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# Coastal Aquifers: Seawater/Saltwater Intrusion. Impact of the coronavirus (covid-19) on the environment, climate change and water resources

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**Abstract**

*This paper describes the general view of Coastal Aquifers: Seawater/Saltwater Intrusion and groundwater problems in coastal aquifer. The Modeling seawater intrusion and groundwater flow pollution of this chapter is to set the stage for the modeling procedure and methodology. The relative impacts of anthropogenic interventions and global climate change on the dynamics of saltwater intrusion in highly urbanized coastal aquifers and the consequences of climate change on groundwater are long term are examining and can be far reaching. One of the more apparent consequences is the increased migration of salt water inland in coastal aquifers. The artificial recharges techniques in semi-arid areas and the Tunisia's experience in artificial recharge (water from the dam and treated wastewater) are described. The 'Tunisia's experience on Artificial Recharge of Groundwater' is the first in the semi-arid areas and has updated information on various aspects of investigation techniques for selection of sites, planning and design of artificial recharge structures, their economic evaluation, monitoring and technical auditing of schemes and issues related to operation and maintenance of these structures. The Impact of the coronavirus (covid-I9) on the environment and water resources COVID-I9 serves as a reminder of the critical importance of water and sanitation services, and should encourage Governments to prioritize the availability and sustainable management of water and sanitation for all, as stipulated in Goal 6 of the 2030 Agenda for Sustainable Development and the Human Right to Water and Sanitation.*

**Key Words***:* Seawater Intrusion, Coastal aquifer, Modeling, Climate change, Coronavirus (covid-19).

## Impact Covid-19 dans les régions Moyen-Orient et Afrique du Nord (MENA)

**Résumé**

*Cet article décrit la vue générale des aquifères côtiers : intrusion d'eau de mer/eau salée et problèmes des eaux souterraines dans les aquifères côtiers. La Modélisation de l'intrusion d'eau de mer et de la pollution par l'écoulement des eaux souterraines de ce chapitre vise à préparer le terrain pour la procédure et la méthodologie de modélisation. Les impacts relatifs des interventions anthropiques et du changement climatique mondial sur la dynamique de l'intrusion d'eau salée dans les aquifères côtiers fortement urbanisés et les conséquences du changement climatique sur les eaux souterraines sont examinés à long terme et peuvent avoir une grande portée. L'une des conséquences les plus apparentes est la migration accrue de l'eau salée vers l'intérieur des terres dans les aquifères côtiers. Les techniques de recharges artificielles en zones semi-arides et l'expérience de la Tunisie en matière de recharge artificielle (eau du barrage et eaux usées traitées) sont décrites. L'expérience de la Tunisie sur la recharge artificielle des eaux souterraines est la première dans les zones semi-arides et a mis à jour les informations sur divers aspects des techniques d'investigation pour la sélection des sites, la planification et la conception des ouvrages de recharge artificielle, leur évaluation économique, le suivi et l'audit technique. des schémas et des enjeux liés à l'exploitation et à l'entretien de ces ouvrages. L'impact du coronavirus (covid-I9) sur l'environnement et les ressources en eau COVID-I9 rappelle l'importance cruciale des services d'eau et d'assainissement, et devrait encourager les gouvernements à donner la priorité à la disponibilité et à la gestion durable de l'eau et de l'assainissement pour tous , comme stipulé dans l'objectif 6 de l'Agenda 2030 pour le développement durable et le droit humain à l'eau et à l'assainissement.*

**Mots clés :** Intrusion d'eau de mer, Aquifère côtier, Modélisation, Changement climatique, Coronavirus (covid-19)., .

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## INTRODUCTION

Many people lack of access to the most basic weapons to shield themselves from COVID-I9: water and soap. UN-water reports that 2.2 billion people around the world do not have safely managed drinking water, while 4.2 billion go without safe sanitation services and three billion lack basic handwashing facilities. Furthermore, an estimated 896 million people use health care facilities with no water service and I.5 billion use facilities with no sanitation service. These conditions present a constant source of stress and disease, particularly for vulnerable and marginalized communities where people sometimes need to skip bathing to save water for cooking [1].
In many arid and semi-arid regions, surface water resources are limited and ground water is the major source for agricultural, industrial and domestic water supplies. Because of lowering of water tables and the consequently increased energy costs for pumping, it is recognized that ground water extraction should balance ground water recharge in areas with scarce fresh water supplies. This objective can be achieved either by restricting ground water use to the water volume which becomes available through the process of natural recharge or by recharging the aquifer artificially with surface water. Both options require knowledge of the ground water recharge process through the unsaturated zone from the land surface to the regional water table. As seawater intrusion progresses, existing pumping wells, especially close to the coast, become saline and have to be abandoned, thus, reducing the value of the aquifer as a source of freshwater. As an aid to effective management, many models have been developed over the years to represent and study this problem. They range from relatively simple analytical solutions to complex state-of-art numerical models using large computing capacity [2].
Groundwater also provides the largest amount of the total water resources in other countries. For example, in Tunisia it is about 95% of the total water resources, in Morocco it is 75%. Continuously increasing development has led to overexploitation of groundwater resources and growing impacts of human actives on aquifers in many countries, such as decline in groundwater levels and deterioration of groundwater quality. Groundwater is said to be contaminated when contaminant concentration levels restrict its potential use. Groundwater pollution caused by human activities can be broadly classified as point-source and non-point-source pollution [3].
Usually, quantity problems are directly related to groundwater extraction by human beings more or less. Over-extraction of groundwater modifies drastically piezometric head fields and groundwater flow patterns, inducing various drawbacks [4]. The term "over-extraction" can be defined as the condition, in which the total amount of groundwater extraction from an aquifer is close to or greater than the total recharge for several years [5]. According to Bouwer [6], degradation of groundwater quality can take place over large areas by the plane (or diffuse) sources through deep percolation from intensively farmed fields, or it can be caused by point source such as septic tanks, garbage disposal sites, cemeteries, mine spoils, oil spills or other accidental entry of pollutants into the underground environment. Next, natural chemical constituent within groundwater as a result of water-rock interaction presented by Todd [7]. Dissolved inorganic constituents in natural groundwaters can be subdivided inti major, minor and trace constituents [8].
Numerical models for groundwater quality and Tunisia's experience in artificial recharge, exploitation and management – rather than on their shared features and theoretical principles. Assessing the quality of this data is extremely difficult and was considered not feasible in preparing this compilation [2].

## GENERAL VIEW OF SEAWATER/SALTWATER INTRUSION AND GROUNDWATER PROBLEMS

Groundwater is the water that occurs in the voids between the subsurface soil particles and in the cracks. The large quantities of groundwater are found in aquifers. Groundwater is the primary source of water for human activities such as agriculture, industry and domestic drinking water especially in regions with limited annual precipitation [7]. Because groundwater is located at deep locations, it is less vulnerable to pollution. However, anthropogenic activities such as fertilization and other pollution sources beside over exploitation of the aquifers create serious problems to groundwater quality. The intensive use of natural resources and the large production of wastes in modern society often pose a threat to groundwater from aspects of quantity and quality. Usually, quantity problems are directly related to groundwater extraction by human beings more or less. Over- extraction of groundwater modifies drastically piezometric head fields and groundwater flow patterns, inducing various drawbacks [4]. The term "over-extraction" can be defined as the condition, in which the total amount of groundwater extraction from an aquifer is close to or greater than the total recharge for several years [5].
There are different types of pollutants that can be found in groundwater, such as nitrate, heavy metals and saltwater. Intrusion of saltwater is the most common contamination occurrence in coastal aquifers [9]. Intrusion


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of saltwater occurs when saltwater displaces fresh water in an aquifer. The phenomenon can occur in deep aquifers with the advance of saline waters of geologic origin, in shallow aquifers from surface waste discharge, and in coastal aquifers from the invasion of seawater [7]. Over pumping of groundwater wells that located near the shoreline is a major cause of encroachment of saltwater into the aquifers and may lead to saltwater intrusion. The total world freshwater supply is estimated to be 4I,022 billion $m^3$ [10]. The freshwater supply of different continents and annual withdrawals for domestic, industrial, and agricultural water uses. As can be seen in this table, annual withdrawal is about 8% of the total freshwater supply, and the agriculture sector, with 69% usage, has the highest rate among the water uses.

The last one is associated with the quantity problems, and hydrogeochemical study is one of the most promising ways to identify sources of contaminant and to solve some kinds of groundwater problems [11, 12]

An estimated eight to ten million cubic kilometers ($km^3$) of fresh groundwater represents the lion's share of all liquid freshwater on Earth, or to be more precise: about 98 to 99% of it [13]. In comparison, the global volume of freshwater in lakes is less than I% of the total fresh groundwater volume. However, the volume of freshwater stored in the Earth's crust represents only one per cent of the total volume of water in the hydrosphere, including the oceans.

Saltwater intrusion is one of the main causes of groundwater quality degradation and a major challenge in the management of groundwater resources in coastal regions. Saltwater intrusion causes an increase of salt concentration in groundwater which places limitations on its uses. Excessive pumping always leads to a dramatic increase in saltwater intrusion. In coastal aquifers, the hydraulic gradient exists towards the sea which leads to flow of the excess freshwater to the sea. Seawater intrusion (SWI) is a special category of groundwater contamination that threatens the health and possibly lives of the people living in coastal areas. The problems of saltwater intrusion into groundwater had become a considerable concern in many countries particularly in coastal areas. Seawater intrusion leads to the depletion of groundwater resources and should be prevented or controlled to protect water resources in coastal regions. The intrusion of saltwater in coastal aquifers has been investigated by several methods including geophysical methods, geochemical methods, experimental studies and mathematical models.

The knowledge of hydrogeochemical processes helps to get insight into the evaluating of contributions of rock-water interaction and anthropogenic influences on groundwater quality. These geochemical processes are responsible for the seasonal and spatial variations in groundwater quality [14, 15]. Groundwater chemically evolves by interacting with aquifer minerals or internal mixing among different groundwater along flow- paths in the subsurface [16, 17, 18]. These processes that govern the groundwater quality were the focus of many previous studies. In Saether [19], were interested in the geochemical processes such as weathering taking place in catchments. The cation exchange in a coastal aquifer was the focus in Martinez [20], they studied the effect of overexploitation of an unconfined aquifer on the groundwater quality in the coastal aquifer of Mar del Plata in Argentina. In Ikeda, [21], found out that investigation on processes of groundwater quality formation including the water-rock interaction and salinization process is a successful way to clarify the hydrological phenomena such as flow and mixing of water in the Southern foot of Mount Fuji. The study in Pulido-bosh [22], treated the effect of agricultural activities, high pumping and dissolution of carbonate rocks on the aquifer's chemical compositions in the coastal aquifer of Temara in the Northwestern region in Morocco. Furthermore, the main target in Kumar [23], was the identification of different hydrogeochemical processes such as dissolution, mixing, weathering of carbonate and ion exchange in the groundwater of Muktsar, Punjab, using conventional graphical plots and multivariate analysis.

Saltwater intrusion in coastal aquifers is a severe problem that many countries have to face at present, due to the fact that it contaminates groundwater aquifers and even surface water, leading to the unavailability of water resource for domestic, agricultural use and other consequences [24]. Seawater intrusion or called "saltwater intrusion" is a specific process of groundwater contamination [25]. This phenomenon draws special attention in the management of the coastal aquifers. As seawater intrusion progresses, a part of the aquifer close to the saline water. In such case, pumping wells operated there have to be controlled. Seawater intrusion (SWI) is a principal cause of fresh groundwater salinization in many regions of the world [26]. The seawater occupies the void space in the aquifer formation beneath the sea. This seawater zone in the aquifer extends to some distance landward from the coast below freshwater zone. Consequently, a zone of transition between freshwater and saltwater exists and it is referred as "interface zone" or more simply "interface" [27].

The causes of this problem differ due to various factors such as geological factors, human activities and regional economic level. Groundwater depletion has been recognized as the biggest driver in most stricken areas. It is


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believed that groundwater will become saltier in the future considering the exploding population, increasing demands for agriculture and all other economic activities together with the changing climate and rising sea level [28]. The intensive extraction of groundwater from coastal aquifers reduces freshwater outflow to the sea and creates local water table depression, causing seawater to migrate inland and rising toward the wells [29,30,31], resulting in deterioration in groundwater quality. This phenomenon, called seawater intrusion, has become one of the major constraints imposed on groundwater utilization in coastal areas. Saltwater intrusion is one of the most widespread and important processes that degrade water quality to levels exceeding acceptable drinking and irrigation water standards and endanger future water exploitation in coastal aquifers. Coupled with a continuing sea level rise due to global warming, coastal aquifers are even more under threat. This problem is intensified due to population growth, and the fact that about 70% of the world's population occupies the coastal plain zones [32,33].

The situation of the groundwater in the Maghreb countries in arid environments (Tunisia, Algeria, Morocco, Libya and Egypt) has been marked by continuous decreases of water levels in coastal aquifers reaching alarming values. This decrease, caused by the synergistic effects of drought, flooding, agriculture and urbanization, has intensified the problem of seawater intrusion.

*In Tunisia,* the Korba coastal aquifer situated in Cap-Bon, Tunisia has been experiencing seawater intrusion since I970 and currently the salt load in this unconfined aquifer has peak concentrations of 5 to I0 g/L. A large increase in the number of pumping wells for irrigation purposes since the I960s has resulted in a lowering to below sea level of the water table in several observation piezometers, and in a consequent deterioration of the water quality. A numerical model that treats density-dependent variably saturated flow and miscible salt transport is used to investigate the occurrence of seawater intrusion in the Korba aquifer of the eastern coast of Cap-Bon in northern Tunisia [8, 34; 35, 36, 37, 38].

*In Algeria*, the Algerian coastal aquifers have also not escaped over exploitation with the Mitidja aquifer suffering from seawater intrusion, especially during the dry season. This aquifer system has a steady decline in water level in the order of 20–50 m per decade, which increases the rate of seawater intrusion on an annual basis. The origin of water salinity on the Annaba coast (NE Algeria) is attributed to several factors such as the geological features of the region, the climate and the salted bevel. The salinity increases steadily when approaching the sea and indicates the influence of marine water [39, 40, 41].

*In Morocco*, areas have been identified in which saltwater intrusion occurs (Temara-Rabat), however the aquifer system also contains marine deposits which contribute to the degradation of the groundwater. The rates of water abstraction in these areas have increased in the last 50 years, resulting in the lowering of the water table and eventually allowing seawater to intrude from coastal areas [22,42, 43, 44].

*In Libya*, the city of Derna is facing severe water shortages due to seawater intrusion. The intrusion has steadily increased from I960 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. Tripoli (Libya) is also affected by saline intrusion, which extends I0 km inland from the coast; in the Gefara plain, this has been accelerated due to high rates of urbanization and increased agricultural activities [45].

*In the Nile delta*, seawater intrusion has been observed 60 km inland as a result of excessive pumping. An extensive saltwater body has developed from upper Egypt to eastern Libya in the past 50 years. The freshwater saline water interface passes through the Qattara depression crossing the Libyan-Egyptian border and finally turning to the S–W reaching the Tazerbo area. The development of the Siwa oasis from the deep Nubian Sandstone Aquifer is close to the freshwater/saline water interface and could cause the saline water to intrude into the freshwater aquifer. The problem is further compounded since on the Libyan side large amounts of water are abstracted for urban development, causing saltwater intrusion along the Libyan coast. This over abstraction in combination with the sluggish flow of the Nubian Sandstone Aquifer causes the saline water body to encroach even further inland with considerable increases in concentration of dissolved solids [46,47,48].

Although a lot of studies focused on the phenomenon of SWI in the worldwide, this important hydrogeochemical process still needs to be more deepen, especially with the modelling tools, because they allow predicting the behaviour of an aquifer system in response to pumping as excitations. If one will do it, decision makers can apply countermeasures to avoid the deterioration of the groundwater quality, which might have socio-economic effects [2].

## TUNISIA'S EXPERIENCE IN ARTIFICIAL RECHARGE

In Tunisia, groundwater is the only dependable source for urban and agricultural water supply. In recent years, groundwater pumping increased with increased population, and water level in the unconfined aquifer has largely obviously declined. Moreover, groundwater quality deteriorates progressively overall in the Cap Bon and in the Tunisian Sahel. Historically, the groundwater salinization has been thought to result from processes related to water–rock interaction and long-term irrigation practices. Tunisia has arid and to semi-arid climate. The average rainfall is 500 to 800 mm per year in the northern part of the country, whereas the South only receives I00 to 200 mm. The global water resources amount to 4.8 billion $m^3$, 2.7 billion $m^3$ surface water and 2.I billion $m^3$ groundwater. The net development rate of surface resources is 57 % and that of groundwater 83 % [2]. Tunisia has an experience in artificial recharge of aquifers since the early I956s. This is devised to increase groundwater resources while regulating surface flow, providing underground storage of this water and avoiding its becoming lost in the sea or in salt depressions, or its evaporation in dams. Currently, there exist more than 64 recharge zones of 23 aquifers. Since the I958s, Tunisia has started the artificial recharge technique. Generally, surface water is used in artificial recharge, by dam's lake and underground dam infiltration, crossing the riverbed infiltration, injection wells, or infiltration basins. Several experiments of recharge by surface water were established, especially in Teboulba aquifer from I970. Artificial recharge of Teboulba coastal aquifer by surface water provides an effective means of struggle against the seawater intrusion and improving the groundwater quality [8]. Artificial recharge of Grombalia aquifer was set during the I975–I978 period at Oued Sidi Said station by three infiltration basins. From I988, artificial recharge of Kairouan aquifer is done by infiltration in riverbed from the El Houereb and Sidi Saad dams. In Manzel Bouzalfa region, artificial recharge was performed by injection of surface water in three wells since I990 [35]. The phenomenon of seawater intrusion in coastal aquifers is governed by the recharge process and pumping in these aquifers. Therefore, it is essential to know the water level in the aquifer and its fluctuations, in order to decide on a possible seawater intrusion and estimate its magnitude. Salinization in the coastal aquifers has become a major concern and has induced considerable economic losses, leading to impaired quality of freshwater aquifers. An excessive withdrawal of groundwater coupled with a significant decrease in recharge also contributes to this problem. The magnitude of saline water intrusion is influenced by the natural geological settings, hydraulic gradient, rate of groundwater withdrawal and its recharge [49, 50]. The salinization of groundwater aquifers makes it unusable for drinking and irrigation. Various explanations for the salinization phenomenon have been suggested: *(i)* seawater intrusion due to over pumping, *(ii)* dissolution and precipitation of some minerals, with cation exchange caused by the marine intrusion along the coastal areas, and *(iii)* the return flow from the inner irrigated coastal areas and chemical compounds of the fertilizers used in agriculture. Salinization of coastal fresh water aquifers by seawater intrusion, geomorphic changes, tidal waves, cyclonic storms and man-made hazards are major causes of the ground water pollution in the coastal areas of Tunisia [2,3,35]. Seawater intrusion is a principal cause of fresh groundwater salinization in many regions of the world [25,26,27]. Seawater intrusion and agricultural pollution are the major sources of groundwater contamination and salinization in coastal irrigated areas. Seawater intrusion was controlled by cation exchange, carbonate weathering and redox processes. Agricultural pollution is enriching the groundwater with $NO_3$, Ca, $SO_4$, and K elements [34].

### A fifty-year artificial recharge of the aquifer by water from the dam

The Teboulba region is situated in the Tunisian Sahel. This region has a semiarid to arid climate with mild, wet winters and dry, hot summers, a mean annual rainfall of the order of 375mm and a mean annual temperature of about 20°C. The studied sector of the region is part of the Sahelian watershed basin, built up on a low-lying coastal plain partly recovered from the sea. The monotonous topography and the geological cover, dominated by Quaternary formations, make it impossible to identify any hydrogeological basin structures. However, the depressions in the interior of the region and the wadis along the coastal zone help to identify the boundaries of more or less individual hydrological basins.

The study site is located on an alluvial plain whose geology is dominated by Quaternary deposits. The Teboulba area has relatively stable tectonics apparent in the tabular sedimentary structure. However, normal faults have clearly affected the structure of the deep layers. The Teboulba plateau, I0 km long and 4 km wide, plunges quite sharply towards the sea while a fairly gentle slope links it to the Moknine sebkha (a salt lake at the elevation of about I3m below sea-level). It contains an alluvial water-table aquifer with lenticular geometry, short horizontal extent and irregular vertical continuity. There are also a few perched aquifers lodged inside the formation in silt-sand layers and lenses intercalated between clay and clay-sand strata. The substratum of the aquifer, consisting of an impervious Mio-Pliocene clay-marl layer, lies at a depth of over 90m. The Teboulba aquifer covers a surface area of around 35 km² and represents a hydrological recharge potential estimated, on average, at 0.65Mm³/y with an exploited volume of IMm³/y. This heavily negative budget (deficit of 0.35Mm³/y) is compensated by reserves but, above all, by an inflow of saltwater from the sea and/or the sebkha and by return flow of irrigation water from the neighbouring regions, estimated at 0.53Mm3/y [51], only a part of which flows towards Teboulba. The overexploitation of the resources, begun hundreds of years ago and particularly intensified in the last decades, has caused a drawdown of the aquifer to an elevation below sea level (over -30m at some points) in a zone that covers almost I2 km2. This depression has provoked an intrusion into the aquifer layers of saltwater from the sea in the north and from the sebkha in the south and, as a consequence, the water quality has deteriorated to the extent that in some areas, it can no longer be used for irrigation [52]. The Teboulba coastal aquifer is located in the sand-silt Plio-Quaternary formations, characterized by an effective porosity estimated at 7%, an average transmissivity of around $2 \times 10^{-4}$m²/s and a storage coefficient of the order of $3.5 \times 10^{-2}$. It is a vivid example of overexploitation. The flow in this aquifer takes several directions but converges generally on the exploitation zone. The flow toward the sea and toward the Moknine sebkha, two natural outlets of the aquifer, is relatively weak due to the strong depression created by the heavy exploitation in the western part of the region. The hydraulic gradients are very variable depending on the lateral facies' changes in the aquifer formation and the drawdown linked to the overexploitation.

The aquifer is naturally recharged mainly by rainwater and, to a lesser degree, by domestic wastewater from infiltration pits and re- infiltration of some irrigation water. Discharge occurs mainly by pumping for agricultural purposes and into the sea and sebkha. Saltwater intrusion from the sea and/or from the sebkha may disturb the hydrodynamics of the aquifer. All these factors make the water balance of the aquifer extremely complex and its hydrodynamic equilibrium very fragile and, above all, highly variable. The history of this operation goes back to the I970s. It concerns the recharge of the aquifer via a connection to the main pipe of the irrigation network [53, 54, 55]. As there was no excess water in the Nebhana dam because of the rainfall deficit during the period from I978 to I99I, the recharge operation was interrupted at the end of I978 and restarted in July I992, lasting until 2000.The monitoring installation was composed of 22 surface wells exploiting the aquifer and three piezometers. The analysis of the piezometric level fluctuations versus time in the control wells indicated two distinct behaviours. The first one showed a rapid and continuous recovery of the water level in the wells close to the zone where the recharge was strong. The second one was the continuous decrease due to the exploitation of the aquifer by the surface wells. This can be explained by the great distance between the recharge zone and these wells and the weak natural recharge rate which does not compensate for the large quantities of water withdrawn by the farmers. Establishing the piezometric maps is sometimes made more difficult by the presence of small perched aquifers inside the weakly permeable lenticular formations.

After intense artificial recharge from I97I, an analysis of the piezometric situation of the aquifer, in 20II, further confirmed the existence of the localised domes, revealed in I97I, but definitely enhanced. The flow direction of the aquifer remained constant but still retained the depression in the western part of the aquifer. Furthermore, the map shows a narrowing of the depression cone compared to earlier situations. The water level had risen, sometimes by more than I3m underneath the recharge site.

The Teboulba aquifer is also recharged by infiltration return flow of treated wastewater used for irrigation. These irrigation volumes were I44,000 m³ in I992, II4,000 in I993 and 255,000 in I994 [51]. Furthermore, this aquifer is characterized by water with a fairly heavy load of salt. Its salinity may reach 4.5 g/L. The highest values have been recorded near the sea and the sebkha whereas the lowest (I.5 g/L) are found toward the centre of the aquifer. The planned remedial action is to bring surface water from the overspill of the Nebhana dam and inject it into a few of the wells among the thousand existing ones. The mean rainfall recharge to the aquifer was estimated with an infiltration coefficient of rainfall of 5% determined by Kamenski's method applied to triple wells aligned along a flow line and monitored every month (aquifer recharge calculated from the rise in its level after a rain event). Luckily, because of the weak permeability of the water bearing layers, the saltwater intrusion has not progressed very far. The aquifer is exploited mainly by 806 surface wells, 465 of which are equipped with motor pumps enabling them to irrigate, by sprinklers, a surface area of about 200 ha. Hydrochemical studies carried out from I940 to I97I show that the salt content in the aquifer water follows the same pattern as the piezometric levels measured between I940 and I97I.

The salinity map for I97I shows values higher than 4.3 g/L, a sign that the aquifer water was becoming brackish. The high salinity values observed in the North and South of the region are explained by the contamination of the aquifer by saline intrusion from the sea and sebkha. This hypothesis is supported by the high chloride contents and the presence of inverse cation exchange reactions, which are characteristic of sea-and freshwater mixing movements [56, 57]. The salinity variations of its water, recorded in the control wells, were not very significant, due to the great surplus of rainfall that year which contributed to the natural recharge of the aquifer, thus maintaining both the piezometric levels and the water quality. The salinity map for the year 20II shows a slight salinity reduction toward the west of the aquifer: the zone characterised by salinity lower than 2 g/L and situated near the recharge site becomes more extensive. This shows the influence of the mixing with less salty water from the Nebhana dam.

**A twenty-six-year artificial recharge of the aquifer by treated wastewater**

Besides reclaimed water reuse for agricultural purposes, seasonal recharge of the shallow and sandy aquifer of Nabeul Oued Souhil has been performed since I985. The field experiment was located in the experimental farm of Oued Souhil (INRGREF) in North- Eastern Tunisia (to about 60 km of Tunis). The climate is semi-arid with 400 mm as mean annual precipitation at Nabeul city, and I9°C as mean temperature. Dominant economic activities are tourism and agriculture with some agro-industries.

The ground water artificial recharge by treated wastewater is the first pilot project in this field to be developed in Tunisia in I986. The aquifer Hammamet-Nabeul is located at the north-eastern coast of Tunisia along the Mediterranean Sea. The shallow aquifer contains more than 3000 surface wells which are used to irrigate citrus. The alluvial aquifer of Quaternarian age is formed by sand with no or very low content of clay. The thickness of this aquifer ranges between I0 and 20 meters. It is underlain by a layer of Pliocenian clay, which reaches a thickness of more than 200 m. The aquifer is bordered at the west by a indifferentiated Pliocene, consisting of sand, sandstone and clay being the main components. Soils in the Oued Souhil area were described as being composed of alluvia of coarse material belonging to the Quaternary marine formation. They are poor sandy to sandy–silty soils with low fine material content suitable for horticultural and orchard cultivation [58]. The vadose zone of the aquifer has been described previously [59, 60] and more recently [61] as varying between I0 and I3 m thick from the river bed to the infiltration basins. The permeability of the aquifer is estimated between $I0^{-5}$ and $6xI0^{-3}$ m/s. The piezometric surface determined the isopotential lines are parallel to the coast. The piezometcic depression existing at the head of the river Souhil is a consequence of the concentrated pumping of pliocenian water in this area. The piezometric gradient varies between I% and 2.5% and corresponds more or less to the slope of the underlying impervious clay layer.

Artificial groundwater recharge is operated at experimental scale in infiltration-percolation basins and the artificial recharge station Nabeul Oued Souhil is composed of four injection basins and I8 piezometers. Some of the observation wells are placed along two lines in direction of ground water movement, the others, between and near the infiltration basins. Groundwater recharge efficiency was proven not only by the increase of the water level in the wells but also by the improvement of the production of the surrounding wells. This experiment allowed an underground storage and an additional treatment step as wastewater slowly infiltrated through the unsaturated zone through the unsaturated zone. However, no clear conclusion could be drawn about the effect of reclaimed water on the bacterial and chemical composition of shallow groundwater since the initial contamination level of most of the wells was relatively high and subject to seasonal variations. According to the state of the art of soil-aquifer treatment [62, 63] improved operation of this facility would lead to a groundwater quality meeting unrestricted irrigation requirement [64].

The ground water artificial recharge by treated wastewater is the first pilot project in this field to be developed in Tunisia in I986. The aquifer of Hammamet-Nabeul subject to the artificial recharge is located at the north-eastern coast of Tunisia along the Mediterranean Sea. It consists of a coastal plain, which covers a surface of about 60 km². The shallow aquifer contains more than 4000 wells, which are used to irrigate citrus. The alluvial aquifer of Quaternarian age is formed by sand with no or very low content of clay. The thickness of this aquifer ranges between I0 and 20 meters. lt is underlain by a layer of Pliocenian clay, which reaches a thickness of more than 200 m. The aquifer is bordered at the west by a undifferentiated Pliocene, consisting of sand, sandstone and clay being the main components. The thickness of this formation can be more than 300 m meters [65]. ln a deep well (about 200 m) located near the border to the alluvial aquifer, brackish water has been found, which is oversaturated in $CaSO_4$. Four wells located several hundred meters upwards, which penetrate only upper levels, are pumping fresh water with a conductivity of about I mS/cm. Several springs exist at the upper level of this formation with water of good chemical quality.

The coastal alluvial aquifers are crossed by five small rivers, the most important of which is the river Souhil with a basin of about 20 km². These rivers are usually dry and water flows only sporadically during the rainy periods. ln spite of this, most of the recharge is provided by these rivers. Several hundreds of dug-wells exist in the area. Due to over-exploitation, the aquifer is practically exhausted: the average thickness of the saturated zone is about 2 to 3 meters. The re- circulation of the pumped water together with the solution of mineral manure have produced an important degradation of the chemical quality of the water [66].

The recharge site is selected on the basis of lithologic character, hydrologic situation, and a favorable geohydrologic environment. This part of the aquifer is a typical homogeneous alluvial deposits consisting of fine to medium sand with some gravel deposits. The gross hydrologic characteristics are relatively uniform throughout the area. Also, the field of experimentation is a public property. The artificial recharge station is composed of four injection basins (Length = 20 m: Wide = 20 m : Depth I.7 m. The side slopes are covered with a layer of synthetic and permeable geotextile tissue (specific gravity = 270 g/m²: permeability = 0.0007 m/s) and I8 piezometers. The piezometric map-as shown the figure 60.5 plotted before artificial recharge reveal that the infiltration basins are placed on a preferential direction of ground water movement. The local hydraulic gradient is about 0.0I5 [66].

Two hypotheses advanced to explain the mechanism of the wastewater recharge throughout the saturated and the unsaturated zone of the aquifer: *(i)* the injected wastewater itself moved and a mixing with the native water is produced. *(ii)* Volumes of injected wastewater were sufficient to totally displace all native formation water and the mechanism is the "piston flow". The use of isotopic tracer supports this last hypothesis.

Some hydraulic properties for, the aquifer was determined during the study: *(i)*. Plots of particles size distribution were constructed using data derived from core samples from test holes. The graphs show that for most of the intervals analyzed; there is a uniform range of fine and medium sand. To determine the theoretic velocity of ground water, we have applied A. Hazen's law (K = c d2I0), based on the data of particles size distribution; the result was that the velocity obtained is about 0.000I m/s (c = I35); *(ii)* Horizontal hydraulic conductivity derived from pumping test interpretations is reported to be about 0.0004 to 0.0005 m²/s; *(iii)* On the site of the artificial recharge, the water table lies I2 m below ground and the saturated zone has a limited depth (less than 4 m) ; *(iv)* The lowest ground water levels occurred during the end of the dry season (summer) and the highest water levels occurred during the end of the wet season( spring). Ground water level fluctuations are about (I-2 m) per year; and *(v)* The piezometric map- plotted before artificial recharge reveal that the infiltration basins are placed on a preferential direction of ground water movement [66].

The aquifer, to survey the hydrodynamic impact of the recharge, water levels have been measured daily before, during, and after the experimentation, in observation wells (I8 piezometers and 22 shallow wells). When wastewater is injected into the basins, it forms a conical mound around the basins. The height of the cone is greatest under the recharge basins and decrease laterally with distance. It appears that the dimensions of the mound are governed by the basin size and shape, recharge rate, duration, and aquifer characteristics.

**Fifty year of treated wastewater reuse for a seawater intrusion hydraulic barrier**

In the case of lake of surface water, and in addition to the use of available surface water to artificial recharge groundwater, the treated wastewater can be used in addition to artificial recharge [67]. Testing artificial recharge by Treated WasteWater (TWW) in Tunisia began in Oued Souhil (Nabeul) (Figure 1) in I986 [66].

In I986, the ground water artificial recharge by treated wastewater at the experimental station in Nabeul Oued Souhil (Irrigation efficiency) is the first pilot project in this field. Besides reclaimed water reuse for agricultural purposes, seasonal recharge of the shallow and sandy aquifer of Nabeul Oued Souhil has been performed since I985. The ground water artificial recharge by treated wastewater is the first pilot project in this field to be developed in Tunisia in I986. The aquifer Hammamet-Nabeul is located at the northeastern coast of Tunisia along the Mediterranean Sea.

In 2008, a new pilot site was established in the region of Korba-Mida (Recharge aquifer and seawater intrusion) to recharge the aquifer with domestic treated wastewater (TWW) of the Korba Wastewater Treatment Plant (KWTP) (Figure 1). The aim was a better evaluation of the mixing processes between seawater, groundwater bodies and the new recharge contributor, and of the changes due to intense groundwater withdrawal, which will be useful from a water resource management perspective aimed at controlling human interference on the Korba plain groundwater. Korba aquifer (northeast Tunisia) is one of typical example of coastal aquifer in semi-arid regions that have been intensively overused during the last years.

The Korba-Mida aquifer is made up mainly of marine sediments deposited in the Dakhla syncline north of Korba city byAbbes and Polak [68, 69], (Figure 2a). The study area is bounded to the north by Wadi Lebna, to the south by Wadi Sidi Othmen, to the west by the elevated mountains consisting of Mio-Pliocene sequences, and to the east by the Mediterranean Sea. The aquifer system is constituted by the superficial and shallow Plio-Quaternary formations and by the deeper Miocene units. The Miocene base is constituted by impermeable marls and contains brackish water with a salinity of 3–4 g/L. The younger upper Miocene is actively pumped at I50–500 m depth upstream of the study site and is tapped for drinking-water supply well in Taffeloun. The deep Miocene aquifer is captive and feeds the upstream Plio-Quaternary; its natural outlet is the sea [2,3,35]. The relationship between both deep Miocene and Plio- Quaternary aquifers is known but not clear. With no distinction in hydraulic terms, the Pliocene and Quaternary deposits form the Plio-Quaternary aquifer. According to electric sections, the

Pliocene part contains a succession of saturated freshwater and brackish-water levels with, in the bottom, layers saturated with variably salty water. It is locally semi-confined due to less permeable deposits and is, the most productive aquifer of the area. Its recharge is provided by direct infiltration of rainwater and stream water. It is severely affected by salinization from seawater intrusion. The Quaternary part is vertically compartmentalized in places. Its recharge occurs principally through incised glacis and outcrops and is favored by the topographic relief formed by Quaternary Tyrrhenian fossil dunes. The main coastal sabkhas are no longer the natural outlets of the Tyrrhenian, due to a reversal of the hydraulic gradient [70].

Numerous works have been examined the geological framework of Korba aquifer [65, 71] from borehole lithology and water wells. It is underlain mainly by Pliocene formations and Quaternary marine platforms. To the authors' knowledge, the origin of such fresh groundwater in this very limited area is not clear but could be linked to the presence of faults affecting Miocene formations and favoring mixing (Figure 2b). Three main geological formations constitute the aquifer system (Figure 2a):

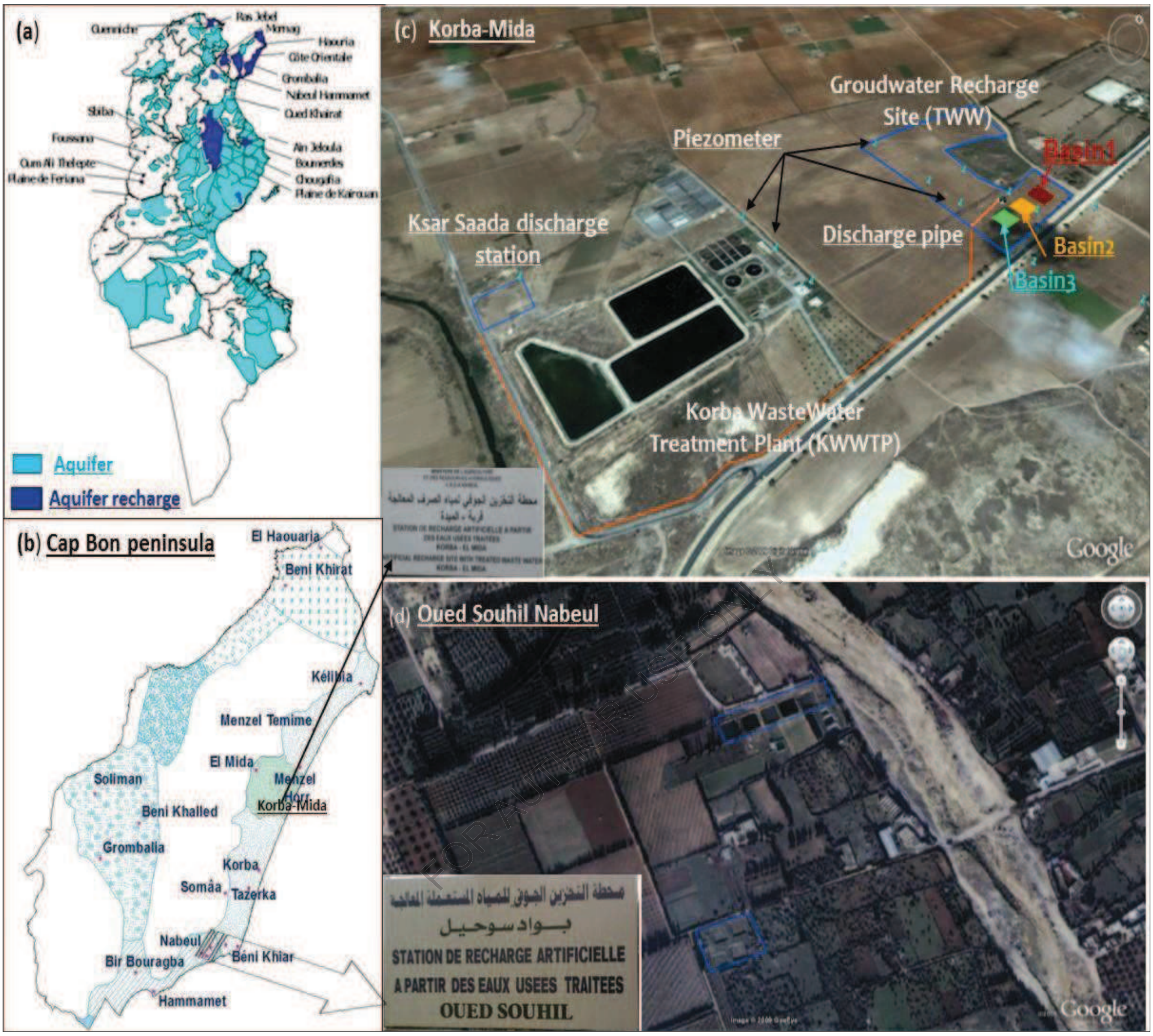


Figure 1. (a) Articial recharge of the aquifer techniques in Tunisia, (b) Location map of the Cap Bon Peninsula (c) Korba Wastewater Treatment Plant (KWWTP), and Korba –Mida ground water recharge site and piezometers (d) Recharge site in Oued souhel (Nabeul) [35].

*(i)* The Middle Miocene is the base of the system and is not exposed except some relics North West of the study area. It is 2700 m thick and is made up of detrital deposits mainly from deltaic bodies. The upper part is composed of lenticular sandstones and marls with lignite levels and clay in the study area (Figure 2a) truncated by riverine systems [69] with a thickness of 500 m.

*(ii)* Marine Pliocene sediments transgress unconformably over the Miocene (Figure 2a) and outcrop NW of Taffeloun. These are composed mainly of interbedded sandstone-sand-marl topped with variably clayey sandstone with a thickness varying between 15 and 160 m [65].

*(iii)* Quaternary deposits in the study site contain upper Pleistocene and Holocene deposits. It can reach 150 m in the Taffeloun area. At the base, the upper Pleistocene deposits with a thickness of 30 m, also called the Tyrrhenian deposits of the last marine transgression, are made up with fossiliferous carbonate sandstones and covered by old consolidate dunes with fossiliferous limestone (Figure 2a). The further Pleistocene deposits, described as three marine platforms, show mixed carbonate, bioclastic and siliciclastic sediments [72, 73]. This facies is truncated by a carbonate sequence and aeolian oolitic deposits. The uppermost continental Pleistocene is represented by continental red deposits and a centimeter- to meter-thick calcrete extending over large areas [73, 74]. At Taffeloun, the calcrete outcrops and its thickness is 15 m (Figure2a).

The mainly cause of salinization is the mixing between freshwater and saltwater under seawater intrusion process. It was clearly observed from the EC profile in the area investigated. All samples show a rapid increase of EC at depths of 5 m below sea-level. These depths represent the interface between freshwater and saltwater. Furthermore, brackish water has been found in the upper aquifer. This finding has been interpreted as being due to the recycling of irrigation water where the uses of fertilizers contribute to the high EC values. Seawater fractions varied from 0.24% to 54.68%. Seawater seems to contribute to the composition of groundwater. The mixing of seawater with fresh-brackish water was confirmed, using Piper diagram. Nevertheless, mixing freshwater-seawater was not conservative and accompanied by other geochemical processes. Plotted in a Piper diagram, the majority of samples are Na-Ca-Cl type.

A number of wells plot on are in the Theoretical Mixing Line (TML) indicating that mixing processes are taking place as a result of their higher $SO_4^{2-}$ and $Ca^{2+}$ content. The most likely source of this Sulphate is from dissolution of the small amounts of Gypsum scattered through the aquifer, present in the catchment area or the evaporation of the irrigation water excess and of the Calcium is also from the dissolution and precipitation of the Calcite. These observations suggest that dissolution of gypsum would be a potential source of both $Ca^{2+}$ and $SO_4^{2-}$. Gypsum source are mainly fertilizers or precipitation by evaporation at the topsoil. The hydrogeological and hydrochemical investigations seem to be a useful tool to better understand the Korba unconfined aquifer of Cap-Bon where saltwater intrusion will eventually spread, particularly during dry periods. Consequently, both groundwater monitoring and management and groundwater conservation are essential for efficient surveillance of the saltwater intrusion.

The coastal aquifer of the Cap Bon Peninsula in Tunisia is one of the first studied examples of groundwater depletion and salinization under a semi-arid climate. The large quantities of water abstracted by the agricultural and industrial sectors since the 1960s have resulted in a spatiotemporal evolution of piezometric depletion and groundwater quality degradation due to seawater intrusion [2,3,35]. Artificial recharge of groundwater has been part of Tunisia's integrated management of water resources since the 1970s [34].

The east coast aquifer of the Cap Bon Peninsula, which lies 100 km east of Tunis, extends for about 45 km and underlies an area of approximately 475 km² (Figure 1). The region has a semi- arid climate characterized by an average annual rainfall (determined from 1964 to 2014) of 480 mm with temporal irregularities; 65% of this is concentrated between November and March. The climatic deficit (rainfall minus evapotranspiration) covers a period of about 10 months, reaching its maximum (160 mm) in July and August. The summers are hot and dry and the winters cold and wet. Average annual temperatures vary between 17 and 19 °C. Monthly evaporation is high (around 1300 mm per year) with humidity between 68% and 76%. The dry season is pronounced, which aggravates the situation given that the highest water demand usually coincides with the period of drought [2,3,35].


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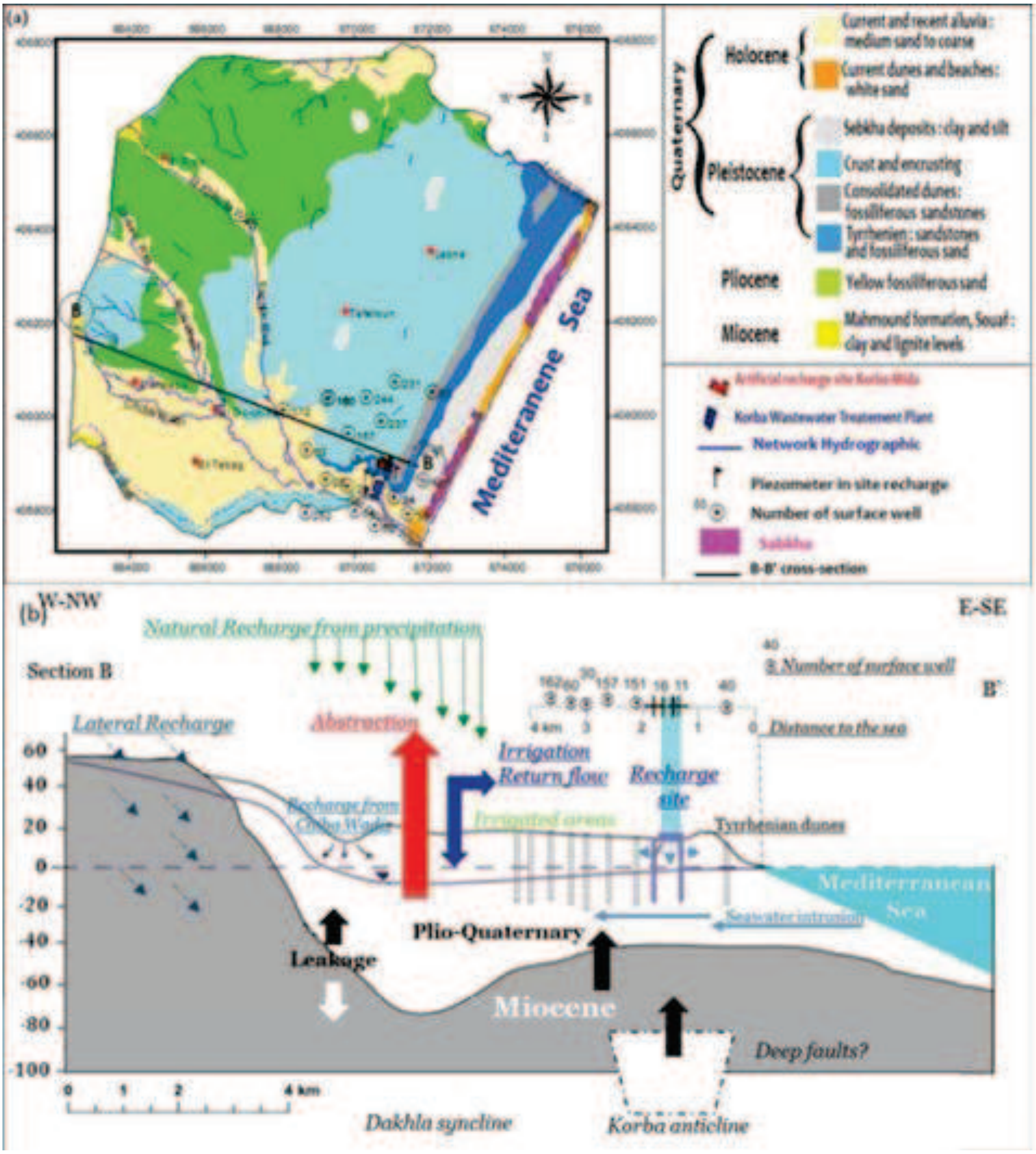


Figure 2:(a) Geological setting of the Korba-Mida basin showing piezometric network and farm-well sampling points; (b) Schematic geological cross-section (BB') through the study area showing the locations of the artificial recharge site, studied wells and piezometers [34,35].

The Korba-Mida aquifer is one of the more productive aquifers of Tunisia, but suffers heavily from water scarcity and salinization due to seawater intrusion. Its exploitation began in the I960s, mainly for irrigation purposes. Pumped abstraction of the groundwater by 2008 was estimated at 50 $Mm^3$, with meteoric recharge at I7 $Mm^3$, and irrigation return flow at I6% of the annual irrigation-water percolation to the aquifer between I993 and 2003 [2,3,35,71;75, 76, 77]. More than 9240 wells were active throughout the region in 2008, mainly pumping the shallow Plio-Quaternary aquifer; the number of wells is proportional to the number of farms [78]. The electrical conductivity values range from 2 to 3 mS/cm and the Ca–$HCO_3$ groundwater type dominates. However, high EC value (between 9 and 30 mS/cm ) appear in the central part of the plain specially in Korba, Diar El Hojjej


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and Tafelloun areas which are relatively marked by the presence of shallow depth piezometric level and the Na–Ca–Cl groundwater type dominates.

The coastal aquifer of the Cap Bon Peninsula in Tunisia is one of the first studied examples of groundwater depletion and salinization under a semi-arid climate. The large quantities of water abstracted by the agricultural and industrial sectors since the I960s have resulted in a spatiotemporal evolution of piezometric depletion and groundwater quality degradation due to seawater intrusion [71]. Artificial recharge of groundwater has been part of Tunisia's integrated management of water resources since the I970s [8]

In 2008, a new pilot site was established in the Korba-Mida area to recharge the aquifer with treated domestic wastewater from the Korba treatment plant. The aim was a better evaluation of the mixing processes between seawater, groundwater bodies and the new recharge contributor, and of the changes due to intense groundwater withdrawal, which will be useful from a water resource management perspective aimed at controlling human interference on the Korba plain groundwater.

Boron adsorption thus concerns a variety of exchange phases such as clay minerals, metal hydroxides, organic matter and carbonates such as calcite [79, 80]. In our case, with the clay content being rather low, the non-conservative behavior of boron does not limit its applicability to the waters injected into the Korba aquifer.

The carbamazepine (CBZ) molecule is uncharged and polar, but can occasionally create weak interactions with soils and minerals [81]; the main phase that will induce adsorption interactions of the CBZ molecule is soil organic matter [82]. As such, CBZ and its metabolites are easily transported into groundwater when treated wastewater is used for irrigation or artificial aquifer recharge, especially where the organic matter content is low. It is only since 2004 that CBZ has been considered as a qualified parameter for detecting wastewater in the aquatic environment [83]. The persistence of CBZ in soils has been assessed [84] as being especially due to the organic matter content [82, 85] causing its sorption and reducing its mobility before mineralization. CBZ clearly accumulates in groundwater under the impact of artificial recharge close to the infiltration ponds. It is conservative under SAT conditions, and is not significantly degraded over two years under the aerobic conditions in the vicinity of the SAT wastewater recharge system [86]; it is even found preserved in groundwater after long flow times within the subsurface zone [87].

In 20II, the highest nitrate concentrations (seven times the potability norm) were measured in wells I62, 60, and 30, with low amounts of ammonium and dissolved manganese. Note that groundwater contamination in the region is due mainly to residual agricultural products like N-fertilizers [74]. The above wells also belong to the wealthier farms, which are known to irrigate more and use more fertilizers than the farms owning wells I57, 40 and I5I. Also, at the scale of the Korba plain, vertical transfers are sufficient to contaminate the entire aquifer from the upstream areas to the coast. The concentrations thus result from a mixing with the upstream groundwater flow and the return flow in unsaturated zone [88]. The increasing salinization of the groundwater combined with agricultural practices are gradually impacting the groundwater quality. The supplies at the time were not, however, sufficient to compensate the effects of traditional water management; recent hydrogeological models have shown that the situation in the central part of the Korba aquifer was critical in 2004 due to overexploitation amounting to I35% of the recharge [2,3,35, 36,77]. Multidisciplinary approaches have been used to study the consequences of seawater intrusion into the Korba plain. For the study of the hydro chemical investigation of the coastal and insular aquifers in Tunisia [35], the authors quantified the salinization in Korba has primarily three origins (geological, seawater and the salts irrigation concentration. This facilitates a qualitative description of the state of the resource. These data also permit to describe the evolution of the seawater intrusion. Obviously, the salinity distribution in the Korba-Mida aquifer is correlated with the piezometric evolution. The vertical salinity profiles measured before artificial recharge in three piezometres allowed delineating a distribution of salt concentrations in the aquifer. The most recent studies, combining geophysics and hydrochemistry, were by [89] who quantified the inland invasion of seawater as reaching I.5 km south of Wadi Chiba and 5 km south of Diar El Hajjej. According to the salinity maps, they identified five salinity zones with the least concentrated (2 to4 g/L salinity) in the northern coastal aquifer and the most concentrated (22 g/L salinity) north of Korba. Salinity was more pronounced along the coast, resulting in a large number of shallow wells being abandoned. Calculations of seawater mixing varied from 0 to 70%, reflecting the heterogeneity of the salinization process [74], the high values were in piezometers of the Korba and Tafelloun area. In order to provide a hydraulic barrier against seawater intrusion, the treated wastewater is infiltrated though ponds and undergoes soil aquifer treatment (SAT), to improve its quality, especially in terms of microbiology.

The Korba-Mida artificial recharge site lies I5 m above sea level (NGT) and contains three infiltration basins, of which two function simultaneously with a feed of 300 to I400 $m^3$/day. A first flow modeling of the artificial recharge site of Korba has been realized to study the impact of injection of treated wastewater [35]. The results obtained by the Modflow simulations, affirm that the artificial recharge will achieve its role of barrier against the sea intrusion and will contribute to the groundwater's resources conservation of the studied area. Transmissivity at the selected recharge site is $4.10^{-3}$ $m^2/s$ and the storage coefficient range between $4.510^{-4}$ and $6.10^{-4}$ [35]. The aquifer's permeability is estimated between $1.610^{-3}$ and $2.10^{-3}$ m/s. Its hydraulic gradient varies between 0.2 to $1.10^{-3}$ m/day, and flow velocity varies from 0.2 to 0.6 m/day. Infiltration tests at the bottom of the 1.5-m-deep infiltration basin indicates infiltration flow between 5 and 60 m/day [35]. These low values are due to the presence of hard sandstone intercalated in the sand at depth and slowing down vertical transfers. The recharged waters from the Korba treatment station are infiltrated after tertiary treatment. The monthly volume of water injected into the artificial recharge site's basins has ranged from a minimum of 5,948 $m^3$ (December 2008) to a maximum of 37,653 $m^3$ (July 2010), with a total of about 1.151 million $m^3$ of treated wastewater being injected into the three basins between December 2008 and March 2012.

Salinity at the recharge site decreased from 10 g/L in 2008 to 3-9 g/L in 2011 [35] here attention must be paid to the role of the fresh groundwater body whose refreshing effect must not be confounded with that of the recharge waters. A slight increase in the piezometric level was also recorded in the wells between 2009 and 2011; here the contribution of artificial recharge to the piezometric levels may be hidden because of continuous abstraction through irrigation wells in the area along with the installation of illegal surface wells, especially for agriculture.

The fresh-water quality plotted in the Piper diagram differs from that of the fresh groundwater and coastal aquifer samples and is closer to that of the deeper aquifer composition reported by Kouzana et al., [89]. The very low Ca, Mg and HCO3 concentrations indicate a more likely equilibrium with sand, sandstone or rainwater than with the Pleistocene carbonates. The B concentration in the 2011 Piezometer 16 sample (2.77 mmol/L) is lower than that of free uncontaminated meteoric water in which the B content is <4 mmol/L [34], and its pH (6.59) is consistent with equilibrium in a siliceous aquifer [34].

The 2009 Cl concentration in Piezometer 5 (42 mmol/L) is close to that of Piezometer 16 in 2009 (40.73 mmol/L), whereas the Cl of Piezometer 5 in 2010 (2.01 mmol/L) is less than that of Piezometer 16 in 2009 and 2011 (5.9 mmol/L). Knowing that artificial recharge had higher Cl concentrations of 30, 67 and 77 mmol/L, these major variations between fresh and brackish facies are interpreted as due to the spatial displacement and temporal mixing of fresh water, Plio- Quaternary water, and recharge water under various hydrodynamic constraints such as the infiltrated recharge volume, withdrawals at close vicinity, and meteoric recharge.

The groundwater over the three years of study was generally enriched in calcium, sulfates and bicarbonates, compared with a simple mixing with seawater. All the wells and some of the piezometers showed an Na deficiency ($Na_{react}<0$), varying from -5 to -22 mmol/L, most commonly combined with a K deficiency (-0.1 to -1.7 mmol/L). Ca concentrations in the wells varied between 10 and 20 mmol/L with the amount of calcium reactant being strictly positive, except for Piezometer 5 in 2010 (-1.7 mmol/L). Strontium was also plotted in excess (points above the 1:1 line) versus $Na^+K$. Reactant magnesium had low positive or negative values (-0.9 to 2.9 mmol/L).

Before initiation of artificial recharge by waste water treated at the Korba-Mida site, the piezometric lines in 2008 (Figure 3a) shows a decrease in hydraulic head towards the north, where ground water discharges to pumping wells and the Sidi Othmen Wadi. The effects of pumping are indicated by a depression (-2 to -7m) in the potentiometric surface in the center of the plain, likely the result of over-pumping. The effects of pumping are indicated by a depression in the potentiometric surface in the center of the plain, likely the result of over-pumping. All the piezometric level are below the sea, over the entire study recharge are (Basins 1, 2 and 3) and varies between zero to -3m from the Basin3 to basin 1, at the center o the basin 2 which is a depression area (Figure 3a) [35].

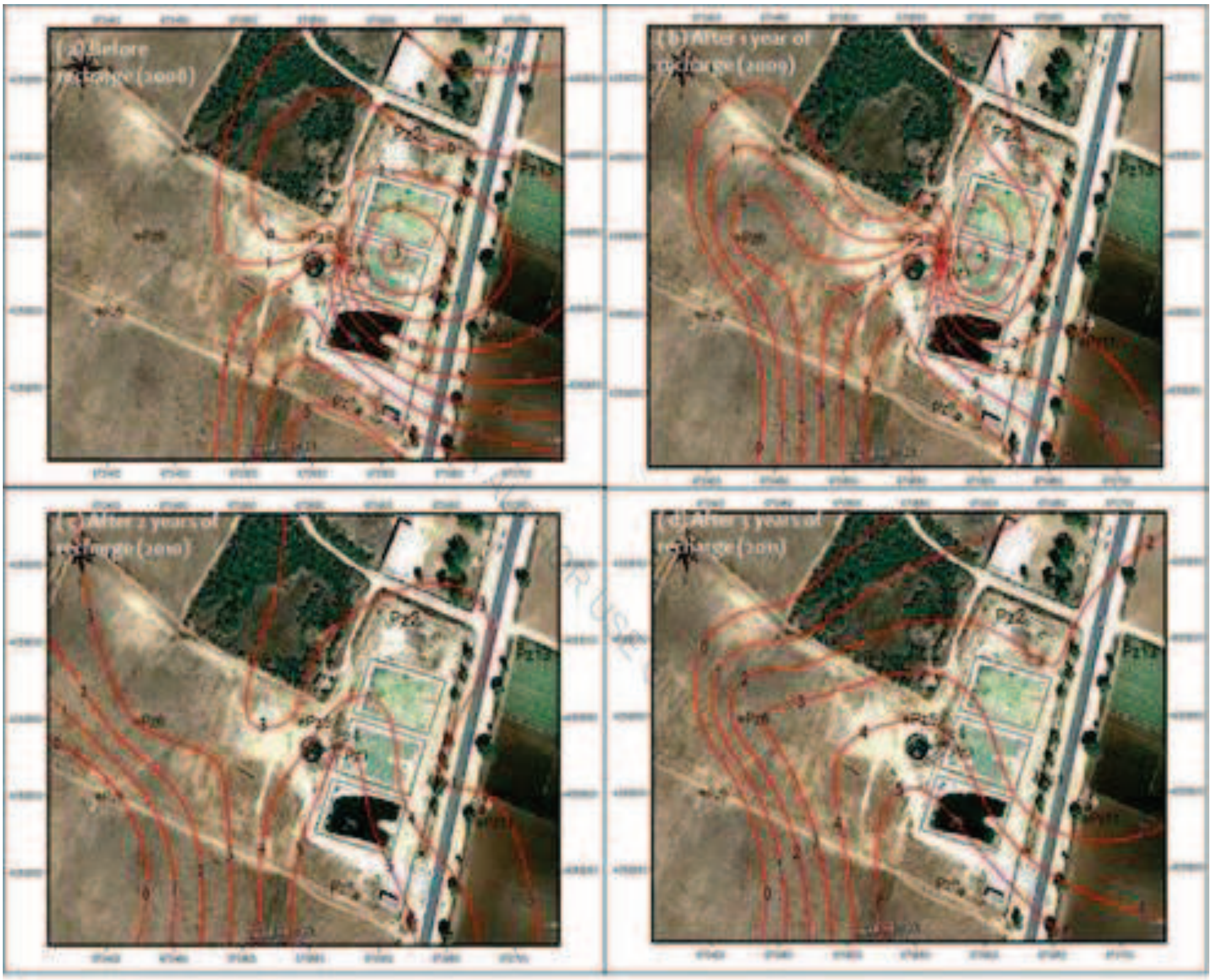

Figure 3 Piezometric evolution (m) at the Korba-Mida recharge site (m): (a) 2008 before recharge, (b) 2009 after injected 342286 $m^3$ of wastewater, (c) 20I0 after injected 7I5898 $m^3$ of wastewater, (d) 20II after injected I.05 million $m^3$ of wastewater [35].

In 20I0, after twenty-five months of artificial recharging by wastewater treated (volume cumulated 7I5898 $m^3$) the higher ground water aquifer in the left side of the recharge site at +3 m and creates a bulging piezometric at the recharge site indicating a convergence of the groundwater flow. The piezometric surface appears with positive values in the recharge site (Fig. 3c). A decrease of salinity of I g/L appears in all the basins I, 2 and 3 (Figure 3c) [35].

The salinity of groundwater in piezometers varied from I to 8 g/L (maximum in $Pz_2$). Ground water salinity in the aquifer increased towards the axis from lebna Wadi to Chiba Wadi (groundwater salinity 22 g/L), this resulting to the high exploitation in this region (Figure 4a) [35].

After I3 months of artificial recharging by treated wastewater, the zero piezometric curve is displaced to its original state to the recharge site area, showing that the drawdown of piezometric heads extending benefits in this region (Figure 4b). In the north of the study area, the salinity changes from a rate between 4 to 5 g/L ($Pz_2$ and $Pz_4$), there has a degradation of water quality of the aquifer (Figure 4b) {35].


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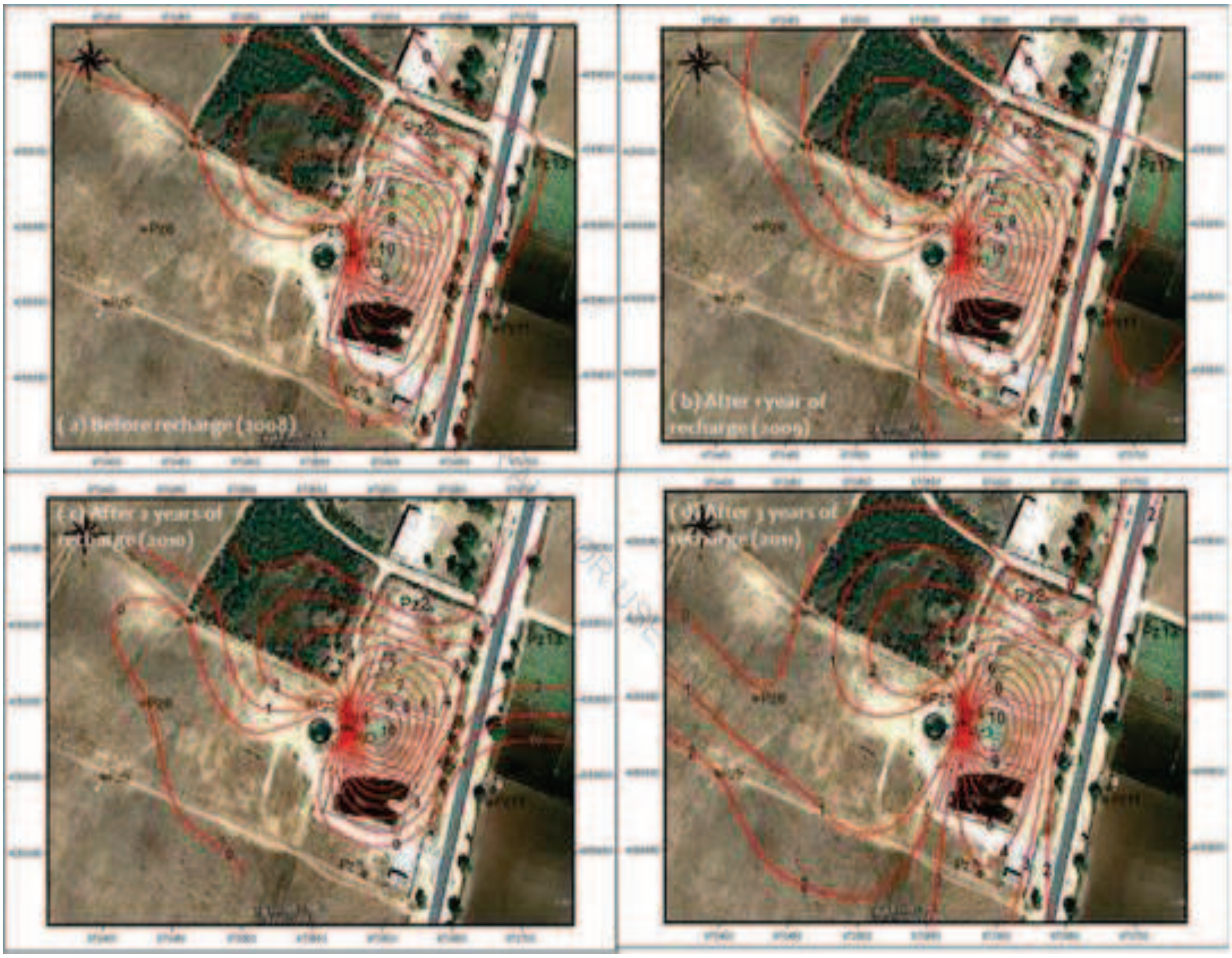


Figure 4 Salinity evolution (g/l) at the Korba-Mida recharge site (m): (a) 2008 before recharge, (b) 2009 after injected 342286 $m^3$ of wastewater, (c) 20I0 after injected 7I5898 $m^3$ of wastewater, (d) 20II after injected I.05 Million $m^3$ of wastewater [35]

Artificial recharge by dam water represents a valuable tool for managing water resources. The installations needed for the recharge operations are simple and relatively inexpensive. Although there are other methods of artificial recharge, the recharge by injection directly into the aquifer is the most efficient one for creating freshwater barriers against saline intrusion. However, clogging of the wells, which was quite random, and the doubts of the farmers concerning this technique might jeopardize the success of the recharge operation. Tunisia has acquired an extensive experience in the field of recharge. However, until now the recharge has remained low and discontinuous in time and space. The superimposition of a 'recharge front' due to the new 'treated wastewater' component modified the previous transitional states away from equilibrium by adding a new constraint, i.e., the development of reductive conditions with the intrusion of high amounts of organic matter and the entry of a new boron and CBZ source. Although the natural amounts of metals in the aquifer is not known, pollutant metals issued from human activities were injected into the aquifer and the oxido-reductive conditions enhanced their mobility. Salinity at the recharge site generally decreased from I0 g/L in 2004 to 2-3 g/L in 20II [35]; here attention must be paid to the role of the fresh groundwater body whose refreshing effect must not be confounded with that of the recharge waters. A slight increase in the piezometric level was also recorded in the wells between 2009 and 20II; here the contribution of artificial recharge to the piezometric levels may be hidden because of continuous abstraction through irrigation wells in the area along with the installation of illegal surface wells, especially for agriculture. Nevertheless, further spatial and temporal studies need to assess the migration of the treated wastewaters plume, which is likely to migrate at depth until reaching the impermeable Miocene substratum.

## IMPACT OF THE CORONAVIRUS (COVID-I9) ON THE ENVIRONMENT AND WATER RESOURCES

On 30 December 2019, an uncommon pneumonia outbreak of unknown aetiology was reported in Wuhan, Hubei province, China [90,91,92]. Virus isolation and molecular analysis indicated a novel coronavirus (family Coronaviridae) provisionally named 2019-nCov [92]. The International Committee on Taxonomy of Viruses (2020) later designated the virus as 'severe acute respiratory syndrome coronavirus 2' (SARSCoV-2) and the World Health Organization (WHO) officially named the associated disease coronavirus disease 2019 [90,91,92,93]. As the world rallies against the COVID-19 pandemic, millions of people in developing communities are already struggling with a public health catastrophe. Without clean water, people are constantly at risk from waterborne diseases such as cholera. Climate change is exacerbating this threat. 785 million people still do not have clean water close to home. Droughts, floods, salt water contamination, poor service management, weak governance and environmental degradation all contribute to this denial of their basic human right. Climate change is accelerating and amplifying these factors, increasing unpredictability of weather patterns and making extreme weather events and natural disasters more frequent and intense. Sewage systems are flooded with increasing frequency, contaminating water sources and the local environment. Severe droughts force people to resort to even less safe sources of drinking water. And the likelihood of other health impacts is increased – for example in Bangladesh, where rising seas raise groundwater salinity, contributing to high blood pressure and heart disease among coastal communities [95]. It is those who have done least to contribute to man-made global warming who are carrying the greatest burden of climate change. People in the poorest countries are living on the brink of the climate crisis, and the poorest communities among them are worst affected, being least able to prepare and protect themselves and their environments. Without durable, climate-resilient water and sanitation systems, people struggle to cope. But well-managed water systems can protect access to reliable water supplies. Decent sanitation systems can resist floods. And, as we are witnessing during the COVID-19 pandemic, hygiene behaviors such as handwashing are a crucial first line of defense against the spread of disease. Our response to today's global health crisis must also address the effects of the climate emergency, and prepare us for the crises of tomorrow, with sustainable water, sanitation and hygiene services that are fit for the future. There is no clinically approved antiviral drug or vaccine available to be used against COVID-19. However, few broad-spectrum antiviral drugs have been evaluated against COVID-19 in clinical trials, resulted in clinical recovery. In the current review, we summarize and comparatively analyze the emergence and pathogenicity of COVID-19 infection and previous human coronaviruses including severe ascute respiratory syndrome coronavirus (SARS-CoV) and middle east respiratory syndrome coronavirus (MERS-CoV). [92,93]. In Tunisia, The COVID-19 pandemic has severely tested a Tunisian government that only came to power in February 2020. On 16 March 2020, the authorities suspended international flights, closed land, and maritime borders, enforced a lockdown, and banned all public gatherings. These measures initially worked well, and the country had only 1,157 cases and 50 deaths as of 22 June 2020 [95]. At least with the initial lockdown, Tunisian society seemed to have endorsed the effort [96]. Tunisia has made an admirable effort to build a democratically ordered state under trying circumstances, and the government has embraced the principle of transparency in managing the current crisis. It has created a user-friendly website to share real-time information about the crisis and government policies to cope with it [97]. Poor health infrastructure, however, remains a challenge, and the country entered the pandemic with only 331 intensive care units (ICU) beds [98]. On 26 March, the Ministry of Health confirmed that it had acquired 2,000 additional ICU beds. As Tunisia is highly dependent on income from tourism and trade with Europe, its economy has suffered a serious setback. These include the creation of a support fund for SMEs, management credit procedures for companies in the tourism and hospitality sectors, and delayed tax levies for most affected businesses. In May 2020, Tunisia requested critical medical supplies from NATO through the Euro-Atlantic Disaster Response Coordination Centre, which is the Alliance's primary civil emergency response mechanism [99].

Investing in long-term water security and access to clean water and sanitation is essential for public health. Governments should prioritize three strategies:

- *(i)* Super-charge investment in clean water access and sanitation.; Experts believe that the capital investments required to meet global goals for water supply, sanitation and hygiene services. Funding for water and sanitation not only builds more resilient and thriving communities, but it can bolster local economies. One study in Antananarivo, Madagascar showed substantial job creation and increased wages from investments in water access, sanitation and hygiene – including everything from construction of water kiosks and laundry blocks, to fixing pipe leaks and clearing drains, to women's management of water kiosks and laundry businesses.
- *(ii)* Effectively manage the water resources we have so that ample clean water is available to communities. Setting water withdrawal limits for industry and agriculture and investing in measures like water-efficient irrigation can help. Water pollution in many parts of the world is also worsening – even in high-income countries effectively reducing available supplies and adding to public health problems. Investments in domestic and industrial wastewater treatment and best practices to reduce nutrient pollution from agriculture can protect water for human use. Effective long-term water management policies, alongside targeted policies that increase water affordability and public provision for all, can help prevent the impacts of future water crises on the poor.
- *(iii)* Massively boost investment in natural ecosystems: Wetlands, forested watersheds and floodplains are the literal wellspring of abundant clean water supplies. Evidence repeatedly shows the value and economic return of these approaches, but they still receive far less investment than traditional engineered infrastructure.


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## CONCLUSION

All around the world, saltwater intrusion is caused by overexploitation of fresh groundwater. Where groundwater is overexploitation from aquifers, water head gradients may cause the migration of sea water toward wells, making the freshwater unusable.

The coronavirus has now reached the pandemic stage and continues to spread globally, and hand washing is the most important precaution by health authorities to stop the virus. COVID-I9 is a deadly reminder that inclusive water supply and sanitation matters for all of us.

Currently, there is no evidence about the survival of the COVID-I9 virus in drinking-water or sewage. The morphology and chemical structure of the COVID-I9 virus are similar to those of other surrogate human coronaviruses for which there are data about both survival in the environment and effective inactivation measures. Thus, this brief draws upon the existing evidence base and, more generally, existing WHO guidance on how to protect against viruses in sewage and drinking-water

Groundwater constitutes an important component of many water resource systems, supplying water for domestic use, for industry, and for agriculture. Management of a groundwater system, an aquifer, artificial recharge and their rates, and control conditions at aquifer boundaries. The quantity and quality problems cannot be separated. In many parts of the world, with the increased withdrawal of groundwater, often beyond permissible limits, the quality of groundwater has been continuously deteriorating, causing much concern to both suppliers and users. In recent years, in addition to general groundwater quality aspects, public attention has been focused on groundwater contamination by hazardous industrial wastes, by leachate from landfills, by oil spills, and by agricultural activities such as the use of fertilizers, pesticides, and herbicides, and by radioactive waste in repositories located in deep geological formations, to mention some of the most acute contamination sources. In many parts of semi-arid areas, ground water development has already reached a critical stage, resulting in acute scarcity of the resource. Over-development of the groundwater resources results in declining groundwater levels, shortage in water supply, intrusion of saline water in coastal areas and increased pumping lifts necessitating deepening of groundwater abstraction structures. These have serious implications on the environment and the socio-economic conditions of the populace.

Saltwater intrusion is the induced flow of seawater into freshwater aquifers primarily caused by groundwater development near the coast. Where groundwater is being pumped from aquifers that are in hydraulic connection with the sea, induced gradients may cause the migration of salt water from the sea toward a well, making the freshwater well unusable.

The protection of groundwater resources has emerged in recent years as a high priority topic on the agenda of many countries. In responding to the growing concern over deteriorating groundwater quality, many countries are developing a comprehensive regulatory framework for the management of subsurface water resources with management referring to both quantity and quality aspects. Within this framework, groundwater models are rapidly coming to playa central role in the development of protection and rehabilitation strategies. These models provide forecasts of the future state of the groundwater aquifer systems and/or the unsaturated zone in response to proposed management initiatives. For example, models will predict the effects of implementing a proposed management scheme on water levels and on the transport and fate of pollutants. The models are now used in the formulation of policies and regulations, the issuing of permits, design of monitoring and data collection systems, and the development of enforcement actions.

In many parts of semiarid areas, water pollution from agricultural sources is plagued with uncertainty of various proveniences. Groundwater quality issues in arid and semiarid lands are very complicated. Human activities result in the groundwater resources being polluted, aquifers being incorrectly exploited and utilized, and abstraction facilities being vandalized. Groundwater development has already reached a critical stage, resulting in acute scarcity of the resource. Overdevelopment of groundwater resources results in declining groundwater levels, shortage in water supply, intrusion of saline water in coastal areas, and increased pumping lifts necessitating deepening of groundwater abstraction structures. These have serious implications on the environ- ment and socioeconomic conditions of the populace. the primary groundwater management issue in many semiarid countries today is pollution. this may derive from a point source, perhaps a leak- ing solvent store at a factory, or it may be diffuse, such as the threat posed by the use of agricultural fertilizers and pesticides. The key to understanding the transport of a pollutant from the ground surface or near surface into an aquifer is an understanding of recharge. Land zonation of different classes of aquifer vulnerability is a valuable tool for management and planning.

The 'Tunisia's experience on Artificial Recharge of Groundwater' is the first in the semi-arid areas and has updated information on various aspects of investigation techniques for selection of sites, planning and design of artificial recharge structures, their economic evaluation, monitoring and technical auditing of schemes and issues related to operation and maintenance of these structures. Tunisia has an experience in artificial recharge of aquifers since the early I956s. This is devised to increase groundwater resources while regulating surface flow, providing underground storage of this water and avoiding its becoming lost in the sea or in salt depressions, or its evaporation in dams.

**References**

[1] UNWATER, WHO and UNICEF launch updated estimates for water, sanitation and hygiene. 20 June 2019.Available from https://www.unwater.org/news/who-and-unicef-launch-updated-estimates-water-sanitation-and-hygiene

[2] Gaaloul N. Water Resources and Climate Change from History to Covid'19 Vaccines in the MENA Regions (Middle East and North Africa). LAP LAMBERT Academic Publishing, 2011.368 p. ISBN: 978-620-4-71658-9. https://www.morebooks.de/shop-ui/shop/product/978-620-4-71658-9

[3] Gaaloul N. Seawater Intrusion into Coastal Aquifer and Climate Change: Impact of the coronavirus (covid-19) on the environment and water resources). Editions Universitaires Européennes, 2020. 229 p. ISBN: 978-613-9-57238-0. https://www.amazon.fr/Seawater-Intrusion-Coastal-Aquifer-Climate/dp/613957238X

[4] Margat, J. De la surexploitation des nappes souterraines [On aquifer overexploitation]. Eaux Souterraines et Approvisionnement en Eau de la France. Ed BRGM, Orléans, 1977, p. 393-408

[5] Custodio, E. (2000) The complex concept of overexploited aquifer. Papeles de la Fundacicion Marcelino Botin, Madrid, 2000, p.1-45

[6] Bouwer, H. I978. Groundwater Hydrology. McGraw-Hill Book Company: United State of America, 1978, 480 p.

[7] Todd, A.D., (I980) Groundwater hydrology. Second edition. John Wiley and Sons, 1980, 552 p. Doi:10.1002/gj.3350170407

[8] Gaaloul, N. Eslamian, S. Artificial Recharge Experiences in Semiarid Areas, in Handbook of Engineering Hydrology, Ch. 2, Vol. 3: Environmental Hydrology and Water Management, Ed. By Eslamian, S., Taylor and Francis, CRC Group, USA, 2014, p. I7-49.

[9] Charbeneau, R., 2000. Groundwater hydraulics and pollutant transport. Prentice Hall.2000, 593 p. DOI:/10.1115/1.1451232

[10] World Resources Institute. World Resources: A Guide to the Global Environment, a joint publication by The World Resources Institute, The United Nations Environment Program, The United Nations Development Program, and The World Bank, Oxford University Press, New York, I998.

[11] Afsin M. Hadrochemical evolution and water quality along the groundwater flow path in Snadikli Plain, Afyon, Turkey. Environmental Earth Sciences, 1997: 31(3):221-230. DOI:10.1007/s002540050183

[12] Stuyfzand, P. J. Pattern in groundwater chemistry resulting from groundwater flow. Hydrogeology Journal, 1999. 7, I527. DOI: I0.I007/sI00400050I77

[13] WHYMAP. Groundwater Resources Map of Africa, BGR, Hannover, Germany and UNESCO, Paris. 2008.Available from http://www.whymap.org/

[14] Matthess, G. The Properties of Groundwater. Wiley: New York, 1982;498 pp.

[15] Kumar, M., Ramanathan, A.L., Rao, M.S. and Kumar, B. Identification and evaluation of hydrogeochemical processes in the groundwater environment of Delhi, India. Journal of Environmental Geology, 2006:53, 553-574. DOI: 10.1007/s00254-006-0275-4

[16] Domenico, P.A. Concepts and Models in Groundwater Hydrology. McGraw-Hill: New York, 1972, 4I6 p.

[17] Wallick, E.L. and Toth, J. Methods of regional groundwater flow analysis with suggestions for the use of environmental isotope and hydrochemical data in groundwater hydrology. In Proceedings of an Advisory Group Meeting of the International Atomic Energy Agency (IAEA), Vienna, Austria, 1976, 37-64.

[18] Toth, J. The role of regional gravity flow in the chemical and thermal evolution of groundwater. "In Proceeding of the first Canadian/ American conference on hydrogeology", Banff, Alta, June, I984.

[19] Saether, O.M., and De Caritat, P. Geochemical Processes, Weathering and Groundwater Recharge in Catchments. A.A. Balkema: Roterdam, 1997, 400 p.

[20] Martinez, D.E., and Bocanegra, E.M. 2002. Hydrochemistry and cation exchange processes in the coastal aquifer of Mar Del Plata, Argentina. Hydrogeology Journal, 2002, I0, p. 393-408.

[21] Ikeda, K. Chemical evolution of groundwater quality in the southern foot of Mount Fuji. Bulletin of the Geological Survey of Japan,1989: 40, 33I-404.

[22] Pulido-Bosh, A., Tahiri, A. and Vallejos, A. Hydrogeochemical characteristics of processes in the Temara aquifer in Nothrwestern Morocco. Journal of Water, Air, and Soil Pollution, 1999: II4, 323-337.

[23] Kumar, M., Kumari, K., Singh, U.K. and Ramanathan, A.L. Hydrogeochemical processes in the groundwater environment of Muktsar, Punjab: conventional graphical and multivariate statistical approach. Journal of Environmental Geology, 2009: 57, 873-884. DOI: I0.I007/s00254-008-I367-0

[24] Johnson, T. Battling Seawater Intrusion in the Central & West Coast Basins. Technical Bulletin. Lakewood: The Water Replenishment District, 2007.


©2022 by the authors | Open Access Journal | ISSN Online: 1737-9350, ISSN Print: 1737-6688

[25] Bear J. Dynamics of fluids in porous media. Dover Publications, New York 1972. DOI: I0.I097/000I0694-I97508000-00022

[26] Bear J, Cheng AHD. Modeling groundwater flow and contaminant transport. Springer, New York. 2010.DOI:10.I007/978-I-4020-6682-5

[27] Bear, J., Cheng, A.H.-D., Sorek, S., Ouazar, D., Herrera, I. Seawater Intrusion in Coastal Aquifers- Concepts, Methods Practices. Kluwer Academic Publishers, Dordrecht/ Boston/ London,1999, 625 p.

[28] Doorman, F. Crisis, Economics and the Emperor's Clothes. Ist ed. Lulu Internet Publisher.2013.

[29] Masciopinto, C. Simulation of coastal groundwater remediation: The case of Nardò fractured aquifer in Southern Italy. Environ. Model. Softw. 2006: 2I, 85–97.

[30] Mjemah, I.C.; Van Camp, M.; Walraevens, K. Groundwater exploitation and hydraulic parameter estimation for a Quaternary aquifer in Dar-es-Salaam, Tanzania. J. Afr. Earth Sci. 2009, 55, I34–I46.

[31] Van Camp, M.; Mtoni, Y.E.; Mjemah, I.C.; Bakundukize, C.; Walraevens, K. Investigating seawater intrusion due to groundwater pumping with schematic model simulations: The example of the Dar Es Salaam coastal aquifer in Tanzania. J. Afr. Earth Sci. 2014: 96, 7I–78

[32] Jones, B.F.; Vengosh, A.; Rosenthal, E.; Yechieli, Y. Geochemical investigation of groundwater quality. In Seawater Intrusion in Coastal Aquifers-Concepts, Methods and Practices; Springer: Kluwer, The Netherlands, 1999, pp. 5I–7I.

[33] Meybeck, M.; Vorosmarty, C.; Schultze, R.; Becker, A. Conclusions: Scaling Relative Responses of Terrestrial Aquatic Systems to Global Changes. In Vegetation, Water, Humans and the Climate; Kabat, P., Claussen, M., Dirmeyer, P.A., Gash, J.H.C., Bravo de Guenni, L., Meybeck, M., Pielke, R.A., Vorosmarty, C.J., Hutjes, R.W.A., Lutkemeier, S., Eds.; Springer: Berlin/Heidelberg, Germany, 2003, pp. 455–464.

[34] Cary L., Casanova J., Gaaloul N., Guerrot C., Combining boron isotopes and carbamazepine to trace sewage in salinized groundwater: a case study in Cap Bon, Tunisia. Applied chemistry, 2013: 34, p.I26-I39. http://www.sciencedirect.com/science/article/pii/S08832927I3000693

[35] Gaaloul N., Rechargeable groundwater : Artificial recharge of groundwater by treated wastewater / Des nappes phréatiques rechargeables : Recharge artificielle des eaux souterraines par les eaux usées traités. ISBN- I3:978-6I3-8-4I47I-I; ISBN-I0:6I384I47I3EAN:9786I384I47II; 2019,132 p.

[36] Kerrou, J., Renard, P., Tarhouni, J. Status of the Korba groundwater resources (Tunisia): observations and three-dimensional modelling of seawater intrusion. Hydrogeol. 2010: 18 (5), 1173–1190.

[37] Paniconi C., Khlaifi I., Lecca G., Giacomelli A., Tarhouni J. A modelling study of seawater intrusion in the Korba Coastal Plain, Tunisia. Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere, 2001: 26 (4) , p. 345-351.

[38] Zghibi, A, Zouhri,L., Tarhouni, J., Kouzana, L. Groundwater mineralisation processes in Mediterranean semi-arid systems (Cap-Bon, North east of Tunisia): hydrogeological and geochemical approaches. Hydrological Processes.2012: 27 (22), 3227-3239. DOI:10.1002/hyp.9456

[39] Djabri L, Laouar R, Hani A, Mania J, Mudry J. The origin of water salinity on the Annaba coast (NE Algeria). Proceedings of symposium HSO2a held during IUGG2003 at Sapporo; 2003 July; IAHS. Publ. No 280; pp. 229-35.

[40] Bouderbala A . Groundwater salinization in semi-arid zones: an example from Nador plain (Tipaza, Algeria). Environ Earth Sci . 2015:73:5479–5496. DOI:I0.I007/sI2665-5080I4-380I-9

[41] Imerzoukene, S.;Walraevens, K.; Feyen, J. Salinization of the coastal and eastern zones of the alluvial and unconfined aquifer of the Mitidja Plain (Algeria). In Proceedings of the I3th SaltWater Intrusion Meeting, Cagliari, Italy, 5–4 June I994; p. I63–I75.

[42] Chaouni Alia, A.; El Halimi, N.; Walraevens, K.; Beeuwsaert, E.; De Breuck, W. Investigation de la Salinisation de la Plaine de Bou-Areg (Maroc Nord-Oriental); Freshwater Contamination; International Association of Hydrological Sciences—IAHS Publication: London, UK, 1997 : 243, p. 2II–220.

[43] El Halimi, N.; Chaouni Alia, A.; Beeuwsaert, E.; Walraevens, K. Hydrogeological and Geophysical Investigation for Characterizing the Groundwater Reservoir in Saidia Plain (north-eastern Morocco). In Development of Water Resource Management Tools for Problems of Seawater Intrusion and Contamination of Fresh-Water Resources in Coastal Aquifers; Walraevens, K., Ed.; Ghent University: Ghent, Belgium, 2000. p. 67–75, ISBN 90- 76878-0I-3.

[44] El Yaouti, F., El Mandour, A., Khattach, D., Benavente, J. & Kaufmann, O. Salinization processes in the unconfined aquifer of Bou-Areg (NE Morocco): A geostatistical, geochemical, and tomographic study. Applied Geochemistry,2009: 24, I6-3I.

[45] Sadeg SA, Karahanoglu N. Numerical assessment of seawater intrusion in the Tripoli region, Libya. Environ Geol; 2008: 40: II5I-68.

[46] Sherif, M. The Nile Delta aquifer in Egypt. In: Bear, J., Cheng, A., Sorek, S.,Ouazar, D., and Herrera, A. (eds), Seawater Intrusion in Coastal Aquifers: Concepts, Methods and Practices, Book Series: Theory and Application of Transport in Porous Media, Kluwer Academic Publishers: The Netherlands, 1999, I4, 559-590.

[47] Sefelnasr, A., Sherif, M.Impacts of Seawater Rise on Seawater Intrusion in the Nile Delta Aquifer, Egypt. Groundwater, 2014: 52, 2, p.364-376. DOI:10.1111/gwat.12058

[48] Gomaa S.M., Hassan T.M., Helal E. Assessment of seawater intrusion under different pumping scenarios in Moghra aquifer, Egypt. Science of the Total Environment, 2021, 781, DOI :10.1016/j.scitotenv.2021.146710

[49] Choudhury K, Saha DK, Chakraborty P.Geophysical study for saline water intrusion in a coastal alluvial terrain. Journal


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of Appl. Geophysics ,2001:46:I89–200

[50] Batayneh, AT. Use of electrical resistivity methods for detecting subsurface fresh and saline water and delineating their interfacial configuration: a case study of the eastern Dead Sea coastal aquifers. Jordan Hydrog.J.2006: I4:I277–I283

[51] Beni-Akhy, R. Etude des impacts anthropiques sur les eaux souterraines du Sahel oriental tunisien : caractérisation hydrogéologique, modélisation mathématique et cartographie de la vulnérabilité' environnementale. PhD thesis, Tunis University, Tunis, Tunisia. 1998

[52] Amri, R. (I992) Note hydrogéologique de la nappe de Teboulba, rapport interne du Commissariat régional au développement agricole, Monastir, Tunisie.1992, 15 p.

[53] Besbes, M. Premier essai d'alimentation artificielle par puits de la nappe de Teboulba, rapport interne de la Direction Générale des Ressources en Eaux, Tunis, Tunisie, 1971.28 p.

[54] Maalel, F. Note hydrogéologique sur la recharge artificielle de la nappe de Teboulba, rapport interne du Commissariat régional au développement agricole, Monastir, Tunisie.1998.10 p.

[55] Rekaya, M. and Amri, R. Note sur les possibilités de recharge artificielle des nappes de Teboulba et Moknine à partir des eaux usées de la Direction Générale des Ressources en Eaux, Tunisie.1992. 20 p.

[56] Bouri, S. and Ben Dhia, H. A thirty-year artificial recharge experiment in a coastal aquifer in an arid zone: The Teboulba aquifer system (Tunisian Sahel). Comptes Rendus. Géoscience,2010 : 342(I), 60–74.

[57] Kloppmann, W., Chikurel, H., Picot, G., Guttman, J., Pettenati, M., Aharoni, A., Guerrot, C.,Millot, R., Gaus, I., and Wintgens, T. B and Li isotopes as intrinsic tracers for injection tests in aquifer storage and recovery systems. Applied Geochemistry, 2009 : 24, I2I4–I223.

[58] Calo, A. Etude pédologique du périmètre de Oued Souhil.1964. 10p.art. no. 146710.2021

[59] Rekaya, M. Expérimentation pilote de recharge arti cielle à partir des eaux usées traitées. Cas de la nappe de l'Oued Souhil (Nabeul).1986, 20 p.

[60] Plata Bedmar, A. and Rekaya, M. Application des techniques nucléaires aux études de recharge artiffcielle d'un aquifère côtier en Tunisie. Report.1987. 20 p.

[61] Kallali, H. and Yoshida, M. Soil and subsoil characterization of Souhil Wadi (Nabeul) pilot plant for wastewater infilltration-percolation. In: Proceedings of International Symposium on Environmental Pollution Control and Waste Management (EPCOWM'2002), Tunis, Tunisia;

[62] Bouwer, H. Role of groundwater recharge in treatment and storage of water reuse. Water Science and Technology, 1991: 24(9), 295–302.

[63] Brissaud, F. and Salgot, M. Infiltration percolation as a tertiary treatment. Hydrotop 94, Marseille, April I2– I5, 1994:Vol. II, pp. 39I–398.

[64] Rekaya, M. and Brissaud, F. Recharge de la nappe de l'Oued Souhil par des effluents secondaires. XXI° J. de l'Hydraulique: Les eaux souterraines et la gestion des eaux, Sophia Antipolis, 29–3I January, 1991, II. 4. I-II. 4.8.

[65] Ben Salem, H. Contribution l'étude de la Géologie du Cap Bon: Stratigraphie, tectonique et sédimentologie. Thèse 3e cycle Université de Tunis-II, Tunis, Tunisie ?1992, 203 p

[66] Plata Bedmar, A. and Rekaya, M. Use of Nuclear Techniques for Arti!cial Recharge Studies of a Coastal Aquifer in Tunisia. IAEA, Vienna, Austria.1988.15p.

[67] Koussis, AD., Georgopoulou, E., Kotronarou, A., Mazi, K., Restrepo, P., Destouni, G., Prieto, C., Rodriguez, JJ., Rodriguez-Mirasol, J., Cordero, T., Ioannou, C., Georgiou, A., Schwartz, J. and Zacharias, I. Cost efficient management of coastal aquifers via recharge with treated wastewater and desalination of brackish groundwater: application to the Akrotiri basin and aquifer, Cyprus. Hydrology Science Journal, 2010: 55(7):I234– I245, 20I0.

[68] Abbès A., Étude géologique et géophysique du Miocène de la Dakhla (Cap-Bon, Tunisie nord-orientale) : application à la prospection des couches lignitifères (Thèse 3e cycle). Faculté des sciences et techniques, Université de Franche-Comté, Besançon, France (1983), p. 199 p

[69] Abbès A., Polak, M. La formation Saouaf dans les synclinaux de la Dakhla (Cap Bon) et de Saouaf (Tunisie nord-orientale).Notes Serv. Geol. Tunis., 46 (1981), pp. 99-111

[70] Gharsalli R., Zouaghi T., Soussi M., Chebbi R., Khomsi S., Bedir M. Seismic sequence stratigraphy of Miocene deposits related to eustatic, tectonic and climatic events, Cap Bon Peninsula, northeastern Tunisia.2013: Comptes Rendus - Geoscience, 345 (9-10), pp. 401-417. DOI: 10.1016/j.crte.2013.07.003

[71] Ennabli, M. Etude hydrogéologique des aquifères Nord Est de la Tunisie par une gestion intégrée des ressources en eau, Université de Nice. Thèse de doctorat d'état, p. 400.

[72] Temani, R., Gaaloul, N., Jedoui, Y., Razgallah, S.. The Upper Pleistocene deposits of Cap Bon (North - Eastern Tunisia): Bio-sedimentology and spatio-temporal evolution. International journal of tropical geology, geography and ecology Tome 1-2, 2008:pp. 83-90.

[73] Elmejdoub, N., Jedoui, Y.. Pleistocene raised marine deposits of the Cap Bon peninsula (N-E Tunisia): Records of sea-level highstands, climatic changes and coastal uplift. Geomorphology 2009 : 112, 179-189.

[74] Ben Hamouda, M.F., Tarhouni, J., Leduc, C., Zouari, K.. Understanding the origin of salinization of the Plio-quaternary eastern coastal aquifer of Cap Bon (Tunisia) using geochemical and isotope investigations. Environmental Earth Sciences,2011 : 63, 889-901.

[75] Paniconi, C., Khlaifi, I., Lecca, G., Giacomelli, A., Tarhouni, J.. Modeling and Analysis of Seawater Intrusion in the Coastal Aquifer of Eastern Cap-Bon, Tunisia. Transp. Porous Media,2001 : 43, 3-28.

[76] Paniconi, C., Khlaifi, I., Lecca, G., Giacomelli, A., Tarhouni, J., 2001. A modelling study of seawater intrusion in the Korba coastal plain, Tunisia. Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere,2001: 26, 345-351.
[77] Kerrou, J., Renard, P., Tarhouni, J.. Status of the Korba groundwater resources (Tunisia): observations and three-dimensional modelling of seawater intrusion. Hydrogeology Journal,2010: 18, 1173-1190.
[78] Gaaloul, N.; Pliakas, F.; Kallioras, A.; Schuth, C.; Marinos, P. Simulation of Seawater Intrusion in Coastal Aquifers: Forty Five'Years exploitation in an Eastern Coast Aquifer in NE Tunisia. Open Hydrol. J.,2012: 6, 3I– 44.
[79] Goldberg, S., Forster, H.S.. Boron sorption on calcareous soils and reference calcites. Soil Sci. 1991:152, 304-310.
[80] Majidi, A., Rahnemaie, R., Hassani, A., Malakouti, M.J. Adsorption and desorption processes of boron in calcareous soils. Chemosphere,2010: 80, 733-739.
[81] Scheytt, T., Mersmann, P., Lindstädt, R., Heberer, T. Determination of sorption coefficients of pharmaceutically active substances carbamazepine, diclofenac, and ibuprofen, in sandy sediments. Chemosphere,2005: 60, 245-253.
[82] Maoz, A. and Chefetz, B. Sorption of the pharmaceuticals carbamazepine and naproxen to dissolved organic matter: Role of structural fractions. Water Research,2010: 44, 981-989.
[83] Clara, M., Strenn, B., Kreuzinger, N. Carbamazepine as a possible anthropogenic marker in the aquatic environment: investigations on the behaviour of Carbamazepine in wastewater treatment and during groundwater infiltration. Water Research,2004: 38, 947-954.
[84] Maeng, S.K., Sharma, S.K., Lekkerkerker-Teunissen, K., Amy, G.L. Occurrence and fate of bulk organic matter and pharmaceutically active compounds in managed aquifer recharge: A review. Water Research,2011: 45, 3015-3033.
[85] Chefetz, B., Mualem, T., and Ben-Ari, J. Sorption and mobility of pharmaceutical compounds in soil irrigated with reclaimed wastewater. Chemosphere,2008: 73, 1335-1343.
[86] Arye, G., Dror, I., Berkowitz, B.. Fate and transport of carbamazepine in soil aquifer treatment (SAT) infiltration basin soils. Chemosphere,2011: 82, 244-252.
[87] Kreuziner, N., Clara, M., Strenn, B., Vogel, B.. Investigation on the behavior of selected pharmaceuticals in the groundwater after infiltration of treated wastewater. Water Sci. Technol. 2004:50, 221-228.
[88] Slama, F. Field experimentation and modelling of salt transfer in Korba coastal plain: Impact of seawater intrusion and irrigation practices, Hydrogeology. University of Neuchâtel, INAT, 2010.p. 128 p.
[89] Kouzana, L., Ben mammou, A., Gaaloul, N. Intrusion marine et salinisation des eaux d'une nappe phréatique côtière (Korba, Cap-Bon, Tunisie). Revue internationale de géologie, de géographie et d'écologie tropicales,2009 : Tome I, pp. 57–70.
[90] World Health Organization (WHO). (2019). Report of the WHO-China joint mission on coronavirus disease 2019 (COVID-19). Available at: https://www.who.int/docs/default-source/coronaviruse/who-china-jointmission-on-COVID-19-final-report.pdf
[91] World Health Organization (WHO).Coronavirus disease (COVID-2019) situation reports. Available at: https://www.who.int/emergencies/diseases/novel-coronavirus-2019/situation-reports
[92] World Health Organization. Coronavirus disease 2019 (covid-19): situation report, 51. Geneva: World Health Organization; 2020.Available from: https://apps.who.int/iris/handle/10665/331475
[93] World Health Organization [Internet]. The push for a covid-19 vaccine. Geneva. [cited 2020 Dec 23]. Available from: https://www.who.int/emergencies/diseases/novel-coronavirus-2019/covid-19-vaccines
[94] Huang C, Wang Y, Li X, Ren L, Zhao J, Hu Y, et al. Clinical features of patients infected with 2019 novel coronavirus in Wuhan, China. Lancet 2020;395:497–506. https://www.sciencedirect.com/science/article/abs/pii/S0140673620301835
[95] World Vision, " COVID-19 surge in Northwest Syria as cases multiply by 14 times in one month", October 2020, https://reliefweb.int/report/syrian-arab-republic/covid-19-surge-northwest-syria-cases-multiply-14-times-one-month
[96] Dworkin, Anthony and Tarek Megerisi. "North Africa", Council on Foreign Relations, 19 March 2020, https://www.ecfr.eu/article/commentary_infected_the_impact_of_the_coronavirus_on_the_middle_east_and_no.
[97] Mezran, Karim, et. al., "The coronavirus crisis highlights the unique challenges of North African countries", Atlantic Council, 30 March 2020, https://atlanticcouncil.org/blogs/menasource/the-coronavirus-crisis-highlights-the-unique-challenges-of-north-african-countries/
[98] Guetat, M. Tunisia and coronavirus: the reality of a poor governance, ISPI Dossier, 12 April 2020, https://www.ispionline.it/en/pubblicazione/mena-region-vs-covid-19-one-challenge-common-strategies-25649
[99] NATO. Tunisia requests international assistance in their response to COVID-19", 6 May 2020, https://www.nato.int/cps/en/natohq/news_175635.htm?


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