Larhyss Journal, ISSN 1112-3680, n°61, March 2025, pp. 401-431

ALGERIA'S GROUNDWATER AN UNTAPPED STRATEGIC RESOURCE FOR WATER SECURITY

REMINI B.

Department of Water Science and Environment, Faculty of Technology, Blida 1 University, Blida 9000, Algeria

reminib@yahoo.fr

Research Article – Available at http://larhyss.net/ojs/index.php/larhyss/index
Received October 10, 2024, Received in revised form February 25, 2025, Accepted February 26, 2025

ABSTRACT

Only water stored underground can withstand climate change. In recent years, dams that store surface water have shown their limitations in the face of a disrupted climate. From the water reserves of dried-up dams, water returns to the sky in the form of vapor. It is groundwater that has kept the population thirst-free. This study, devoted to the assessment of groundwater in Algeria, is part of a free project on the water issue in Algeria, which began in the 1990s. Two regions stand out for their different characteristics. In northern Algeria, groundwater is stored in open aquifers, which are not far from the ground. These waters, hidden in open aquifers, have been estimated at 2 billion m^3 and are used 100/100. However, in southern Algeria, two types of aquifers are present: open aquifers and confined aquifers. Unassessed, billions of m^3 of the Sahara's groundwater have not been used. Regarding the waters of the confined aquifers, we have inventoried 6 aquifers which are located on Algerian territory. These are the aquifers of the Northern Sahara aquifer system, the Iulleden-Tanzrouft-Taoudeni aquifer system, the Mourzouk aquifer, the Mourzouk aquifer, the Tindouf aquifer, the Bechar-Er-Rachidia aquifer, the Meghnia aquifer. Without mentioning the groundwater, and if we only consider the poorly rechargeable aquifers (which number 6), Algeria has a water surface area of approximately 1,285,000 km^2, or a rate of 54% of the Algerian territory. Indeed, Algeria has not yet exploited the full potential of water stored in underground reservoirs. So, to properly manage these quantities of water in southern Algeria, we have proposed dividing the Sahara into four hydrographic basins. These are the Western Saharan Piedmont-La Saoura-Hamada Guir-Tindouf hydrographic basin, the Tassili N'Ajjer-Ahaggar-Tanezrouft hydrographic basin, the Touat-Gourara-Tidikelt hydrographic basin, and the Mzab Chebka-Oued Righ-Souf-Ouargla hydrographic basin. Northern Algeria still retains these four hydrographic basins. Therefore, the Algerian territory will be divided into eight hydrographic basins.

Keywords: Groundwater, Deep aquifer, Water table, Depletion, Algeria

INTRODUCTION

Once precipitation reaches the terrestrial surface, it is partitioned into three distinct pathways: a portion flows as surface runoff, other infiltrates into the subsurface to recharge groundwater reserves, while the remainder evaporates and returns to the atmosphere in vapor form (Rouissat and Smail, 2022). Of these three hydrological components, the volume of water that ascends back into the atmosphere through evaporation and transpiration overwhelmingly surpasses the quantities that contribute to surface and subsurface reserves (Hamimed et al., 2017; Boutoutaou et al., 2020; Benchaiba et al., 2022; Remini, 2024). Among these latter two, groundwater—often referred to as "invisible water"—is markedly more secure and resilient than surface water, particularly in the context of accelerating climate change (Ouhamdouch et al., 2016; Assemian et al., 2021; Chadee et al., 2023; Nakou et al., 2023).

Stored in deep, natural geological formations, groundwater is inherently shielded from the deleterious effects of evaporation and sedimentation, which frequently compromise surface water resources (Paulo Monteiro and Costa Manuel, 2004; Kheraz, 2012; Hountondji et al., 2020; Meroni et al., 2021; Merzougui et al., 2022; Later and Labadi, 2024). In contrast, surface water, typically accumulated in artificial reservoirs such as dams, remains highly susceptible to climatic variability and extremes (Remini, 2024).

Climate change has profoundly disrupted traditional hydrological patterns, replacing the formerly predictable sequence of four seasons with a protracted dry period punctuated by brief, intense episodes of precipitation, often culminating in floods (Benslimaneet al., 2020; Aroua, 2020; Abd Rahman et al., 2023; Baudhanwala et al., 2023; Ben Said et al., 2024). During these prolonged arid intervals, evaporation rates soar, resulting in the accelerated depletion of surface reservoirs—especially those with limited storage capacities. Indeed, recent years have borne witness to the desiccation of several Algerian dams following extended droughts, including those at Benkhedda (Tiaret), Foum El Gherza (Biskra), and Mefrouch. Consequently, surface water resources are becoming increasingly vulnerable, with their reliability severely undermined by the impacts of climate change (Adjagodo et al., 2016; Aboubakar et al., 2017).

In contrast, groundwater aquifers exhibit a remarkable capacity to withstand such environmental stresses, offering a strategic buffer against hydrological uncertainty (Matoussi, 2014; Remini, 2021c). This resilience underscores the critical role of groundwater in ensuring Algeria's water security in the face of climatic adversity (Remini, 2023; Remini, 2024). At present, Algeria is undergoing rapid socio-economic transformation, with substantial advancements in agriculture, industry, mining, and social infrastructure. Sustaining this trajectory of development necessitates a commensurate augmentation of the nation’s freshwater reserves, a prerequisite for securing long-term water availability (Aroua, 2018; Aroua-Berkat and Aroua, 2022; Aroua, 2023). Regrettably, the prevailing arid and semi-arid climatic conditions pose a significant impediment to such aspirations, threatening to constrain the country’s growth potential.

Seawater desalination has emerged as an important complementary solution, offering a reliable source of potable water through the proliferation of desalination plants along Algeria's extensive Mediterranean coastline, which stretches over 1,200 kilometers. However, in addition to its marine environment impact (Belkacem et al., 2017; Amitouche et al., 2017), it is unlikely that desalination alone can satisfy the nation's escalating water demands (Remini, 2023b). With a population exceeding 45 million, expansive agricultural zones spanning thousands of hectares, and large-scale mining and industrial projects, Algeria requires an estimated annual water volume surpassing 20 billion cubic meters. Meeting this demand through desalination alone would present formidable technical and economic challenges.

Water scarcity is universally recognized as one of the most critical challenges of the 21st century. Its implications transcend environmental concerns, influencing socio-economic stability, public health, and geopolitical dynamics (Aroua, 2022; Remini, 2023a; Ihsan and Derosya, 2024). Nowhere is this issue more pressing than in the arid and semi-arid regions of the world, where climatic and anthropogenic pressures exacerbate the fragile equilibrium of water supply and demand. Thus, water supply management has become one of the priorities for all countries due to water scarcity and population growth (Patel and Mehta, 2022; Kouloughli and Telli, 2023).

Over the past few decades, Algeria has witnessed significant demographic and economic transformations. Rapid population growth, urban sprawl, and intensified agricultural practices have escalated the demand for water beyond the capacities of conventional water supply systems.

Despite the construction of numerous dams and reservoirs aimed at harnessing surface water for irrigation, drinking water, and industrial use, these infrastructures face serious challenges. Siltation, evaporation, and climate change-induced variability in inflows have considerably reduced their storage capacity and operational efficiency over time (Remini and Bensafia, 2016; Remini and Toumi, 2017). In some cases, major dams have experienced critical drying, particularly during extended drought periods (Remini, 2010a).

Surface water resources, historically the backbone of the nation's water strategy, are under pressure and threatened by exhaustion, compelling policymakers and water resource managers to explore alternative and sustainable sources of water supply. The attention is currently paid to the water desalination as an alternative to the water supply.

Groundwater represents an invaluable yet underutilized resource in Algeria's quest for water security. The country's hydrogeological structure is characterized by a diversity of aquifers that vary widely in terms of their geographical distribution, depth, recharge rates, and water quality. These aquifers are distributed across three principal hydrographic regions: the Tellian Atlas in the north, the High Plateaus in the center, and the expansive Sahara region in the south. The northern aquifers, while more accessible, are under intense exploitation and face significant contamination risks from urban and agricultural activities. In contrast, the Saharan aquifers, notably the Continental Intercalaire and the

Continental Terminal, encompass vast volumes of fossil water but are subject to logistical and environmental challenges associated with their exploitation.

Despite their strategic significance, Algeria's groundwater resources have historically been neglected in terms of systematic assessment, management, and protection. Data on aquifer capacities, recharge rates, and extraction impacts remain fragmented and outdated, hampering the development of coherent groundwater management policies. Additionally, the absence of integrated water resource management (IWRM) frameworks has resulted in uncoordinated exploitation practices, over-pumping, and deteriorating water quality in many regions. The reliance on traditional extraction methods without adequate regulation or monitoring has further exacerbated aquifer depletion, particularly in the northern and central regions.

The strategic mobilization of groundwater resources is no longer an option but a necessity for Algeria, particularly in light of anticipated climate change impacts. Projections indicate a continued decline in surface water availability, increased temperatures, and more severe drought events, all of which will place additional stress on existing water infrastructure. Groundwater, with its relative resilience to climatic variability and its capacity to act as a buffer during periods of surface water scarcity, offers a viable solution to these mounting challenges. However, the sustainable exploitation of these resources requires an integrated approach that balances short-term water supply needs with long-term aquifer sustainability and ecosystem health.

Moreover, the geopolitical and socio-economic significance of groundwater in Algeria cannot be overstated. Many rural and remote communities, particularly in the southern regions, depend almost exclusively on groundwater for their domestic and agricultural needs. The development of groundwater resources is therefore central to regional development strategies, food security, and poverty alleviation efforts. Nevertheless, these initiatives must be grounded in scientific research, technological innovation, and robust governance frameworks to prevent the unsustainable depletion and degradation of aquifers.

Recent studies and international experiences underscore the importance of adopting advanced hydrogeological mapping techniques, implementing managed aquifer recharge (MAR) strategies, and promoting water-use efficiency to optimize groundwater exploitation (Chibane and Ali-Rahmani, 2015; Abaidia and Remini, 2020; Qureshi et al., 2024). Additionally, public awareness campaigns and stakeholder engagement are critical components of any sustainable groundwater management program, fostering community participation and ensuring equitable access to water resources.

This study aims to provide a comprehensive assessment of Algeria’s groundwater resources, emphasizing their spatial distribution, hydrogeological characteristics, and potential for sustainable exploitation. Groundwater resources represent a viable and indispensable alternative to mitigate the adverse effects of climate change on water availability. Yet, these vast subterranean reserves remain poorly characterized and underappreciated within Algeria’s water management discourse. In particular, the extensive aquifer systems of the Algerian Sahara-containing immense quantities of untapped freshwater—have yet to be fully assessed or exploited in a strategic manner. This article endeavors to shed light on these hidden reserves, providing an overview of the volumes stored within these deep underground reservoirs and underscoring their potential contribution to reinforcing Algeria's water security.

STUDY AREA AND METHODOLOGY

With a surface area exceeding 2,380,000 km², Algeria, the largest country on the continent, is located in North Africa. Algeria is one of the countries of North Africa. It is the largest country on the African continent, bordering the Mediterranean to the north with a coastline of over 1,600 km. Algeria shares its land borders with Tunisia to the northeast, Libya to the east, Niger and Mali to the south, Mauritania and the territory of Western Sahara to the southwest, and Morocco to the west (Fig. 1).

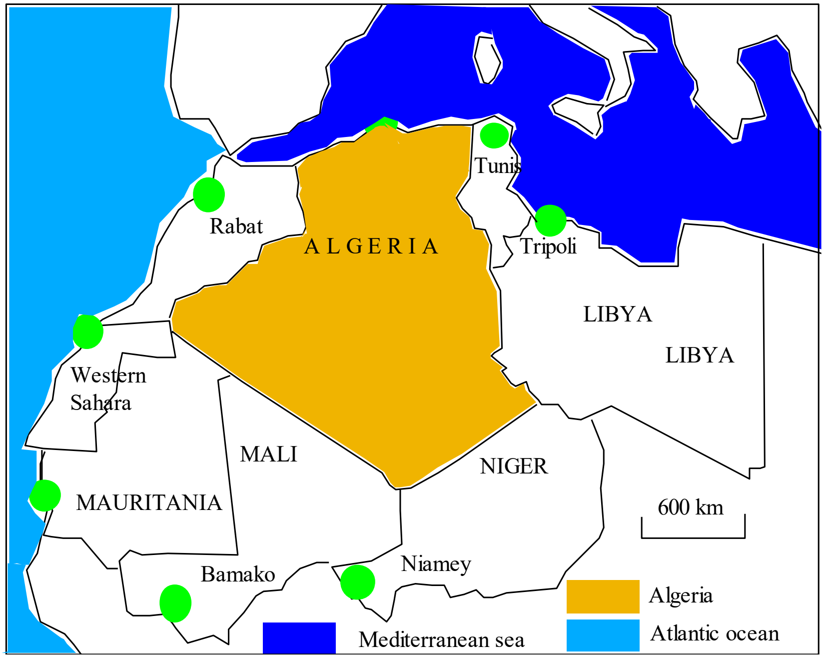

Figure 1: Geographical location of Algeria (Remini diagram, 2005)

A large country, Algeria boasts a varied terrain divided into three main parts. These are the Tell in the north, the highlands, and the Saharan Atlas in central Algeria. Behind these mountains lie the oases synonymous with the beginning of the Sahara. This desert expanse, the most beautiful on the planet, covers approximately 85% of Algerian territory and is part of the largest desert on the planet. Covering an area of over 8.5 million km^2, the Sahara is occupied by Ergs, plateaus, Regs, and Hamadas, lakes, wadis, rocky massifs, Sebkhas, Chotts, and Gueltas.

This first part of a major project on the assessment of water resources in Algeria is dedicated to the study of groundwater resources. It is interesting to recall that this work began during the nineties which ended in 2005 with the publication of a book on the water problem in Algeria and an article published in Larhyss journal (Remini, 2005, Remini, 2010). This time a new parameter comes into play; it is climate change and its impact on water resources. The scarcity of water pushed the Algerian government to opt for the desalination of sea water. Indeed, Algeria has become today a major player in the production of water from the sea. It should be noted that groundwater resources have not been evaluated since independence. In addition to our experience on the ground for more than 25 years. A very thorough bibliographic study was initiated several years ago.

RESULTS AND DISCUSSIONS

The Importance of Groundwater in the Era of Climate Change

Climate change is characterized by a long period of drought ending with a short period of wet weather characterized by rapid and aggressive flooding. The first victims of this unhealthy climate are surface waters, which are unable to withstand such a phenomenon. Interestingly, there is no better solution than collecting and storing surface water in artificial reservoirs (dams). However, the capacity of these water dams is threatened with extinction by two phenomena: evaporation and siltation. The duration of the drought has become prolonged, with no water falling for 3 to 5 months and temperatures exceeding 45°C. This has led to a significant initial loss of reservoir capacity through evaporation (Remini, 2005). The second loss of dam volume has been attributed to the phenomenon of silting of these dams, thus reducing their capacity by successive deposits of mud over time. These mud deposits are a consequence of solid transport, which records concentrations exceeding 100 g/l during flood periods (Larfi and Remini, 2006). The depletion of the useful capacity and even the dead volume of the dam is a victim of the effect of climate change. Therefore, the dam is unable to play its role, which is to supply the population with drinking water and irrigate agricultural land. This has pushed the population to turn to groundwater. But today we are witnessing pressure on the exploitation of invisible waters, which are the only ones that can withstand climate change. Natural reservoirs called aquifers are hidden in the subsoil and are protected from evaporation and siltation.

Groundwater in Algeria

Algeria holds a significant amount of water underground. However, this natural reservoir remains poorly estimated today. Poorly understood, groundwater deserves to be revisited and studied more seriously, especially given the climatic disturbances affecting our planet, particularly North African countries. Two parts of Algerian territory are distinguished by their hydrogeological, geomorphological, and climatological differences: northern Algeria and the Algerian Sahara. Thus, the Algerian territory has been divided into five hydrographic basins. Northern Algeria is divided into four hydrographic basins, while southern Algeria is represented by a single hydrographic basin: the Algerian Sahara (Fig. 2).

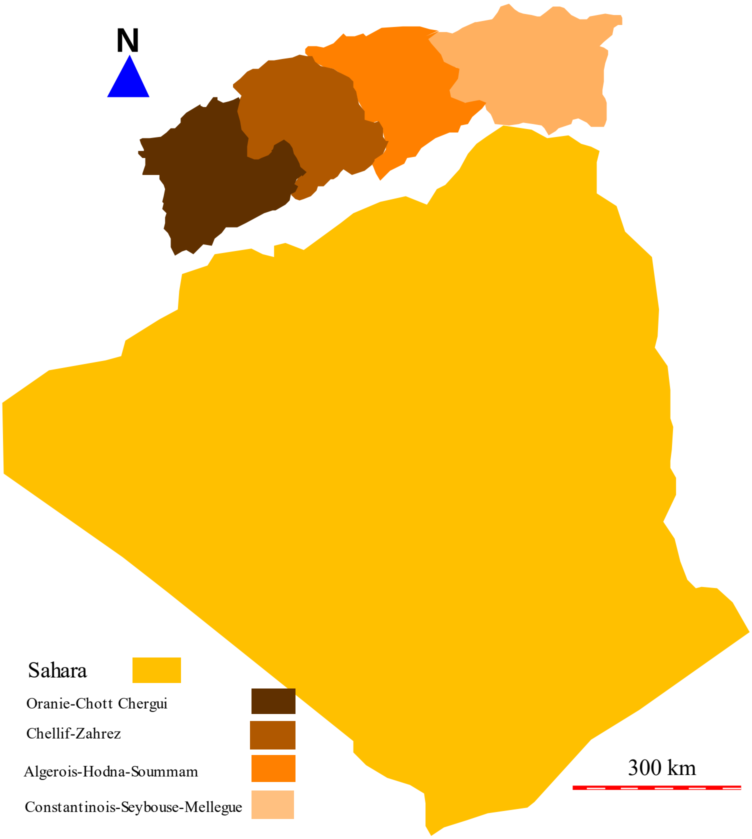

Figure 2: The 5 hydrographic basins of Algeria (Source: Basins Agency, Diagram Remini, 2005)

Groundwater in Northern Algeria

For proper water resource management, northern Algeria is divided into four river basins (Fig. 3):

- Basin of Constantinois- Seybouse- Meµllegue
- Basin of Algérois- Hodna-Soummam
- Basin of Chellif Zhrez
- Basin of Oranie –Chott Chergui

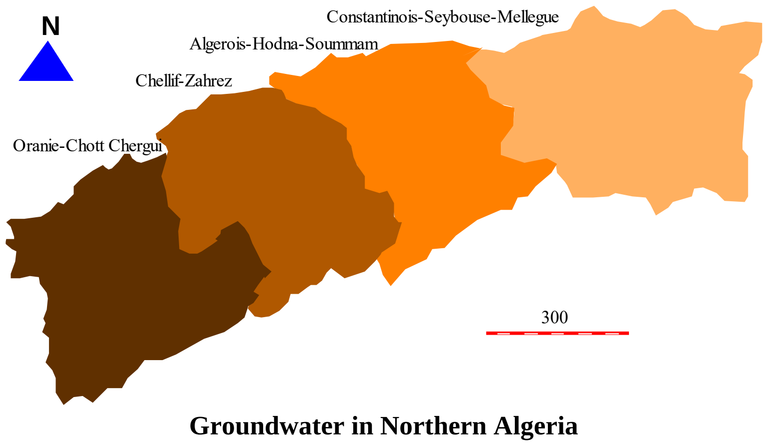

Figure 3: Hydrographic basins of northern Algeria (Source: Basins Agency, Diagram Remini, 2005)

Known and studied, groundwater resources in northern Algeria are estimated at more than 2 billion m3. They are exploited at more than 90%, or 1.9 billion m^3, and many aquifers are currently in a state of overexploitation. This assessment is based on more than 50,000 water points (boreholes and wells) identified by the National Agency for Water Resources. Today, this figure is revised upwards. With climate change causing the drying up of some dams and the use of underground reservoirs to satisfy the population's thirst and meet irrigation demands, access to these invisible waters requires drilling into the ground. Wells and boreholes have multiplied in recent years, which has caused drawdowns in several aquifers in the four river basins. Even some aquifers have narrowly avoided depletion, particularly the Mitidja aquifer. Table 1 gives estimates of groundwater resources in northern Algeria.

Table 1: Groundwater potential of northern Algeria

Regions / Désignations	Oranie C. Chergui	Chéliff Zahras	Algérois S. Hodna	Constantinois Sey. Mellègue	Total North Algeria
Mobilizable underground resources Mm^3/year	400	245	775	580	2000
Groundwater resources mobilized Mm^3/year	375	230	745	550	1900

Reading Table 1, it appears that the region of Algiers Soummam Hodna has the largest volume of groundwater compared to other regions. This is due to the presence in this region of important aquifers, such as the Mitidja aquifer, which is currently overexploited because its waters constitute the main source of supply for the city of Algiers. Table 2 (a, b, c, and d) shows the main aquifers of the four regions of northern Algeria. However, today, these natural underground reservoirs can no longer meet their demands for irrigation or domestic water. This is a consequence of the impact of climate change on surface water. Indeed, evaporation and siltation have contributed to the drying up of several dams in northern Algeria, particularly the Algiers-Soummam watershed, such as the Keddara (Boumerdes) and Boukourdane (Tipaza) dams. This new situation has created pressure on the extraction of water hidden in the subsoil.

Table 2: Main aquifers of northern Algeria

a) Basin of Oranie - Chott Chergui

Aquifers	Potentials (10^6 m^3/year)	Volume taken (10^6 m^3/year)
Maghnia Plain	15	15
M'leta Plain	6	2
Plain of Sidi Bel Abbes	30	30
Mostaganem Plateau	30	30
Mascara Plain	60	60
Chott Chergui	54	31
Saida region	52.5	24.4
Bredeah	24	22.7
Tlemcen Mountains	45	40
High plains of Tlemcen	60	60

b. Basin of Chellif - Zahrez

Aquifèrs	Potentials (10^6 m^3/year)	Volume taken (10^6 m^3/year)
Upper and Middle Chellif	8.5	8
Mina Plain	17	14
Sersou Plateau	12	10
Ain Oussera Plain	27	9
Zahrez	50	26

c. Basin of Algérois - Soummam - Hodna

Aquifers	Potentials (10^6 m^3/year)	Volume taken (10^6 m^3/year)
Mitidja Plain	328	335
Lower and Upper Sebaou	53	33
Lower and Middle Isser	14	12
El Hachem River	3.8	3.8
Soummam Valley	100	80
Ain Rich Plain	8	8
Basin of Chott Hodna	133	81

d. Basin of Constantinois - Seybouse - Mellegue

Aquifers	Potential (10^6 m^3 /year)	Volume taken (10^6 m^3 /an)
Ain Mlila Plain	22	7.5
Alluvium Oued Djendjen	10	15
Alluvium Wadi Nile	20	15
Annaba Bouteldja Tablecloth	45	47
Oued Seybousse Valley	17	17
Oued Saf Saf Valley	12	12
Collo Plain	4	3
Tebessa Plain	18	18
Taoura Syncline	6	3
Cheréa Plateau	28	28
Tolga tablecloth	60	60
Oued M'zi Valley	199	195.5
Biskra River	19	19
Medjerda Mellegue	29	25

Groundwater in Southern Algeria

Represented by the Saharan watershed, southern Algeria covers 85% of the country's total territory, with an area of approximately 2,156,000 km² (Fig. 4). Characterized by almost zero rainfall, only flash floods occurring in large rivers such as the Mzab, Mzi, Saoura, Zergoun, Namous, Labiod, Ejdi, and Metlili wadis contribute to groundwater recharge during flood periods (Fig. 5). Unlike northern Algeria, which contains open aquifers (groundwater tables), the subsoil of southern Algeria is very rich in water resources, stored in two natural reservoirs: open aquifers (groundwater tables) and closed aquifers (confined aquifers).

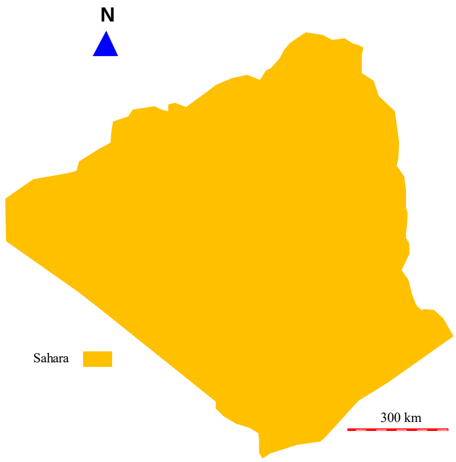

Figure 4: The limits of the Sahara watershed

Figure 5: Oued Metlili; a place of groundwater recharge during flood periods (Photo Remini, 2005)

Open Water Tables (Ground Water Tables)

These small, generally shallow underground reservoirs store millions of cubic meters of floodwater. However, this subject remains little studied and even uncontrolled in some regions. In several parts of the Sahara, simply digging 1 to 3 meters deep reveals a sea of water hidden underground. For example, in the Touggourt Oasis, we dug down a small palm grove about 2 meters to discover large quantities of good-quality water. We would like to confirm that there are several locations in this Saharan territory similar to the Touggourt Oasis. However, we have no idea about the number and size of these open water tables. This may be due to the difficulties of traveling and even working in a desert expanse spanning over 2 million km². Only the few unconfined aquifers are understudied, but lack sufficient data and information to assess their characteristics, such as the aquifers of Ghardaïa, Metlili, Menea, Ouargla, El Oued, Adrar, Touggourt, and others.

Compared to the waters of the unconfined aquifers of the four river basins of northern Algeria, those of the Sahara River basin are of poor quality (brackish water), caused by the discharge of drainage water from neighboring palm groves. The particular phenomenon that occurs in the Sahara River basin, and more specifically in the Northern Sahara, is groundwater upwelling. Something that does not exist in northern Algeria, this upwelling phenomenon is caused by the withdrawal of water from closed (confined) aquifers located below the unconfined aquifers close to the ground surface. The intense irrigation of several agricultural hectares causes a return of water after irrigation (drainage water) to the upper water table. Due to the presence of a substratum, the absence of contact between the upper water tables (free water table) and the lower water tables (confined water table) causes in a first stage the saturation of the water table. In a second stage, the appearance of the rising water becomes more visible; the quantity of water that infiltrates become greater than the quantity drawn (the inflows are greater than the outflows). It was during the eighties that this phenomenon of rising water appeared at the level of the oases of the valley of Souf and Ouargla (Figs. 6 and 7). But at the beginning of the nineties, the rising water accelerated due to the heavy exploitation of the deep confined water tables of the aquifer system of the Northern Sahara.

Figure 6 : Remontée de l'eau spectaculaire dans la vallée de Souf. Asphyxié par la remontée des eaux, les palmiers dattiers cèdent leurs places aux roseaux (Photo. Remini, 2010a).

Figure 7: Ouargla, spectacular rise in water levels in the lower districts of the town, forcing residents to leave their homes (Photo. Remini, 1998).

The Sahara's Confined Aquifers

Theoretically, the region that can withstand climate change and even prolonged drought is the region that harbors non-renewable or low-renewable aquifers. Paradoxically, this region is none other than a desert region called the Sahara. Huge quantities of groundwater are hidden in the aquifers of large sedimentary basins, most of which are shared by several countries and are non-renewable or low-renewable. There are 273 transboundary aquifers in the world according to the 2008 inventory (Guyomard, 2011). With 83 transboundary aquifers, Africa is the continent with the most aquifers (Sahara and Sahel Observatory, 2020). The Sahara contains nine large fossil aquifers (Table 3 and Fig. 8).

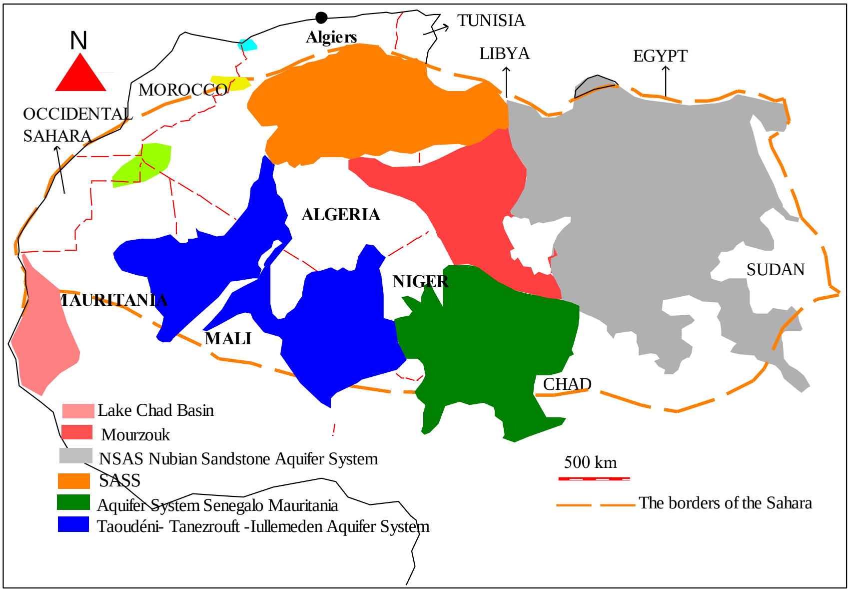

Figure 8: Diagram of the main poorly rechargeable aquifers of the Sahara (Source SSO, Remini, 2021a)

Table 3: Caractéristiques of the major aquifers of the Sahara (Remini, 2021b) Sources: FSCD, 2020; Seguin and Gutirrez, 2017; OSS, 2020.

N°	Aquifer system	Volume km^3	Area 10^3 km^2	Annual withdrawal (km^3/year)	Shared countries
1	Nubian sandstone	370 000 à 500 000	2200	2,3	Egypt-Libya, Sudan, Chad
2	Northern Sahara	60 000	1000	2,75	Algeria, Tunisia, Libya
3	Taoudéni/Tanezrouft/ Iulleden	15 000	2500	0,34	Algeria, Nigeria, Niger,

					Burkina Faso, Benin, Mali, Mauritania
4	Lake Chad Basin	5 800	1500	0,25	Chad, Cameroon,
5	Mourzouk	4 800	450	1,7	Algeria, Libya, Niger
6	Senegalese-Mauritanian	1 500	340	0,26	Mauritania, Senegal, Gambia, Guinea-Bissau
7	Tindouf	800	210		Algeria-Western-Sahara
8	Er Rachidia – Béchar	320	70	0,2	Algeria-Morocco
9	Djeffara	170	43		Tunisiea , Libya
10	Meghnia	85	3,5		Algeria-Morocco

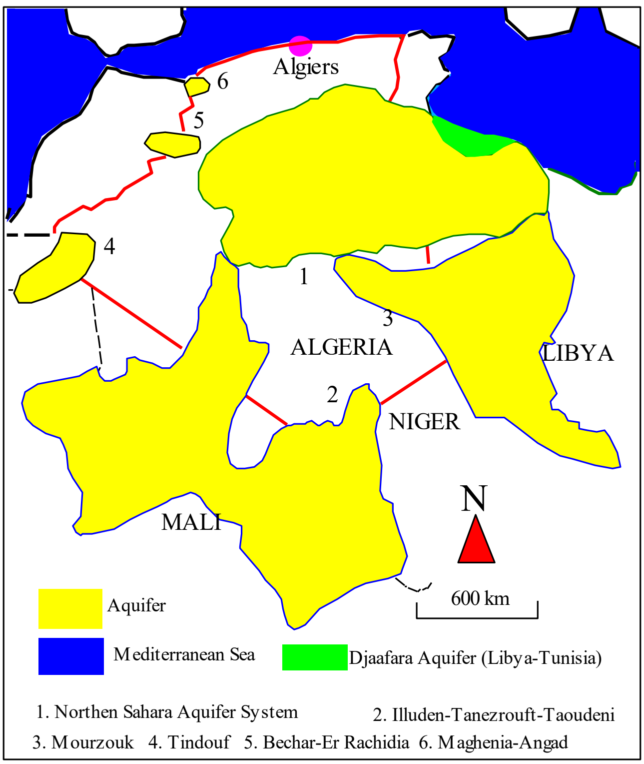

Figure 9: The main aquifers of the Sahara (Source OSS, Remini diagram, 2010b)

The theoretical reserves of the largest aquifer systems in the Sahara have reached the value of 590,000 billion m^3 and are shared between 10 countries as shown in Table 3. Algeria is surrounded by the aquifer systems: the Sahara Aquifer of the Northern Sahara, Mourzouk, Iulleden-Tanezrouft-Taoudeni, Tindouf and Er-Rachidia-Bechar, the Tindouf Aquifer System. And the Meghnia Aquifer (Fig. 9).

Table 4: Characteristics of Algeria's major aquifers (Remini, 2005); Sources: FSCD, 2020; Seguin and Gutirrez, 2017; OSS, 2020

N°	Aquifer system	Volume km^3	Area 10^3 km^2	Annual withdrawal (km^3/year)	Shared countries
1	Northern Sahara	60 000	1000	2,75	Algeria, Tunisia, Libya
2	Taoudéni/Tanezrouft/ Iulleden	15 000	2500	0,34	Algeria, Nigeria, Niger, Burkina Faso, Benin, Mali, Mauritania
5	Mourzouk	4 800	450	1,7	Algeria, Libya, Niger, Chad
4	Tindouf	800	221	-	Algeria, Western Sahara
5	Er Rachidia – Béchar	0,320	70	0,2	Algeria, Morocco
6	Meghnia	0,085	3,5	-	Algeria, Morocco

The Northern Sahara Aquifer System

The area of the Northern Sahara Aquifer System (NSAS) covers 1.019 million km^2 in the territories of Algeria (700,000 km^2), Tunisia (80,000 km^2) and Libya (250,000 km^2) (Tathe et al, 2013, FSCD, 2020). The Northern Sahara Aquifer System (NSAS) is a superposition of two main deep aquifer layers; the Complexe Terminal (or Continental Terminal) (CT) formation, and the Continental Intercalaire, the deepest (CI). The water reserves of the NSAS are estimated at 60,000 km^3 spread over two superimposed aquifers: the Continental Intercalaire (CI), with a depth reaching 3000 m in certain places, and the Complexe Terminal (CT) with a depth of 300 to 500 m. (Fig. 10).

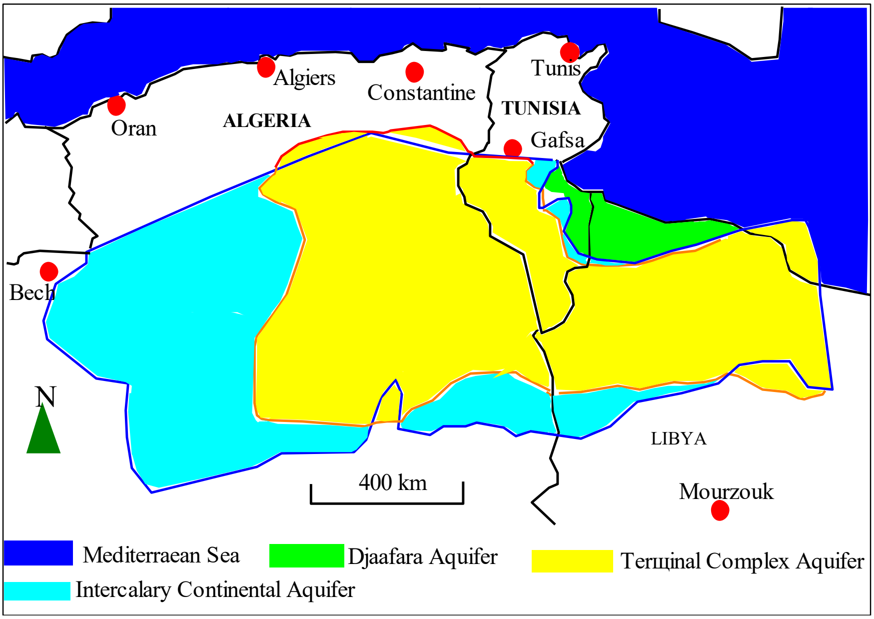

Figure 10: Diagram of the Northern Sahara Aquifer System (SSO Source, Remini Diagram, 2021a)

For more than 20 centuries, more than 1000 foggaras have been built around the periphery of the Tademaït plateau to capture the waters of the Continental Intercalaire aquifer. Considered as the water tower of the oases of Touat, Gourara and Tidikelt which induced the birth of a green ribbon of thousands of date palms (Remini et al, 2014). It is at the borders of the Tademaït plateau that the Continental Intercalaire aquifer discharges these waters. It is at these water discharge points that the foggaras were placed to drain these waters towards the gardens which are located below. These foggaras we called the foggaras of the Albian. On the other hand, there are other types of foggaras which capture the waters of the Erg aquifer. These foggaras are located in the oases of Gourara and more particularly in the oases of Ouled Said, we call them the foggaras of the Erg. This confirms that the farmers knew the hydrogeology of their environment well and they know where these invisible waters come from. Today, after 20 centuries, about 300 foggaras of the Albian are perennial and continue to operate 24/24 (Figs. 11 and 12).

Figure 11: Gallery of the foggara Lasalma in the oases of Timimoun which captures the waters of the Continental Intercalaire aquifer (Photo. Remini, 2019).

Figure 12: The large kasria of the foggara El Meghier of Timimoun, a watershed element of the Continental Intercalaire aquifer (Photo Remini, 2010a)

The foggaras exploit the waters of the aquifer system of the northern Sahara, with almost constant quantities of water. However, since the 1940s, the date of the first Albian drilling, water withdrawals from the gigantic underground reservoir by the 3 countries (Algeria, Libya and Tunisia) have been clearly increasing. The exploitation of the water table has continued to grow since the 1960s, withdrawals by the three countries were multiplied by 5 in the year 2000. For example, withdrawals increased from 0.6 billion m^3/year at the beginning of the 1970s, to 2.7 billion m^3/year in 2012 (Sahara and Sahel Observatory, 2014). More than 8,800 water points (boreholes and wells) have been inventoried, including 5,300 in the Terminal Complex and 3,500 in the Continental Intercalaire. The sampling points, drillings and wells, are distributed as follows: 6,500 in Algeria, 1,200 in Tunisia and 1,100 in Libya (Figs. 13 and 14).

Figure 13: Equipment for performing deep drilling (Photo Remini, 2021)

Figure 14: A borehole exploiting the Terminal Complex aquifer in the palm groves of Oued Righ (Photo Remini, 2021a)

Withdrawals reached the value of 2.75 km^3/year of water, or 40% of the total volume of withdrawals (OSS, 2017). According to Margat (2008) and the Northern Sahara Observatory (2008), the 3 countries each withdraw high volumes from the Northern Sahara Aquifer System (NSAS): 1.68 km^3/year for Algeria, 0.55 km^3/year for Libya and 0.46 km^3/year for Tunisia. The value of 8 km^3/year of withdrawals will be reached in 2030. In return, recharge was initially estimated at 1 km^3/year. Today, new research confirms that the aquifer recharge rate is 1.4 km^3/year (Remini, 2021c). The Continental Intercalaire aquifer is a water reservoir that extends over 700,000 km^2, its temperature exceeds 60°C. Its salinity increases along the flow axes from 1 to 1.5 g/l near the recharge zones to reach 7 g/l near the Tunisian chotts. Drilling depths of more than 1,500 meters are necessary for capture in the regions of Ouargla, Oued-Righ and Ouled Djellal. On the other hand, this aquifer is captured by shallow drilling and foggaras in the southwestern part (Adrar) where it outcrops. For example, in the Ziban region and more particularly in the palm groves of Tolga, Ourlel, Foughala, it is necessary to drill more than 2,200 m to extract the waters of the Continental Intercalaire. At the outlet, hot water of more than 60°C and a salinity not exceeding 2 g/l (Figs. 15 and 16). It should be noted that the first deep drilling carried out in the Ziban region dates back to 1954 in the Ouled Djelal Oasis.

Figure 15: Water from the Continental Intercalaire at over 60°C stored in a basin before being transported to the palm groves (Photo, Remini, 2021b)

Figure 16: Intended for irrigation, open-air canal for transporting water from the Continental Intercalaire (Photo, Remini, 2021b)

The Terminal Complex aquifer covers an area of 350,000 km^2, limited to the eastern basin of the Northern Sahara (Zahrouna, 2010). It is a shallow aquifer (100 to 400 m) with artesian boreholes in the center of the basin. Its recharge, although low relative to reserves, comes from the wadis of the Mzab Saharan Atlas and exceptional rainfall in the Grand Erg Oriental. The waters of the Terminal Complex are weakly mineralized at the edges (recharge zones of the Mzab, Saharan Atlas, and Grand Erg Oriental) (1 to 2 g/l) and become highly mineralized at the outlet of the Melghir and Merouane chotts (6 to 7 g/l).

As previously indicated, in the Souf Valley, the waters of the Northern Sahara Aquifer System have caused groundwater to rise. On the other hand, in the Oued Righ valley, these waters, once drained, are transported by the 120 km canal towards the Chott Merouane. It is thanks to this canal that the phenomenon of rising water has been avoided in the Oued Righ valley (Figs. 17 and 18).

Figure 17: Waters of the Northern Sahara Aquifer system in the palm groves of the Oued Righ valley. Once irrigation is completed, the drainage water is collected in the main canal (Photo, Remini, 2010a)

Figure 18: Drainage water is transported to the 120 km long main canal towards the Chott Melghir (Photo, Remini, 2010a)

The Iulleden-Tanezrouft-Taoudéni Aquifer system

The Taoudeni-Tanezrouft-Iullemeden aquifer system is located south of the Sahara Desert. It is composed of the Iullemeden aquifer system (IAS) to the east and the Taoudéni-Tanezrouft aquifer system (TTAS) to the west, and covers an area of 2.5 million km^2. Ranked as the largest aquifer system on the African continent with its 2.5 million km^2 area, the Tanezrouft-Illumeden-Taoudéni aquifer system (ITAS) is of the same order of extent as the Nubian Sandstone aquifer system, which has an area of 2.6 million km^2. An area of nearly 2.5 million km^2 (2,629,303 km^2) is shared between 7 countries: Algeria (450,925 km^2, 17%), Benin (57,338 km^2, 2%), Burkina Faso 130,174 km^2, 5%), Mali (1,089,407 km^2, 41%), Mauritania (256,374 km^2, 10%), Niger (524,813 km^2, 20%) and Nigeria (120,272 km^2, 5%) (Sessinou, 2021) (fig. 19).

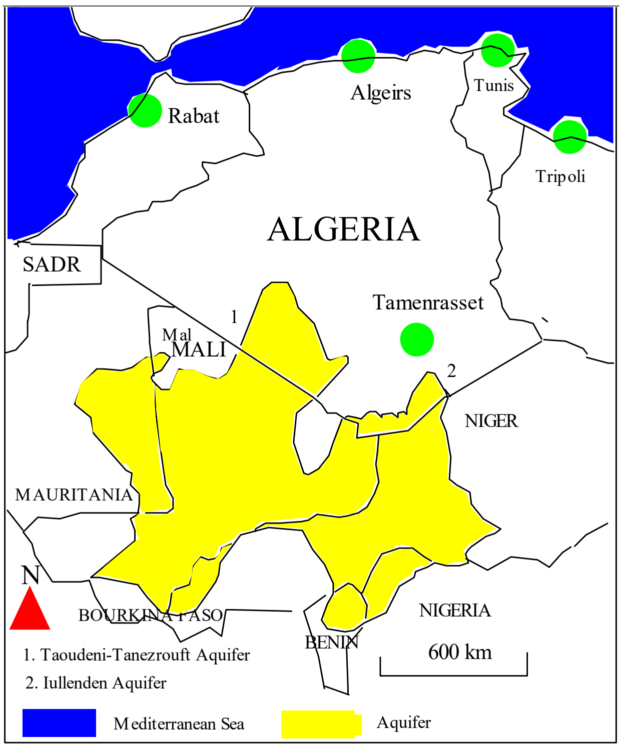

Figure 19: Simplified diagram of the Taoudeni-Tanezrouft-Iullemeden Aquifer System (SSO source, Remini Diagram, 2005)

The aquifer formations presented in the Iullemeden and Taoudéni-Tanezrouft basins are two superimposed aquifers of the Continental Intercalaire at the base and the Continental Terminal at the top. The main watercourse of the Niger River crosses the Aquifer System for nearly 2,480 km, including 1,700 km in Mali, 540 km in Niger, 140 km in Benin and 100 km in Nigeria (Sahara and Sahel Observatory, 2017). The Iullemeden Aquifer System

(IAS) basin stores more than 2,000 billion m^3 of non-renewable water resources. The Niger River feeds the Taoudéni-Tanezrouft aquifer with more than 1.5 billion m^3 while the Iullemeden aquifer receives approximately 3.3 billion m^3 in Nigeria (Sahara and Sahel Observatory, 2015; Ousmane, 2008). More than 350 million m3 are withdrawn each year from the Taoudeni-Tanezrouft-Iullemeden basin to meet drinking water and livestock needs. Total water withdrawals therefore represent less than 2% of the aquifer's renewable potential (Sahara and Sahel Observatory, 2015). However, total reserves are estimated at 1,810 million m^3 (Guyomard, 2011). The potential for renewable water resources has been estimated at 11 billion m^3 per year in the Taoudeni/Tanezrouft basin and 8 billion m^3 per year for the Iullemeden basin. It should be noted that the Iullemeden and Taoudéni-Tanezrouft basins represent a potential for renewable water resources estimated by the OSS at 19 billion m^3 per year. Of these 19 billion m^3/year, only 350 million m^3 (less than 2%) are abstracted annually (Sessinou, 2021). Water abstraction (all uses combined) has been estimated at 63 million m^3/year and 284 million m^3/year, respectively. Recharge through rain infiltration is by far the main source of groundwater renewal: more than 80% in the SAT and nearly 95% in the SAI (OSS, 2017).

Aquifère de Mourzouk

With a surface area of 450,000 km^2, the Mourzouk aquifer is shared between 4 countries: Algeria, Libya, Niger and Chad (fig. 20). Exploitation of this deep reservoir reached the value of 1.7 billion m^3/year, which produced a drawdown of -1 to -2 m/year during the period 1974-2000. This gives a cumulative drawdown of -25m to -50 m depending on the location. The Mourzouk basin is threatened with depletion in the same way as those of the Arabian and Indus basins (Demeersman, 2015). The aquifer system is two-layer and its thicknesses can reach 2,500 m in places. The theoretical volume of the reserve is 4,800 billion m3. Recharge is estimated at 0.15 billion m^3/year (Sahara and Sahel Observatory, 2020).

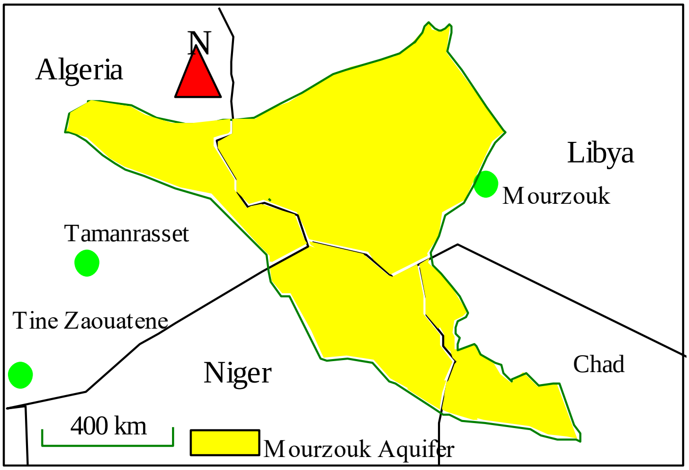

Figure 20: Simplified diagram of the Mourzouk aquifer (Remini diagram, 2005)

Tindouf Aquifer

No in-depth study has been conducted on this natural reservoir buried deep in the far south of Algeria. Covering an area of 450,000 km^2, the Tindouf aquifer can store a volume of 800 billion m^3 of water (Sahel and Sahara Observatory, 2020). There is very little information or data available; the transboundary Tindouf aquifer is shared between three countries: Algeria, Western Sahara, and Mauritania.

Bechar-Er-Rachidia Aquifer

Shared between Algeria and Morocco, the Bechar-Er-Rachidia transboundary aquifer covers an area of 70,000 km^2 and can store a volume of water of 320 billion m^3.

Meghnia Aquifer

With an estimated capacity of 85 billion m^3, the Meghnia transboundary aquifer is shared between Algeria and Morocco.

The Sahara in 4 basins means better management of the Sahara's water resources

As we have previously studied, the Sahara is full of water. Three major aquifer systems are located in the Algerian subsoil. These are the Northern Sahara Aquifer system, the Taoudéni-Tanezrouft-Iulleden Aquifer system, and the Mourzouk Aquifer. In addition to these natural underground reservoirs, there are small aquifers such as those of Tindouf, Bechar-Er-Rachidia, and Meghnia. All these aquifers occupy a total area of 1,285,000 km^2, or a total percentage of 56% of the Algerian territory. This is a huge figure; we can say that we have a sea of water in the Algerian soil. Finally, the Sahara subsoil is very rich in fresh water. We can say that the water hidden in billions of m3 in captive aquifers is a gift from heaven. With climate change, only these waters from poorly recharged aquifers can withstand long periods of drought. However, we have little information regarding open water tables or groundwater tables. Few studies have been conducted on this subject. Therefore, billions of cubic meters of water are stored in small natural reservoirs, but these are ignored by hydraulic services, and consequently, significant quantities of water are not used for irrigation or drinking water supply. On the ground, in addition to the wind dynamics that prevail on the ground, which causes the formation of sand dunes. By grouping together, these sand dunes form ergs. In return, hydraulic dynamics have accelerated in recent years due to the unhealthy climate that prevails in North African countries. Flash floods occur in several places in the Sahara, particularly in the Mzab Valley, the Saoura Valley, and even in the Tamanrasset region. Billions of cubic meters of water flow and evaporate. At the same time, Algeria has launched megaprojects in recent years throughout the Sahara, focusing on agriculture, mining, and industry. These projects require significant amounts of water; surface water storage and groundwater extraction require drilling and wells, and therefore, proper water resource management in the Sahara is essential. Therefore, it is becoming impossible to continue managing all these water problems with a single watershed. To address this problem, we have proposed dividing the Sahara into four watersheds to better manage water resources in a territory that exceeds 2 million km^2 (Fig. 21)

- Hydrographic basin of Piémont Saharien occidental- Saoura- Hamada Guir-Tindouf
- Hydrographic basin of Tassili N'Ajjer-Ahaggar-Tanezrouft
- Hydrographic basin of Touat-Gourara-Tidikelt
- Hydrographic basin of Mzab Chebka-Oued Righ-Souf- Ouargla

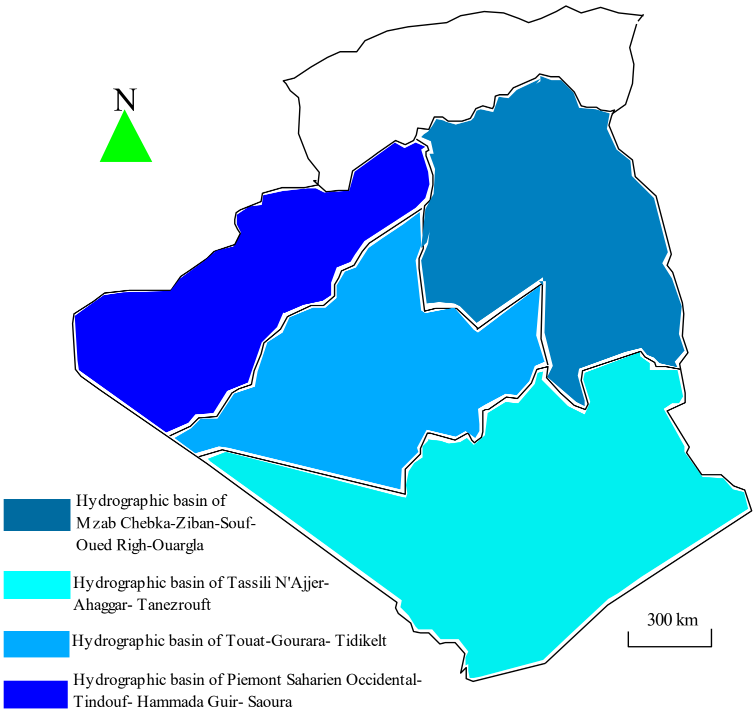

Figure 21: The limits of the 4 hydrographic basins of the Algerian Sahara (Remini diagram, 2005).

CONCLUSIONS

As mentioned earlier in this paper, groundwater is the only resource that can withstand climate change. Protected from climatic hazards and pollution effects, groundwater is of good quality unlike surface water which is confronted with various pollutions even if in quantity surface water is more abundant. However, what we have just seen in the last twenty years with a sick climate, are the dams that store surface water which have seen their waters evaporate into the sky following long periods of drought. It is the water stored in the underground reservoirs that have prevented the thirst of the population. This modest contribution on groundwater in Algeria provides for the first time an approach on groundwater reserves. In addition to the Northern Sahara aquifer system shared between Tunisia and Libya, Algeria still has significant water resources in the Iulleden-Tanezrouft-Taoudeni aquifer system, with a total area of 2.5 million km^2 located in the far south. Another groundwater deposit with an area of 450,000 km^2 is shared between Niger, Libya, and Chad. Algeria also has smaller aquifers such as those of Tindouf, Bechar, and Maghnia. In total, Algeria has a water surface area of approximately 1,285,000 km^2, representing 54% of the Algerian territory. Therefore, billions of cubic meters of water are stored in natural reservoirs located deep within this beautiful country. Even the waters that are hidden only a few dozen meters from the Saharan soil and which are estimated at billions of m^3 have never been evaluated or even used for drinking water supply or irrigation. Indeed, Algeria has not yet exploited the full potential of the water stored in underground reservoirs. Only a more serious study is required to highlight and evaluate all these invisible water resources. Obviously, without forgetting rigorous management of all these water masses that are hidden in the subsoil of the Sahara. Without forgetting also that Algeria has just started major projects, whether industrial, agricultural or mining, all require large quantities of water. It is in this sense that it is impossible today to continue to manage this hydraulic dynamic throughout the Sahara with a single hydrographic basin. It is for these reasons that we have proposed dividing the Sahara into 4 hydrographic basins. These basins are the following:

- Hydrographic basin of Piémont Saharien occidental- Saoura- Hamada Guir-Tindouf
- Hydrographic basin of Tassili N'Ajjer-Ahaggar-Tanezrouft
- Hydrographic basin of Touat-Gourara-Tidikelt
- Hydrographic basin of Mzab Chebka-Oued Righ-Souf- Ouargla

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Since the 1990s, I have traveled throughout the country, particularly the Sahara, in search of everything related to water. The oasis dwellers have taught me a great deal about their hydraulic expertise. I would like to sincerely thank all the people I met during my travels in the oases of the Algerian Sahara. From the National Water Resources Agency to the provincial hydraulic directorates, a huge thank you to all those who provided me with the necessary data and information. Through this work, I discovered a magnificent people, a great country, a beautiful country: Algeria.

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