NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

Bulletin of Geography. Physical Geography Series, No. 27 (2024): 45–56
http://doi.org/10.12775/bgeo-2024-0009

Oued Souf (Algerian Sahara): balancing rising groundwater and agricultural sustainability

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Abstract. This research addresses the issue of rising groundwater in the Algerian Sahara, a paradoxical phenomenon given that the desert is typically associated with dryness. The cause of this rising water is the recharge of aquifers by wastewater from local activities resulting from poor water resource management. This has led to overexploitation of water resources in Oued Souf, posing an environmental threat and agricultural loss in the Ghouts. To sustainably manage these resources, it is essential to establish a management system involving all relevant stakeholders. Ultimately, sustainable groundwater management requires effective management of Sahara aquifers. This involves avoiding overuse and overexploitation, limiting excessive pumping, employing artificial recharge methods to replenish water reserves, and regulating water flows in watersheds to reduce rising water levels in the Sahara.

Key words:
Souf,
water rise,
pollution,
environmental threat,
agricultural production

Introduction

Over the decades, the issue of climate change has become a major concern worldwide. The consequences of global warming are now being felt in many regions, particularly in arid regions such as the Sahara. The Algerian Sahara is a region rich in underground resources, which provide a lifeline for the national population (Merabet 2021). Beyond hydrocarbons, water is a significant resource in the Algerian Sahara. Despite the arid climate, underground water tables are present and are utilized for purposes such as irrigation and human consumption. The main aquifers in the region are the Continental Intercalaire and Terminal Complex aquifers. (Tabouche 2004; Amrani 2021). Indeed, suboptimal utilization of subterranean resources can precipitate environmental threats. Water management in Algeria is a complex challenge that requires a multidisciplinary approach and international cooperation (Kouzmine 2007). Governments, local communities, civil society organizations and businesses all need to work together to develop effective water management policies that take into account the needs of people and the environment. Indeed, the overconsumption of water is a result of unsustainable agricultural and industrial practices, as well as rapid population growth and urbanization (Smets 2003; Kouzmine 2007).

The French geographer Côte, in his 1998 article "Sick Oases from Too Much Water", describes how the Algerian Sahara has been experiencing a phenomenon of rising groundwater levels for over half a century (Bouselsal 2014). The farmers have drilled numerous wells for irrigation, resulting in a significant decrease in the water table level. This decline has necessitated tapping into other groundwater reservoirs, namely the continental and intercalary aquifers, which exhibit high flow rates.

The situation is worsened by the sandy composition of the soil and the region's inadequate drainage system: water utilized by the populace, whether for agricultural, potable or other purposes, ultimately seeps back into the water table, polluting it and rendering the water unsuitable for consumption. An impermeable layer separates the water table from other aquifers. Due to the local population's lack of awareness regarding the groundwater situation and the continuous growth of wastewater, these pollutants accumulate within the water table and, due to the impermeability of the soil, resurface. The rising water levels in the Oued Souf region are primarily attributed to the overexploitation of groundwater reservoirs, which have been characterized by a significantly high daily extraction rate in recent years (Kadri 2018). The phenomenon of rising groundwater remains a significant challenge for the Oued Souf region, and nowhere are the problems as acute as in Souf (Côte 2006; Kadri 2018), which must face a growing demand for water for agricultural, industrial and domestic activities.

As Côte (1998) notes, the situation in this arid region is paradoxical, with the region suffering from too much water. Preserving the ecological balance of the Soufi ecosystem is a major challenge that depends largely on the region's demographic evolution and the public policies undertaken to regulate risk factors. In addition, the survival of production systems in Oued Souf is seriously threatened, calling into question their viability and equilibrium. This situation is due to the degradation of natural resources that began several decades ago with the rise of groundwater polluted by wastewater (Drouiche 2013). This phenomenon was unknown in this desert region a few decades ago. Crucial questions of natural resource sustainability must be addressed in the Oued Souf valley, which is facing the phenomenon of rising groundwater. How can demographic growth and rapid urbanization be reconciled with the preservation of natural resources and the Souf ecosystem, knowing that the balance of the region's production systems is threatened by the degradation of natural resources and that the aesthetic and identity symbol of the region, the ghout, is disappearing? What public policies and concrete actions should be implemented to preserve the Soufi ecosystem and ensure its sustainability in a context of increasing agricultural and anthropogenic pressure?

The case of the Algerian Southeastern Sahara

The Oued-Souf province located in the north-east of the Northern Sahara, is mainly comprised of a chain of dunes known as the Grand Erg Oriental, bordered to the north by the Chotts zone (Merouane and Melghir) and to the south by the extension of the Erg Oriental (Adaika 2020; Bouterid 2021). This research focuses on the Souf Valley, which covers an area of 35,752 km² and has a topographic plate without an outlet consisting mainly of plains and depressions, with a desert climate and very low annual precipitation. The Oued Souf region, situated within the geological context of the low desert, exhibits distinctive features of an extensive depositional basin, characterized by successive formations of sand dunes, with altitude varying notably between 127 meters in the municipality of Rabah and 59 meters in that of Ghammar. This topography is the result of sedimentary and aeolian processes over a long geological period. Within this region, intermittent depressions are observed where altitude can descend to 25 meters below sea level, attesting to the complexity of the geodynamic phenomena at play. The gentle slopes, typically less than five millimeters, significantly impede land development initiatives, especially concerning drainage works and hydrological considerations. The geological nature of the region shows that it is located above a vast sedimentary basin covered by quadri-temporal formations mainly composed of sand, offering high permeability. However, the bottom of the surface layer is made up of impermeable clay, which limits the flow of water. This particular geographical configuration of the region is of paramount importance for the study of geological and environmental processes in the Souf Valley.

Furthermore, according to the *General Census population and housing* (GCPH) of 1987, the population grew from 280,000 inhabitants in 1987 to 500,000 according to the GCPH of 2008, with an average annual growth rate of 2.6% (ONS Office National of Statistics 2008), and according to the latest estimates from authorities, the population reached 716,905 inhabitants in 2021. This increase has led to rapid urbanization and consequently has caused increasing pressure on the natural environment. The rapid population growth in Oued Souf is both a consequence of economic transformations and a factor of fragilization of the environment and the precariousness of the local society.

Citation: Bulletin of Geography. Physical Geography Series 2024, 27, http://doi.org/10.12775/bgeo-2024-0009

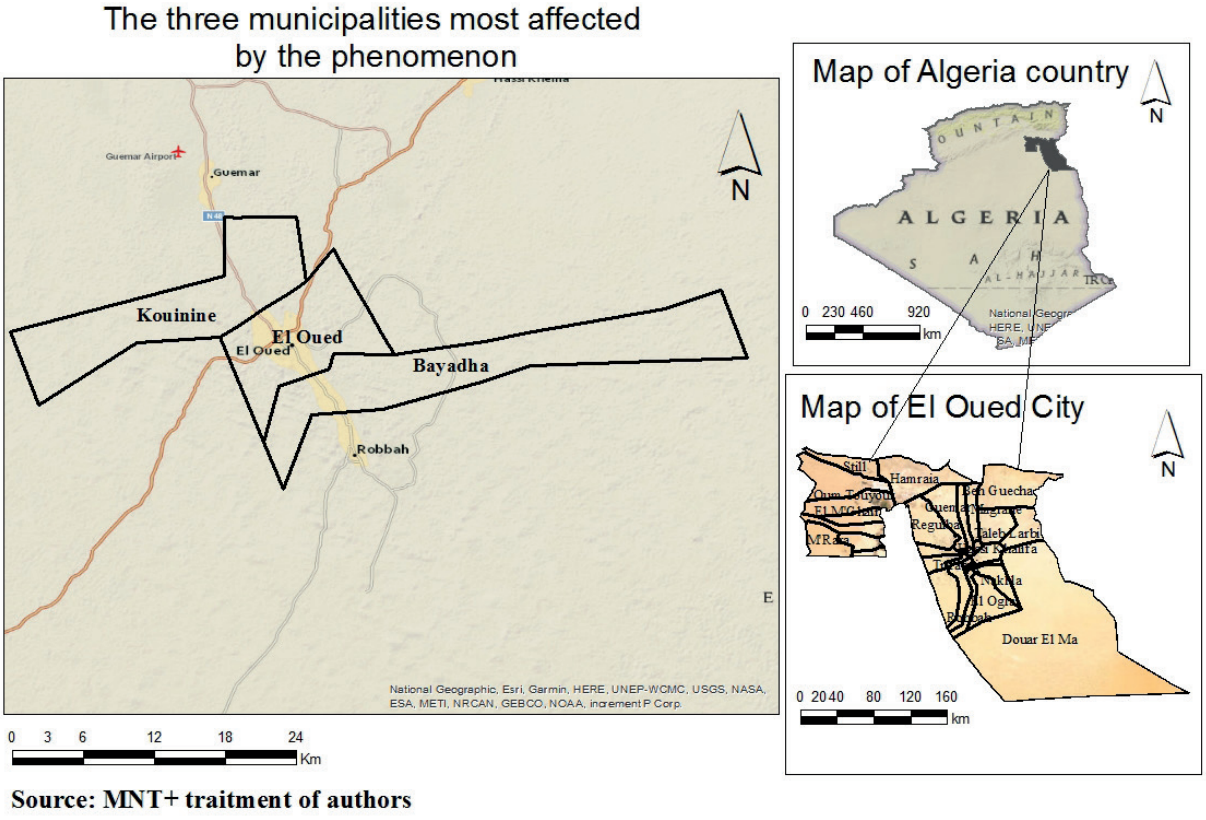

Fig. 1. Localization of the study area: map showing the Oued Souf Region in Algeria and the three municipalities most affected by rising water

Methods and data

The exploration of the environmental and agricultural situation in the Oued Souf region relies on two essential sources of data. Firstly, we conduct an in-depth analysis of the groundwater rise in the region, examining the factors that have led to the evolution of this phenomenon, including the overexploitation of water resources, particularly in the agricultural sector. To do so, we gathered data from scientific literature as well as administrative sources such as agricultural and hydraulic services and the 2022 annual report of the wilaya (region/province). Secondly, we present the characteristics of the natural context of the extended territory and the challenges related to agricultural development, adopting a qualitative approach. We then present quantitative and qualitative data on the state of ghouts (traditional agricultural system, primarily of the Saharan oases of Algeria) and the consequences of the groundwater rise, such as the decrease in ghout surface area and production, leading to a transformation of the crops planted in the region. We also address the socio-economic implications of this transformation, particularly regarding the livelihoods of local farmers.

We then present the measures taken by national and local authorities to address this situation, who have engaged in partnerships with foreign actors to study and propose solutions aimed at reducing the impacts of groundwater rise on the environment, agriculture and water quality. We examine major projects implemented, such as the construction of dams and drainage channels, as well as efforts to restore the region's natural ecosystem. We rely on reports from national agencies and offices of hydraulic and sanitation to present data on the effectiveness of these measures, as well as remaining challenges to be addressed.

The rising of groundwater: a hydrological imbalance phenomenon

The southern region of Algeria is home to the world's largest water table, with reserves of over 50,000 billion m^3 (Water.fanack.com). However, overconsumption and poor management of water resources have led to the phenomenon of water table rising in the Algerian Sahara.

This occurs due to an imbalance between the volume of water produced and the amount of wastewater and drainage, as dry zones are characterized by a closed hydraulic system where the basin is constituted of an influential base. Prior to the appearance of the water table rising phenomenon, there was an inverse phenomenon of declining groundwater levels. The people in the Souf region relied on groundwater for their needs and activities, particularly agriculture, and the period from the 1960s to the 1980s marked a balance between the use of surface layer water and the disposal of excess water and irrigation, which maintained a constant water level in the groundwater in the study area. With population growth and the extraction of water by electric pumps, the water level in the groundwater began to decline, and so the inhabitants sought water in other layers of the terminal complex and intercalary continental layers, despite the absence of a sewage system and natural outlets such as wadis in the region, this transition occurred. The 1969 flood is considered a direct cause of the increased volume of the first layer, particularly in the municipalities of Hassi Khalifa and Reggane, where water levels in the Ghout reached 15 meters. The initial occurrence of water rising phenomenon dates back to late 1984 until 1987. This phenomenon manifested within the Ghout, where excess water emerged onto the first layer. The most affected municipalities are those with the highest population density, notably Oued Souf, El Bayadh and, in third position, Koinine.

The first well in the terminal complex layer was drilled in 1956, and this was followed by one well per year between 1957 and 1969, which increased

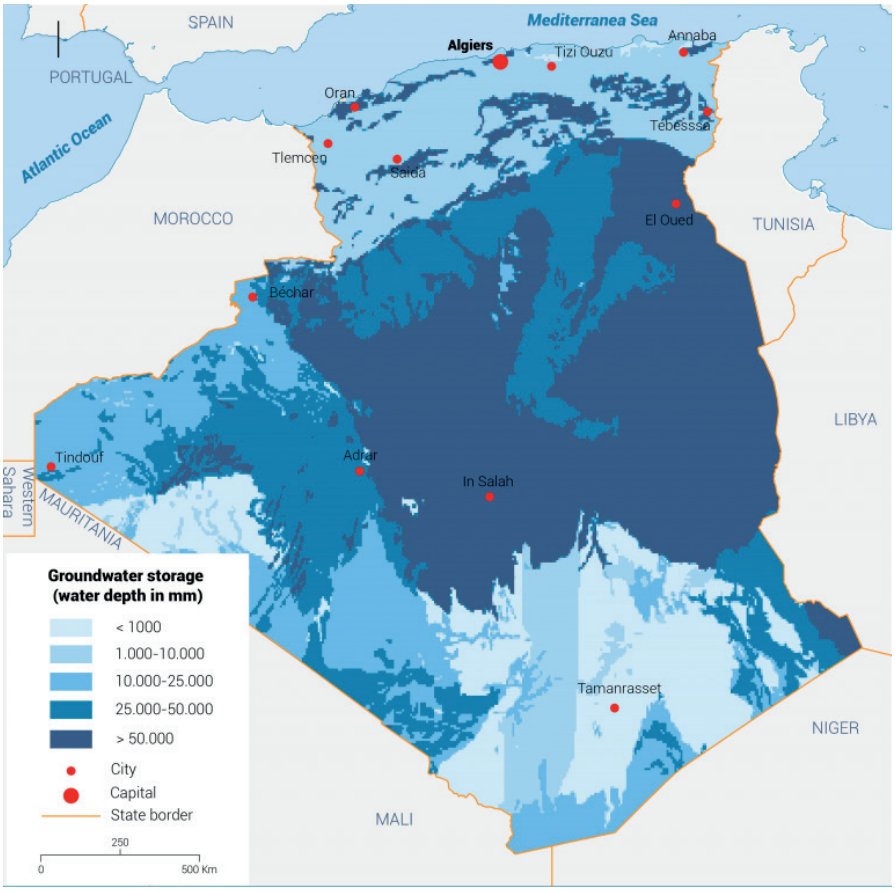

Fig. 2. Groundwater storage water depth in Algeria
Source: water.fanack.com

Citation: Bulletin of Geography. Physical Geography Series 2024, 27, http://doi.org/10.12775/bgeo-2024-0009

to about two wells per year between 1970 and 1980, reaching about 100 wells drilled in the terminal complex layer between 1980 and 1987. These layers are characterized by very high flow rates, reaching up to 230 L/s. During the same period, the drinking water network had a higher coverage rate of 85%, with a hourly supply volume of almost 24 hours/day, which led to an increase in individual water consumption from 70 L/day in 1966 to a rate exceeding 600 L/day in 1988, surpassing the quantity indicated by the ministry between 150–180 L/day. As for water drainage, it was always in the phreatic layer due to the geological and pedological nature of the aquifer, which is the reason for pollution and the rising of wastewater to the surface of the soil. The increase in individual water consumption rates has, along with agricultural and industrial activity, created a paradox in the phreatic layer; since 1981, despite these demands, the water table has been unable to manifest as surface moisture on the soil. The ghouts were the most degraded regions, where the water reached a height of 2 m, and by 1993 the phenomenon had worsened, with water flooding almost all the ghouts with a height reaching up to 5 m.

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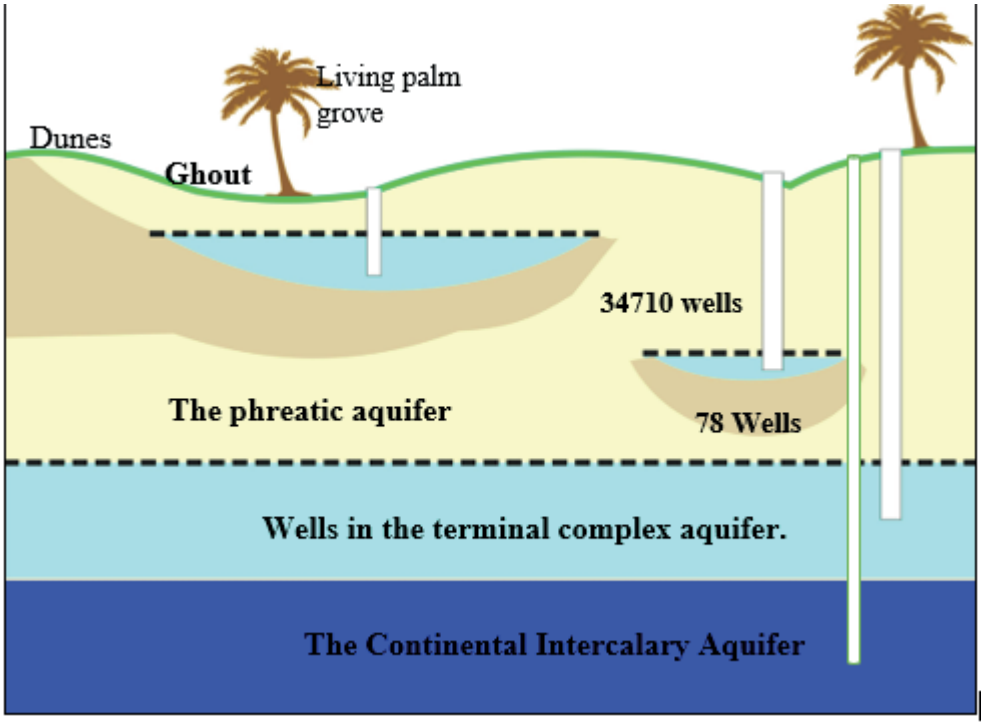

Fig. 3. Number of wells in the phreatic aquifer in Oued Souf, 2022
Source: DSA+ treatment of authors

Figure 3 depicts the number of wells (vertical bars) in the aquifers of the region. The upper, yellow layer is the phreatic aquifer, the light blue layer is the terminal complex aquifer, and the deep blue layer represents the deepest aquifer. Hydraulic stakeholders observe a significant concentration of wells in the phreatic aquifer, a trend attributed to the proliferation of well construction since the 1950s to meet daily needs. Since the 1980s, increasing awareness of the issue of overexploitation of water resources has prompted authorities to regulate this practice, marked by the progressive prohibition of new drilling activities. In the first aquifer, the total number of recorded wells amounts to 34,788, while precise data regarding other aquifers remain to be consolidated.

Ghouts, traditional model of phoeniciculture

Ghouts are traditional agricultural systems that have allowed arid areas to be cultivated for centuries. In the oases of Oued Souf, palm tree ghouts were developed to irrigate palm groves using groundwater. Although these systems are similar to other ghouts, they are distinguished by more intensive water use, with narrower channels for more precise and efficient irrigation. However, excessive exploitation of irrigation wells has caused the groundwater level to rise, leading to soil salinization and a loss of fertility of cultivated lands. This situation has had a negative impact on the sustainability of ghouts in the region, putting them at risk of disappearing if local authorities do not take action. According to the latest statistics from the agricultural services department, the number of ghouts affected by the phenomenon has reached 33% of the total, or 2,937 ghouts, of which 890 are damaged and 2,047 are affected by moisture.

The photo illustrates the contrast between the conditions of two ghout areas: the first living and adorned with palm trees, and the second filled in after being submerged by wastewater from the phreatic aquifer. This scenario has resulted in substantial losses for farmers as their palm trees were inundated, leading to their complete demise. Consequently, farmers have filled in all these ghout areas vulnerable to the phenomenon of rising water tables. On the verge of destruction are 230,000 palm trees, part of the region's 8,900 ghouts with a total of over 724,500 palm trees planted using traditional methods. Almost a quarter of the date palm trees have disappeared, representing a huge percentage and having significant economic repercussions on the local population. This situation has played a significant role in transforming agriculture in the region, prompting the local population to turn to other forms of agriculture. To counteract this, initiatives must be put in place to protect and rehabilitate the Oued Souf ghouts, with the aim of ensuring their sustainability.

Fig. 4. Comparison of a living ghout with palm trees and a filled-in ghout submerged by rising wastewater
Source: Direction of agricultural services + elaboration by authors

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Table 1. Distribution of agricultural land in Oued Souf

	TAA	UAA	Pasture Surface	Agricultural perimeter in Rehabilitation
Area (ha)	1,047,900	86,270	784,660	176,970

Source: DSA, 2022

Oued Souf, a national agricultural hub between vulnerability and development potential

Agriculture in Oued Souf is a key economic activity, with date palm cultivation being particularly significant. Currently, agriculture accounts for 44% of the total workforce in the region. This region is a major hub for the production and commercialization of dates in Algeria, offering a wide variety of date types. Dates from Oued Souf are celebrated for their quality (Bouguedoura 2010). According to the latest statistics from agricultural services in the region in 2022, date palm production reached 1,223 million quintals on an area of ~15,400 hectares, with the municipality of Hassi Khlifa ranking first with a production of over 180,000 million quintals. The abundant water availability and state efforts through the implementation of several development programs to encourage agricultural growth have allowed for a remarkable transformation towards potato production. Today, Oued Souf has become one of the country's main agricultural centers, diversifying its crops and contributing significantly to the national economy.

The presented table provides an overview of the hectares allocated to different categories of land use in the studied region, namely Total Agricultural Area (TAA), Utilized Agricultural Area (UAA), Pasture Surfaces (PS), and Agricultural perimeter in Rehabilitation. The total agricultural area exceeds one million hectares, while only 86,270 hectares (8%) are utilized agricultural areas. Despite the small area, agricultural production remains substantial and plays a crucial role in the country's economy, particularly potato cultivation. According to the latest 2022 statistics from the agricultural services department, potato farming leads with an area of 40,200 hectares and a production of 12 million quintals. It is followed by date palm cultivation, which covers 15,400 hectares and yields 1,223 million quintals. In third place are cereals, occupying 8,000 hectares and producing 131,000 quintals. Other agricultural crops such as forage, peanuts and tobacco are of similar importance to other crops in the region.

In addition, the government has implemented several development programs to stimulate agricultural investment and encourage citizen participation. These include *Law 83/18*, which regulates land ownership for agricultural development, and *Law 10/03*, which outlines the conditions and modalities for exploiting private state-owned agricultural land. As a result, *Law 10/03* has facilitated the establishment of 486 individual and collective agricultural investors on a total of 484 hectares, while *Law 83/18* has allocated 81,857 hectares to 14,801 beneficiaries. These initiatives underscore the significance of agriculture in the region. The agricultural development policies have notably transformed the area, leading to a substantial increase in water use for irrigation. Irrigated crops constitute 70% of the total water consumption in the region, underscoring their substantial impact on local water resources.

The total irrigated area is estimated at 75,800 hectares, accounting for 88% of the total utilized area. The table indicates that center pivot irrigation covers over half of this area, amounting to 45,050 hectares, resulting in agricultural land being shaped into circular forms to facilitate this irrigation method.

Table 2. Iirrigated areas and irrigation methods in the Souf region

Irrigation Methods	Gravity irrigation	Center pivot irrigation	Drip irrigation	Total
Area (ha)	4,566	45,054	26,180	75,800

Source: DSA, 2022

However, it is important to note that this irrigation method involves significant water consumption due to the sandy nature of the soil. The rapid absorption of water by sand makes it challenging for farmers to accurately determine the water needs of their crops. Therefore, Pivot irrigation is frequently conducted for durations exceeding what is necessary. This practice can lead to substantial water wastage.

This situation has presented the region with a dilemma, between the need to combat the phenomenon of rising water tables and the desire to promote the development of the agricultural sector, which accounts for 70% of the region's water consumption. Indeed, overconsumption of water due to irrigation practices increases pressure on groundwater tables, thus aggravating the phenomenon of rising water tables. However, it is essential to find a balance between these two objectives, to ensure the economic development of the region while preserving its natural resources and ensuring its long-term sustainability.

Fig. 5. Center pivot irrigation system in operation
Source: DSA, 2022

Efforts by authorities to address this phenomenon

The rising water tables in Oued Souf are a concerning and dynamic phenomenon, primarily caused by the overexploitation of groundwater resources. It is considered a current eco-agricultural threat, and effective solutions are still under study. Proposed solutions must be tailored and require a customized approach, as they are not exhaustive. Close coordination among governments, NGOs and local communities is essential to address the rising water tables in the Sahara. As a starting point, monitoring and managing the water table, particularly by regulating water use, is crucial. This region has long suffered from rising water tables, prompting numerous studies by the government and academics to better understand the phenomenon. Its impacts include soil salinization, degradation of water quality, and reduced availability of potable water (Gouaidia et al. 2012).

To address this issue, authorities have launched several water conservation projects, including constructing a sanitation network, establishing a green belt of trees, and promoting more sustainable agricultural techniques to reduce water demand. Training programs for farmers have also been

Fig. 6. Proximity of rising wastewater to urban areas in Oued Souf
Source: Field internship for M1 students. Rural 2023

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implemented to raise awareness of sustainable water management. The absence of a sanitation network in the region has created ecological problems, allowing large quantities of wastewater to flow into urban centers, creating stagnant, malodorous water and spreading diseases (Fig. 5). Moreover, in the absence of a comprehensive sanitation network, water table levels can rise by 5–8 meters in the Souf region. This situation prompted the government to initiate a large-scale project to construct a sanitation network in the city.

The first intervention of the state was through the dissemination of the sanitation network project. Prior to the flooding, the city of Oued Souf had a low coverage of the sanitation network, whose construction began in 1984, but the construction has never achieved a coverage of 7% of the province's population. In 2005, the state awarded the project to the partners of the Sino-Algerian company "Sino Hydro-Kosidar" and the company "GCP" to conduct a comprehensive study on the network and begin construction work. In 2009, the operation of the network began with a total coverage of 78% in all municipalities of the city (AGEP, 2002). The network consists of three basic complexes for a sewage treatment system, which are the collection and transfer network "responsible for the collection and storage of sewage, with individual channels and connections", the filtration and disinfection stations, and a sewer network. At the city level, there are 47 pumping stations over an area of 690 km² and four filtration stations (Fig. 6). The disinfection process allowed the conversion and reuse of water, avoiding a real environmental disaster. The established network operates using modern equipment to treat wastewater after its collection in basins connected to the four large aeration and filtration treatment stations located in the municipalities of Guenine, Reqiba, Sidi Aoun and Hassani Abdelkrim.

Additionally, as part of this project, the partners worked on moving the wastewater outlet away from the city. Beforehand, the water was drained in the Al-Shatt neighborhood, just 4 km from the municipality headquarters. After the study conducted by the engineering offices, one of the reasons for the rising waters was the wastewater outlet's proximity to the urban areas. Therefore, during the construction of the new sanitation network, a new evacuation point was scheduled, away from the municipality and urban areas. This is the area called "Shatt al-Haloufa", located about 30 km from the wilaya

Fig. 7. Pump used by operators to absorb wastewater from the ground at the Oued Souf Wastewater Treatment Plant
Source: Field internship for M1 students. Rural 2023

headquarters and situated on the limits of the Sidi Aoun municipality. Filtered or excess wastewater is pushed to the surface and transported by a main south–north conversion canal over a length of 47 km, then pushed to the final discharge in the Shatt Halufa region to the north of the wilaya. This method makes it possible to control the increase of waters, protect groundwater from pollution, and improve the quality of life of residents.

On the other hand, the public authorities have created a separate vertical drainage system from the sanitation network, which drains surface water vertically. It is located at the El Oued municipality, with 58 wells with a network length of 34 km, equipped with pumps that start automatically to pump water as soon as the level reaches a certain point. The sanitation project is a major national development project approved by the country's national authorities and with a huge budget and foreign partners. It aims to control the phenomenon of rising waters in Oued Souf, to get the region out of its wastewater flooding, and to offer a sustainable solution for wastewater management. It limits the use of the groundwater by controlling its level and absorbing excess water, and thus changes the old practice of draining wastewater into traditional wells by connecting all houses to a drainage network directed towards the final exit of the region (ONA 2003).

The efforts made by the government regarding the drainage system and the installation of wastewater

treatment plants have significantly reduced the phenomenon of water rising, as indicated by Khezzani (2018) in his article. However, it should be noted that pumping stations cannot entirely prevent this phenomenon. Malfunctions in these stations can lead to its resurgence and cause subsequent damage. Additionally, concerning the development of agricultural lands, the government has specified a perimeter of four hectares, divided into one hectare of olive trees, one hectare of palm trees, and two hectares of potatoes, with the objective of minimizing the rate of water usage for irrigation.

Trees: Allies against rising waters in arid areas

Planting trees and reforestation play a crucial role in mitigating soil erosion and restoring ecosystems. Additionally, they enhance the water absorption capacity of soils, contributing to overall environmental stability. These measures can help reduce the rise of water and prevent its impact (Ferlin, 1981). Selecting tree species to mitigate groundwater rise in the Sahara involves several factors, including their adaptability to arid conditions, root system depth and extent, and water absorption capacity. Notable examples include Acacia raddiana (Campa 1998; Jaouadi et al. 2012; Blanco 2015) and *Prosopis juliflora* (Mesquite) (Ganry 1995; Davies et al. 2017). These trees can absorb water from the soil through their roots, as well as through the transpiration of their leaves and evaporation from their surfaces. Additionally, trees can also slow down the flow of water on the ground by absorbing the water and providing obstacles to its movement. This can help reduce the amount of water that reaches the groundwater and therefore its rising. Local authorities launched a Green Belt project by creating a buffer zone with a chain of these trees in the most degraded and endangered municipalities. The Green Belt Project aims to surround the municipalities in the Oued Souf region with a 100-km-long forested strip covering 150 hectares. The project includes 21 surrounding areas, mainly composed of fast-growing forest trees adapted to the local climate and with a strong water absorption capacity – particularly, Eucalyptus (Chemala 2019). Furthermore, to rationalize water use, local authorities have encouraged the adoption of the modern irrigation technique the "Waterbox", representing a significant improvement in irrigation methods for trees in arid areas (Kartakis et al. 2015; Smith et al. 2023). This agricultural irrigation system provides an ideal environment for the vertical growth of plants, thus improving their moisture absorption capacity. This modern technique optimizes water use in agriculture, leading to significant water savings (Smith 2023).

Conclusion

The groundwater recharge phenomenon in the Sahara may seem paradoxical, as the desert is typically associated with drought and water scarcity. However, this recharge is primarily due to the infiltration of wastewater from local activities, which replenishes the aquifers (Messekher 2012). Poor water resource management is the main cause of rising groundwater levels. This includes the overuse of deep aquifers and the discharge of large quantities of residual water into the phreatic aquifer, exceeding its hydraulic transfer capacity to the natural outlet (Khechana 2014). The overexploitation of water resources in Oued Souf has led to environmental threats and agricultural losses, particularly in the ghouts.

To sustainably manage these resources, it is essential to establish a management system that involves all stakeholders, including communities, government services, economic actors, and citizens. The major project to create a sanitation network in the Oued Souf valley was the first government intervention to mobilize all stakeholders in managing groundwater recharge and promoting the conscious use of water for economic activities. However, the measures outlined in the sanitation project alone are insufficient without addressing other factors contributing to environmental preservation. Efforts to limit overexploitation include water conservation projects, modernization of agricultural techniques, promotion of recycled water use, and the establishment of regulations to encourage appropriate irrigation methods for the region.

Techniques such as the construction of retention basins or infiltration wells can help reduce rising groundwater levels. Sustainable groundwater management is crucial for preventing this rise. Water conservation efforts can prevent the overexploitation

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of aquifers and maintain a stable water table. In essence, sustainable groundwater management involves effectively managing the Sahara's aquifers by avoiding overuse and overexploitation. This can be achieved by limiting excessive pumping and using artificial recharge methods to replenish water reserves. Additionally, regulating water flows in watersheds, such as the Chott-Meghigh, is another effective solution to combat rising groundwater levels in the Sahara.

Disclosure statement

No potential conflict of interest was reported by the authors.

Author contributions

Study design: DI; data collection: DI, LA, MA ; statistical analysis: DI, LA; result interpretation: DI, LA, MA; manuscript preparation: DI, LA, MA; literature review: DI, LA, MA.

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Received 29 February 2024
Accepted 30 August 2024