate and quantify marine intrusion into coastal aquifers.

In Algeria, several works have carried out to highlight seawater intrusion such as Imerzoukene et al. (1994), Morsli et al. (2017), Saaidia et al. (2017), Djabri et al. (2013), Bouderbala et al. (2016), Moulla et al. (2013), and Steyl and Dennis (2010). As an indication, the work carried out within the framework of the intrusion study is based on the analysis of geochemical and isotopic data of groundwater. Thereby, Morsli et al. (2017) used a multidisciplinary approach (piezometric data, chemical data, and geophysical method) to demonstrate that intensive pumping associated with the rainfall deficit and the lithological nature are the main factor controlling seawater intrusion in Algiers aquifer. At the same way, Saidiaa et al. (2017) have identified seawater intrusion in the plain of Collo, northeastern Algeria. They have indicated that a reversal of hydraulic gradient took place at the level of the aquifer and the flow is reversed towards the continent.

Studies have shown that the coastal groundwater in Algeria is under the influence of over-exploitation and suffers from seawater intrusion (Imerzoukene et al. 1994), especially during the dry season and periods of poor rain. The groundwater system suffers from a continuous decrease in the water level between 20 to 50 m per decade, which increases the speed of seawater infiltration at the level of coastal areas (WBG 2020).

Saltwater intrusion in Tunisian coastal aquifers

Tunisia is bordered to the north and east by the Mediterranean Sea. It is ranked fourth, after Egypt, Morocco, and Libya, on the basis of the length of coastline (WFB 2006). It is characterized by intense agricultural, tourist, and industrial activities on its coastal areas accompanied by an urban extension. This has led to a high demand for freshwater to meet the needs of economic activities and the expansion of the population. Like other Mediterranean countries, Tunisia has initiated a sustainable management of its water resources and in particular the monitoring of coastal aquifers. Thereby, Tunisia has been experiencing seawater intrusion since 1970 and currently the salt load in this unconfined aquifer has peak concentrations of 5–8 g/L (Kouzana et al. 2009).

The last decades have seen a scientific watch and monitoring work in the coastal zone has multiplied. In southern Tunisia, the Jeffara coastal sheet, which stretches from the Skhira region to the Lybian border, has been the site of several studies (Agoubi et al. 2013; Kharroubi et al. 2014; Telahigue et al. al. 2018; Souid et al. 2017; Trabelsi et al. 2013). Others have focused on the eastern Sahel zone of Sfax and Mahdia (Boughriou et al. 2018). The Cap Bon area was the subject of (Tabelsi et al. 2013; Paniconi et al. 2001; Zghibi et al. 2019; Chekirbane et al. 2013; Chaabane et al. 2018), while the northern part of Tunisia (Hammami et al. 2017; Ben Ammar et al. 2014) are focused on northern part of Tunisia.

In Tunisia coastal areas, marine intrusion into coastal aquifers has been demonstrated by geoelectric methods (Agoubi et al. 2013; Chaabane et al. 2018) and major chemical elements (Trabelsi et al. 2013; Agoubi et al. 2013; Kharroubi et al. 2014; Ben Ammar et al. 2014; Telahigue et al. al. 2018; Souid et al. 2017). To identify the processes and chemical reactions that govern the salinization of water tables and determine the limit of marine intrusion, the researchers resorted to interpreting the results using the correlation of major elements with chlorides, the variation of the ratios ionic, the calculation of ionic deviations, and saturation indices.

Cap Bon region northeastern was the subject of several studies and multiple approaches were used (Kouzana et al. 2009; Slama et al. 2010; Trabelsi et al. 2013; Zghibi et al. 2019). Chaabane et al. (2018) used a geoelectrical investigation, using Wenner confguration with a 64-electrode spacing of 5 m to highlight saltwater intrusion in the Maâmoura region. Authors provide a conceptual framework for the understanding of the freshwater–saltwater interface. Zghibi et al. (2019) were coupled ModFlow and MTD models to improve understanding of seawater intrusion into the Korba aquifer in Tunisia. They indicate that seawater wedge as usual scenario is expected to reach 1.8 km from the shoreline.

Works undertaken out in Jeffara plain, southeastern Tunisia, used geochemical data (Kharroubi et al. 2014; Telahigue et al. 2018; Souid et al. 2017; Trabelsi et al. 2013) and geostatistical analysis of geoelectrical data (Agoubi et al. 2013). These works have demonstrate that, in this part of tunisia, the Jerba island and Jorf area are the most vulnerable to seawater intrusion. Boughariou et al. (2018) have undertaken a work using hydrochemical and statistical studies combined with MODPATH numerical model to highlight saltwater intrusion in the Sfax coastal aquifer, southeast Tunisia. Results indicate that the groundwater quality has deteriorated due to natural and anthropogenic processes with a different influence of mineralization factors and revealed seawater intrusion by focusing on the most vulnerable areas which are Chaffar and Djbeniana. The Bizerte water table in the North is highly stressed, which has resulted in a reversal of the hydraulic gradient and, therefore, the advancement of the salty wedge (Hammami et al. 2017; Ben Ammar et al. 2014).

Tunisia diverted the waters of the abstract river to irrigate the agricultural areas in the tribal region and the southern suburbs of Tunis. Libya launched the Great Man-Made River project, which transports more than 6,000,000 m^3 per day of underground water for agricultural irrigation and meeting urban needs in coastal areas.

Based on the foregoing, coastal water resources in Tunisia are among the most studied areas in North African countries. However, it is necessary to evaluate the work results and to define a knowledge database on this topic in order to better manage waterways to ensure sustainable development.

Coastal Libyan aquifer saltwater intrusion

Libya is over 90% desert, with most agriculturally productive land limited to a strip abutting the Mediterranean Sea. Annually, rain is of 100 mm and arable land amounts to about 2.2 million hectares and represents only 1.7% of the total country's area (FAO 2011).

Libya has a coastal area that stretches for 1170 km from the Tunisian border in the west through the capital Tripoli, Gulf of Sirt to egyptian boarder in the East. This area is the most populated in Libya. Economic activities (agricultural and industrial) are located there. A review of recent works in Lybia showed thant the main coastal aquifers are the Jeffara plain (Abdalla et al. 2010; Gejam et al. 2016; Alfarrah and Walraevens 2018), which extends from the Tunisian border to Tripoli, Green Montain and Sirt (Elhassadi 2008; Gossel et al. 2010), and Benghazi region (Al Faitouri et al. 2018). These aquifers are in great demand to meet the needs of the population in the coastal part in the north of the country.

In Libya, several works have been undertaken to highlight the salinization of coastal aquifers and the factors that control it (Abdalla et al. 2010; Gejam et al. 2016; Alfarrah and Walraevens 2018; Elhassadi 2008; Gossel et al. 2010; Al Faitouri et al. 2018; Ekhmaj et al. 2014; El Aswad et al. 2019; Gejam et al. 2016; Salem et al. 2018).

This work shows that several authors have used multiple approaches and different tools for the study of the intrusion in the coastal areas of Libya. They resulted in the intense exploitation of fresh water causing a lowering of the water level in coastal aquifers and causing marine intrusion into most aquifers.

The Jeffara plain and mainly at the level of Capital Tripoli the marine intrusion is the developed one (Steyl and Dennis 2010; Alfarrah and Walraevens 2018; El Aswad et al. 2019; Gejam et al. 2016; Shleag et al. 2014). The same findings were also noted for the water tables in the Sirt region (Brika 2018) and in the east of the country in the Benghazi area (Sadeg and Karahanoğlu 2001).

The city of Derna, in the western part of Libya, is facing severe water shortages due to seawater intrusion (Elhassadi 2008). The saltwater intrusion has steadily increased from 1960 to 2005, a period during which potable water was available; since 2005, a loss of 75% in well production in this aquifer system has been observed.

Most of works have focused on the region of Tripoli, Al-Jabal Al-Akhdar (Green Montain), and eastern part of the Sirt Gulf. Almost, the Jefara plain is deeply studied from 2010 (Steyl and Dennis 2010; CEDARE 2014) to 2019 (El Aswad et al. 2019). Studies undertaken out in this coastal area have used several approaches such us geoschemistry (Alfarrah and Walraevens 2018) and numerical model (El Aswad et al. 2019). Impact of pumping rate on seawater intrusion in Jefara Plain, Libya, was the subject of CEDARE (2014) and Gejam et al. (2016). Shleag et al. (2014) have studied the effect of climate, soil type, and distance from the sea to the seawater intrusion and water quality in Azawia, as part of Jeffara plain. Studies, based on physical and chemical analysis of groundwater samples collected from the Jeffara coastal aquifer, indicate salinization and pollution of the aquifer. The results demonstrate high values of the parameters electrical conductivity, Na^+ , K^+ , Mg^{2+}, Cl^-, and SO_4^{2-}, which can be attributed to seawater intrusion, where Cl^- is the major pollutant of the Jeffara aquifer. Then, a few old works on Benghazi aquifer were found (Sadeg and Karahanoğlu 2001).

Libya has diverted groundwater from inland areas to meet the needs of coastal areas depending on Great Man-Made River. But, this experience may have a negative impact on the groundwater resources of inland Libyan areas.

The available studies have largely used the geochemical approach. More studies on seawater intrusion on the Libyan coasts are necessary to gain a broader understanding of the phenomenon of salinization of coastal waters with the adoption of diversified and advanced research methods for a more comprehensive knowledge base.

Saltwater intrusion in Egypt coastal areas

Egypt has an important coastal strip extending from its Libyan borders in the west to the border with Sudan on the Red Sea in the East, along a length of 2450 km, and thus ranks first in North African countries. Egypt was considered one of the water-rich countries of North Africa (WBG 2020), but the average per capita availability of fresh water has increased from around 1893 m^3 per year in 1959 to around 900 m^3 in 2000 (El-Raey 2010). This places the country below the water scarcity threshold. It is expected that the per capita share of water will continue to decline to 534 m^3 by 2030 (DRS 2010), less than the international water poverty limit, with the expected increase in Egypt's population, which increases competition for water (Abdel-Dayem 2011).

Egypt mainly depends on the Nile water for agricultural irrigation and economic use. However, the coastal areas, where economic activities intensify, depend mainly on groundwater, which ranks second after the Nile River in the list of water resources in Egypt (Mabrouk et al. 2013). Excessive demand on groundwater, excessive abstraction, and climate change (Mabrouk et al. 2013) will lead to the deterioration of water wealth in coastal areas and exacerbate the problem of sea water intrusion. Several works have been undertaken on water salinization in Egyptian coastal areas, whether on the Mediterranean coast or the Red Sea. Studies differ in the used approaches (geochemistry, geophysics, mathematical modeling, stable isotopes). Then, the common goal is to identify areas that suffer from the deterioration of fresh groundwater as a result of seawater intrusion.

Thereby, Sefelnasr and Sherif (2014), El-Kiki (2018), and Sallam (2018) studied the effect of seawater intrusion on the delta region and solutions that help to reduce this phenomenon. Studies have demonstrated that the delta region is the most threatened by saltwater intrusion. Sefelnasr and Sherif (2014) have developed, based on 150 sampled points, a numerical model using FEFLOW in which they combined the effect of increased groundwater pumping, due to the possible decline in precipitation and shortage in surface water resources, with the expected landward shift of the shore line. Two scenarios were presented, the first with a 0.5 m seawater rise while the total pumping is reduced by 50%, the second a 1.0-m seawater rise and the total pumping is changed (Sefelnasr and Sherif 2014). They concluded that large areas in the coastal zone of the Nile Delta will be submerged by seawater and the coast line, which accelerate the marine intrusion into aquifer and the advancement of the saline wedge.

Others have looked at the impact of the climate changes and their effects on water resources in the Delta area (Mabrouk et al. 2013). Authors consider the decline of the Nile River water levels due to climatic change can affect groundwater quality in Nile Delta aquifer, and may be at the origin of the marine intrusion in this aquifer. Eissa et al. (2018) have works on saltwater intrusion in Ras El-Hekma, northwestern Coast, Egypt. They demonstrate that a progressive extension of the seawater intrusion distance has been extended from 1700 to 5000 m from the tip of Ras-El Hkema to inland. Authors confirm that in the model of that seawater intrusion, in which hydrogeological and geochemical characterization were combined, saltwater intrusion is caused by the unbalance between the pumping withdrawal rates and the natural recharge from precipitation. Several studies have been carried out in Red Sea coastal aquifers (Gomaa et al. 2017; Isawi et al. 2016). A great salinization is observed in Sinai coastal area (Isawi et al. 2016), Marsa Alam and El-Qusier aquifers (Gomaa et al. 2017). Authors indicate that hydrochemical results reflect variation in water salinities and NaCl water type is the most dominant that could be the result of seawater mixing. Likewise, some works carried out in Sharm EL-Shiekh Area, Southern Sinia, such as in Isawi et al. (2016), have shown, using geochemical data, Saltwater Mixing Index (SMI) and stable isotopes, that the groundwater is contaminated by saltwater intrusion around 16%.

According to the results, it appears that studies on the extent of seawater intrusion along the coastal strip in Egypt have included many areas, whether on the Mediterranean coast or the Red Sea as they are mainly focused on the delta region, which is the most important area in Egypt. The delta region is considered one of the most important coastal areas exposed to sea water leakage as a result of natural factors such as the rise of the sea in Egypt and the excessive exploitation of water resources as a result of population density and the low water level of the Nile Valley. Recent studies have to a large extent used geochemical and isotopic approaches and numerical modeling methods (Isawi et al. 2016; Sefelnasr and Sherif 2014). Other studies have also adopted statistical and statistical approaches. Therefore, the Egyptian coasts need more strategic studies to draw realistic conclusions about the danger of seawater intrusion in the coastal areas on the coasts of the Mediterranean, the Red Sea, and the Sinai Peninsula.

The review of seawater intrusion studies along the North Africa coastline from Mauritania to the Egypt-Sudan border reveals some interesting findings. A large number of studies were found on seawater intrusion in most countries such as Egypt, Tunisia, Morocco, and Algeria of equal importance, while these studies were in Libya and Mauritania to a lesser extent, but they are non-existent in the western Sahara region. The importance and frequency of seawater intrusion studies varies according to the priorities of some countries such as Libya, Mauritania, and the western Sahara region, which appear to be linked to other more urgent issues such as food security and economic and political stability (Idowu and Lasisi 2020).

It was found that important studies related to seawater intrusion in Egypt is in the Nile Delta, while it included separate areas on the Red Sea costal, the Gulf of Aqaba, and the northern coast on the Mediterranean Sea. Furthermore, studies related to seawater intrusion in Libya covered the areas extending from Al-Jufra Plain from the western region to Misrata. In contrast, studies related to the eastern region were found such as Derna and Benghazi (Sadeg and Karahanoğlu 2001; Elhassadi 2008). Saltwater intrusion studies also covered most of the Tunisian, Algerian, and Moroccan coasts. In Mauritania, most of the founded studies focused on sea level rising threatening of the coastal area and groundwater salinization (Steyl and Dennis 2010; El-Raey 2012; Mohamed et al. 2017; Mohamed et al. 2020). Studies have revealed that the technique most used is the geochemical method along with statistical techniques and the seawater intrusion index (SWII). Some studies used geographic information system (GIS) linked to geochemical methods for mapping the extent of seawater intrusion. Whereas the geophysical approach was adapted to a lesser extent as it was combined with geochemical method. Other studies included other techniques such as stable isotopes, GALDIT superposition index, and numerical modeling techniques.

A holistic view of the seawater intrusion study's findings shows that seawater intrusion extent varies from country to another (Fig. 4). Seawater intrusion depends of aquifer hydrogeological settings, hydrodynamics, and well abstraction rates. It is shown in Fig. 4 that the most saltwater intrusion is observed in Nile Delta in Egypt (30 km, after Sefelnasr and Sherif 2014), In Mauritanian costal area, according to Friedel and Finn (2008), saltwater intrusion exceeds 25 km, and in Jeffara plain, Libya, the seawater intrusion inland is about 15 km, after CEDARE (2014). Nonetheless, at other aquifer in the African coastal region, it does not exceed a few hundred meters. As an indication, according to Agoubi et al. (2013), the extension of the marine intrusion in the Jorf aquifer, southeastern Tunisia, is of the order of 1200 m.

From a global view, sightings of seawater intrusion in North Africa intersect with other sightings in other coastal countries in Africa and worldwide. In this way, the review by Werner (2010) on the saltwater intrusion along the coastlines of Australia concluded that the marine intrusion depends on hydrogeological aquifer configuration, exploitation, and sea level rise. A more recent review on saltwater intrusion in Horn Africa region by Idowu and Lasisi (2020) shows that geochemical techniques coupled with statistical and analytical tools are the most prevalent approaches used. Furthermore, the extents of saltwater water intrusion vary significantly from location to location but rarely extend beyond a few km inland in the coastal region. Generally, it can be concluded from these comparative studies and seawater intrusion review in different places that each coastal part has its own unique hydrogeological settings that control the seawater extent (Idowu and Lasisi 2020).

Future challenge and saltwater intrusion management

Most of the studies found show that the challenges posed by climate variability and change in North Africa are widely recognized (IPCC 2007). In addition, complex natural and anthropological factors negatively affect coastal freshwater, both quantitatively and qualitatively. While not exhaustive, this paper pinpointed some general challenges with North Africa countries related to seawater intrusion and can amplify freshwater costal water salinization. Generally, these challenges can be identified in the following: (i) unexpected climate changes, as temperatures recorded for the month of August 2020 exceeded the usual rate, which portends a complex climate situation that may lead to the lack of rain and its frequency. (ii) Rising sea levels threaten many low-lying areas of North Africa. (iii) Rapid population growth. Statistical studies indicate that the population of North Africa will double by 2050 and this will increase the demand for fresh water, especially in the more densely populated coastal areas. (iv) The acute shortage of fresh water, especially in coastal areas, threatens a water crisis in most North African countries.

To mitigate these challenges and reduce potential risks, many North African countries have sought to adopt sustainable water management and good governance by taking measures to protect water resources, reduce seawater intrusion, and develop water resources. The available studies indicated that Manage Aquifer Recharge (MAR) was one of the main approved solutions (Chaieb 2014; Comte et al. 2016; Ebrahim et al. 2020). MAR is practiced in greatest abundance in North African coastal areas. In a recent review on MAR in African countries by Ebrahim et al. (2020), it was indicated that Tunisia, Algeria, Egypt, and Morocco present evidence of MAR implementation. Treated wastewater is used in countries with limited water resources such as Tunisia (Kouzana et al. 2009; Chaieb 2014) and Morocco (Bennani et al. 1992). Some river water is also used to aquifer. According to Bouchaou (2012) and Bouragba (2011), Souss-Massa aquifer in Morocco is recharged using river water.

According to Comte et al. (2016), the management of coastal groundwater poses a further challenge due to its vulnerability to seawater intrusion and the specific physical and socio-economic characteristics of the coastal zone. The review of Steyl and Dennis (2010) is one of the very few works that provide insights on common issues with regards to groundwater management in coastal aquifers of Africa.

Finally, the studies referred point to the fact that more steps in terms of research and management need to be taken in North African countries. The challenge of inadequate data and a need for a more robust data inventory was stressed. For instance, more expertise and experience were needed on the part of local researchers. In areas where the impact of seawater intrusion is more apparent, such as Nile Delta in Egypt, Mauritanian coastal area, and Jiffara plain in Libya, effective management was suggested to reduce seawater intrusion future effects (Comte et al. 2016, Ebrahim et al. 2020).

Conclusion and recommendations

This paper reports systematical saltwater intrusion schemes over the North African countries and review experiences. This work has compiled information on several cases of saltwater intrusion in North Africa. In view of this review's findings, we can conclude:

- Coastal areas in North Africa have experienced demography expansion that increases freshwater demand as well as a quantitative and qualitative degradation of groundwater from coastal aquifers.
- The work undertaken in the North African region is quite numerous and interesting with the exception of the west Sahara region. The most used methods are chemical analyses, statistical analysis sometimes coupled with GIS, and the GALDIT index. The results were able to highlight the marine intrusion in the majority of coastal areas.
- The extent of the marine intrusion differs from one area to another and depends on the hydrogeological parameters of the aquifer and its rate of exploitation. The extension of the intrusion of seawater does not exceed a few kilometers in most of the areas studied, but it is too remarkable in the Jiffara plain in Libya, the coastal region of Mauritania, and the Nile Delta where the extension exceeds a few tens of kilometers.

– The management of coastal aquifers and the fight against marine intrusion in these countries are relatively limited. Some countries show significant experiences in this area such as the case of Tunisia, Morocco, and Egypt. However, the management of coastal aquifers remains limited in other countries.

From a future perspective, it is likely that there will be an urgent need for North African countries as well as similar regions for a paradigm shift in coastal aquifer management in the coming years to protect freshwater resources in light of the challenges of climate change, sea level rise, and increased population growth.

Finally, partnerships at the regional and international levels are necessary to enhance research, exchange experiences and focus joint research projects to ensure rational water management and achieve food security for North African regions that will need effective partnership and joint planning for groundwater sustainable development.

Author contribution This work is the contribution of the corresponding author.

Data and materials availability The data supporting this review are from previously reported studies, which have been cited in this manuscript.

Declarations

Competing interests The author declares no conflict of interest.

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