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THE SAHARA: A WIND DYNAMICS ON SURFACE AND WATER IN DEPTH

LE SAHARA : UNE DYNAMIQUE EOLIENNE EN SURFACE ET HYDRIQUE EN PROFONDEUR

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ABSTRACT

The Sahara desert has yet to give away all of these secrets. For a long time, this immense arid expanse was known as a land without water. In return, the Sahara is known to be a place where wind activity reigns. Since the 1930s, during the search for black gold, immense non-renewable or poorly renewable aquifers have been discovered. The Sahara desert is animated by a double dynamic; wind turbine on the ground and water in the basement. This is how great Ergs were formed in the four corners of the Sahara. In return, in the basement, immense bodies of water have formed.

Keywords: Erg, Aquifer, Wind dynamics, Water dynamics, Sahara.

RESUME

Le désert Sahara n'a pas encore donné tous ces secrets. Depuis longtemps cette immense étendue aride était connue comme un territoire sans eau. En contrepartie, le Sahara est connu un lieu où règne une activité éolienne. Depuis les années trente lors de la recherche de l'or noire, des immenses aquifères d'eau non ou peu renouvelables ont été découverts. Le désert Sahara est animé d'une double dynamique ; éolienne sur le sol et hydrique dans le sous-sol. C'est ainsi que des grands Ergs ont été formés dans les quatre coins du Sahara. En contrepartie, dans le sous-sol, des immenses nappes d'eau se sont constituées.

Mots clés : Erg, Aquifère, Dynamique éolienne, Dynamique hydrique, Sahara.

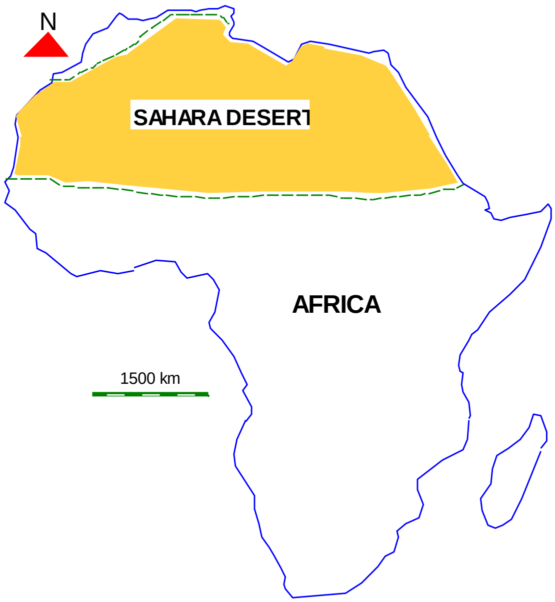
INTRODCUTION

The Sahara, this hot desert which until today has not divulged all these secrets. Covering an area of 8.5 million km^2, the Sahara is classified as the first great hot desert and the second great desert of all the deserts (hot and cold) on the planet behind the Arctic. With an average annual rainfall of 60 mm/year and temperatures of up to 50 °C in summer, the Sahara has always been considered a water-poor region. In return, the Sahara is considered a place of dust and sand. The beauty of the Sahara is exceptional compared to other deserts in the world. It is above all the presence of mega-rocky massifs such as Hoggar, Tassili N'Ajjer, Eglabs, Tibesti and Ennedi that made the difference with other deserts. The distribution and arrangement of these rocky reliefs and depressions induce a very active wind circulation (Remini, 2001; Remini and Mainguet, 2004; Remini, 2020). This led to the formation and shaping of immense Sand Ergs such as: the Grand Erg Occidental, the Grand Erg Oriental, the Grand Erg de Bilma, Erg Chech, Erg Er Raoui, Erg Iguidi (Remini, 2011; Remini, 2020; Remini et al, 2004; Mainguet and Remini, 2004). Under these piles of sand, gigantic aquifers have been built up over the centuries.

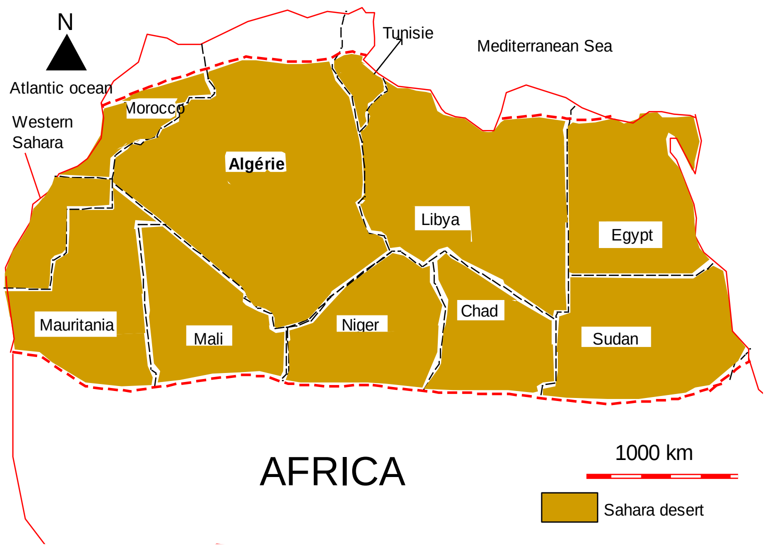
Today, the wind dynamics prevailing on the soil of the Sahara desert and all the repercussions on the environment are not yet under control. It is only recently that the scientific community has discovered the appreciable quantities of sands that make the annual transatlantic journey to reach the continent of the Americas (Remini, 2017; Remini, 2018; Remini, 2020). The same observation can be drawn from the water dynamics which manifests itself under the soil of the Sahara. It was only recently in the early thirties that aquifer systems were discovered by drilling the ground to extract black gold, but rather it was blue gold that was withdrawn at around 2000 meters. depth. In the Algerian Sahara, and more precisely on the southwestern outskirts of the Tademaït plateau, hundreds of foggaras have been collecting water from the Continental Intercalaire aquifer for more than 10 centuries. Surely at the time, the oasis inhabitants did not know that their ksour were built on a sea of fossil water with a volume of around 60,000 billion m^3. Finally, it was not until the early 1940s that the first deep drilling was carried out in the region to finally discover that the Sahara desert is not an expanse without water, but rather a region very rich in water. Today the subsoil of the Sahara is throated with water; five large transboundary basins with a total area of 8 million km^2 are shared between 9 countries of the Sahara and 6 countries of the Sahel. This article provides an overview of the dual dynamics; wind and water that manifest on the soil and in the subsoil of the Sahara.

STUDY REGION

The most beautiful and the largest hot desert on the planet, the Sahara with an area of more than 8.5 million km^2 is located in the north of the African continent. It spans 11 countries: Algeria, Mali, Mauritania, Niger, Tunisia, Morocco, Sudan, Chad, Libya, Egypt and Western Sahara (fig. 1 (a and b)). All this area of the Sahara is occupied by Ergs, plateaus, Regs, and Hamadas, lakes, wadis, rocky massifs, Sebkhas, Chott, Gueltas.



a) Figure of the African continent



b) Limits of the Sahara desert

Figure 1: Geographical location of the Sahara (Remini, 2018; Remini, 2020)

In addition, there are hundreds of oases and oases in the Sahara which are wetlands within a dry environment. The sand or dune space formed by the Ergs represents only 1.7 million km^2, or 20% of the entire surface of the Sahara. The rocky massifs occupy an area of 820 km^2, or 10% of the area of the Sahara (Remini, 2020). While the majority of the Sahara Desert is made up of Regs; a flat and stony space. The great sea of sand is considered the third largest in the world and the first in the Sahara. Covering an area of 272 km^2, the great sea of sand is located between Libya and Egypt Sahara, ahead of the Grand Erg Oriental with an area of 190 km^2.

During the period 1990-2020, we crisscrossed the Algerian Sahara, we visited several types of oases, the ksour, the large Ergs: Occidental, Oriental, Erraoui, Chech. Without forgetting of course all the beauty of Hoggar and Tassili N'Ajjer. The different techniques for drawing groundwater such as foggaras were visited on each trip to the Grand Erg Occidental. Data and records on water in the Sahara have been collected from the owners of the foggaras.

RESULTS AND DISCUSSIONS

Wind dynamics on the soil of the Sahara

On planet earth there are ten deserts (fig. 2). With an area of 8.5 million km^2, the Sahara is considered the largest. The Sahara Desert is shared between 10 countries: Algeria, Western Sahara, Tunisia, Morocco, Libya, Egypt, Chad, Mauritania, Sudan and Niger. The Sahara is bounded on the north by the Atlas Mountains, on the west by the Atlantic Ocean, on the east by the Red Sea and on the south by the Sahel.

However, the Sahara is quite different from other deserts, not by its size or beauty but above all the wind dynamics that manifest itself on its soil. Moreover, the Sahara is the desert which exports more fine sand and dust to the oceans and the continents than the 9 other deserts on the planet. More than half of the dust deposited in the oceans comes from the Sahara desert. In second place comes the Arabian desert, followed by that of Central Asia and finally the desert of China. In contrast, the deserts of America and South Africa are the least active. But no one answered this question about this particularity of the Sahara. Quite simply, the originality of the Sahara lies in the arrangement of the 13 mountainous reliefs which gives a very favorable space to a very active wind dynamic. Quite simply, the Sahara desert is an open-air laboratory.

Wind is the main carrier of sand. Mega-obstacles, by their geometric configurations, and topographic depressions (lakes, Chotts and Sebkhas) form and shape ergs. So, under the effect of these rocky massifs, large ergs "arise"; some may be an exporter of sand, others of deposits with the consequences of the fate of the oases installed on the outskirts of the Erg. They can be threatened with disappearing under the sand, or on the contrary will be reborn in a desert cleared of sand.

The Ergs represent only 20% of the entire surface of the Sahara. The largest Ergs of the Sahara are: the great sea of sand, the Grand Erg Occidental, the Grand Erg Oriental, the Grand Erg de Fachi Bilma, the Erg Erraoui, the Erg Iguidi, the Erg Chech, the Erg Rebiana , Erg Issaourene, Erg Edeyen d'Oubari, Erg Edeyen Mourzouk and Ergs Mauritaniens (fig. 3). Generally, these Ergs are formed in areas of deposits induced by the effect of rock masses on wind circulation. There are 10 mega-obstacles in the Sahara, occupying 10% of the total area of the Sahara. These are the landforms: Hoggar -Tassili N'Ajjer, Eglab, Tibesti, Ennedi, Air, Adrar des Ifoghas, Adrar and Messak (fig. 4).

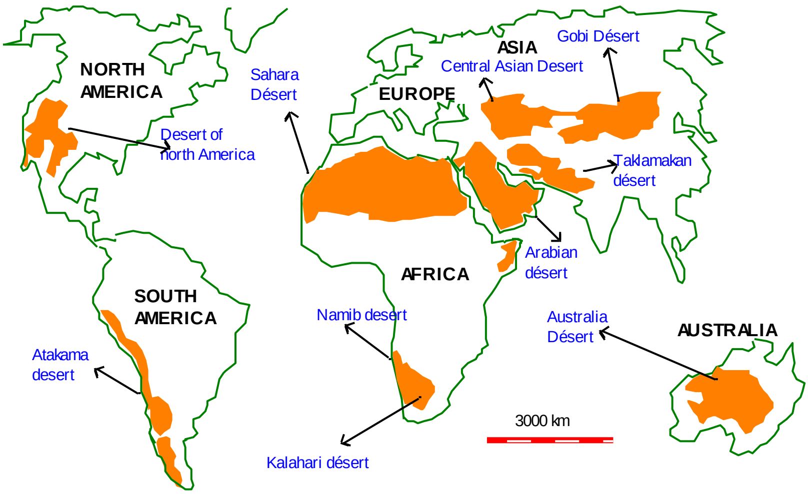


Figure 2: Deserts of the world (Remini, 2020)

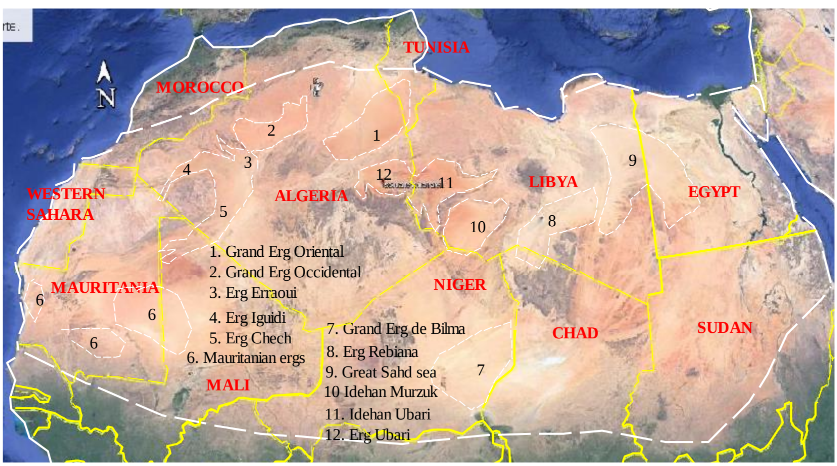


Figure 3: The Ergs of the Sahara formed and shaped under the effect of rock massifs (Google Earth-Schema Remini, 2021)

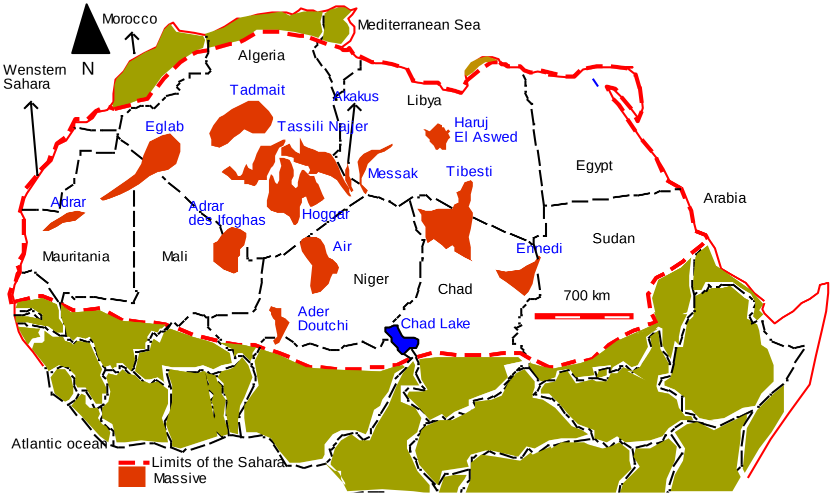


Figure 4: Arrangement of mega-obstacles in the Sahara desert (Remini, 2020)

Among the largest ergs of the Sahara are the Grand Ergs Occidental and Oriental (Photo 1 and 2). The first is the deposit area upstream - wind from Erg Erraoui, obstacle Erg due to the slowing down of the wind currents transporting sand against the Eglab massif. The second was formed as a result of the slowing down of the wind-carrying currents of sand due to the counter-slope of the topographic surface on which it rests. The area of these large ergs is driven by considerable wind dynamics, threatening erosion and silting up the peripheral regions (Photo 3 and 4).

Photo 1: A view of the Grand Erg Occidental (Remini, 2018)

Photo 2: A view of the Grand Erg Oriental (Remini, 2018)

Photo 3: A palm grove in the oasis of Timimoun under the dunes of the Grand Erg Occidental (Remini, 2008)

Photo 4: A school in the oasis of Timimoun is under the sand from the Grand Erg Occidental (Remini, 2008)

As we mentioned at the beginning of this article, the Sahara is animated by a very active wind dynamics thanks to the arrangement of the rock massifs which created privileged places of uplift of the sand particles in the atmosphere. Moreover, the Sahara is the desert which exports more fine sand and dust to the oceans and the continents than the other deserts of the planet. More than half of the dust deposited in the oceans comes from the Sahara desert. In second place comes the Arabian Desert, followed by that of Central Asia and finally the desert of China. In contrast, the deserts of America and South Africa are the least active.

The success of exporting dust by the Sahara to other continents and more particularly to the other shore (the new world) is the result of the particular pattern established by the brilliant arrangement of the rocky massifs which gave the Sahara desert its originality. Such architecture has created a wind dynamic which causes the mobility of the sand especially in periods of spring and autumn. This is how the movement of sand adopts saltation as a mode of transport. It is dust, not sand, that flies over the Atlantic Ocean thanks to air currents. So, it is the fringe of fine particles that is affected by the transatlantic journey. In addition, it is not in just any corner of the Sahara that we observe a rise of dust, but it is at the level of very specific places. Three places of dust uplift were defined by the arrangement of mega-obstacles in the Sahara: Bodélé (Chad), Tanezrouft (Algerian) and Air (Niger) (fig. 5).

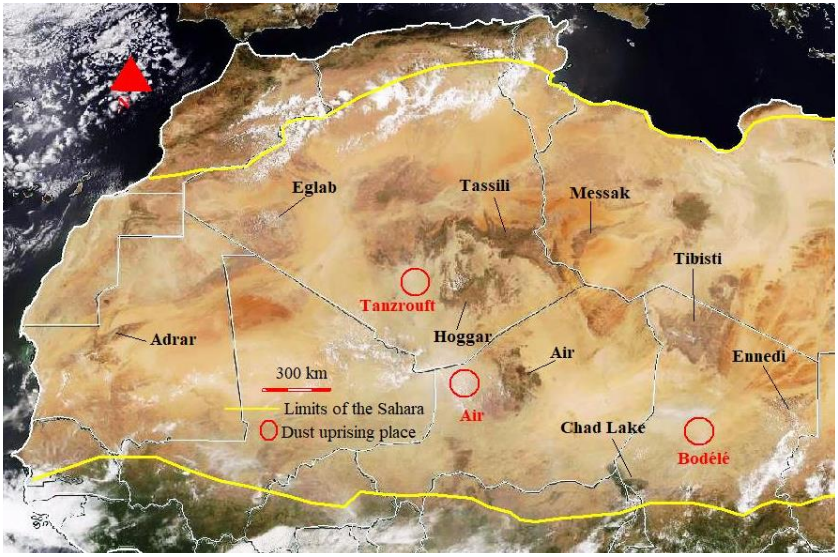


Figure 5: Location of places of dust uplift in the Sahara desert (@NASA Erath worldview) (Remini, 2020)

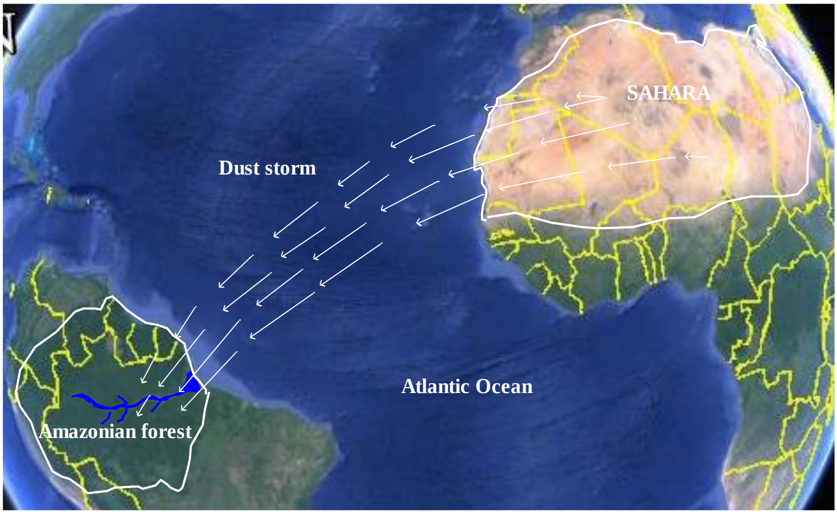


Figure 6: Rough diagram of the flyover of dust and phosphoric particles between the Sahara and the Amazon basin (Google Earth)

The Sahara annually exports quantities of dust to the continents of the Americas. It should be remembered that without the dust of the Sahara, the Amazonian forest no longer exists. What a paradox, Saharan dust fertilizes the lands of the Amazon and allows the largest forest on the planet to grow. A wet region is connected to a dry region. The torrential floods that occur in the Amazon basin cause a significant departure of sediments towards the Amazon River, including a quantity of phosphorus estimated at 22,000 tons/year. And as luck would have it, the same amount of phosphorus is offset by the dust rich in fertilizers from the Sahara. Every year, an amount of 182 million tons of dust leaves the Sahara and flies over the Atlantic Ocean over a distance of more than 70,000 km to reach the Amazon. A mass of phosphorus estimated at 22,000 t/year lands on the Amazon rainforest (fig. 6) (Remini, 2017; Remini, 2018; Remini, 2020).

Godzilla, a huge dust storm of high concentration from the Sahara Desert flew over the Atlantic Ocean during June 5-26, 2020, reaching the Caribbean and the Americas. The study we conducted showed that the uprising of the dust storm took place on June 5, 2020 in the desert of Tanezrouft (Algeria). It is at the Col areas located on either side of the mega-obstacle: Tassili - Hoggar that strong winds from Libya are accelerating following a decrease in pressure. As a result, this situation caused severe erosion and dust heaving in the sky. This is the first departure from the Algerian Sahara of the largest amount of dust in more than half a century (fig. 7 and 8).

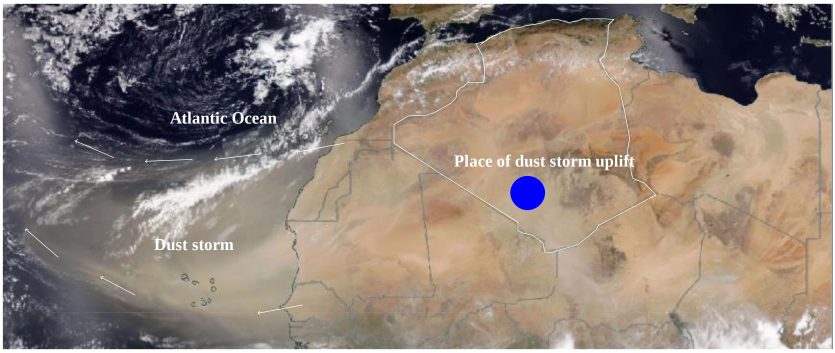


Figure 7: The dust storm Godzila which flies over the Atlantic Ocean to reach the continents of America and the Caribbean (@NASA Erath worldview)

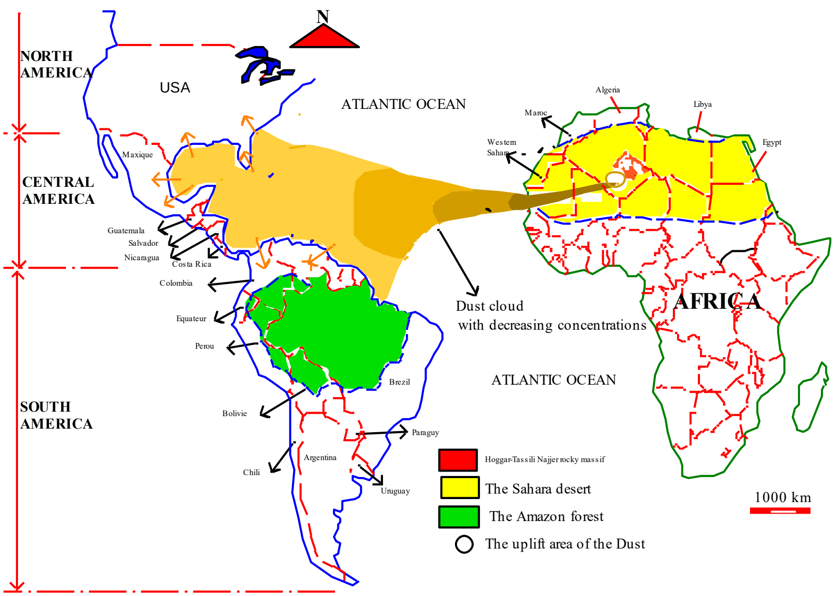


Figure 8: Rough diagram of the journey of the dust from Tamanrasset to the Americas (Remini, 2020)

Water dynamics in the subsoil of the Sahara

The subsoil of the Sahara is driven by intense water dynamics, where underground flows form large reservoirs of water (Photo. 5). The subsoil of the Sahara is waterlogged, since it contains 5 large transboundary aquifers: the Taoudeni-Tanezrouft-Iullemeden Aquifer System, the Mourzouk Aquifer System, the Northern Sahara Aquifer System (SASS), the Aquifer System of the Nubian Sandstones and the Lake Chad basin (Fig 9 and Table 1).

Photo 5: The Grand Erg Oriental. A wind dynamics on the surface and water in depth characterized by the Aquifer System of the Northern Sahara (2018)

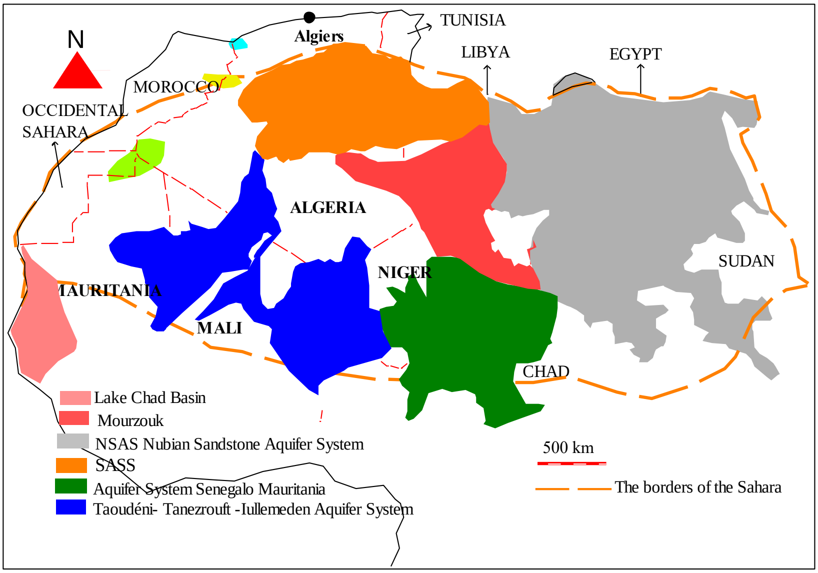


Figure 9: The main aquifers of the Sahara (Source OSS, 2017, modified by the author)

Table 1: Main deep aquifers of the North African hemisphere and piezometric trends of large confined aquifers (Seguin and Gutierrez, 2016)

Name of aquifers	Countries concerned	Area (10^3 km^2)	Average piezometric change (m/year)	Current operation (2011) (km^3 /an)
NSAS Nubian Sandstone Aquifer System	Egypt, Libya, Sudan, Chad	2200	-2m/year between 1955 and 1975	2,3
Northern Sahara Aquifer System (SASS)	Algeria, Libya, Tunisia	1000	-0.2 to -2m/year in 50 years (1950-2000)	2,9
Lake Chad Basin	Niger, Nigeria, Chad, Cameroon Central African R.	1500	-0.1 m/year in 30 years (1963–1998)	0,25 (2000)
Taoudeni Aquifer System (SAT) and Iullemeden (SAI)	Niger, Nigeria, Chad, Cameroon Central African R.	SAT: 2 000 SAI : 500	-0.2 m/year (1980-2000) compensated by recharging over the period> 2000	SAT=0,06 SAI=0,28
Murzuk Basin	Algeria, Libya, Niger	450	-1 to -2m /year in 25 years (1974-2000)	1,7
Senegal-Mauritanian Basin	Mauritania, Senegal	300	-0.2 to -0.4 m/year (1969-1999)	0,26(2003)

We give an overview on the basins of the aquifers of the subsoil of the Sahara:

Aquifer System: Taoudeni-Tanezrouft-Iullemeden

The Taoudeni-Tanezrouft-Iullemeden aquifer system (SATTI) is the largest aquifer on the African continent, of the same size as the Sandstone aquifer system of the Nubian Sandstone Aquifer system (fig. 10). With an area of 2.6 million km^2, or exactly 2,629,303 km^2, the cross-border Taoudeni-Tanezrouft-Iullemeden basin is shared between seven 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%) (OSS, 2017) (fig. 14). The Taoudeni-Tanezrouft-Iullemeden (SATTI) aquifer system is located in the south of the Sahara desert is composed of the Iullemeden (SAI) aquifer system in the east and that of TaoudéniTanezrouft (SAT) in the west, covers an area of 2.6 million km^2. It is traversed by the Niger River for more than 2,480 km, including 1,700 km in Mali, 540 km in Niger, 140 km in Benin and nearly 100 km in Nigeria (Observatoire du Sahara et du Sahel, 2017). This watercourse supplies the Taoudéni-Tanezrouft aquifer with more than 1.5 billion m3 while that of Iullemeden receives about 3.3 billion m^3 Nigeria (Observatoire du Sahara et du Sahel, 2015; Ousmane, 2008). More than 350 million m^3 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 renewable potential of the aquifer (Sahara and Sahel Observatory, 2015). On the other hand, total reserves are estimated at 1,810 million m^3 (Guyomard, 2011).

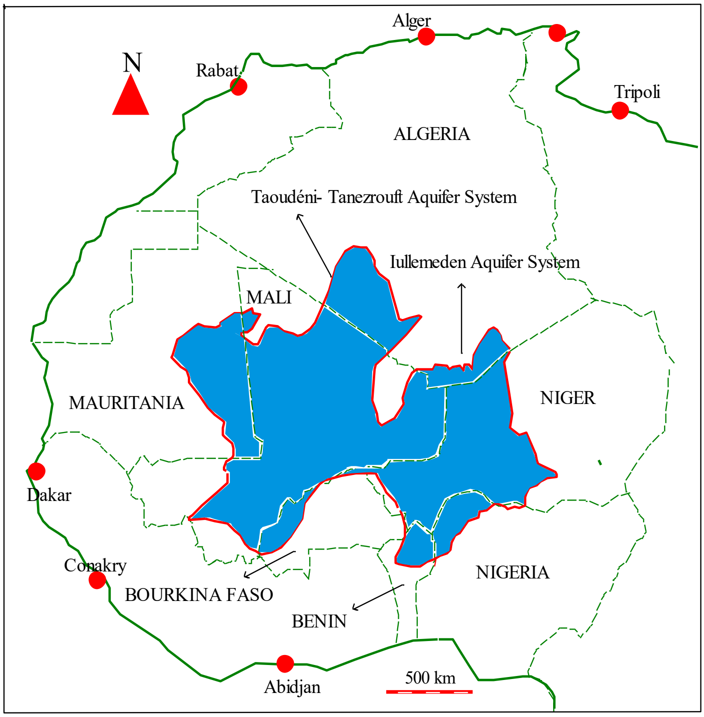


Figure 10: The limits of the Taoudeni-Tanezrouft-Iullemeden Aquifer System (Source OSS, 2017, modified by the author)

The mathematical models developed by the project “Integrated and Concerted Management of Water Resources in the Iullemeden - Taoudéni- Tanezrouft and Niger River Aquifer System (GICRESAIT)”, launched in 2010, have made it possible to determine the potential for renewable water resources and abstractions. of water (Table 2). The exploitation modeling indicates moderate drawdowns given the thickness of these aquifers, estimated at 300 m on average (OSS, 2015). More than 80% of the Iullemeden aquifer system, - Taoudénit-Tanezrouft remains very little, somewhat vulnerable to the drop in piezometric levels.

Table 2: Potential and withdrawal from the TTI Basin (Sahara and Sahel Observatory, 2015).

	Water potential	Specimens
Taoudéni-Tanezrouft basin	355 m^3/s (11 milliards m^3/s)	2 m^3/s (63 million m^3/s)
Iullemeden basin	243 m^3/s (8 milliards m^3/s)	9 m^3/s (284 million m^3/s)

NSAS Nubian Sandstone Aquifer System

Covering an area of 2.2 million km^2, the Nubian Sandstone Aquifer System is operated by 4 countries: Egypt, Libya, Sudan and Chad with an abstraction rate of 2.3 million m^3/year. The waters of the Nubian Sandstone Aquifer System are fossil waters and therefore are not renewable. The so-called Nubian Sandstones formation, present in Egypt, Sudan, Chad and Libya. In the latter country, it supplies 6,500,000 m^3 of water per day to coastal towns via the "great artificial river" fed by 1,300 wells more than 500m deep.

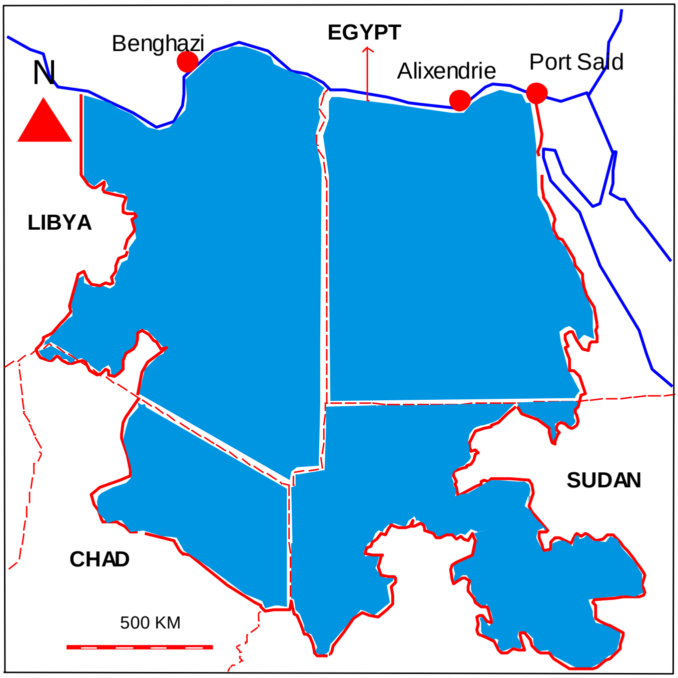


Figure 11: The limits of the Nubian Sandstone Aquifer system (Source OSS, 2017; modified by author)

The Aquifer System of the Northern Sahara

Le bassin du SASS couvre une étendue de plus d'un million de km^2 répartit comme suit (fig. 12): 700.000 km^2 en Algérie, 80.000 km^2 en Tunisie et 250.000 km^2 en Libye. Son volume est estimé à 60.000 milliards de m^3 dont 10 000 milliards de m^3 exploitables. Les prélèvements ont atteint 2,2 milliards de m^3 en 2000. La valeur de 8 milliards de m^3 de prélèvements sera atteinte en 2030. En contrepartie, la recharge a été estimée à 1 milliard de m^3/an. Aujourd'hui, de nouvelles recherches confirment que le débit de la réalimentation de l'aquifère est de 1,4 milliards de m^3. En contrepartie, les prélèvements ont atteint la valeur de 2,75 milliards de m^3 d'eau, soit 40% du volume total des prélèvements (OSS, 2017).

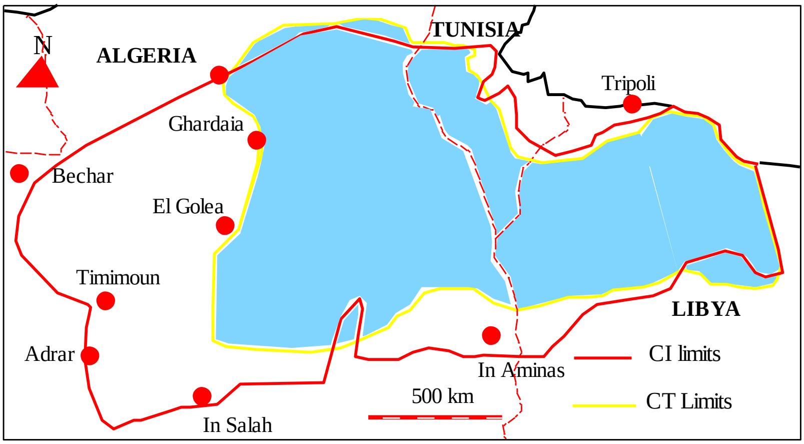


Figure 12: The limits of the Aquifer System of the Aquifer System of the Northern Sahara (SASS) (Source OSS, 2017; modified by author)

The Mourzouk Basin

The Mourzouk basin with a capacity of 450,000 km^2 is shared between 3 countries: Libya, Algeria and Niger. The current exploitation of the aquifer is estimated at 1.7 billion m^3/year. This caused a drawdown of the water table from 1 to 2 meters during the period: 1974-2000. The Mourzouk basin is threatened with exhaustion along with those of the Arabian and Indus basins (Demeersman, 2015).

Watch out for the exhaustion of the water tables

Saudi Arabia is a territory with a total area of 2,149,690 km^2. With an average annual rainfall of 60 mm, Saudi Arabia is a hyper arid country. Under the Arabian Desert the Rub Al Khali exists a multitude of fossil water aquifers, but it remains fragile and limited. The main desert farming areas are located in the central aquifers and in the north, towards the borders with Jordan in the province of Tabouk (Raiga-Clemenceau, 2020). For more than 40 years (period: 1970-2010), Saudi Arabia has developed agriculture in an arid environment, the Rub Al Khali desert. Based on the non-renewable water table, irrigation is carried out using pivots. It was during the 2000s that agricultural production exploded and more particularly the cultivation of wheat using large amounts of water from the aquifer (fig. 13).

For example, between 1980 and the year 2000, more than 300 billion m^3 of water, 2/3 of which was from non-renewable sources, was used only for agriculture (Matthieu and

Romain, 2016). Saudi Arabia suspended wheat farming around 2016 due to a lack of groundwater and the situation is likely to worsen. Today, it is estimated that more than 80% of the kingdom's fossil water resources have been consumed by the agricultural sector (Raiga-Clemenceau, 2020). Continued wheat farming risks draining aquifers. The depletion of the fossil ground has now reached a very advanced stage. Before reaching such a disaster, it is important to know the groundwater pressure index. Also called the GDS Index (Groundwater Development Stress Index), the pressure indicator represents the ratio between annual withdrawals and annual recharge flow (Taithe et al, 2013).

Let $I_p = W_p / R$

With

Ip: Pressure indicator,

Wp: Volume withdrawn (m^3/year)

R: Volume infiltrated (m^3/year).

For example, countries that use fossil water find themselves with a pressure indicator (GDS Index) greater than 100% since the recharge flow is practically zero (non-renewable or weakly renewable water tables). For example, the pressure index for the SASS is between 50 and 100%, since these aquifers are not very rechargeable (Taithe, 2013). Such a value indicates that this fossil water aquifer system must be managed with caution.

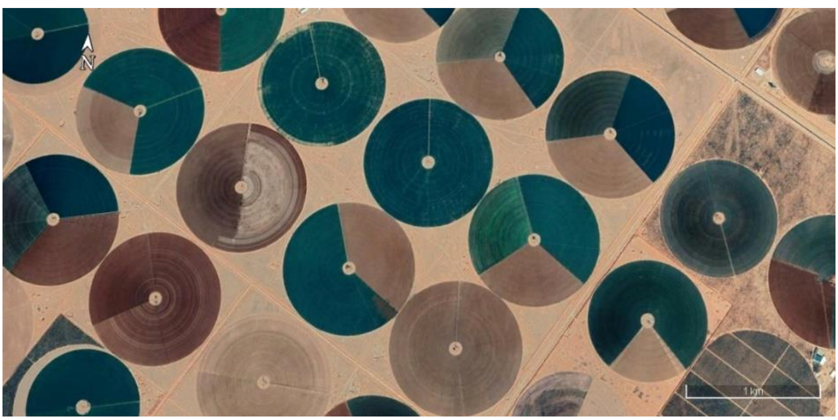


Figure 13: Saudi Arabia: Pivot irrigation agriculture (Google Earth)

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I warmly thank the people of the ksour who helped me a lot to finalize this modest paper. It was this population that made me discovers this vast expanse that is the Sahara. It is thanks to this population that I discovered a beautiful country. It is thanks to this population that made me love Algeria. Visiting the Hoggar, the Tassili N'Ajjer, Timimoun, Ghardaïa, the Grand Erg Occidental, the Grand Erg Oriental, is something unforgettable. Algeria, one of the most beautiful countries on the planet.

CONCLUSIONS

As we mentioned at the beginning of the paper, the Sahara did not give away all these secrets. Today on the soil of the Sahara, little is known about wind dynamics. The movements of the dunes, the massive departure of particles from an Erg silting up oasis spaces remain little studied. Studies of the formation and uplift of dust storms in the atmosphere are in their infancy. Under the surface of the soil of the Sahara, we have little control over water dynamics. Usually, giant pockets of fresh water have formed for centuries. These are little or non-renewable underground reservoirs. The boundaries and limits of these aquifers are often very poorly understood. The volume of an aquifer is often poorly assessed. Difficulties in understanding the connection between aquifers. Managing an aquifer requires a lot of knowledge of underground hydraulics. In times of crisis, poor management can lead to rapid and irreversible degradation of aquifer water. Beware of the irreversible depletion of aquifers and more particularly, non-renewable aquifers, a rare phenomenon which can occur in times of drought associated with non-rational management.

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