



North Western Sahara aquifer system hydrothermal and petroleum reservoirs dynamics: a comprehensive overview

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Abstract

In the last decades, anthropogenic activities (e.g., intense agricultural activity, over-exploitation of water and petroleum resources, surface and groundwater contamination) caused many serious socio-economic and environmental problems (e.g., water and soil deterioration, increasing of water salinity, intense desertification, poor land management). These activities along with natural interventions have caused severe problems (e.g., quality degradation, depletion, and contamination) to the groundwater resources of the North Africa's transboundary aquifer system, the North-Western Sahara Aquifer System (NWSAS). The sustainability of these valuable resources is facing increasing threats. The damages of natural resources and ecosystems have reached an irreversible stage as manifested by local hydrocarbon contamination. In an attempt to mitigate these interventions, this study aims to evaluate the hydrodynamic behavior and reservoir connections of the deep and "fossil" groundwater resources in southern Tunisia. A review of hydrogeological, isotopic, structural, and geochemical data coupled with field data analysis, modeling, and survey were presented. Results indicate that this hydrocarbon pollution is derived by the excessive groundwater abstraction that modifies groundwater flow and distribution. Given the complex geological and structural features of the subsurface reservoirs, sedimentary and hydrodynamic proprieties (e.g., deep fluid circulation and high pore pressure gradient) act like conduit mixing leaky barriers. The detailed review of these features simplified by conceptual models characterizing the flow paths at different scales and under various conditions represents a baseline report for decision-makers to offer scientifically reasonable sustainable management strategies.

Keywords Groundwater exploitation · Hydrocarbon contamination · Mixing georesources · Transboundary basin · Sahara platform

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Introduction

Increasing demands for demographic growth, agriculture needs, and industrial activities has increased the exploitation of the available water resources worldwide (Ahmed et al. 2011, 2014, 2021; Hamed et al. 2014, 2018, 2021). The majority of the planet's water supply is either saline or difficult to mobilize, with seawater, ice caps, glaciers, inland seas, and brackish groundwater constituting 99.5% of all water on earth (Kalaswad et al. 2004). Only 0.5% of the earth's water resources are accessible for human, agriculture, and industry consumption. The availability of groundwater resources at sufficient quantity and adequate quality for different utilization needs become a major source of concern for various scientific, economic, and social sectors. The issues related to the exploitation of this vulnerable resource in a sustainable way and the relative impacts of the mismanagement have caused serious environmental problems in many regions in the last decades, especially in areas arid and semi-arid where the dependency on these resources is of 100% (Trabelsi et al. 2007; Onodera et al. 2009; Benedetti-Cecchi et al. 2010; Li et al. 2015; Yakirevich et al. 2013; Mtoni et al. 2013; Demdoun et al. 2015; El Gayar and Hamed 2018; Fallatah et al. 2018; Niyazi et al. 2018; Ncibi et al. 2020a, b). Thus, most of the hydrogeological studies in recent years have focused on water chemistry evolution and management issues related to groundwater pollution, salinization, aquifer depletion, saltwater intrusion, and quality degradation (Eissa et al. 2015, 2016; Su et al. 2014; Nouri et al. 2007; Guo et al. 2014; Ahmed et al. 2014; Mouici et al. 2017; Besser et al. 2017; Hamad et al. 2018a, b; Besser and Hamed 2019). These studies indicated that inappropriate groundwater exploitation strategies may induce several environmental problems that could reach irreversible levels that would be difficult to remediate namely land subsidence, desertification, agricultural land degradation, human health diseases, and disequilibrium of natural ecosystem (Abdelkader et al. 2012; Hadji et al. 2013, 2014a, b; Hamed et al. 2013a, b; Mokadem et al. 2016; Besser et al. 2018; Besser and Hamed 2019; Anis et al. 2019; Karim et al. 2019; Kerbati et al. 2020).

The sustainable exploitation of groundwater resources relies on an accurate evaluation of increasing degradation (qualitative and quantitative) risks which requires about a deep understanding of the specific natural and anthropogenic factors influencing groundwater availability. This deeper understanding extends to proper quantification of aquifer recharge, discharge flows, interactions groundwater-surface water, hydrogeological processes such as evaporation, dissolution, mixing, water origin, groundwater chemistry, geochemical evolution, major

and minor elements distribution, geochemical reaction with the aquifer, evolutionary pathways of groundwater, geo-structural features, the increasing pressure on groundwater, and groundwater withdrawal. The assessment of the spatiotemporal variation of these key parameters at various hydrogeological scales may facilitate selecting the adequate options of risk control and remediation, monitoring groundwater hydrodynamic evolution, modeling water flows, knowing aquifer capacity for the provision of sustainable water, and evaluating the magnitude of ecological and environmental changes related to man-induced perturbations (Eissa et al. 2013; Li et al. 2015).

Groundwater pollution, commonly observed in irrigated lands and/or near industrial and municipal wastes, represents one of the most difficult environmental issues to assess and to remediate. This is especially true in the case of complex hydrogeological systems including multi-layered aquifers and transboundary resources for which there are multiple contaminant sources and the flow pattern and migration pathways reveal perpetual lateral and vertical variations (Dragon and Groski 2015). Previous works indicated that, despite the high costs associated with accessing deep reservoirs, they define growing relevance to secure permanent supply for different water-dependent sectors. The depletion of these multi-layered and transboundary groundwater resources within the context of unpredictable climate variability brings out the uncertainties contouring the characterization and the investigation of deeper aquifers. These partially known proprieties amplify the probability of both contamination and mixing between different fluid reservoirs and reduce the percentage of early effective remediation (Hamed et al. 2013a, 2018; Besser and Hamed 2019). Consequently, the sustainable development of these resources requires detailed knowledge about these dynamic systems on the basis of sensitive methods for reliable monitoring. This is especially the case for dry and hot environments, where groundwater resources support high pressure, especially for agriculture. The lateral and vertical variability of aquifer proprieties, groundwater quality, and water hydrodynamic behavior require the implementation of control systems, different scales of assessment cycles, especially in the case of shared transboundary systems. The integration of multiple scales of evaluations may facilitate effective management process.

Water resource availability in North Africa has already been affected by environmental change and could be facing jeopardization in future environmental, economic, and demographic scenarios. Numerous studies utilized global hydrological models based on expected trends in precipitation and temperature. These models indicated the influence of land cover on river discharge and water resources. Climate and land cover change which include both artificial

and natural reforestation, overexploitation of geothermal groundwater, and expansion of farming and touristic areas are likely to amplify water stress in the Mediterranean region specially in MENA regions (Hamed 2021).

In southern Tunisia, for example, a significant correlation is reported between groundwater exploitation and deterioration. Evidence for this has been presented through the hydrodynamic evolution of aquifers, the accumulation and exploitation of petroleum, and the expansion of agriculture (Abdelkader et al. 2012; Hadji et al. 2013, 2014a, b; Hamed et al. 2013a, b; Mokadem et al. 2016; Besser et al. 2018; Besser and Hamed 2019; Anis et al. 2019; Karim et al. 2019; Kerbati et al. 2020). Moreover, climate variability coupled with increasing socio-economic pressure has identified southern Tunisia as an area of interest concerning the effects of anthropogenic activities on the variation of deep groundwater aquifers of NWSAS, the vulnerability of transboundary systems, climate change, and the environment at large. Previous investigation and field observations showed that the area underwent a remarkable change in hydrogeological properties (e.g., flow paths, aquifer geometry, chemical control, pollution, distribution of hydrogeological conditions, mixing, and geo-structure and deeply influenced by different human activities). In order to carry out an effective program for sustainable development of the North Western Sahara Aquifer System (NWSAS) deep aquifer in southern Tunisia “Oriental Erg of North Africa Sahara,” it is essential to assess risks of oil and gas production, intensity of irrigated agriculture, and climate variability. Identifying the factors that influence the severity and the magnitude of groundwater availability requires a review of the detailed history of exploitation; high long-term perspective evolution of groundwater exploitation over decades as well as the interference risks and contamination issues should be carefully analyzed. The present work provides a review by analyzing the evolution of water chemistry and hydrodynamic behavior in response to increasing supplies within the context of oil–gas trace upward migration into groundwater aquifer and irrigated agricultural impacts on groundwater quality degradation. It attempts to outline the preferential pathways of contaminant migration and report the principal findings related to the rehabilitation of the contaminated resources. This overview examination, via a development of different schematic illustration and conceptual models (Figs. 2 and 4), provides information on the upward component and down gradient progress of different fluid flows and the functioning of geotectonic features of the study area. This study also attempts to address questions concerning mixing interference risks and how fluid actively circulation systems operate in sedimentary basin as large as the NWSAS. Furthermore, it gives insights on the range patterns closely related to

anthropogenic activities as well as climate change repercussions on paleo-groundwater systems manifested, principally, by a shift of well productivity and water qualities.

Context of the study area

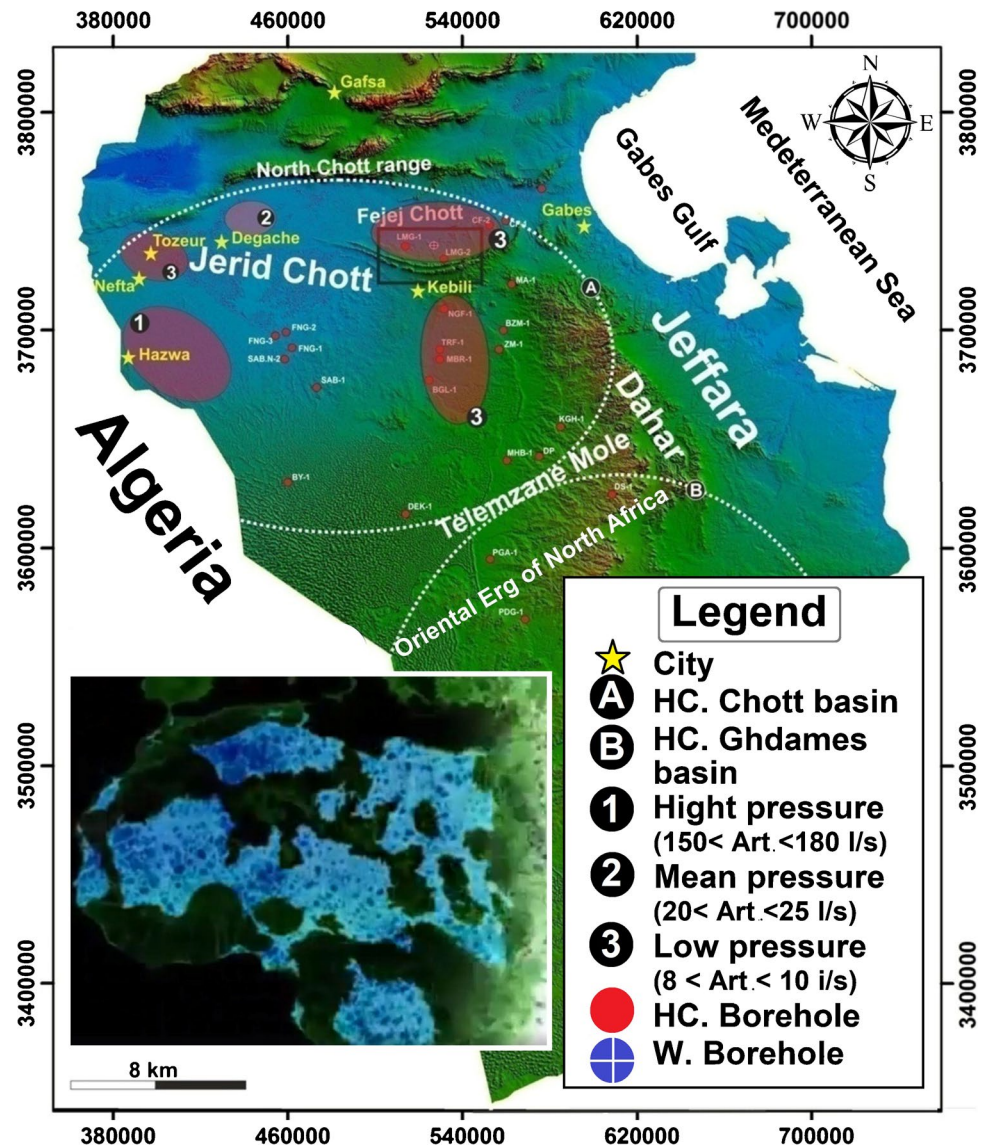
Physiography

The study area is located in southern Tunisia between longitudes 07.5° to 10.0° East, and latitudes 30.5° to 34.0° North. It is bordered by the Libyan territory and the Mediterranean Sea in the east, the southern Atlas in the north, the Algerian territory in the west, and the sandy dunes of the Great Oriental Erg in the south (Fig. 1). This transboundary (Algeria, Tunisia, and Libya) area of about 50,000 km² constitutes a transition zone between two different structural domains: the faulted southern Atlas, characterized by major thrust faults and diapir structure, and the stable domain of the Saharan platform (Zargouni 1985; Ahmadi et al. 2006; Lazzez et al. 2008; Zouaghi et al. 2011). The region has a generally flat topography, with the exception of the Dahar plateau and the Tebaga anticline of Kebili (Fig. 1). The physiographic features of the region are the results of multiple tectonic phases and important subsidence periods, associated with the influence of paleo-climate variability manifested by complex heterogeneous subterranean system architecture (Hamed et al. 2012).

The study area has a continental semi-arid to arid climate, characterized by short, cool, moist winters and long, dry, hot summers. The maximum temperature is about 50 °C. The region is known for the scarce rainfall of about 100 mm/year based on 90 years of record. The precipitation showed great irregular and sporadic distribution that resulted in a rare, non-perennial hydrographic network. The arid to desert climate of the study area is amplified by high evapotranspiration of about 2000 to 2500 mm/year.

The outcrops in the study area range from Permian, represented by Tebaga Formation (Dahar) in Medenine region to Quaternary (Zargouni 1985; Bouaziz et al. 2002). Structurally, the Saharan transition zone area is affected by several events expressed in the long history of the region. The main fault systems trends to the NW–SE and W–E directions. The study area is characterized by different geological features: the anticlines (Norther Chotts Range), monoclines cuestas (Dahar plateau), Saharan platforms, regional major faults (Khenchela-Gafsa-Tripolitaine, Negrine-Tozeur and Agadir-El Hamma), active grabens creating endoreic basins (Chotts), and local salt structures (Hadifa Diapir). To the western Tunisian border, the sandy dunes of the Great Oriental Erg cover up the major part of the Saharan platform domains (Fig. 1).

Fig. 1 Spatial distribution of the NWSAS groundwater transboundary aquifers and the petroleum reservoirs in Southern Tunisia. Also shown is the distribution of the hydrocarbon (HC) pressures. W denotes water borehole



Natural resources

Groundwater resources

The subterranean basin of southern Tunisia is characterized by very complex, thick lithological units and intense faulting resulted from the successive tectonic phases and subsidence, especially during the Mesozoic. The preserved sequence forms one of the largest multi-layered aquifer systems in the world. The NWSAS transboundary structure consisting of two principal aquifer systems (the Complex Terminal [C.T] and the Continental Intercalaire [C.I]) within the Cretaceous-Early Tertiary heterogeneous formations. The youngest deposits of the Plio-Quaternary are represented by the shallow aquifer that gives locally important potential to be used for agriculture and/or supplementary resources during water shortage periods.

The C.I aquifer is one of the two aquifer members that combine the NWSAS. It is shared by Algeria, Tunisia, and Libya, extending over an area of more than one million km² represented by confined-to semi-confined aquifers. The NWSAS is comparable in scale to the Nubian Sandstone Aquifer System (NSAS) shared by Egypt, Sudan, Libya, and Chad as well as Great Artesian Basin of Australia and covers some 600,000 km² with a potential reservoir thickness of between 120 and 1,000 m (Fig. 1). The aquifer is mostly unconfined, unlike the eastern counterpart. Its depth increases from north to south and from west to east. It has the shape of a depression that disappears further south where it becomes confined. TDS increases southward along the recognized flow path (2 ≤ TDS ≤ 20 g/L). Major elements increase with the increase of TDS. The radiocarbon activities of the groundwater are very low, varying between 0.27 and 70.3% modern Carbon. The confined part of the reservoir shows depleted

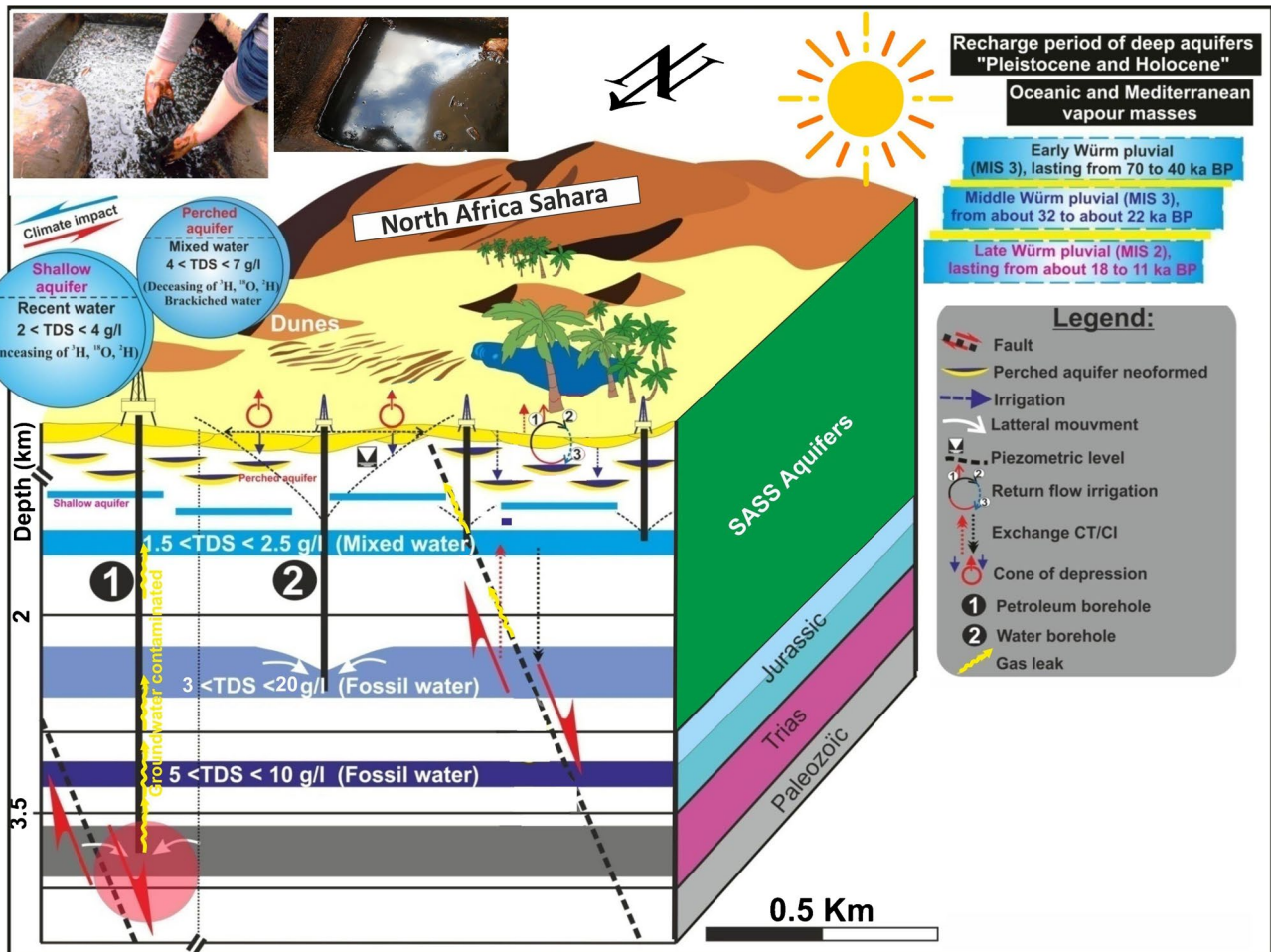


Fig. 2 Conceptual model showing the NWSAS groundwater hydrodynamic and the intercommunication with the petroleum reservoirs

isotopes data (^{18}O and ^2H) and low ^{14}C content, reflecting the absence of modern water (^3H) at the discharge zone. The combined evidence shows that the recharge coincides with cooler, humid periods during the Late Pleistocene-Holocene (Early Würm pluvial-MIS3 “70–40 Ka B.P”, Middle Würm pluvial-MIS3 “32–22 Ka B.P” and Late Würm pluvial-MIS2 “18–11 Ka B.P”) (Fig. 2) which existed across the entirety of Saharan Africa (Hamed et al. 2008, 2010, 2014; Mokadem et al. 2016; Besser et al. 2018).

The NWSAS, as a multi-layered transboundary aquifer system, is characterized by complex hydrodynamic of groundwater likely controlled by the heterogeneity of the hosted aquifer, anisotropy of hydraulic continuity flows, and the local variability of the geo-structural features (UNESCO 1972; Edmunds and Gaye 1997; Guendouz et al. 2003; Al Gamal and Hamed 2014; Hamed et al. 2012, 2013b; Besser et al. 2017, 2018, 2019; Besser and Hamed 2019). The latter significantly affect the aquifer properties and uncertainties in groundwater flows as well as leakage rates and locations.

The NWSAS system has been studied extensively since the end of the 1960s because of the increasing number of supply wells that have historically extracted drinking and irrigation water for local residents. Due to the harsh climate conditions, the irregularity of rainfall, and hydro-graphic runoff of large rivers, severe water shortage has led to continuous exploitation of CI and CT aquifers in order to keep up permanent supply for the stable development of local society and economy especially the intensive agriculture and industrial development. This has raised concern, in a hot, dry areas such as southern Tunisia, about groundwater level failing, increasing salinity, aquifer depletion, and overall sustainability of groundwater resources in both terms of quality and quantity. The disequilibrium caused by these cumulative impacts induces unpredictable response of water systems as well as shifts to the natural flow. This progressive evolution requires a systematic overview of baseline conditions and pristine properties along with the continuous evolution of the system in order to develop rehabilitation measures.

Petroleum resources

Two petroleum basins have been identified in Southern Tunisia, Oriental platform, starting with the Chotts basin, and Ghadames basin, which is bordered to the North by the Telmzane High (Fig. 1).

Ghadames basin It is one of the huge oil/gas producing areas in North Africa due to its large extent and thickness. This basin hosts many high productive petroleum systems targeted in the sandstone formations of Paleozoic (Ordovician, Devonian, Silurian, Carboniferous) and Triassic ages (Fig. 3). It encompasses more than 350,000 km² over

western Algerian, southern Tunisia, and northeastern Libya (Klett et al. 2000).

The principal source rocks are Silurian Tannezuft and Middle to Upper Devonian shale Formations (Daniels and Emme 1995). The minor potential source rocks are represented by the Silurian to Middle Devonian mudstone (Daniels and Emme 1995). The main oil reservoirs in Southern Tunisia are listed as follows from deepest to shallowest: (i) the El Hammra sandstone (Ordovician), (ii) Acacus Formation (B and A), middle Silurian, and (iii) TAGI sandstone of middle Triassic.

Chotts basin Four principal oil and gas fields are in production within this basin, namely, Sabria- El Farnig, Zoumit,

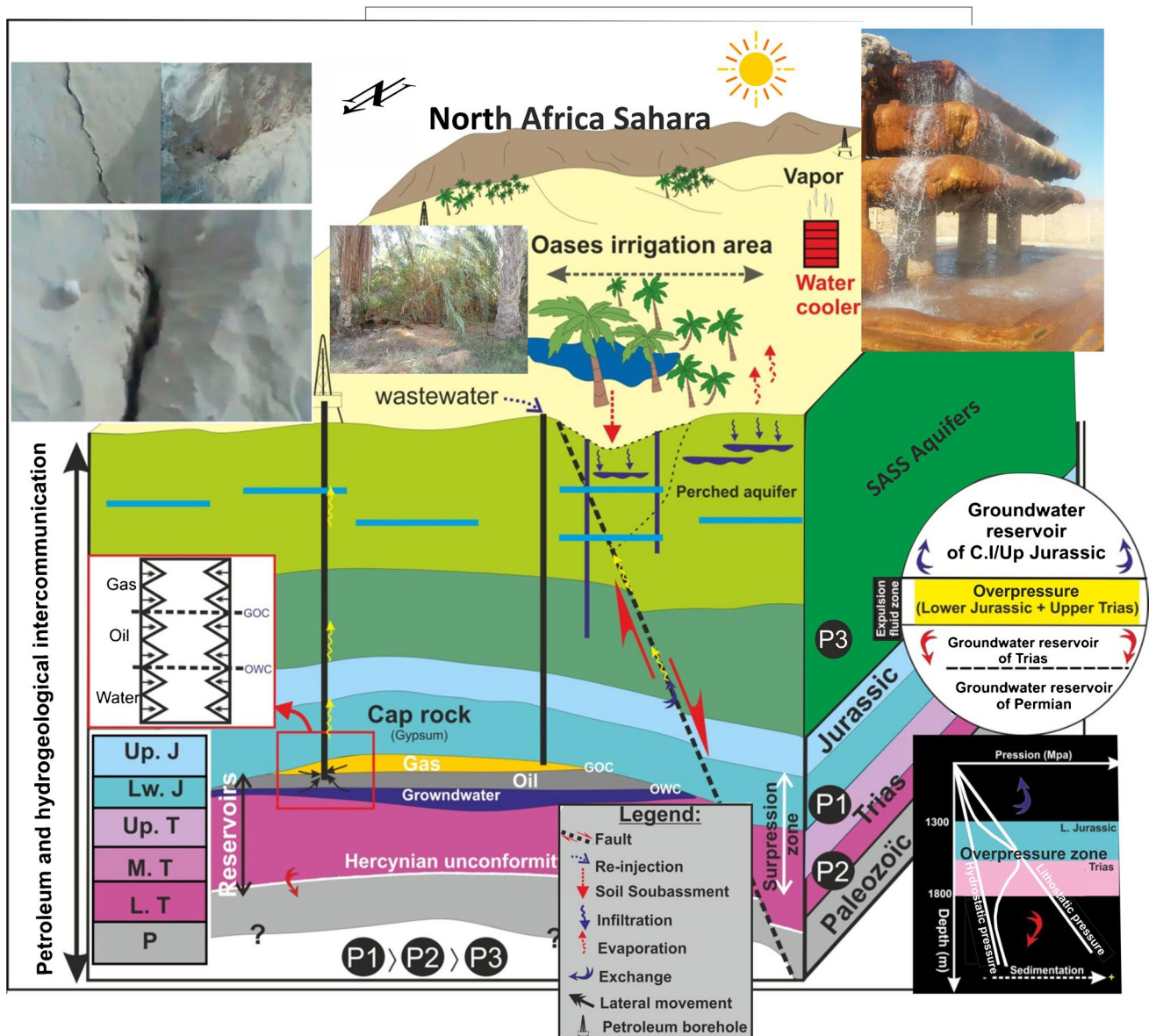


Fig. 3 Conceptual model showing the consequence of the petroleum over-exploitation on groundwater in Southern Tunisia

Baguel-Tarfa, and Limaguess. The main source rocks are the Azzel Formations (Ordovician), Fegaguira Formation (Upper Silurian-Early Devonian), and Zoumit Formation (Permian). The reservoirs, however, are characterized by variable lithology and potential from the Ordovician deposits to Upper Jurassic sediments (Gadri et al. 2015; El Mekki et al. 2017). The exploitation of these resources began in 1979.

Soil resources

Agriculture is the key economic sector of southern Tunisia especially in Chotts region (Tozeur and Kébili), which is an area devoted mainly to the production of high-quality dates of Bio-Deglet Ennour (among the finest qualities in the world). Because harsh climate conditions induced the lack of surface water and the irregular rare rainfall, irrigated agriculture is the primary driving force behind the economic development of the study area. Groundwater irrigation areas have rapidly expanded and currently cover more than 15,000 Ha. The production of water wells in southern Tunisia is vital to supply the demands of an agriculture area that span more than 260,000 Ha and covered is by plastic greenhouses.

The intense abstraction of the geothermal groundwater ($35 < \text{temperature} < 90$ °C) from CI to meet the increasing agriculture needs lowered water table and decreased water pressure (especially in the region 3; Fig. 1). This will have numerous impacts on water quality, quantity, and local agricultural development as well. This abusive consumption could lead to others serious socio-economic and environmental problems such as soil subbasement, intense desertification, and poor land management (Fig. 3).

To understand the complex groundwater system of southern Tunisia following a major perturbation (e.g., degradation of CI groundwaters), one must conduct a careful re-examination of groundwater flow dynamics and the long-term geochemical evolution of the whole hydrogeological system, especially in context of the regional petroleum systems and the agricultural projects. This, coupled with the conventional classification of water types, soil composition, and pollution sources within the geologic and tectonic context of the region, will determine how vulnerable of the hydrologic systems are to different forms of environmental degradation.

Evolution of water chemistry

Water chemistry

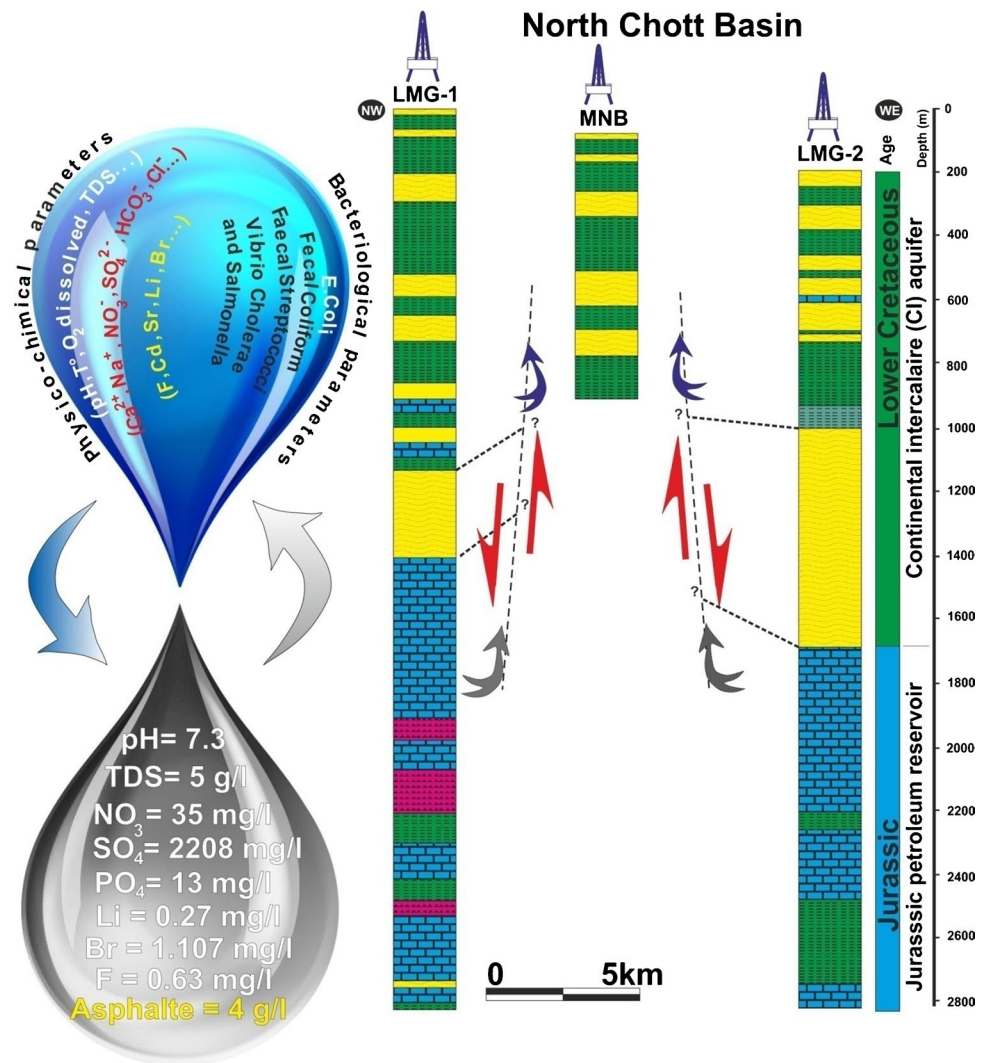
The knowledge of groundwater chemistry and the assessment of its spatiotemporal variability is a helpful tool in identifying the major factors influencing

hydro-geochemical water composition, namely mixing, weathering, and pollution. However, the evaluation of water composition should be refined by complementary analyses of different environmental components and their interactions with the water reservoir so that management strategies can be designed in a sustainable way for different resources (Fig. 4).

The chemical compositions of groundwater of the CI aquifer indicates that, besides the weathering dissolution of the hosted aquifer materials during the long residence time, are influenced by mixing between different water bodies as well as the dynamic balance between recharge and discharge rates within the hydrogeological system. According to previous studies, the multi-layered aquifer system (Hamed et al. 2013a, 2014; Besser et al. 2019), is characterized by a great variability of chemical composition that may be identified using the “lumped parameters” approach. This approach determined that the groundwater in the aquifer system of NWSAS has a threefold components: (i) a modern recharging water, fresh with low salinity, moderately depleted in delta values of isotopic water composition ($\delta^{18}\text{O}$ and $\delta^2\text{H}$), (ii) the salty water resulting from the leaching of evaporates included in the litho-stratigraphic sequence of Cretaceous sediments, and (iii) the palaeowater or “fossil water” of the C.I., which is moderately saline and highly depleted in delta values of isotopic water composition ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) (Hamed et al. 2013a, 2014; Besser et al. 2019). Accordingly, the description of NWSAS as non-renewable (e.g., fossil) aquifer, devoid of any meaningful recharge, a rather stagnant water body, disconnected from any surface water body is misleading and represents an obvious inaccuracy in terms of management and conservation.

The isotopic composition of the NWSAS waters reveals remarkable markers of paleoclimate; evidence of a humid period of Holocene and Pleistocene (Hadji et al. 2013; Hamed et al. 2013a, 2014; Mokadem et al. 2016; Besser et al. 2019). The low renewable rate associated with semi-confined and confined conditions of CI and CT aquifers defines high mineralized waters following a stratification of salinity and temperature. This is manifested by an aligned springs and is deeply controlled by the hydraulic conductivity of the multi-layered aquifer system and the increasing pressure on water resources, leading to variable chemical distribution. The interaction of hydrothermal fluids with aquifer materials changes their composition over time. This contributes to the formation of different mineral deposits and associated alteration of aquifer materials. The principal factors governing the variability of groundwater composition, within the complex architecture of the basin, can be explained by:

Fig. 4 The lithological, structural, and hydrogeological characteristics of the NWSAS aquifers in Southern Tunisia



- Percolation and retention of groundwater dependent on the porosity and permeability of the aquifers (CT and CI)
- Varying concentrations of bicarbonates, sulfates, chlorides, and alkali metals depending on the composition of the surrounding rocks and the length of time that the water has been in contact with them (residence time from Algeria to Tunisia: Algeria Monts to Chott of Djerid and El Fejej depressions of North Africa)
- The formation of ore deposits (e.g., halite deposit in the Tunisian Chott) through subsurface flow of CT and CI groundwaters
- Sub-aerial and subaqueous (sub-lacustrine discharges) hot springs and degassing volcanoes, evidence of hydrothermal activity commonly observed in volcanic and tectonic lakes in Southern Tunisia
- Hot springs evidence of anomalous heat flow due to the high concentration of radioactive elements in the crust
- Hydrothermal veins, indicative of hydrothermal fluid flow via predefined conduits or fractures and/or perme-

able faults through which fluids circulate; variable texture and morphology of vein crystals (usually quartz and carbonates) relative to the nature of the hydrothermal system from which the veins were sourced

To evaluate the different patterns on long-term evolution of chemical composition of groundwater, it is necessary to identify flow paths to outline pollution diffusion. However, such detailed information requires cross-disciplinary data to develop different scenarios that depict of short and long-term evolution according to geogenic and anthropogenic influence (geochemical of hosted formation, hydrogeological characterization, geo-tectonic context, exploitation rate, distribution, etc.).

Agricultural pollution

In hot, dry areas like southern Tunisia, the agriculture is a key economic activity and a significant source of food

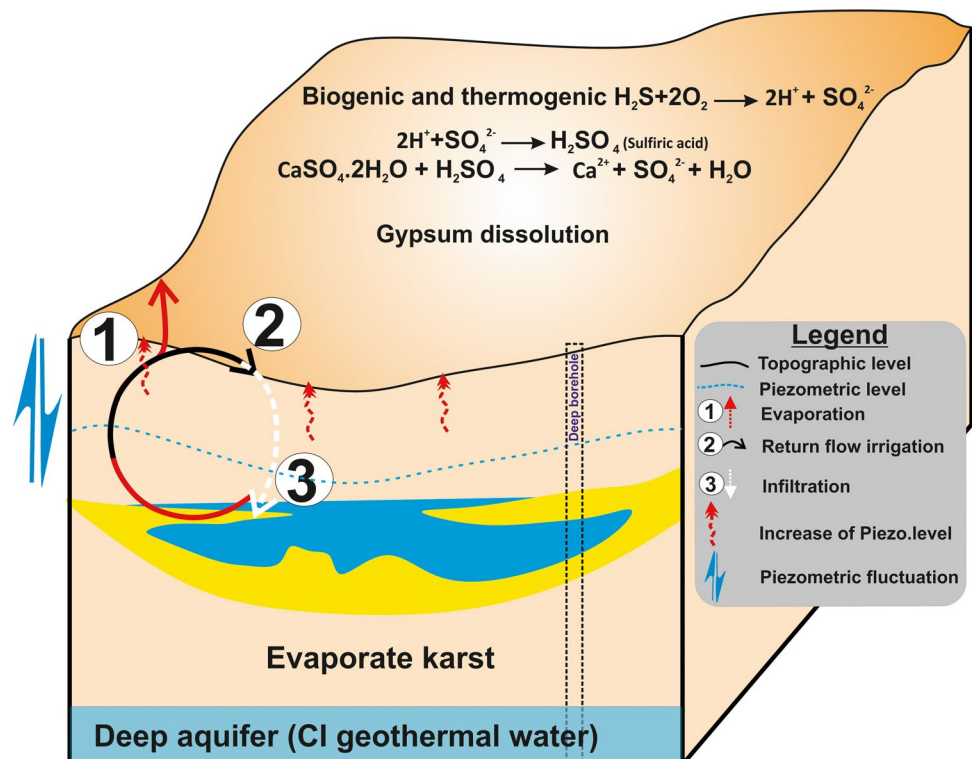
and livelihood of the local population. It is of paramount importance to understand and accurately evaluate the profound impacts that agriculture has on groundwater and soil resources. It is also crucial to understand the long-term implications on the sustainability of natural resources and agricultural production under harsh conditions that come with the desert environment, its associated climate, and limited water resources.

Agricultural lands in Southern Tunisia are fine-textured silty, sandy, clayey and loamy. These soils are classified as GYPSOIL (Omar et al. 2020; Besser and Hamed 2021), and given the lack of precipitation, high temperature and evapotranspiration rates, calcium carbonate, and halite show increasing risks of degradation related to frequent gypsum crust formations. This reduces the vertical hydraulic conductivity of the upper soil layers, inhibiting soil aeration, lowering the water infiltration, and perched aquifer neoformation. Furthermore, tremendous pressure on groundwater resources defines a critical abstraction from these limited resources for supplying irrigation needs lowering the water table. This overexploitation will eventually reduce agricultural production because of land degradation and soil productivity losses related to bad water quality used for irrigation and increasing salinization and alkalization issues. In fact, irrigation with saline and mineralized groundwater may affect plant growth, reduce land productivity, and seriously damage sensitive crops. Increasing salinity of irrigation water is generally associated with increasing content

of sodium which induces high risks of sodicity (Fig. 5). Salinization and alkalization issues may increase osmotic pressure, induce physiological drought, and adversely affect soil structure by damaging soil fertility and aggregate stability. It may also increase risks of soil crusting and clogging. Other problem observed in oasis is the waterlogging. This problem will subsequently cause the appearance of specific insects, which will degrade dates (e.g., Essam et al. 2020) (Fig. 6). The new-formed wetlands in oasis agrosystems of southern Tunisia lead to the appearance of migratory birds from European regions, especially Spain and France.

When irrigation uses water amounts that exceed the real requirements of cultivated crops, the risk of water infiltration increases. In regions where fertilizers have been heavily applied (large fertilizer inputs with intense irrigation rates), surface soil leaching can occur. This usually forms a continuous layer nitrate-contaminated groundwater beneath both agricultural lands and oasis alike (Hamed et al. 2013a, b; Dragon and Gorski 2015; Foster et al. 2018). These processes lead to increased salinity in the upper aquifer defining the commonly observed issue of groundwater contamination by nitrogen and pesticides. The presence of elevated nitrate, phosphorous and potassium concentrations can be used to retrace the penetration of irrigation return flow in the upper aquifer. Regarding this downward penetration of saline returns, this “gaining” potential of groundwater has become a major environmental concern for the suitability of the shallow aquifer (Galloway et al. 2004; Aquilina et al. 2012).

Fig. 5 Conceptual model showing the agricultural irrigation and the problem systems of the oasis water drainage in Southern Tunisia



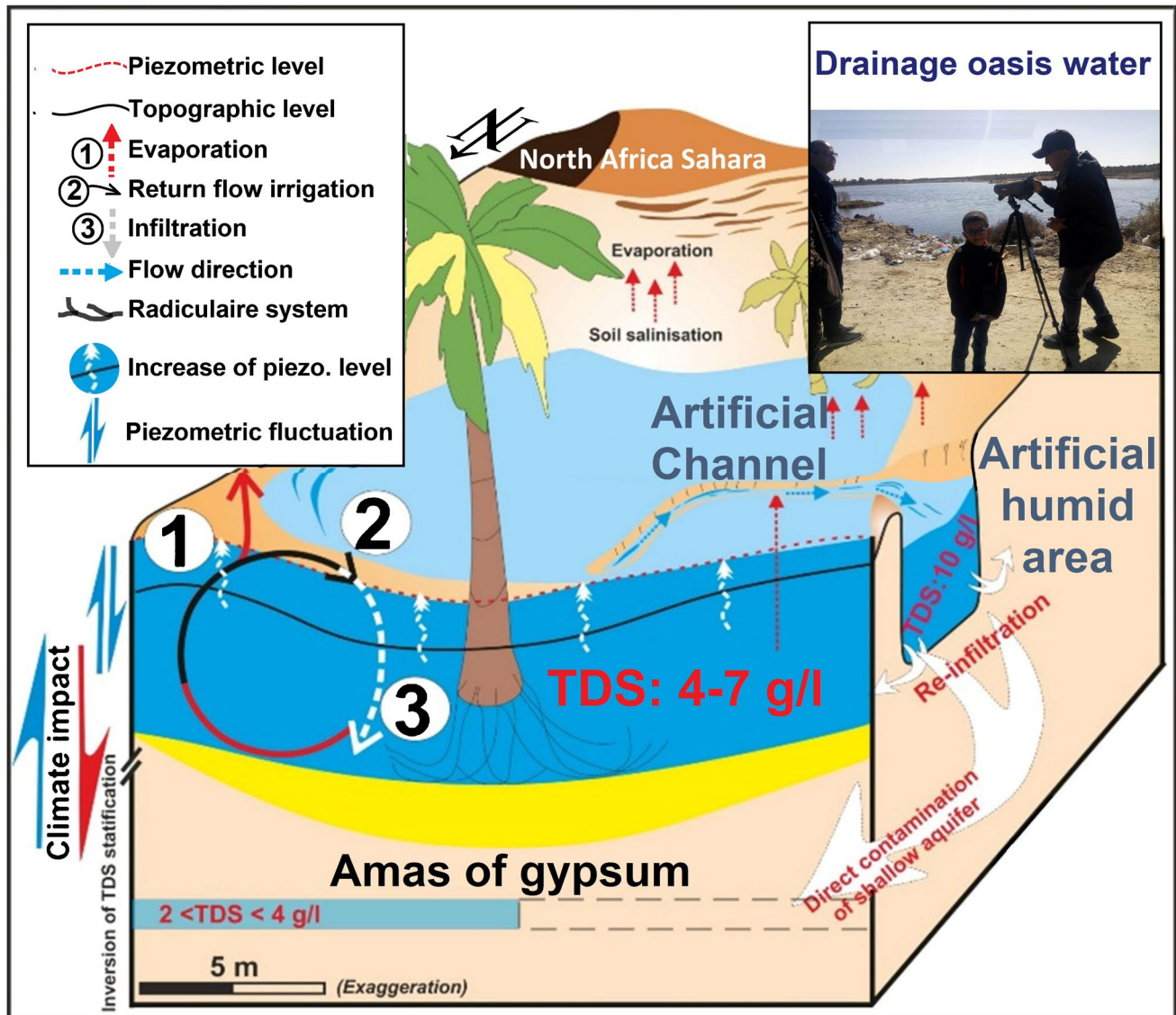


Fig. 6 The mechanism formation of perched evaporate aquifer in Southern Tunisia

Despite the risks involved, the agro-economic zone is of major importance due to development of irrigated agriculture, especially in developing countries. Intense irrigated agriculture modifies the hydrogeological cycles, changes groundwater hydrodynamic, leads to groundwater deterioration, increases trace elements concentrations in aquifer replenishment, and induces long-term agricultural land degradation (Schmidt and Sherman 1987; Galloway et al. 2004; Singh et al. 2006; Aquilina et al. 2012).

Climate variability impacts

This conceptual model (Fig. 7) presents the coupled effects of human and climate stresses on groundwater quality in the SASS or NWSAS aquifer of North Africa (Oriental Erg). This model summarizes the direct and indirect impacts of

climate variability on surface water and groundwater in the Tuniso-Algerian transboundary basin. These effects are explained by further amplification of aforementioned consequences such as degradation of the water quality (10–90 g/L); water and soil salinization; decrease of pressure in deep wells that resulted in high energy consumption; mixing between the water reservoirs and petroleum reservoirs due to the aquifers disequilibrium and/or the anthropogenic industrial activities in the Erg basin; saltwater intrusions (e.g., SASS depression of Chott lands); land desertification; and decreasing of the date productivity.

The hydraulic conductivity of the hydrogeological system (within the semi-confined to confined NWSAS and within the unconfined shallow Quaternary aquifer) intensified with the continuous exploitation of these resources, vertical flows tend to predominate over horizontal flows

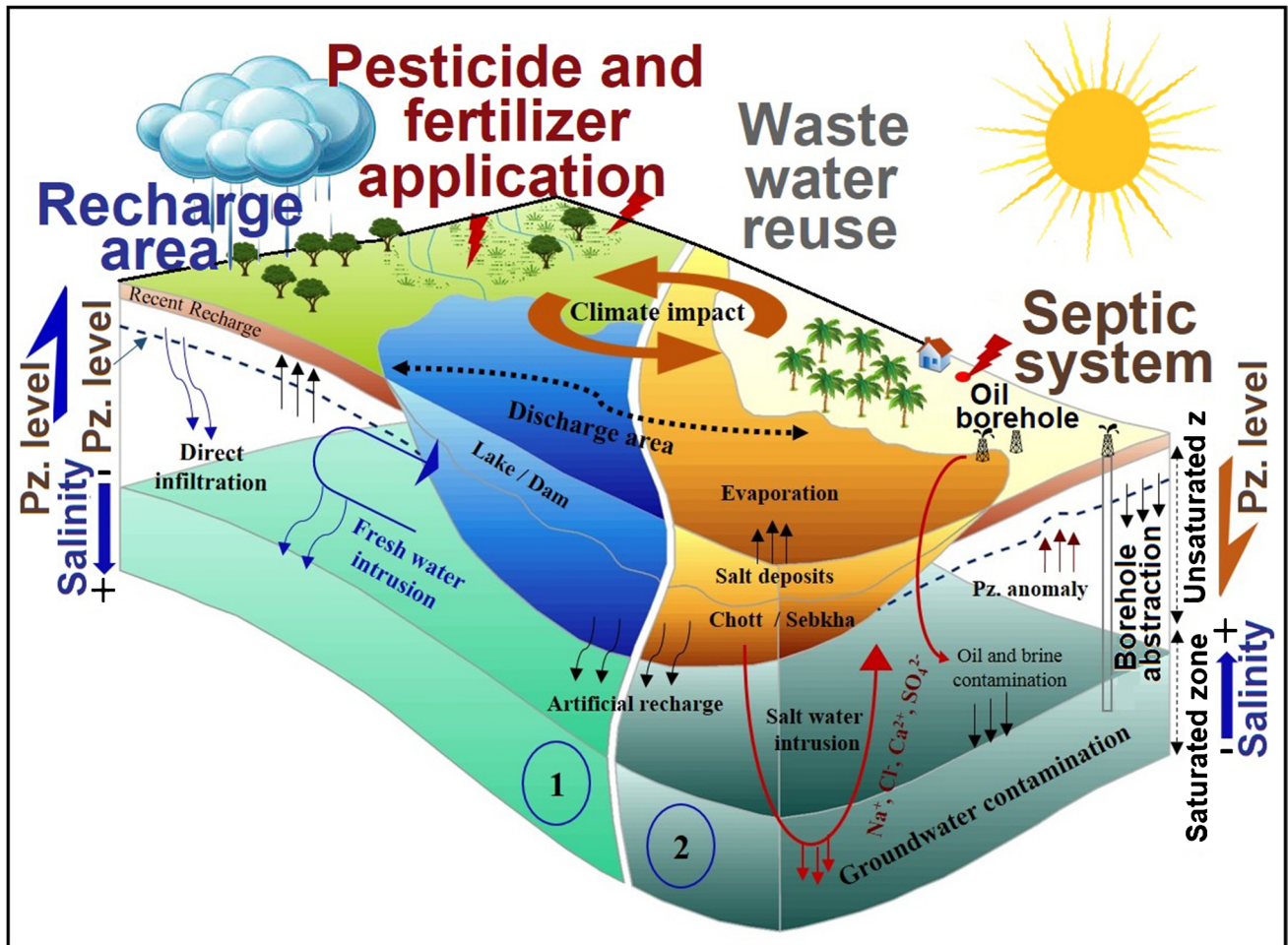


Fig. 7 Schematic conceptual model showing the climate impact on NWSAS groundwater in Southern transboundary basin of Tunisia

related to natural factors, namely, local lithological and structural features and human activities (water balance vs. depression cone). This leakage recharge from the underlying confined water-bearing strata and the infiltration recharge of irrigation water in oasis land can also give a small percentage of groundwater recharge. Besides the natural discharge towards the sea and the salt lakes (sabkhas), the lateral outflow, artificial exploitation, and leakage discharge are also included in the main discharge patterns. Likewise, the aquifer of the area shows vertical and lateral heterogeneity and anisotropy. Thus, the water quality cannot be considered homogeneous within the same aquifer. Local variations pointed to the high anisotropy in the leakage flows. In areas, where the rechargeability is very low and the waters are stagnant, drilling data and geochemical analyzes have shown higher salinity (TDS=90 g/L), with a richness of gray organic matter and a foul odor showing the confinement of these waters. This figure also shows the deep desertification. However, recycling this unconventional water should be considered, as

it can be discharged into the wadies without any treatment and can help to solve the problem of over-exploitation of the water resources in this area (Fig. 8a, b).

Aquifer hydrodynamic and hydrocarbon pollution

To assess the severity of the groundwater contamination in southern Tunisia fields, contamination should be redefined within the context of hydrogeological-petroleum, as few studies have been carried to identify the interactions between water and petroleum in these sedimentary basins. In the hydrocarbon producing regions, mixing of groundwater with petroleum and/or field brines imposes additional challenges in groundwater withdrawal, chemical evolution and water type variability, especially for changes that occur suddenly or locally. The increasing risks of contamination are especially high in rural regions, where regulations over groundwater for agricultural, industrial, domestic, and



Fig. 8 **a** Deep well of C.I. (confined aquifer and non-renewable groundwater) in Southern Tunisia and **b** unconventional water rejected on drainage network in Southern Tunisia

touristic use are insufficient. The water supply for public use with no effects related to natural or man-made mixing seems to be challenging. The oil and gas industry have settled regulations and procedures to control and reduce the occurrence of such ecological risks. However, such accidents of contamination catastrophes are still recorded, at regular basis, mostly due to human errors or dilapidated equipment failure.

This study indicates that groundwater quality deterioration is pronounced in the Chotts area as the mixing between groundwater resources and petroleum reservoirs has been detected at several wells in the El Fedjej area. The sharp variation in chemical parameters in addition to the difference in groundwater type implies that leakage of water is from different water-bearing strata and the oil field-brine petroleum near the Chotts area. This is indicated by high organic contaminant concentrations that reach 4 g/l for the asphalt (Fig. 5). It is also expressed by high salinity levels and increasing concentrations of certain trace elements and heavy metals that are not explained by the geogenic origin. Consequently, this investigation highlights that major potential source of

groundwater salinization include water–rock interactions, hydraulic continuity, interferences of Chotts aquifer, and gas-oil fields brines. In other locations, the contamination is manifested by an oily sheen and/or strong odor in water distribution canals. Even low amounts have many impacts on groundwater quality and make the resources unfit for agricultural and domestic consumption. This contamination is expressed by increasing salinity of waters and/or high trace concentrations, indicating leakage of oil-field brine into the aquifer groundwater resources (Hamed 2011; Besser et al. 2018, 2019; Besser and Hamed 2019).

The study of pore pressure profile in the Gahdames basin showed that a high amplitude overpressure interval is dressing up between water tables and hydrocarbon resources. The same authors demonstrate that is difficult for fluids to migrate naturally between these reservoirs over the overpressure interval because it creates a hydraulic barrier. Consequently, the observed hydrocarbons' traces in shallow water tables are explained by borehole leakage that constitutes the singular weak point.

The distribution of groundwater chemical composition provides a qualitative and quantitative understanding of mixing fractions and groundwater vulnerability as obtained from cross plots concentrations and geochemical analyses proof of dispersion model. The conceptual models given in Figs. 2, 4, and 5 present a schematic illustration to assess fluid movement within the elusive and tectonic subterranean basin of southern Tunisia in response to pressure differences. The evolution of groundwater chemistry reflects the change in aquifer configuration due to geotectonic features of the basin, which have substantial impacts on groundwater flow closely related to the dip direction and scale of faults and fractures. In fact, these tectonic features are generally found to act as a complex conduits leaky barrier system favoring vertical flow mixing (thermal springs, contamination, etc.), downward movement, and transfer of water masses within the hydrogeological system. Thermal spring and geochemical ratios are indicative of fault acting as hydraulic conduits connect shallow, semi-confined, and deep circulation of groundwater. Locally, faults and fractures may act as barriers to fluid flows.

In multi-layered aquifer systems, groundwater flows have different options related to the lateral variation of thickness, lithology, tectonic features, and leaky barrier enhanced by the lowering of the groundwater table. This indicates that geologic pathways due to oil production, infrastructure, and geo-structural features may induce contamination of groundwater overlying oil-bearing formations. The fault-induced architecture of Chotts basin in horst and graben structures creates low-lying zones and preferential pathways representing major links for groundwater flow gradual movement on a small-scale. This leakage is enhanced by the current exploitation rate that exceeds 100 to 120% in an unsustainable way.

Considering that the groundwater cycle being slower than the rate of the human development, the assessment of groundwater response and disequilibrium is essential to evaluate the cumulative impacts of anthropogenic activities on the magnitude and the rapidity of the perturbations. In fact, the review of the collected data relative to the abstraction from the polluted aquifer in southern Tunisia indicates that the exploitation attains its highest level of contaminated Chotts basin. These observations support the assumption that large drawdown relative to wells associated with improperly sealed wells induces significant groundwater flow changes, leakage, and deep cones extent. This uncontrolled dispersion of increased wells and pumping increases the vulnerability of the deep partially known aquifer induce ongoing mixing of different water bodies and/or leakage from oil producer wells.

The concentration of organic pollutants of pre-contamination fraction in samples must be below the largest acceptable limits for different uses, while the petroleum hydrocarbon associated with the contamination since 2015 exceeds 4 g/l would more likely be from deep subsurface reservoirs that may be related to an anthropogenic source. Each source from the hypothesis leaves its relative individual fingerprints in groundwater chemistry in quality suitability for particular uses and in decontamination measures. Chemical fingerprinting techniques are used to decide the mixing percentage of different water bodies and hydrocarbon reservoirs. Petroleum hydrocarbon can also be present in groundwater due to accidental spills occurring at oil and gas fields. The assessment of monthly and annual exploration during the exploitation period may indicate the intensity of contamination and cycle of increasing risks. Furthermore, abandoned petroleum wells and/or generally provide vague causes of contamination with no detailed description of the type and depth of the damage. A general water wells sampling is recommended to identify the origins of contamination, investigate the leaking oil boreholes, and planning for mitigation actions.

The high concentrations of the organic contaminant in CI water well may be associated with exploitation conditions that exceed the regenerative capacities of the aquifer, inducing cones of depression that may be equilibrated with the increased pressure in deep reservoirs. This facilitates the movement of fluid upwards through natural and/or man-made conduits. It also shows more evidence of deeper subsurface detected in the comparison of pollutant, chemical fingerprints with major sources and combination of revelry collected and historical data.

Management process

Important knowledge about natural resource development in a sustainable way and not a commodity to be used according to its highest economic return is required for

planning land management strategies. Historically, salinization, pollution, and waterlogging issues have been the focus of different research and recovery measures. Regard to the best environmental use of natural resources requires available information about land degradation issues and the extent of groundwater declining as well as the degree of the vulnerability of the aquifer system. The partners that share the aquifer system (e.g., Algeria, Tunisia, Libya) need to establish mechanisms of data sharing in an objective way about water quality degradation, monitoring system of water table declining, areas development, irreversible impacts on natural resources related principally to irrigation-water use efficiency, crop production, climatic variability, and efficient irrigation lamina.

The choice of the most adequate feasible and ecologically friendly rehabilitation actions within a particular socio-economic context and uncertain climate variability is putting tremendous pressure on groundwater management in terms of demands and resources. Thus, natural resources management should be re-examined at different levels starting from the private sector and ending at the transboundary level. It should include the various parties that might have conflicting interests.

Considering the sustainable land development is a common environmental challenge, implemented measures should be re-evaluated to consider the partially known proprieties of the aquifer system and focus on sustaining groundwater resources for future generations. The modification of natural flow patterns and interference risks should be carefully evaluated as well to allow financial aid that will incentivize better practices preserving quantity and quality of water resources (Fig. 8).

The main axes governing management plans are:

- Identification of Chotts basin as a groundwater restriction zone, aiming to constrain the expansion of irrigated area, and stabilizing zone groundwater levels while maintaining groundwater flows.
- Constraining groundwater abstraction, facilitating the control and the management of the pollution spread, and avoiding progressive pollutant migration.
- Understanding the geo-structural features inducing the interference and mixing between different fluid reservoirs.
- Reducing the pressure on groundwater resources via the use of the non-conventional resources to ensure the highest possible economic return and the sustainability of natural resources.
- Developing different scenarios of the hydrogeological evolution of groundwater under various conditions.
- Developing communication channels between government and business is an important component of any groundwater management strategy. For example, part of

the groundwater levies might be earmarked for extension, technical advice, or subsidization of groundwater conservation efforts. To some degree, such persuasive measures may soften the impact of the blunt regulatory measures that are needed to stop the urban pumping race.

Synthesis

Beyond measurements for analytical geochemical investigation and monitoring of NWSAS in southern Tunisia, this study defines a different way of natural system response to man-made perturbations, partially known and generally described with a high degree of uncertainty. This study provides an enhanced understanding of the risks of interferences between fluid reservoirs and discusses the magnitude of overexploitation and mismanagement of groundwater resource issues in response to natural and anthropogenic factors. The integration of previous published data and interpretation of field observations allowed the division of southern Tunisia in three main areas according to the degree of contamination-degradation and/or on the presence of the risks of contamination-degradation: safe (extreme south), vulnerable (Tozeur area), and contaminated (Kebili region). However, this classification seems to be incomplete and insufficient, considering the hydraulic continuity of the aquifer and the simultaneous anthropogenic activity and livelihood conditions in different regions. Geochemical analysis of oil contamination and soil data used to refine this interpretation indicated the groundwater groups and quality clusters depend on the migration of hydrocarbon/brine pollutant towards the underlain aquifers via geo-tectonic framework gradient expressing complex tectonics and subsurface various rate of groundwater exploitation.

The oil–gas–brine pollution delineates preferential pathways including uncemented wellbore and improperly abandoned wells, permitting oil-field fluid to reach aquifers through complex hydrosystems that are deeply influenced by anthropogenic activities and involve several compartments (water, soil, hydrocarbons). The continuous exploitation further induces modifications of fluid storage and drainage in the subsurface hosted formations and controls the hydrodynamic and hydrochemical behavior of groundwater resources in unpredictable ways. The impacts are measured through the spatio-temporal distribution of groundwater chemical composition across the study area within the uncontaminated and polluted reservoir. The review of quality evolution during decades of exploitation testifies to the new distribution of well characteristics water hydrogeochemical, pollutant transit. It also updates the hydrogeological data based on different hypotheses of contamination. Thus, the stimulation of economic pressures (agriculture, hydrocarbons), occurring

70 years in the deeper system, is crucial in understanding pollutant dynamics and aquifer regenerative capacity.

It can be concluded from this re-examination that the active management plans must be carefully revised to reduce the anthropogenic pressure as the risks will continue to increase so long as the perturbations remain high. The higher the disequilibrium of the natural system remains, the longer the remediation will take. The maintenance of groundwater resources hinges on the understanding of the spatial aquifer response to exploitation and pollutant diffusion regarding the increased demand and frequency of drought periods. Since groundwater dependency reaches 100% in the study area, this economic issue should not be ignored even though the contaminated area represents less than 10% of total southern Tunisia. Future works are to build on this study, incorporated HC-water reservoir interactions, with pumping requirements and economic benefits to provide long time characterization and a large-scale water system evolution.

Finally, to evaluate the magnitude of the environmental changes and the contrasting large and permanent ecological impacts, the local investigation will be needed for a more detailed understanding of hydrogeological functioning and the hydrodynamic evolution of the resources. This may offer rapid and perceivable results for the assessment of pollution trends in this reactive system. Furthermore, the local investigation is required to evaluate small-scale fractured zones and chemical evolution, which may have a significant role in preventing the spread of contamination.

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Declarations

Conflict of interest The authors declare no competing interests.

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