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RESEARCH ARTICLE

Multiscale and multifactor sea-groundwater interactions in southwestern Mauritania

Interacciones multiescalas y multifactoriales mar-agua subterránea en el suroeste de Mauritania

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ABSTRACT

Coastal aquifers in semi-arid zones are particularly exposed to environmental changes because of their low annual recharge and the increasing anthropogenic pressure. This is particularly the case in the Trarza phreatic aquifer (SW Mauritania), which is the uppermost northern part of the great Senegalese-Mauritanian sedimentary basin. The interactions between the Atlantic Ocean and the Tertiary-Quaternary aquifer have evolved considerably during the last millennia and these continuous changes concern the nature and location of processes at work, their intensity and their current consequences. In this vast region with a very flat topography, hydrodynamic and geochemical observations are still rare and currently allow only the main features of recent history to be reconstructed. The analysis of old and recent data reveals that eustatic variations and the annual flood of the Senegal River were in the past the most important factors of equilibrium between fresh water and sea water, even very far from the present coastline. Today, anthropization, in particular hydraulic developments and urbanisation, adds to the complexity of the system. At a more local scale, denser observations in the Nouakchott urban area or in the Diawling natural park provide a better understanding of current dynamics.

Key points

- Trarza phreatic aquifer (SW Mauritania) is exposed to changes because of low annual recharge and increasing anthropogenic pressure
- The interactions between the Atlantic Ocean and the Tertiary-Quaternary aquifer have evolved considerably during the last millennia
- Data reveal that eustatic variations and annual flood of Senegal River controlled the equilibrium between fresh and sea water

Keywords: Anthropization; Mauritania; Palaeohydrology; Seawater intrusion; Semi-arid area.

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RESUMEN

En las zonas semiáridas los acuíferos costeros están particularmente expuestos a los cambios ambientales debido a una recarga anual muy baja y al aumento de la presión antropogénica. Este es el caso del acuífero freático de Trarza (sudoeste de Mauritania), ubicado en la parte superior y norte de la gran cuenca sedimentaria senegalesa-mauritana. Las interacciones entre el Océano Atlántico y el acuífero terciario-cuaternario han variado considerablemente durante los últimos milenios y estos continuos cambios afectan a la naturaleza y la ubicación de los procesos, a sus intensidades y a sus consecuencias actuales. En esta vasta región de topografía muy plana, las observaciones hidrodinámicas y geoquímicas son escasas y sólo permiten reconstruir los principales aspectos de la historia reciente. El análisis de datos antiguos y recientes revela que las variaciones eustáticas y la inundación anual del río Senegal fueron en el pasado los factores más importantes de equilibrio entre el agua dulce y el agua de mar, incluso muy lejos de la línea de costa actual. Hoy, la antropización, en particular las obras hidráulicas y la urbanización, aumentan la complejidad del sistema. A una escala más local, algunas observaciones locales más densas en la zona urbana de Nouakchott y en el parque natural de Diawling permiten comprender mejor la dinámica actual.

Puntos clave

- El acuífero freático de Trarza (SO de Mauritania) está en proceso de cambio por una baja recarga anual y presión antropogénica creciente
- La interacción entre el Océano Atlántico y el acuífero (Terciario-Cuaternario) ha evolucionado considerablemente durante el último milenio
- Los datos revelan que las variaciones eustáticas e inundaciones anuales del río Senegal controlaban el equilibrio entre agua dulce y marina

Palabras clave: Antropización; Intrusión de agua marina; Mauritania; Paleohidrología; Zona semiárida.

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1. Introduction

The world population is more and more concentrated in cities and in coastal areas (e.g. Barragan and de Andres, 2015). This double process leads to an increased pressure on coastal water resources (e.g. Jiménez-Martínez *et al.*, 2016), with a very high risk of overexploitation and consequent marine intrusion into coastal aquifers. Low coastal areas are obviously the first exposed, because of the rise of sea level, as an inevitable consequence of the global warming, and increased wave erosion (Melet *et al.*, 2018). This will especially impact the 10% of the human population living in areas with an elevation lower than 10 m above the sea level, in all continents (e.g. Oppenheimer *et al.*, 2019).

Semi-arid regions are more exposed than others to this multifaceted threat since groundwater recharge is most often low or very low (e.g. Leduc *et al.*, 2017). The balance between outflows and inflows is then particularly fragile and easily altered by the multiple forms of anthropization. The increasing water demand is due to the demographic growth allied with a better supply and higher standards of life. Economic activities also contribute to the increased water demand, especially agriculture that may represent up to 80% of the total water consumption in many countries like in the Mediterranean region (e.g. Molle and Sanchis-Ibor, 2019). Drivers of changes in water resources that may seem modest are not always that minor: small hydraulic structures and changes in the vegetation cover may have crucial long-term impacts (e.g. Favreau *et al.* 2009). The overall fragility of the semi-arid socio-hydrosystems is aggravated by severe droughts, which are a recurrent phenomenon in these areas nowadays (e.g. Ben Kabbour *et al.*, 2005; Parisi *et al.*, 2018) and could be even more frequent in the next decades.

Unfortunately, measurements in the semi-arid areas are often rare, which does not allow a detailed identification of hydrogeological processes at work and trajectories of evolution for both qualitative and quantitative dimensions (e.g. Duque *et al.*, 2018). In most semi-arid regions, high mineralisation is expected because of the importance of evaporative uptake and the relatively slow groundwater velocity, allowing for extensive exchanges between water and the rock matrix. However, this frequent pattern is subject to exceptions such as the Continental Terminal upper aquifer in south-west Niger where natural mineralisation is lower than 100 μS.cm^{-1} (e.g. Favreau *et al.*, 2002), while it is frequently 10 or 30 times more in North African aquifers (e.g. Massuel *et al.*, 2017). The coastal areas are in a more difficult situation because the marine intrusion adds complexity and is often still poorly identified (e.g. Werner *et al.*, 2013). The increasing salinity of groundwater does not relate in a simple way with seawater contamination. As an example, all studies about the aquifer of Eastern Coast of Cap Bon peninsula in northeastern Tunisia emphasized the overexploitation and the increased mineralization. They were much fewer noticing that this phenomenon concerned also the upstream aquifer, far from the coastline, but close to irrigated areas where fertilizers are intensively used (e.g. Zghibi *et al.*, 2013), which prevents any direct correlation between increasing total salinity and aggravated sea water intrusion.

Moreover, contemporary observation must be systematically placed in a long hydrogeological temporal perspective. Over the last millennia, climate change has had a major impact on sea level and precipitation patterns, thus on the recharge of coastal aquifers and on the location of the mixing zone between fresh and salt water. These changes have also altered the transport of sediment along the coasts, and thus the opening or closing of coastal ponds towards the sea and the progression or retreat of deltas (e.g. Vallejos *et al.*, 2018). Among the major phenomena active on a geological scale, subsidence like in the Po plain in Northern Italy or continental uplift like in the Pacific arid coast of Chile and Peru (e.g. Garrett *et al.*, 2020) are also to be mentioned, which may have further aggravated or mitigated the other phenomena. Even if these various forces are not immediately visible in the present landscape, they may continue to have an impact on regional hydrogeology, particularly in the groundwater geochemistry (e.g. Akouvi *et al.*, 2008, Colombani *et al.*, 2017). This universal remark applies even more to aquifers in semi-arid regions, whose memory is often much longer than in temperate regions due to the low renewal of the water resource (e.g. Edmunds *et al.*, 2004, Müller *et al.*, 2016).

The present paper exploits all the hydrogeological information available on the Trarza aquifer, in southwestern Mauritania. From this set of heterogeneous and scarce measurements, influences of seawater on groundwater are investigated, especially in areas where human activities are important like the Nouakchott area, home of about one third of the country population. The research is also developed much farther from the actual coastline: because of its low renewal rate, the Trarza groundwater keeps traces of older hydrological conditions when the sea level was much higher. Understanding this complex history may contribute to a better management of the present groundwater resources.

2. Study area

The area considered here belongs to the northern part of the Senegal-Mauritania sedimentary basin, north of the Senegal River. The basin is geologically limited to the north and east by the Mauritanides mountain range and contains several aquiferous layers. The phreatic aquifer is limited hydraulically by the Senegal River to the south and the Atlantic Ocean to the west (Fig. 1). Because information is very rare in the northern and eastern fringes of this wide basin, this study is mainly focused on the Trarza part of the phreatic aquifer, i.e. an area of about 40,000 km² between Nouakchott, the Mauritanian capital, the Senegal River and the metamorphic formation of Mauritanides.

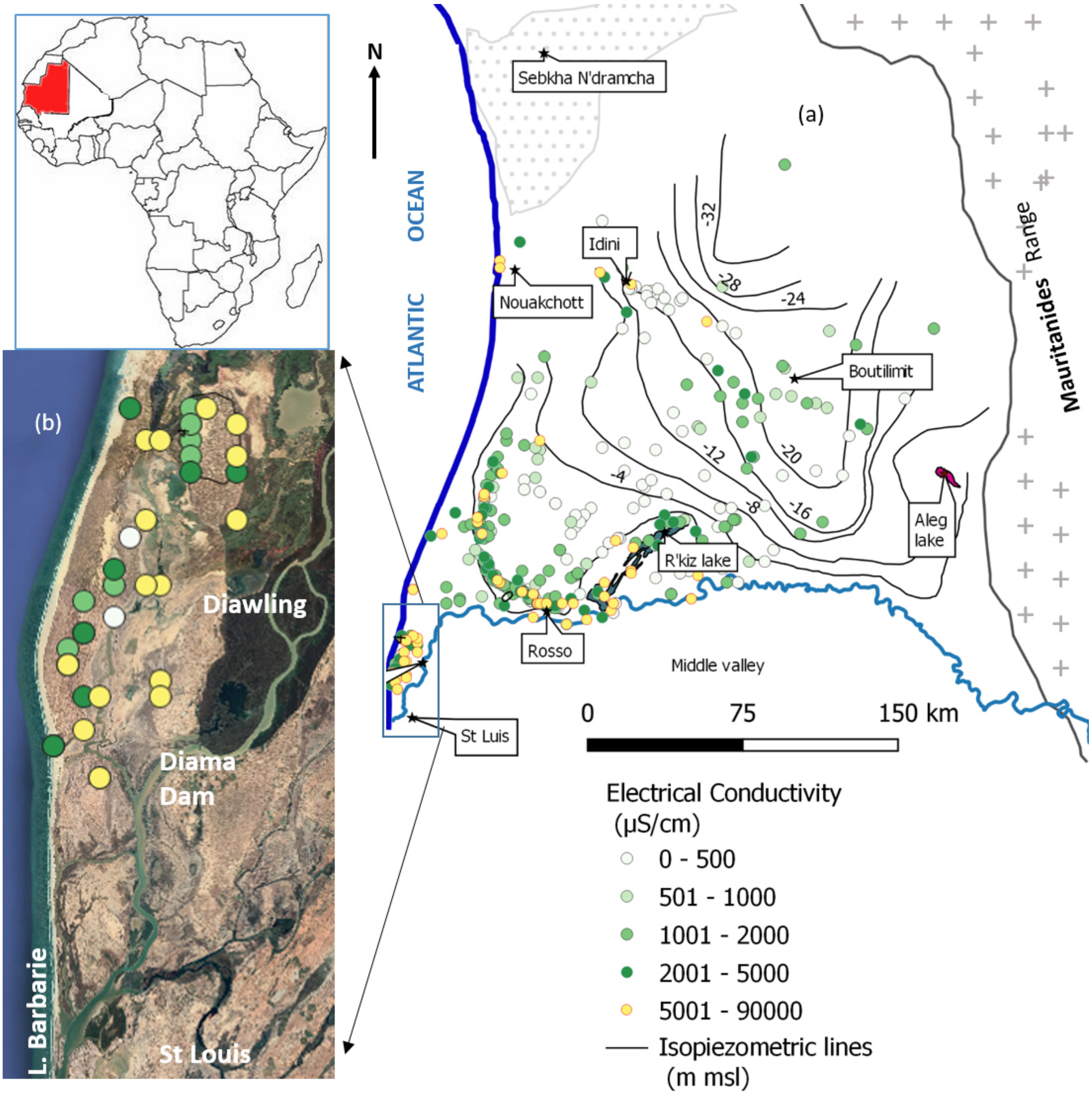

Figure 1. Location of the study area, (a): piezometric contour lines and electrical conductivity of groundwater, (b): electrical conductivity distribution in the Diawling area.

Figura 1. Localización de la zona de estudio (a) piezometría y conductividad eléctrica de las aguas subterráneas.

The Trarza region is very flat: at a distance of 100 km from the coast, the ground elevation does not exceed 50 m and it is sometimes even below the present mean sea level. The landscape is mostly made of long stripes of aeolian dunes and interdune depressions. Their length varies from some kilometres to a few hundred kilometres. The elevation of dunes is up to 40 m and the interdune width is up to 1 km. This geomorphology is inherited from the driest periods of the Quaternary history: the most important dunes, dated back to the Ogolian period, between 20 and 12 ka BP (Elouard, 1959), are often considered as fixed while more recent dunes are still able to move.

The regional climate is typically Sahelian, with a short rainy season usually from June to September and a much longer dry season. The beginning, the duration and the intensity of the rainy season directly depend on the West-African monsoon (e.g. Sultan *et al.*, 2003). At the regional scale, there is a decreasing gradient for the annual rainfall from south to north: about 250 mm in Rosso, on the Senegal River, and only 100 mm in Nouakchott. Like everywhere in the Sahel, rainfall varies greatly in time and over space and a violent rainy event may be observed close to a dry area, even in flat landscapes like western Mauritania (e.g. Amani *et al.*, 1996).

Beneath the aeolian dunes, the Trarza phreatic aquifer is an accumulation of Tertiary (Continental Terminal) and Quaternary detrital sediments laying over Cretaceous limestones (Paloc, 1962). They were deposited in various environments (lacustrine, aeolian and marine), which explains the frequent changes in granulometry and mineralogical content. The depth from the ground surface to the water table varies between a few metres, close to the Atlantic Ocean and the Senegal River, and 70 m, in the northeastern part. It depends obviously on local conditions of relief (e.g. top of a dune vs. interdune depression, coastal plain vs. foothills), with an overall deepening towards the northeast. Groundwater flows towards the northeast, and the area of lowest water-table elevation (deeper than 30 m below the present mean sea level) is close to the Mauritanides range, considered as an impervious boundary. This feature is very similar to closed piezometric depressions that are frequent in the Sahel (e.g. Favreau *et al.*, 2002 in SW Niger; Leduc *et al.*, 2000 in the Lake Chad Basin). The explanation commonly accepted for these singular hydrogeological shapes is the evapotranspiration uptake, very small because it acts at tens of metres below the ground surface but efficient enough for maintaining significant hydraulic gradients.

In its coastal border, the Trarza aquifer is in direct connection with the sea, which implies an easy exchange in both directions depending on their respective hydraulic heads. This obviously applies at all temporal scales, from the tidal effect to the Holocene eustatic variations.

The Senegal river valley is very flat: in the last 200 km of its downstream course, the mean slope of the river is lower than 0.01 ‰. In its former natural regime, the mean annual flow was 670 m^3 s^{-1} in Dagana (period 1903-1984), with monthly extremes of 0 and 3200 m^3 s^{-1}. The very small flow of the Senegal River in the dry season allowed the penetration of the seawater far from the mouth of the river, frequently up to more than 200 km. The seawater intrusion in the Senegal River bed is now blocked by the Diama dam, which has been operating since 1986, but surface water and groundwater in the lowest part of the delta are still influenced by sea water, depending on the flow released by the Diama dam. In 1989, the construction of the Manantali dam in Mali added a supplementary control on the river flow by regulating the annual flood.

Apart from Nouakchott, with more than one million inhabitants, the population is mostly rural and sparse (less than 300 000 inhabitants in the whole administrative region of Trarza). The traditional water consumption for people and cattle is very sparing, and the recent development of irrigation only affects very limited areas, mainly in the Senegal River valley. The Trarza aquifer has supplied Nouakchott with water pumped from the Idini site until 2011 when it was replaced by a transfer of the Senegal River surface water. The Idini pumping site is still active, at a much lower rate, for feeding many towns and villages and the eastern suburbs of Nouakchott.

3. Data and methods

In a vast and sparsely populated country with a semi-arid to arid climate, the small number of hydrogeological information is not surprising, especially when it comes to monitoring physical and chemical quality. The first step was therefore to recover as much as possible of the data that has been produced over the last 60 years and can still be accessed, mostly in technical reports. This data comes from both large-scale spatial campaigns and one-off observations. The reconstructed set is therefore quite heterogeneous, in terms of spatial and temporal density as well as reliability and representativeness. For example, the oldest data are generally of good quality, but their precise location may be uncertain (e.g. Paloc, 1962), while the conditions of collection for more recent data may be less well known. Within this mass of information, water-table levels are much more numerous than measurements of the electrical conductivity (EC), which are much more numerous than analyses of major elements: between 1959 and 2009, the measurements available in these three categories are 1165, 613 and 96 respectively for the three major surveys. The Idini area is the most systematically and densely surveyed area in the aquifer.

These old measurements were supplemented by recent campaigns involving hydrodynamic, geochemical and isotopic measurements in about 200 sites over the last decade (e.g. Mohamed *et al.*, 2014). The comparison of old and post-2010 data is possible through 81 wells common to Paloc (1962) and AGIR 2011, 97 wells common to UN 1973 and AGIR 2011, 16 wells common to Paloc (1962) and our own survey, 13 wells common to UN 1973 and our own survey. Depending on the local conditions at the time of measurement, the water table levels observed may be stable or, on the contrary, influenced by pumping in the surrounding area, since real piezometers dedicated to scientific observation are exceptional.

In our recent piezometric surveys, the physical and chemical characteristics of groundwater (temperature, EC, pH, and alkalinity) are measured in situ with an accuracy of ±0.1°C for temperature, 1% for EC and ±0.02 pH unit, respectively. Chemical and isotopic analyses were done by the GEOPS laboratory at the University of Paris-Saclay (France), with an uncertainty of ±0.2 ‰ for $\delta\ ^{18}O$ and ±2 ‰ for $\delta\ ^{2}H$.

The regional information is complemented by local surveys, especially with (1) a few automatic recorders (since 2016 at the regional scale, and since 2017 in the Nouakchott area), which gives a much better accuracy about quick changes in groundwater level; (2) vertical profiles of EC in the Nouakchott urban area (19 wells in April 2015; measurements in both descending and ascending directions in the entire water column); (3) a specific monthly survey of 29 wells in the Diawling national park (since 2004).

4. Results

4.1. Overall stability of the water-table level

Piezometric measurements were used in two ways. The first was the analysis of the temporal evolution of each site with sufficient measurements. The second was the construction of regional piezometric maps for each of the major field campaigns and their later comparison. Both analyses led to the same surprising result: for 60 years, the Trarza aquifer has not undergone any significant piezometric evolution (Fig. 2). The only real exception is the Senegal River valley, where the river regime is now completely regulated by the Diama and Manantali dams. This has led to an increase in the river average level and consequently to a rise in the nearby water table, and the smoothing of the floods during heavy rains has ensured the maintenance of a base level that is about 2 m higher than previously.

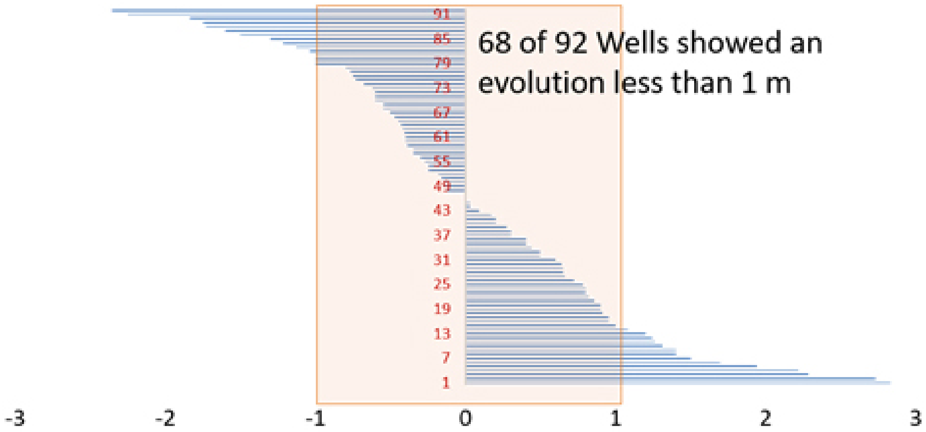

Figure 2. Change in groundwater level (horizontal axis in m) between 1973 and this study.

Figura 2. Evolución del nivel piezométrico (eje horizontal en m) entre 1973 y la actualidad.

This stability over 60 years is relatively original in the Sahel, where many large aquifers have been marked by the great droughts of the 1970s and 1980s and/or by anthropization of surface conditions and recharge, in particular changes in vegetation cover (e.g. Favreau *et al.*, 2009). Such stability allows to concatenate without correction data that are sometimes distant in time, with a final accuracy much better than initially expected.

The contemporary piezometric map (Fig. 1) was then produced from more than 300 sites. It shows a general groundwater flow from the south and west towards the north, i.e. from the Senegal River and the Atlantic Ocean towards the depression in the north where the water-table is met at a depth greater than 30 m below sea level. The water-table levels are below the level of the Senegal River, and close to or below that of the Atlantic Ocean. Along the coastline, the density of the available points does not allow the isohypse contour lines to be finely drawn, especially because the local topographic conditions disturb the general pattern: in dunes, where rainfall infiltrates easily and may create a small piezometric mound; in interdune depressions that are sometimes below sea level and where evaporation uptake can be strong.

The regional pattern of long-term stability does not prevent the existence of local interannual changes like the groundwater rise in Nouakchott (detailed in the Discussion chapter) and short-term fluctuations (seasonal, daily) like the tidal influence. In Nouakchott the average amplitude of the tide is 0.93 m and its attenuated signal is observed in two piezometers continuously monitored (14 and 3 cm at distances from the coast of 300 m and 550 m respectively), which provides a value of permeability of 1.6 10^{-4} $m.s^{-1}$, in good agreement with the sediments characteristics in the area.

4.2. Groundwater salinity

The groundwater salinity, expressed by EC, has a very high spatial variability with values ranging from 0.05 to 67 $mS.cm^{-1}$, which means that the highest values are significantly above the ocean mineralisation (Fig. 1). High values are mostly measured in shallow cemented wells located along the ocean coast as well as near the R'kiz Lake and in the middle valley of the Senegal River but in fact there is no clear distribution of mineralisation that could be linked with the flow directions. Low values of mineralisation may be measured near the sea. At the local scale, major contrast frequently exists over a short distance. This is particularly the case in the interdune depressions, with an increasing gradient of salinity towards the depression centre.

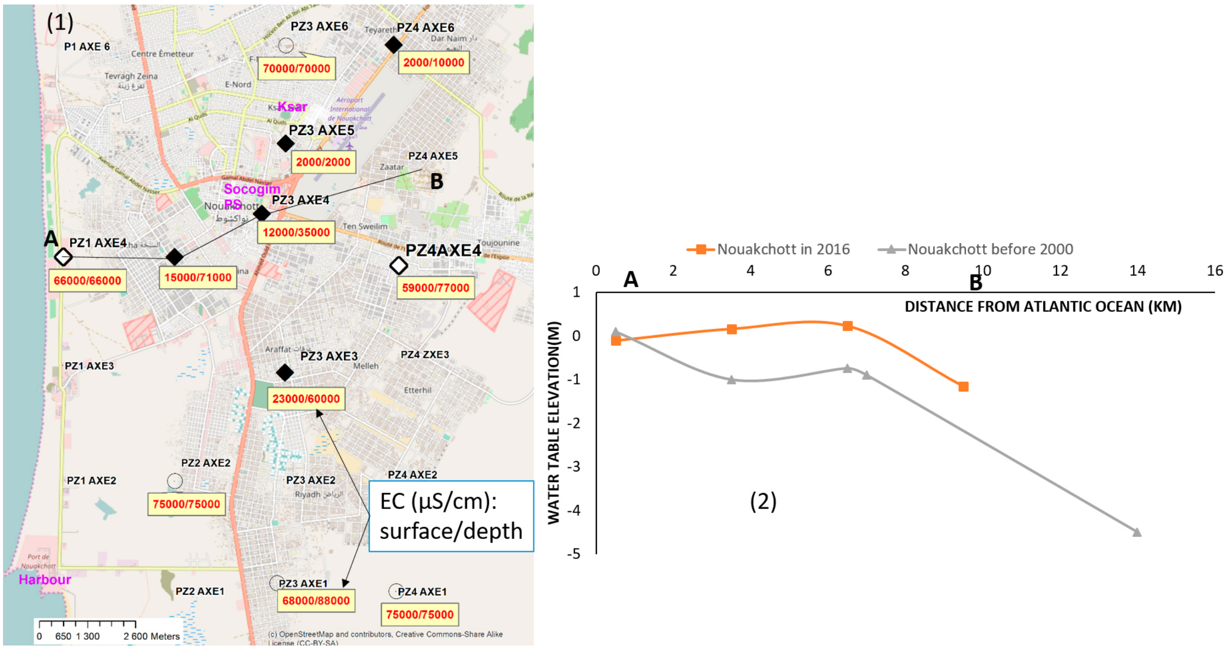

Figure 3. Groundwater EC in the Nouakchott area in 2017: (1) Measurements at the top and bottom of the surveyed wells, (2) Long-term changes in the water table from west to east.

Figura 3. CE de las aguas subterráneas en el área de Nouakchott en 2017: (1) Medidas en superficie y en el fondo del pozo de observación; (2) Cambios a largo plazo en el nivel freático de Oeste a Este.

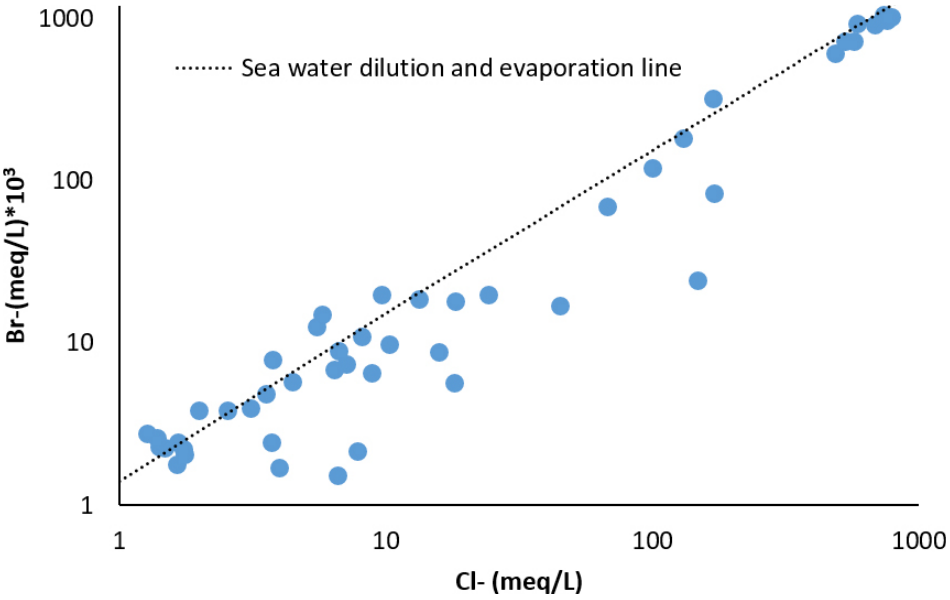

Figure 4. Br-Cl diagram of groundwater samples.

Figura 4. Diagrama Br-Cl de las muestras de agua subterránea.

Vertical profiles of EC in the Nouakchott urban area provide another dimension of groundwater salinity, with various shapes of stratification. In the city centre, the interface between the upper brackish water and the lower seawater is found at a depth between 6 m and 10 m while it lies between 0 and 2 m in more peripheral areas (Fig. 3).

The groundwater dominating facies is Cl^-- Na^+, even far from the present coastline and most groundwater samples have a Br^-/Cl^- ratio close to the seawater ratio (Fig. 4). This suggests an important marine contribution to groundwater, but without any obvious gradient in the spatial distribution.

The lack of a clear regional pattern is also met in chemical and isotopic analyses (^{18}O and ^{2}H), and in ages measured with ^{14}C (8 samples, ranging from the present, in the river valley, to 8800 years BP measured 60 km from the coast) (Mohamed *et al.*, 2014).

5. Discussion

The very heterogeneous distribution of current salinity suggests a variable mixture of river water, ocean water and infiltrated rainfall, whose interpretation will have to integrate several scales of time and space. This complex pattern can be understood much better when going back in the past, before the construction of the Diama dam for the lower valley of the Senegal River and even further back in time in connection with eustatic variations for a very large coastal zone.

5.1. Paleoclimatic changes

During the Quaternary, global climatic changes were particularly strong and rapid. The first consequence of alternating glacial and interglacial episodes was a very strong variation in sea level. In the study area, paleoclimatic reconstructions are progressing but are still largely uncertain (e.g. Maley and Vernet, 2015; Certain *et al.*, 2018), particularly with regard to the duration and intensity of dry and wet episodes. Interpretations should be particularly cautious since other regions of the Sahel studied before have illustrated the risk of drawing too quickly regional conclusions from local observations (e.g. Gasse, 2002).

As a result of these multiple climatic changes, the current morphology of the Mauritanian coast is therefore only one instant in a varied geological history that must be seen in a dynamic way. The first reason is the low altitude of the region, where transgressions and regressions cover or uncover large areas, even for relatively limited variations in sea level. This explains why traces of beach can be found very far from the current coastline. The second reason is the sandy and unconsolidated nature of the recent sediments, allowing them to be easily relocated by wind and water.

The last two major Quaternary transgressions in Mauritania are related to the Inchirian (120,000-30,000 years BP) and the Nouakchottian (7,000-4,000 years BP). Their actual height is still debated. At the Inchirian maximum, around 33000 years BP, the sea was probably between 2 and 4 m above the present level and penetrated up to 120 km inland (Elouard *et al.*, 1969, Lebigre, 1991). At the Nouakchottian maximum, around 5500 BP, the sea was probably between 1 and 2.5 m above its present level and also covered large areas: north of Nouakchott in the Gulf of Tafoli (present sebkha N'Dramcha), it extended up to 90 km from the present coastline, and in the south in the delta of the Senegal River, the sea water rose as far as Boghé, 230 km from the present mouth (Michel, 1973).

During these two transgressions, the lower parts of the landscape, especially the interdune depressions, were submerged by the sea. The sea water may have been trapped in places depending on particular hydrodynamic conditions and elsewhere salts have been left in the surface sediments. This is why direct and indirect traces of sea water are still found in groundwater in many places along the coast and near the Senegal River, its tributaries and distributaries (Mohamed *et al.*, 2014). Since the last transgression, this memory has been slowly diluted by the low infiltration of rainfall in much of the region, but the annual upwelling of seawater in the Senegal River bed maintained a regular supply of salt to the groundwater area until 1986.

Consequences of the last transgression affect much wider areas than the coastal strip. For the closed piezometric depressions of the Sahelian hinterland, the only reasonably reliable explanation is the evapotranspiration uptake in a context of small permeability but the piezometric depressions close to the coast, in Mauritania and Senegal, may be explained by a particularly long and not yet completed transitory process of groundwater readjustment following the last transgression (Dieng *et al.*, 1990; Lacroix and Séméga, 2005). In the Trarza aquifer, this alternative hypothesis is still to be investigated by a detailed numerical modelling of groundwater flow.

5.2. Seasonal dynamics of the Senegal River flooding

Before the construction of the Diama dam, seawater was able to flow upstream in the bed of the Senegal River. It could thus contaminate the alluvium, which is in direct contact with the rest of the Trarza groundwater. The length of the seawater invasion was directly related to the river flow. During particularly dry periods, such as the severe droughts of the 1970s and 1980s, when the low-water flow was very low, a temporary earth dam was even built in the bed to prevent this seawater intrusion.

Under natural conditions, the easy contact between the river, the alluvium and the rest of the aquifer allowed a two-way exchange between the river and groundwater according to their respective hydraulic heads. The risk of saltwater intrusion from the Senegal River thus extended well beyond the current coast (Illy 1973, Michel, 1973). Unfortunately, the old measurements do not have the spatial and temporal density sufficient to characterize precisely the seasonal dynamics of this salt contamination.

The Diama dam, designed for blocking the seawater intrusion, disrupted this seasonal alternation. The average water level in the dam is now maintained at a height of between 1.5 and 2.5 m a.m.s.l. The river is therefore always higher than the water-table and the exchange between the river and groundwater has become a one-way flow of water from the river to groundwater (Mohamed *et al.*, 2014, Diaw *et al.*, 2019), leading to a progressive decrease in groundwater salinity close to the raised river (Gning *et al.*, 2017).

However, the Delta area around and downstream of Diama remains a hydraulically complex zone linked to oceanic conditions, the flow of surface water passing through Diama and the various hydraulic infrastructures (dikes and gates allowing the filling and emptying of large basins connected to each other and also to the river and the sea). Alongside these well-controlled works, human interventions are sometimes less controlled. In October 2003, a particularly high level of the Senegal River could have led to flooding the big seaside city of Saint Louis in Senegal. To prevent this disaster, an artificial breach was opened in the Langue de Barbarie, which is a narrow strip of land between the Senegal River and the Atlantic Ocean, downstream of Diama. The width of this breach, a few metres at the origin, reached 5 km, causing a drop in the river level in all the downstream part and a significant change in the freshwater-salt water balance in the entire area. Coastal sediment transport from north to south will probably modify again the width and position of this breach, as it has done often in the past.

5.3. *Exceptional dynamics in the coastal area*

In 1950, a particularly high flood of the Senegal River caused its waters to rise in the Aftout es Saheli, the very long topographic depression parallel to the Atlantic Ocean that is separated from it by a narrow dune barrier. This exceptional flood reached Nouakchott and probably went even beyond. The flood took three months to reach Nouakchott and the water remained for several months in the Aftout es Saheli valley. The flood thus recharged groundwater in a narrow strip of aquifer only a few kilometres wide but about 200 km long (Duchemin, 1951). According to the testimonies of the oldest inhabitants, the rise of the water table was observed in wells before the arrival of the surface water. Another even bigger flood would have taken place in 1890 (Duchemin, 1951) but details are lacking, and this is even worse for the previous very big floods of 1843 and 1853.

In the entire coastal area south of Nouakchott, groundwater is thus a mixture of seawater, rainwater infiltrated in situ in favourable years, and water of the Senegal River only a few times a century. These exceptional floods transported to groundwater the salts deposited on the land surface and in the unsaturated zone during the previous decades. The final mineralization of this exceptional contribution to recharge was much higher than that of the river itself, but none of these great floods was observed with dedicated hydrogeological measurements that would give an order of magnitude of the phenomenon. Taking into account the vertical and horizontal heterogeneity of the local hydrodynamic characteristics, it is therefore not surprising to notice strong variations of the mineralization over short distances along the coast.

These exceptional floods are spectacular by the length and duration of submersion in the littoral zone but they also affected the entire lower valley of the Senegal River. However, contrary to the littoral zone, the increased recharge in the river valley does not fundamentally change its chemical quality, even though the infiltration zone is larger and the recharge duration longer than during an ordinary flood.

Even if such exceptional floods are no longer expected because of the two dams built on the Senegal River, the hydrogeological dynamics of the coastal region between the Delta and Nouakchott will deeply change in the coming decades. A large canal is being built in the Aftout es Saheli valley. It will bring the Senegal River water up to 65 km northwards with the objective of developing irrigation in this particularly sparsely populated area. The canal will induce an artificial recharge, directly through leaks from the canal and indirectly through the return of excess irrigation water to groundwater. This recharge will be permanent, unlike the exceptional floods that naturally went up the Aftout es Saheli in the past. In a region where measurements are particularly rare, monitoring of progressive changes in piezometry and mineralisation would be particularly welcome, especially the balance between the input of fresh water from the river and the accumulation of salts in irrigated soils, and their later leaching to the saturated zone.

5.4. *Anthropization in Nouakchott*

The dams regulating the Senegal River now limit the spread of the river floods far from its valley but the Mauritanian capital is threatened by other forms of anthropization that significantly alter the water-table level and the groundwater mineralisation. The topography of the Nouakchott area is very flat, sometimes below sea level. The Quaternary water-table was originally very close to the ground surface. This very salty groundwater was not consumed at all for drinking water purposes. The population has grown from a few hundred people to more than one million in 60 years, but urban growth has not been accompanied by sufficient development of wastewater collection networks (Nouaceur, 2013). Most domestic wastewater is therefore discharged into the ground via cesspits. In addition, since 2011, the city has been supplied with water pumped from the Senegal River, replacing the previous catchment in the Trarza aquifer at Idini. Population growth and the greater availability of water explain why drinking water consumption has tripled since 2011, going from 60,000 m^3 per day pumped in Idini to 180,000 m^3 per day today. The increase in both the amount of water available and the pressure in the pipes have increased the water inflow into the ground, which is a mixture of clean water due to leaks in the pipes and wastewater discharged into the cesspits. The first consequence is a generalised rise in the piezometric level (Fig. 3-2), which goes up to the groundwater outcrop in the lowest parts of the city and causes serious land and health problems, including the abandonment of some urban districts (Mohamed *et al.*, 2017). This situation is even worse in the rainy season when the ground becomes saturated and the surface area of stagnant water increases over time (Ould Sidi Cheikh *et al.*, 2007). The second consequence is a decrease in the mineralisation of groundwater, which was originally very salty, and an increase in its organic pollution (Fig. 3-1).

Further from the city centre, on the seafront, the major developments carried out in the last decades, especially the construction of the modern harbour and the illegal removal of sand, modify the coastline, with areas of sediment accumulation and other areas of strong erosion. In the area of greatest erosion, the retreat of the coast exceeds 300 m (Wu, 2007). The weakening of the dune barrier leads to increasingly frequent marine intrusions, both on the surface during storms and subsurface through highly permeable sand formations, as observed for example in 1987, 1992 and 1997.

In the coming decades, the rise in sea level as a consequence of the global warming will further weaken the coastal zone by more submersion during storms and will lead to a new form of seawater intrusion. In order to anticipate future developments, hydrodynamic information is still insufficient, since the lack of local exploitation of brackish groundwater and the piezometric rise do not particularly encourage authorities to develop groundwater monitoring in the city. Piezometric or mineralisation measurements as well as permeability estimation are therefore rare.

It is likely that the creation of two other large harbours, the first at 60 km north of Nouakchott and the second at about 30 km north of the mouth of the Senegal River, will induce the same weakening of the coastline, with a similar erosion and the same increased risk of submersion during storms. The first harbour adjoins the vast topographic depression of Sebkha N'dramcha and the second harbour is at the border of the Diawling Natural Park, a Ramsar site supposed to be a protected area.

6. Conclusions

Interactions between seawater and groundwater in southwest Mauritania are particularly visible in the coastal area. Brackish water is met nearly everywhere because of the combination of a flat and low landscape, sometimes below sea level, and a very weak annual infiltration of rain. The equilibrium between seawater and continental water may change rapidly as a consequence of environmental changes and, overall, human activities. This is particularly the case when the coastline is modified, directly by harbour development and indirectly by material extraction, which weakens and fragments the coastal dunes and allows more frequent submersion events. The seawater wedge may then advance considerably inwards and mark the groundwater mineralisation for a long time. Conversely the massive rejection of fresh water and waste water in Nouakchott has created a less salty mound in groundwater of the capital area.

In fact, the study of the seawater intrusion cannot be limited to the present coastal area. Even at a distance of more than 100 km away, groundwater keeps geochemical traces of previous transgressions that are preserved by the low recharge. In more recent times, until the Diama dam in 1986, another major seawater intrusion occurred each year in the Senegal river valley in the low flow season. This invasion was spectacular, often exceeding 200 km, but probably had a limited impact on the riparian groundwater quality because of the very small difference in heads between the water table and the seawater of the river. Conversely, a few times a century, the biggest floods of the Senegal River were able to submerge a wide area and even reach the Nouakchott site. The fresh water running in the Aftout es Saheli depression was able to leach salts from the unsaturated zone to groundwater, simultaneously with a massive recharge of low mineralized river water.

The balance between freshwater and saltwater in the Trarza aquifer thus appears to be a constantly unstable dynamic, reacting to drivers operating in the short and long-term, at a variable frequency and affecting variable areas.

In the next decades, new forms of heavy anthropization will still impact the regional hydrology, especially the Aftout es Saheli canal and the new big harbours. They will combine with external natural drivers (sea level rise due to global warming and possible rainfall variation in the upstream Senegal basin), and local mixed drivers (local rainfall infiltration and vegetation cover). The future balance between seawater and groundwater is then largely unpredictable today.

Regional piezometry could rather evolve upwards, as already observed in Nouakchott or in the Senegal River valley, or as expected (Aftout es Saheli). This evolution would then be contrary to that of many other coastal areas where groundwater is overexploited. From a qualitative point of view, the various inputs from the Senegal River should decrease the current groundwater salinity in the coastal zone, while it is often naturally high. The main threat in the long-term will probably come from the increased fragility of the coastal bar. The risk of temporary submersion during storms is very real and the example of the breach in the Langue de Barbarie, still unclosed more than 15 years after it was artificially dug, should encourage us not to open a Pandora's box that could not be closed. More systematic and integrated observations of the natural environment could give scientists a better understanding of the many interconnected dynamics at play and enable decision-makers to anticipate possible difficulties.

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