MAURITANIA SENEGAL

Integrated and Sustainable Management of Shared Aquifer Systems and Basins of the Sahel Region

RAF/7/011

SENEGALO-MAURITANIAN BASIN

2017

EDITORIAL NOTE

This is not an official publication of the International Atomic Energy Agency (IAEA). The content has not undergone an official review by the IAEA. The views expressed do not necessarily reflect those of the IAEA or its Member States. The use of particular designations of countries or territories does not imply any judgement by the IAEA as to the legal status of such countries or territories, or their authorities and institutions, or of the delimitation of their boundaries. The mention of names of specific companies or products (whether or not indicated as registered) does not imply any intention to infringe proprietary rights, nor should it be construed as an endorsement or recommendation on the part of the IAEA.

REPORT OF THE IAEA-SUPPORTED REGIONAL TECHNICAL COOPERATION PROJECT RAF/7/011

SENEGALO-MAURITANIAN BASIN

COUNTERPARTS:

Mr Mouhamadou Doudou FALL (Senegal)

Ms Ndeye Khoudia Sarr FALL (Senegal)

Mr Brahim Labatt HMEYADE (Mauritania)

Mr Sidi Haiba BACAR (Mauritania)

EXPERT:

Mr Yves TRAVI (France)

Reproduced by the IAEA

Vienna, Austria, 2017

Table of Contents

1. INTRODUCTION

1.1. Particular water problems in the target basin

The onshore Senegal Mauritanian Basin which includes parts of Mauritania, Senegal, Gambia and Guinea Bissau is the largest of the northwest African Atlantic margin basins, and covers roughly more than 300 000 km^2. It approximately extends between 10° (Southern limit) and 21° Lat N (Northern limit).

Three main aquifer systems providing exploited ground water resources can be distinguished in the SMB: i) the superficial aquifer system covering and often discontinuously, the whole SMB, ii) the intermediate aquifer system including Eocene and Palaeocene carbonate formations and the deeper aquifer system. The later, mainly of Maastrichtian age, almost covers the whole sedimentary basin, with variable hydro geological potential. It is the only transboundary aquifer which is shared by Senegal, Gambia, Mauritania and Guinea-Bissau. The IAEA-supported project RAF/7/011 is the first attempt for solving common hydrogeological questions.

Unfortunately, despite some contacts and exchanges with Gambia and Guinea Bissau authorities, it was not possible to establish a joint project with these two countries as they are not IAEA's Member States. Therefore, only Senegal and Mauritania are officially involved in the project. In addition, towards the North, when reaching Mauritania, the Maastrichtian aquifer displays very poor quality water, and considering also a very low hydraulic conductivity, it is not really exploited. As a consequence, the project's main concern is more to investigate and assess common problems rather than to study and manage the same aquifer.

It is now well known that major hydrological problems of arid or semi-arid zones particularly include recharge, palaeo recharge and salinization. Recharge may occur through direct infiltration of rain, lateral seepage of rivers or flood water, and upward leakage from deep aquifers. All these different cases exist in Senegal and Mauritania, and in this context the Senegal River, which separate the two countries, can play a major role by replenishing boundary aquifers for both Senegal and Mauritania sides. Salinization may originate from present or former sea water intrusion (the case in Mauritania and Senegal) or from mixing with connate deep water (the case in Senegal) and water can also be concentrated through evaporation. It has been demonstrated for a long time that Isotope techniques are powerful tools for tackling these problems, particularly when they are combined with hydrogeological and hydrochemical data.

1.2. Previous studies on isotopes and hydrochemistry in the target area and their results.

Many studies on isotopes and hydrochemistry have been conducted in Senegal since the 70's, but only few in Mauritania. They consist in academic works (Thesis, publications, reports...) or IAEA/UN projects, sometimes jointly carried out.

Academic Works

For Senegal, among the major works, the following may be mentioned: Gaye theses (1980, 1990), Faye A. Theses (1983, 1994), Diagana thesis (1994), Travi thesis (1988), Sarr thesis 2000, Faye S. thesis 2005, Diaw M. thesis (2008), Madioune Diakher Thesis (2012).
For Mauritania: Semega Thesis (1995), Mohamed thesis (2012).

Previous IAEA, UN or other international supported projects in the target area

-
- **Senegal**

United States Development Programme (Special fund) Project, SEN 9, 1972 supported by IAEA for environmental isotopes investigations: "Studies/Establishment of a Master Plan for Water Supply and Sewerage for the city of Dakar". This first investigation located near the City of Dakar, highlighted the heterogeneity of the recharge in shallows aquifer and the role of barrier played by some fault limiting the "Horst de NDiass" structure.

Research Contract N° 9862/RB : « Etude des isotopes du milieu dans les principaux aquifères du bassin sédimentaire du Sénégal » (1981-1983). This study was conducted by the University of Dakar, geology Department. Stable isotopes of water molecule, tritium and carbon-13/carbon-14 were used for a first global isotope survey. About 130 sites were sampled in the different aquifers of the Senegal Sedimentary Basin.

The national IAEA supported Projects SEN/002 (1984) and SEN/003 (1987) focussed on specific sub basins: the western part of the Senegal basin, around the "Horst de Ndiass and the Casamance sub basin. These 2 projects allow the conditions of recharge of shallow aquifers (direct recharge from precipitation and upward leakage from the deep Maastricthian aquifer) to be better clarified.

The national IAEA-supported TC Projects SEN/8/005 and SEN/8/006 (2002-2005) “Hydrogeological study of the deep aquifer of the Maastrichtian” provided new hydrochemical and isotopic data that allowed a better understanding of the structure of the aquifer and of the ground water flow, and their impact on the mineralisation.

The IAEA-supported Regional Project RAF/8/012 (1987-1992) “Développement des techniques isotopiques en Hydrologie dans les pays du Sahel” involved the participation of four countries: Senegal, Mali, Niger and Cameroon. It supported the studies carried out under the previous IAEA-supported project SEN/8/003, extending the investigated zone to hard rock aquifers in the Eastern part of Senegal and the CT aquifer in the Central Ferlo Plain. The interconnection between river waters (Senegal River) and local groundwater were also assessed as well as tracing infiltration of rainwater in the unsaturated zone (UZ).

The Regional Model project RAF/8/022 (phase I) (1995-1998) involved the participation of four countries, namely Egypt, Ethiopia, Morocco and Senegal. The project aimed to apply isotope techniques in combination with other hydrogeological investigations to practical problems in the development and optimum management of groundwater resources. For Senegal, it aimed to have a significant socio-economic impact on water supply to over 1.5 million people in the Dakar region, mainly around the “Ndiass Horst Aquifers”.

-

- **Mauritania**

The national IAEA-supported project MAU/8/002 ‘Use of Isotope Hydrology Techniques for the Study of the Trarza's Aquifer and Discontinued Aquifers in Southern Mauritania’was conducted from 2007 to 2010. It aimed at characterizing and managing one of the country’s major aquifers, the Trarza aquifer, located in Mauritania’s coastal basin. The purpose was to improve available information on water resources in the region, and thereby improve the ability to make sound decisions on where and how to extract water efficiently. Using conventional isotope techniques, the project allows differentiating and characterizing the different aquifer levels (about 100 samples for stable isotope analyses, 60 samples for tritium and 20 for $^{14}C/^{13}C$).

1.3. Objectives of the project RAF/7/011 in the target basin

Considering the hydrogeological situation in the SMB, the objectives of the project must be divided in two categories: common objectives and specific objectives.
Mauritania is specifically concerned by recharge of shallow aquifers in the Trarza plain, Boulanouar, Bennichab, Brakna and the problem of salt water probably mainly originating from present or ancient sea water intrusions.

In Senegal, the western part of the deep aquifer (Maastrichtian) is largely over exploited leading to groundwater depletion and degradation of groundwater quality and causing serious problems for Dakar water supply. In this context, the DGPRE ("Direction Générale des Ressources en Eau") in charge of groundwater, planned to transfer groundwater from the West part of the basin toward the West side, and engaged some studies for better defining the limit between salt water and fresh water in the deep aquifer. In addition to classical hydrogeological investigation, relevant information was expected from both hydrochemical and isotopic data. Furthermore, explanation of the origin and evolution of the salt water is an interesting scientific challenge.

The geographically and practical common interest is situated around the Senegal River which can replenish the aquifers (Q/CT and Maastrichtian on the Senegal side; Q/CT and Eocene on the Mauritanian side). The palaeo recharge has already been investigated in the past (Travi, 1988, Faye, 1994) but based stable isotope conclusions remains hypothetic because now only few boreholes could be sampled for ^{14}C analysis allowing to date the water from the river toward the basin. New recent boreholes have allowed this question to be revisited by the project on the two sides of the River.

2. STUDY SITES

2.1. Location, overall topography

The northern limit of the Senegal Basin is the Precambrian Reguibat Shield in Morocco, and the southern limit is the Bové Basin of Guinea (Fig. 3). The eastern edge of the basin is separated from the Taoudeni Basin by Precambrian rocks of the Mauritanide Mountains that were uplifted during the Late Paleozoic Hercynian Orogeny (Bellion, 1987).

The Senegalese landscape consists mainly of the rolling sandy plains of the western Sahel which rise to foothills in the southeast (Fig. 1). The northern border is formed by the Senegal River, southern more other rivers include the Gambia and Casamance Rivers.

Mauritania is generally flat, its 1,030,700 square kilometres forming vast, arid plains broken by occasional ridges and cliff like outcroppings. It borders the North Atlantic Ocean, between Senegal and Western Sahara. Approximately three-fourths of Mauritania is desert or semi desert. The plateaus gradually descend toward the northeast to the barren El Djouf, or "Empty Quarter," a vast region of large sand dunes that merges into the Sahara Desert. To the west, between the ocean and the plateaus, are alternating areas of clayey plains (regs) and sand dunes (ergs) (Fig. 1). As a result of these morphological and climatic conditions, no permanent watercourse raises in Mauritania, except for the Gorgol, a temporary tributary of the Senegal (right bank). In periods of heavy rainfall this right bank is also fed by considerable runoff from the Mauritanian regions of Guidimaka and Aftout, which are drained by a very dense hydrographic network. Outside these regions, the hydrographic network is weak and dispersed; it has no flow to the ocean and is partly blocked by sediments and eolian deposits.

From South to North the study (investigated) zone extends from the southern part of the Senegalese basin to about 21° N (Northern part of SMB).

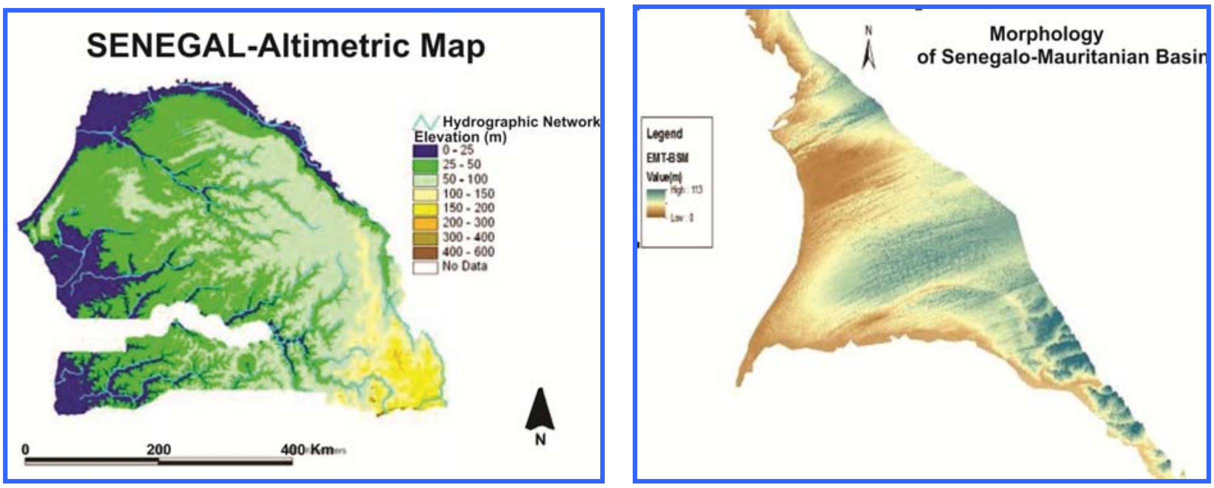


Figure 1: Topography maps of Senegal and Mauritania

2.2. Climatology

Senegal has a tropical climate with pleasant heat throughout the year with well-defined dry and humid seasons that result from northeast winter winds and southwest summer winds. The dry season (November to April) is dominated by hot, dry, Harmattan wind. Dakar's annual rainfall of about 600 mm occurs between June and October when maximum temperatures average 30 °C and minimums 24.2°C; December to February maximum temperatures average 25.7°C and minimums 18°C (64.4 °F). Interior temperatures are higher than along the coast (for example, average daily temperatures in Kaolack and Tambacounda for May are 30°C and 32.7°C (90.9 F) respectively, compared to Dakar's 23.2°C, and rainfall increases substantially farther south, exceeding 1,500 mm annually in some areas. The northernmost part of the country has a near hot desert climate, the central part has a hot semi-arid climate and the southernmost part has a tropical wet and dry climate (Fig. 2).

In Mauritania, the climate is characterized by extremes in temperature and by meagre and irregular rainfall. Annual temperature variations are small, although diurnal variations can be extreme. The harmattan, a hot, dry, and often dust-laden wind, blows from the Sahara throughout the long dry season and is the prevailing wind, except along the narrow coastal strip, which is influenced by oceanic trade winds. Mauritania has four ecological zones: the Saharan Zone, the Sahelian Zone, the Senegal River Valley, and the Coastal Zone. Most rain falls during the short rainy season ("hivernage"), from July to September, and average annual precipitation varies from 500 to 600 millimetres in the far south to less than 100 millimetres in the northern two-thirds of the country.

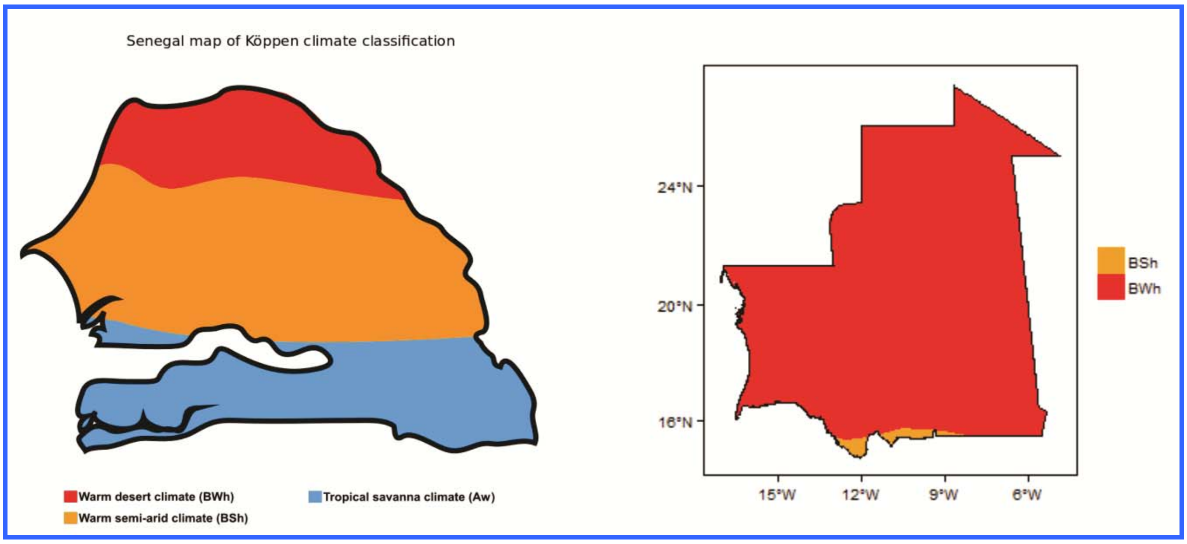


Figure 2: Senegal and Mauritania climate maps according to Köppen classification (In Madioune et al. 2016 and Upton and Ó Dochartaigh 2016).

The rainfall variability in space and time and climatic parameters are illustrated in Fig. 3.

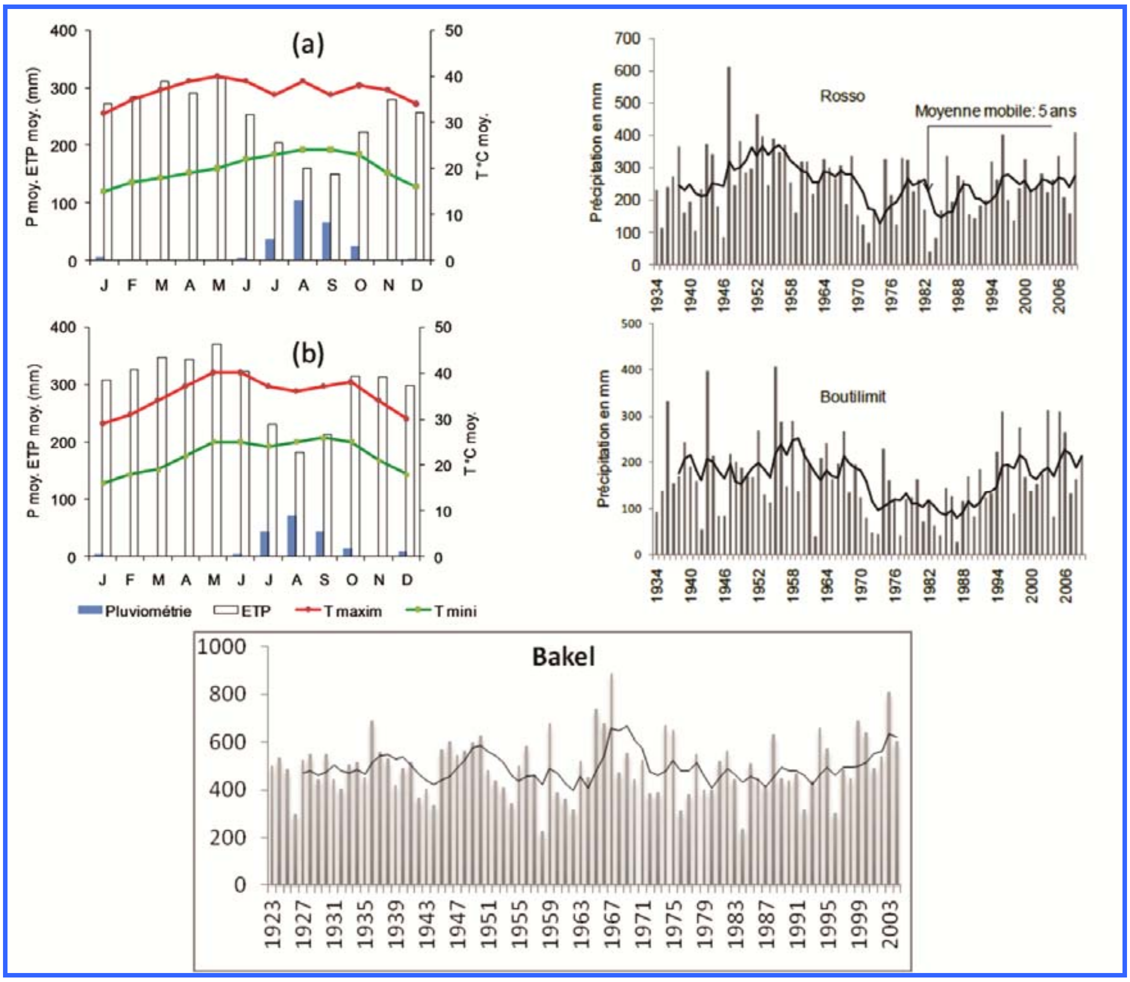


Figure 3: Meteorological parameters observed at the Rosso, Boutilimit and Bakel stations

2.3. Hydrology

The water resources of the Senegal River Basin (340 000 km^2) are shared between Mali, Senegal and Mauritania. The rainy uplands of Guinea are the source of a major part of the river water. At the River mouth, close to the city of Saint-Louis, the mean annual flow is 732m^3/s, ie a total volume of 23 milliards m^3, with large annual fluctuations ranging from 8 to 45 milliards m^3. Normally the flooding period is situated between July and October. Then the flow rapidly decreases and become very low (minimum average monthly discharge of 9 m^3/s in May).

A variety of water uses are found on either side of the Valley (Mauritania in the North and Senegal in the South). Some are traditional and pre-existed the infrastructures. Modern ones were introduced as part of the overall planning process of water resources development (commissioning of Manantali and Diama dams).

In Mauritania, the renewable surface water resources are estimated to be about 11 km^3/yr, mainly provided by the Senegal River, and by small dams located in the Southern and Central part of the territory. At the beginning of the twenties, the extracted water volume was estimated at about 1 700 M m^3 (88% irrigation, 9% for domestic use and 3% for industrial activities).

On the Senegal side, the Senegal River supply the Guiers lake which can store about 500 M m^3 and provide about 120 000 m^3/y for Dakar Water supply. The alluvial aquifers are partly made of clay and fine sands, which represent the Post Nouakchottian deposits, and also coarse and gravelly alluvium, clayey sand dated from the Ogolian period and the old and middle Quaternary. The alluvial aquifer is the principal bed of the river and its water flow varies with the high and low flow stages of the river.

The history of groundwater development/evaluation in the Senegal River Basin could be summarized in two periods, before and after commissioning of the dams (Fig. 4). During the early stages of the development of the valley different localized investigations have been carried out to characterize the hydrodynamics functioning and the recharge mode of the alluvial aquifer in the valley. The pre-dam situation has been established for the delta (Audibert, 1970) and for the valley (BRGM, 1964 et 1965; IRAT, 1965 et 1967; Illy, 1973, Saos et al., 1984), indicating some complex relationship between the Senegal River and the aquifer system.

Subsequent investigations carried out during the post-dam period (Bonkel, 1989; USAID/OMVS, 1990, EQUESEN, 1990/1991, Diao. 1992; Diagana, 1994, Dieng, 1997, Touzi, 1998, Diaw, 2008) have confirmed this inter-relationship and shed some light on the possible impacts and management issues of surface water resources influencing groundwater and its sensitivity to the changing climate conditions.

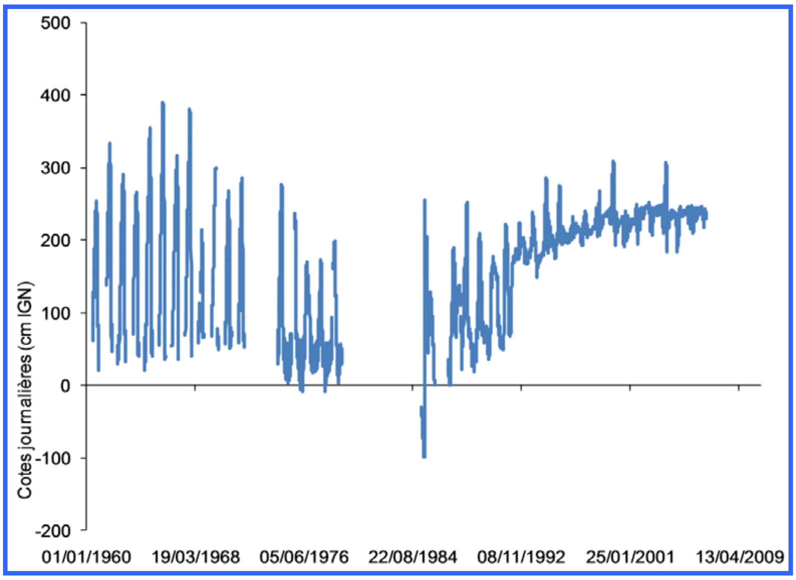


Figure 4: Evolution of the Senegal River before and after the Diama Dam building (1989) (In Mohamed, 2012)

2.4. Vegetation types, land use

In the year 2000, Senegal's savannas, woodlands, and forests still cover more than two-thirds of the country (Fig.5)

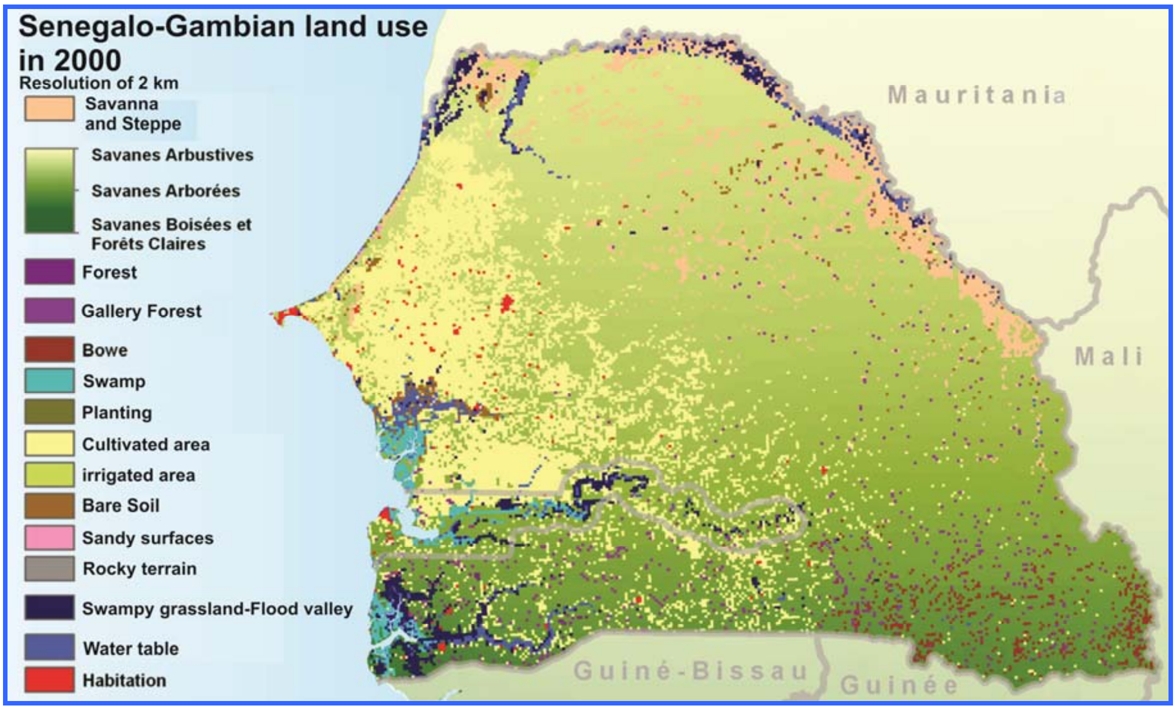


Figure 5: Vegetation and land use in the Senegalese part of the Basin (Land use/Land cover of West Africa, USGS; In Madioune et al., 2016)

In Mauritania, belts of natural vegetation, corresponding to the rainfall pattern, extend from East to West and range from traces of tropical forest along the Senegal River to brush and savannah in the southeast. Only sandy desert is found in the Centre and North of the country.

Sandy surfaces increased from about 46,000 km^2 to about 64,000 km^2 over Mauritania's Sahelian and Saharan-Sahelian regions (over 37 percent increase). Severe drought in the 1970s and 1980s played a major role in driving this shift in land cover. Sand dunes and flat sandy areas previously stabilized by herbaceous and shrub cover have become mobile and active (Fig.6).

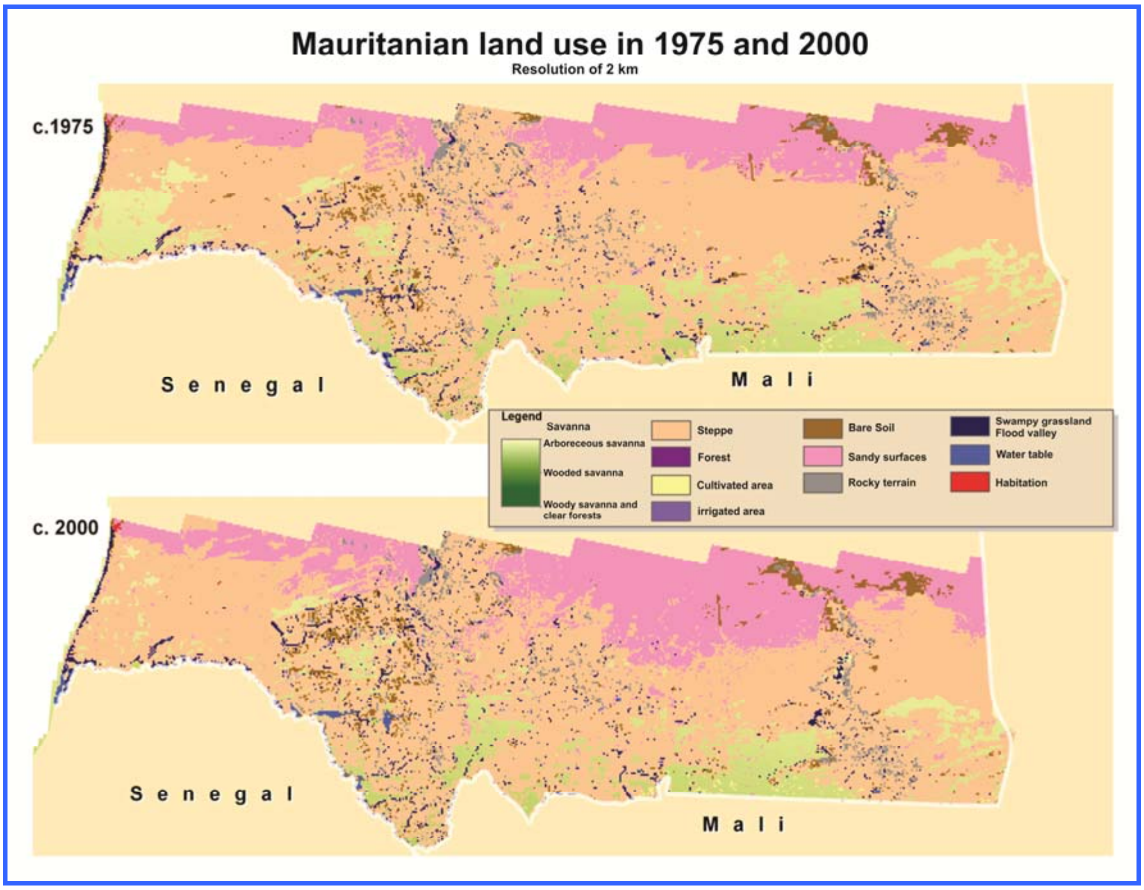


Figure 6: Land use in the Mauritanian part of the Basin (Land use/Land cover of West Africa, USGS 2013)

2.5. Geology and hydrogeology

As indicated above, three main aquifer systems providing exploited ground water resources can be distinguished in the SMB (Madioune and al., 2016).

1) Shallow aquifer systems (Quaternary and CT) discontinuously cover the whole sedimentary SMB. It is dominantly made of sand and sandy clay, which vary in proportion across its extent. The aquifers are intergranular, and the best groundwater potential occurs in sand layers. It comprises the following aquifers:

- In Senegal: infrabasaltic (occurs below basalts), Thiaroye, Littoral Nord, alluvial, Continental Terminal and Oligo-Miocene aquifers;

- In Mauritania: Boulanouar (3,000 km^2), Bennichab (1,200 km^2) and Trarza (20,000 km^2) aquifers (Fig.7). In the 2 countries is the alluvial aquifer on the both sides of the Senegal River.

This aquifer system overlies the more consolidated deposits of the Eocene, Palaeocene, and the Maastrichtian. The Shallow aquifer system ranges between 0 to 150 m thick, with a water table depth between a few metres to a depth of 72.5 m.

Typical values for aquifer parameters for the superficial aquifer system are:

• Permeability = 1 x 10^{-5} to 8.9 x 10^{-4} m/s

• Transmissivity = 8.64 to 1728 m^2/day

• Storage coefficient = 0.01-0.15

• Borehole yield = 50-183 m^3/h

Nitrate contamination is known to occur in certain places

2) **The Intermediate aquifer system** includes Eocene and Palaeocene formations, and mainly comprises limestone, often karstic or affected by faults. The Eocene aquifer is exploited in the central western part of Senegal and along the Senegal River. The Palaeocene aquifer occurs mainly in western Senegal, around Pout. These aquifers constitute one of the main sources of drinking water for Dakar. The Intermediate aquifer system ranges between 40 to 120 m thick, with a water table depth between a few metres to 102.5 metres depth.

Typical values for aquifer parameters for the Intermediate aquifer system:

• Permeability = 1 x 10^{-5} to 2.5x10^{-8} m/s

• Transmissivity = 1.728 – 9504 m^2/day

• Storage coefficient = 0.05 - 0.10

• Borehole yield = 54 – 300 m^3/h

High iron, fluoride and salinity are seen in the Central Western part of Senegal, saline intrusion in the coastal areas.

3) **The deeper aquifer system**, mainly of Maastrichtian age, extends across the whole of the Senegal Mauritanian Basin and generally consists of sand, sandy-clay and calcareous

sandstone. Groundwater storage and flow are largely intergranular. This aquifer constitutes the main source of groundwater supply in Senegal. It is a transboundary system but is not exploited in Mauritania due to low hydraulic conductivity and high salinity. The deeper aquifer system is about 250 m thick, with a water table depth between a few metres to 140 metres. Typical borehole depth varies between 25 and 680 m. It is typically highly productive, although aquifer properties vary according to local characteristics (lithology, thickness, etc.) (Fig.8). Except for the Eastern and Western borders, the aquifer is generally confined.

Typical values for aquifer parameters for the deeper aquifer system are:

- Permeability = 1 x 10-5 m/s
- Transmissivity = 0.95 – 652578 m²/day
- Storage coefficient = 1 x 10-4 – 6 x 10-4 in the Western Central part
- Borehole yield = 80 – 362 m³/h

Recharge occurs from direct rainfall and indirectly from rivers, and is estimated at about 103 x 10^6 m³/a to the Maastrichtian deeper aquifer system. It is mainly recharged in the Western part in Diass horst where formations outcrop, and at the contact with the basement formations and the unconsolidated formations in the South-Eastern part of Senegal.

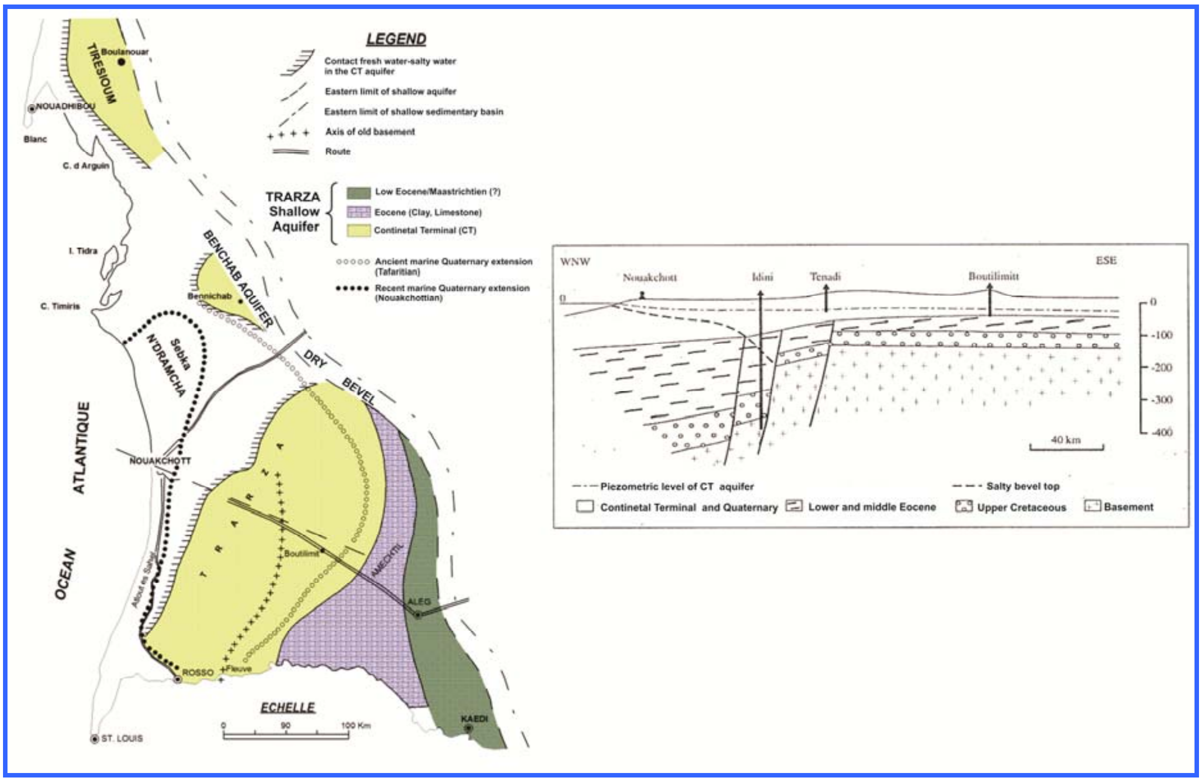
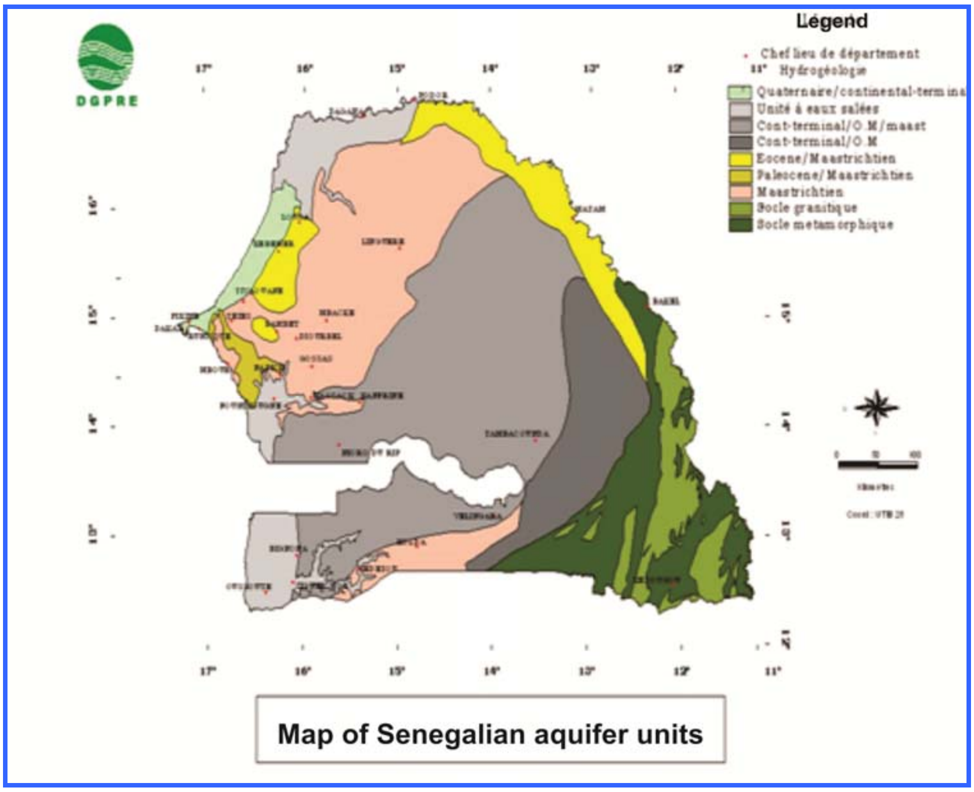


Figure 7: Hydrogeological map of the Mauritanian part of the SMB and SSW/WNW cross-section



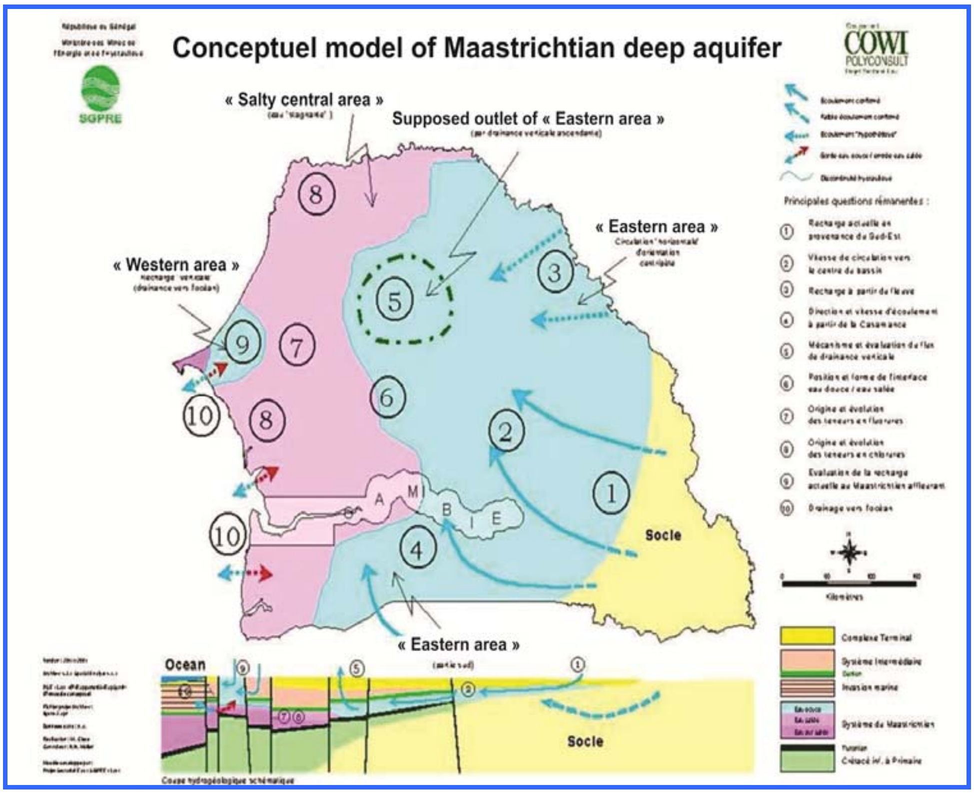


Figure 8: Hydrogeological map and deep aquifer conceptual model in the Senegalese part of the SMB

Groundwater depletion occurs locally due to over abstraction. High iron, fluoride and salinity are seen in the Central Western part of Senegal. Saline intrusion is observed in the coastal areas, but high salinity is often attributed to very old sea water (connate water).

2.6. Water supply and water resources management in the basin

Senegal and Mauritania have significant groundwater resources but the distribution of availability and demand do not match. This means that some groundwater systems are over exploited, leading to groundwater depletion: this has been observed in the Palaeocene and Maastrichtian in the Diass aquifer system. Groundwater and surface water management in Senegal, including water policy, are the responsibility of the "Direction de la Gestion et de la Planification des Ressources en Eau (DGPRE)". Permits are required for drilling and water abstraction. Currently, there is no legislative protection for groundwater in vulnerable areas, and water disposal is not controlled. Data show that in 2008 there were at least 7000 recorded groundwater sources in Senegal, both boreholes and large diameter (hand dug) wells, with geological log information for about 1400 of the existing boreholes (Table 1). Groundwater levels are monitored twice a year: before and after the rainy season. This work is funded through the Ministry of Hydraulics and Sanitation.

Groundwater quality is measured twice per year, before and after the rainy season, funded by the Ministry of Hydraulics and Sanitation. This work is sometimes extended by NGOs, researchers or others who want to better understand water quality.

Table 1: Groundwater withdrawal in Senegal. (Source: World Bank)

Annual Freshwater Withdrawal (2013)	2.611 Million m^3
Annual Freshwater Withdrawal for Agriculture	92.98%
Annual Freshwater Withdrawal for Domestic Use	4.412%
Annual Freshwater Withdrawal for Industry	2.611%
Rural Population with Access to Improved Water Source	60.3%
Urban Population with Access to Improved Water Source	92.5%

These data are collected and stored by the « Direction de la Gestion et de la Planification des Ressources en Eau » (DGPRE) and the « Société Nationale des Eaux du Sénégal » (SONES).

In Mauritania, a water point database exists, with entries for nearly 14,000 boreholes and both traditional and modern wells, but has little supporting information (such as geological logs or records of groundwater levels). 500 borehole measurements have been provided by SNDE ("Société Nationale de l'Eau") in 2005, 400 in Trarza area and 100 in Brakna area (Table 2).

Table 2: Groundwater withdrawal in Mauritania (Source: World Bank)

Annual Freshwater Withdrawal (2013)	1,350 Million m^3
Annual Freshwater Withdrawal for Agriculture (2013)	90.6%
Annual Freshwater Withdrawal for Domestic Use (2013)	7.1%
Annual Freshwater Withdrawal for Industry (2013)	2.4%
Rural Population with Access to Improved Water Source (2012)	47.7%
Urban Population with Access to Improved Water Source (2012)	52.3%

3. DATA ACQUISITION AND METHODOLOGY USED

For Mauritania three sampling campaigns have been carried out in 2013, 2014 and 2015. Samples were collected from Continental Terminal/Quaternary and Eocene aquifers. The locations of samples are shown in figure 9. A total of 156 groundwater samples, 4 surface samples and 4 rainfall events (2014 campaign at Nouakchott and Kaedi), has been collected and adequately conditioned for chemical, stable isotopes and tritium analyses. For such analyses the samples were sent to the LRAE laboratory of the National Engineer School of Sfax (ENIS) (Tunisia). Nine samples (2015 campaign) were analysed for ^{14}C in the isotopic Centre at Groningen).

Data processing has been carried out using the software ArcGis, MapInfo, Diagramme and Phreeque C; the data of this project have been jointly studied and compared with the former data of the national IAEA-supported project (MAU/8/002).

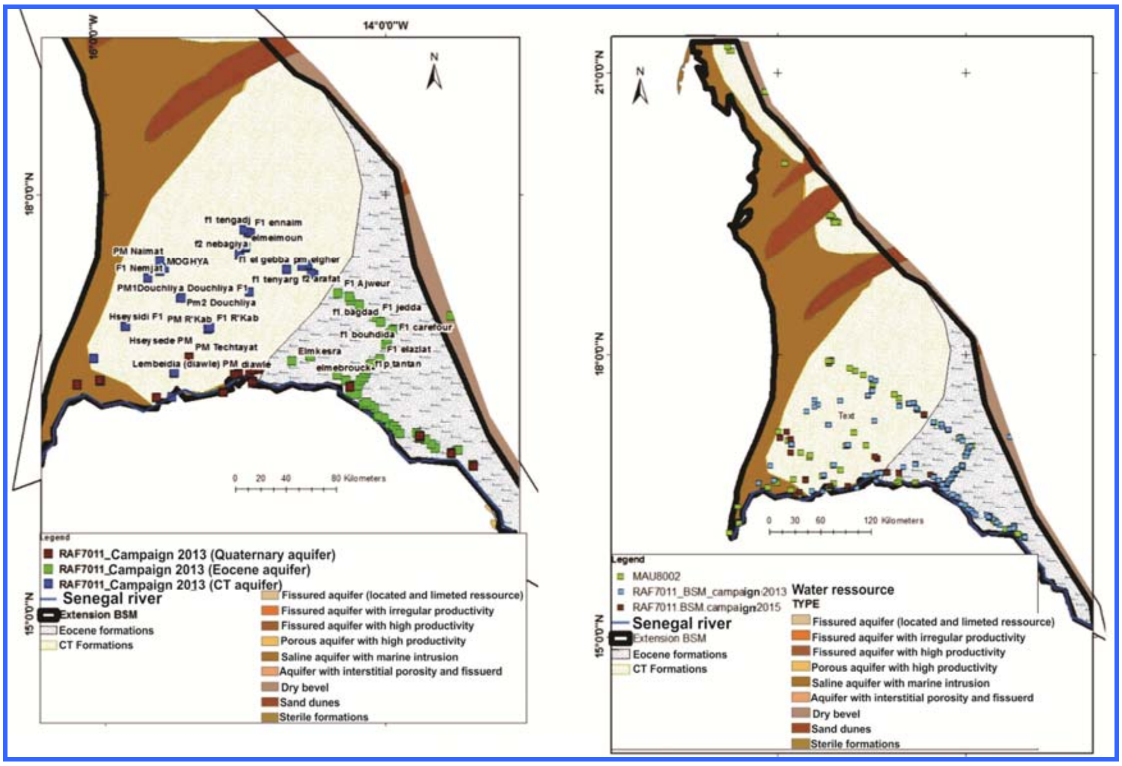


Figure 9: Location of sampling points in the Mauritanian part of SMB

For Senegal two main sampling campaigns have been carried out in November 2013 and in June 2016. The global zone investigated is shown in figure 10. The two sectors have been selected for trying to takle the problem of salinisation limit in the central part of the basin and of recharge and palaeo recharge along the Senegal River at North Eastern side of the Senegalese Basin. Detailed sampling location of the 2 campaigns is shown on Figs. 11 and 12. The aim of the second campaign was to verify an eventual chemical and isotopic content evolution related to possible recharge by rainfall and/or Senegal River and identified palaeo recharge from Senegal River.

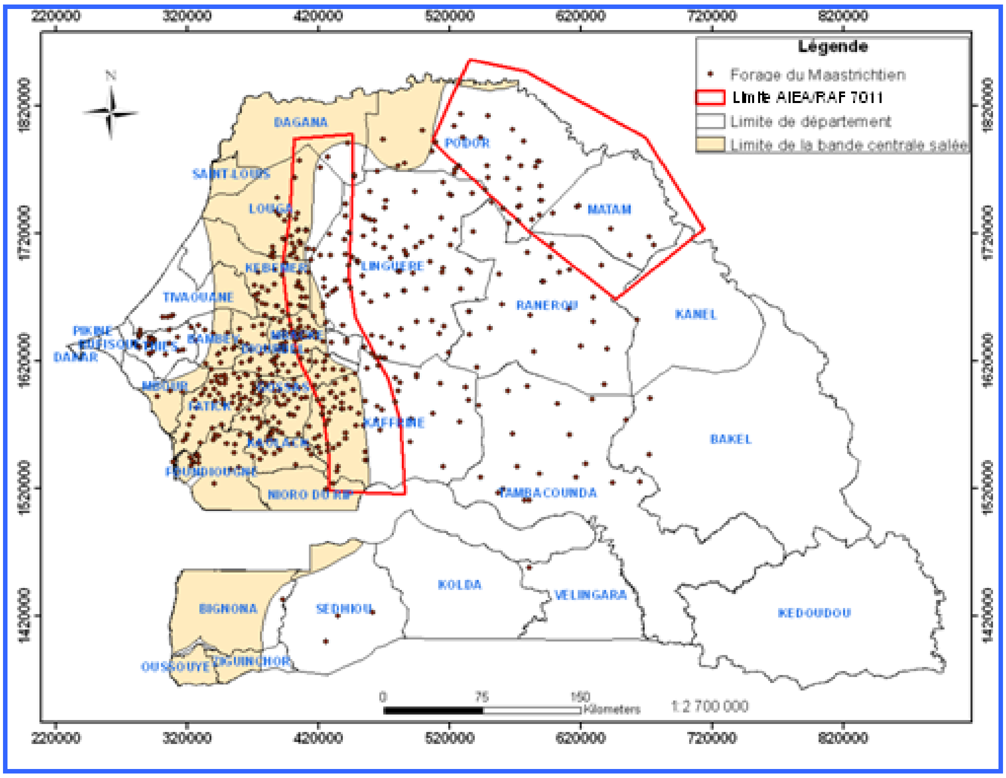


Figure 10: Sampling area in the Senegalese part of the SMB

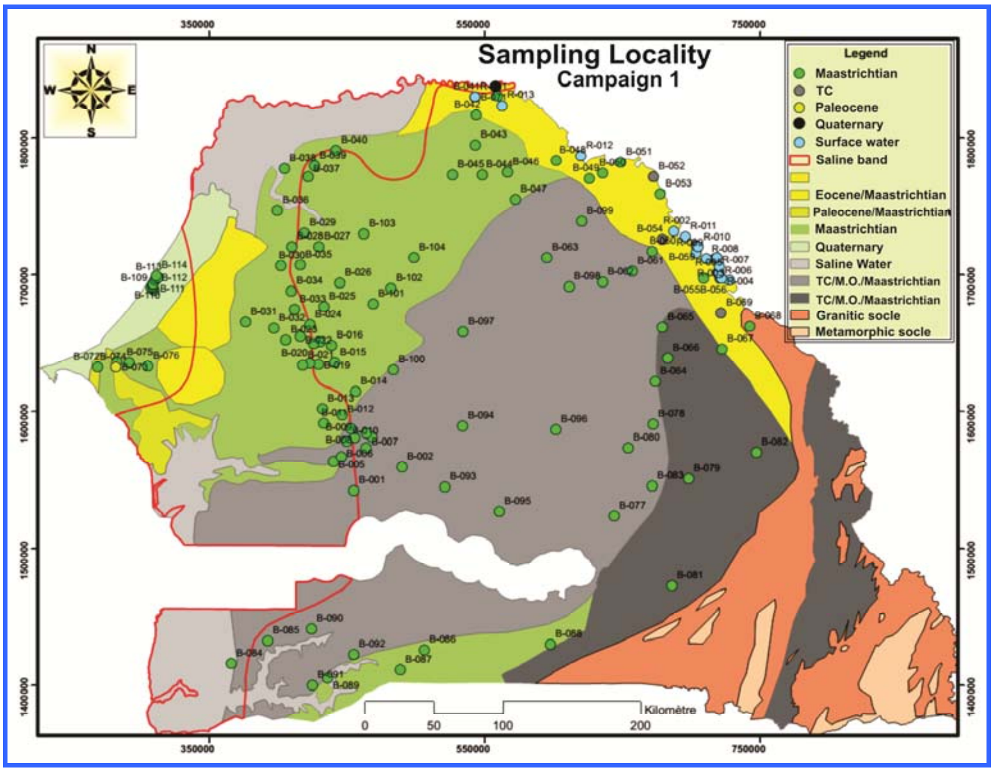


Figure 11: Sampling points in the Senegalese part of the SMB

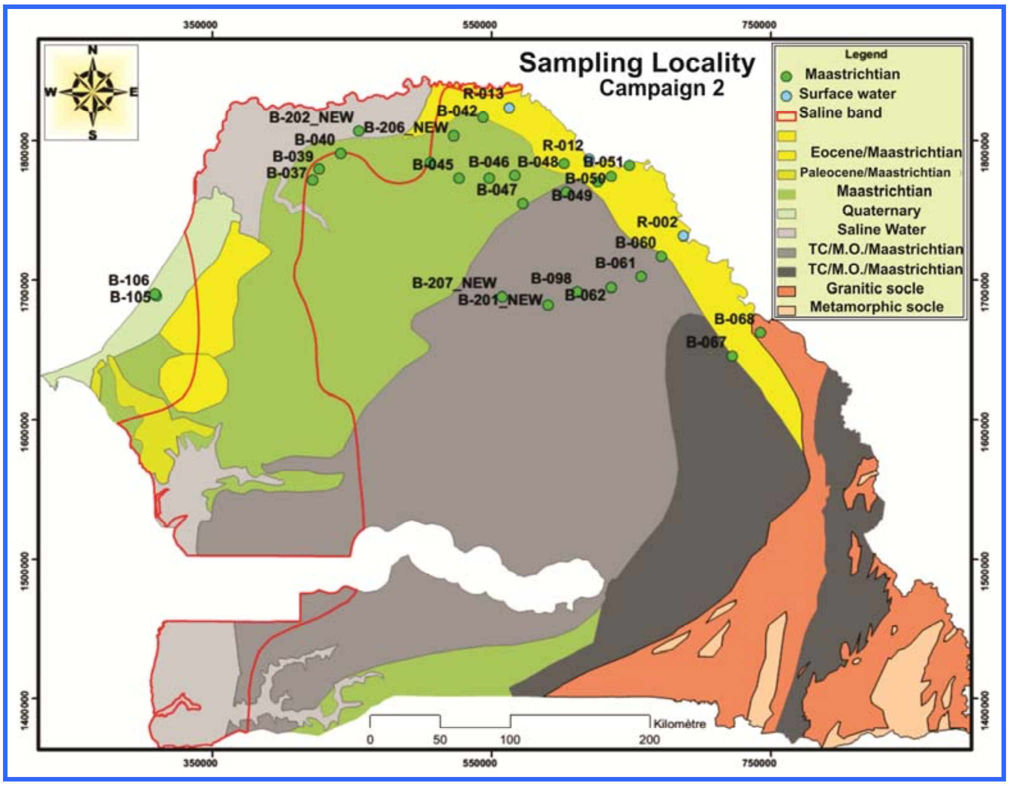


Figure 12: Sampling points of the second campaign in the Senegalese part of the SMB

Classical physico chemical parameters (pH, EC and T) were measured in situ. Samples were prepared for chemical, stable isotope and tritium analyses during the two campaigns, and carbon-14 analyses during the second campaign. Chemical analyses includes the minor elements F, Fe (tot) and Br. Trace elements including Li and B have also been analysed for some samples of the Maastrichtian aquifer, close to the saline limit, for trying to caracterize connate water. The first campaign samples were sent to the CNESTEN Lab in Rabat (Morroco), the second one to the LRAE in Sfax (Tunisia). The ^{14}C analyses (26) have been carried out at the Isotopic Centre, University of Groningen (Nederlands). Data processing has been carried out using the softwares ArcGis, Diagramme and PhreequeC.

4. RESULTS AND INTERPRETATION

4.1. General chemical and isotopic characterisation

Mauritanian part of the Basin

The distribution of the water points on the Piper diagram (Fig.13) shows mixed sodium-carbonate waters on the cation side, with a relatively similar evolution for the three aquifer systems. On the contrary, these aquifer systems are relatively well distinguished on the anionic side of the diagram. The quaternary points evolved between HCO_3^- and Cl^- end members and the Eocene water points are more influenced by the SO_4^{2-} end member. In the CT almost all ground water are dominated by Cl^- content with a slight influence of SO_4^{2-}.

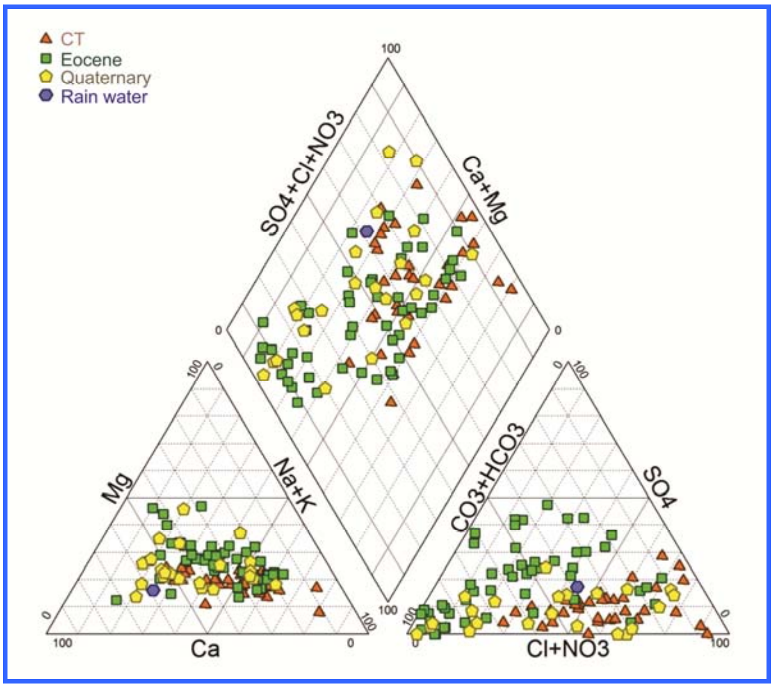


Figure 13: Piper Diagram of Mauritanian ground water (first campaign)

Further explanation of chemical processes is necessary considering the samples location and the flow path directions. Globally quaternary sampling points lie close to the Senegal River, while CT and Eocene aquifer have been sampled along the River and along lines starting from the River towards the central part of the Trarza plain.

Calcium and HCO_3^- evolution clearly indicates saturation with respect to calcite at about 500 mg/L TDS. We may note that Ca increases again especially for Eocene and some Quaternary samples. Na increases regularly with respect to the TDS evolution, in agreement with what is observed in the Piper diagram, reflecting more a mixing with sea water or evaporite dissolution probably enhanced by an evaporative process than a cation exchange process, (Fig.14).

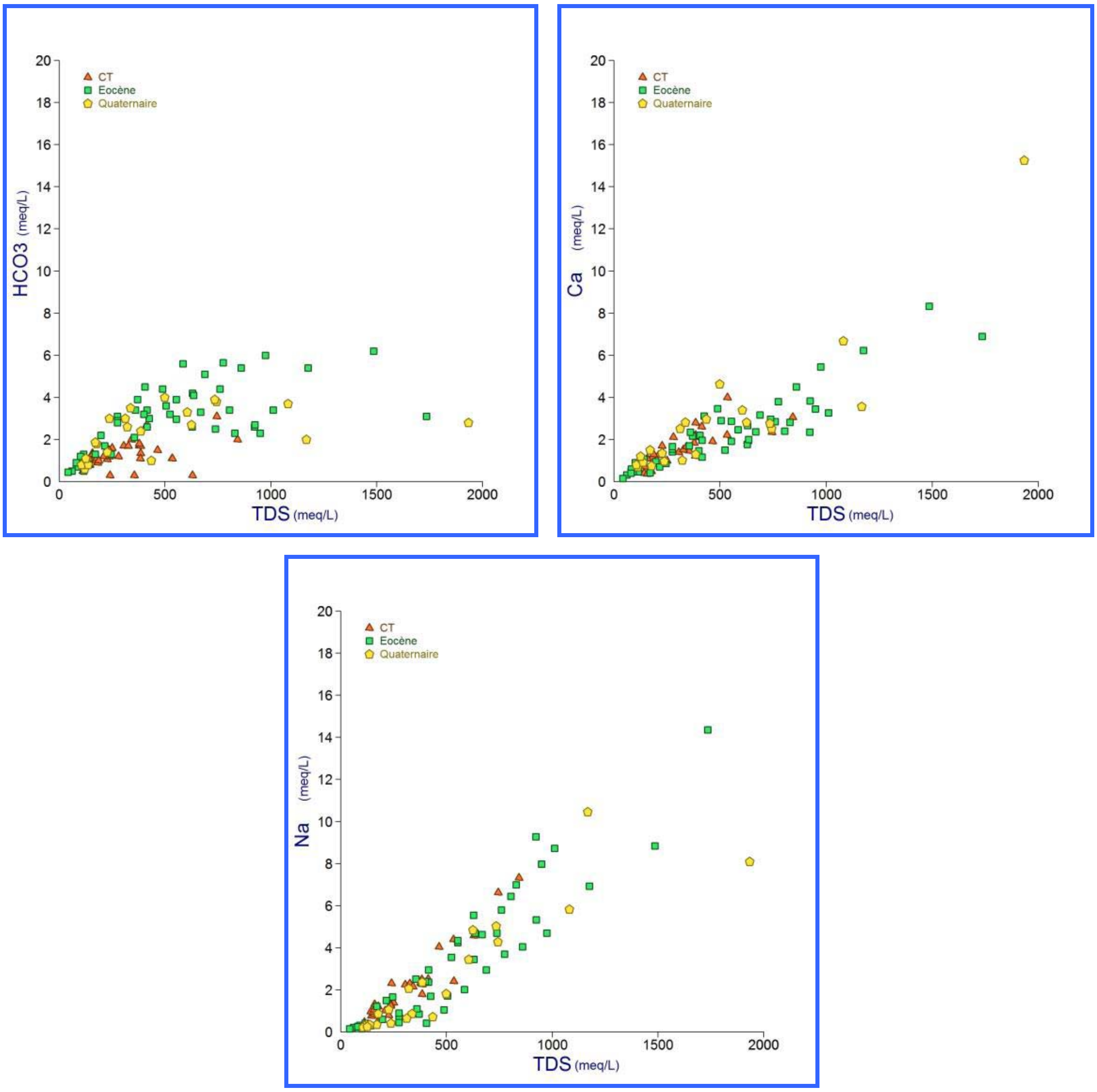


Figure 14: Relationships between some major elements and TDS (Ca^{2+}, Na^{+} and HCO_3^{-})

The stable isotope composition of groundwater varies over a relatively wide range, from -6, 5‰ to +1 ‰ for $\delta^{18}O$ and -10‰ to -43‰ for $\delta^{2}H$. The stable isotope data presented on the diagram clearly indicate a significant influence of an evaporative process. This process mainly affects the ground water of the quaternary aquifer.

The intersect of the evaporation slope with the global meteoric Water line displays a value about -6,2‰ which seems relatively close to the rainfall input signature as discussed below. Nevertheless, some Eocene water slightly less depleted and lying close to the Global Meteoric Water Line could originate from River water.

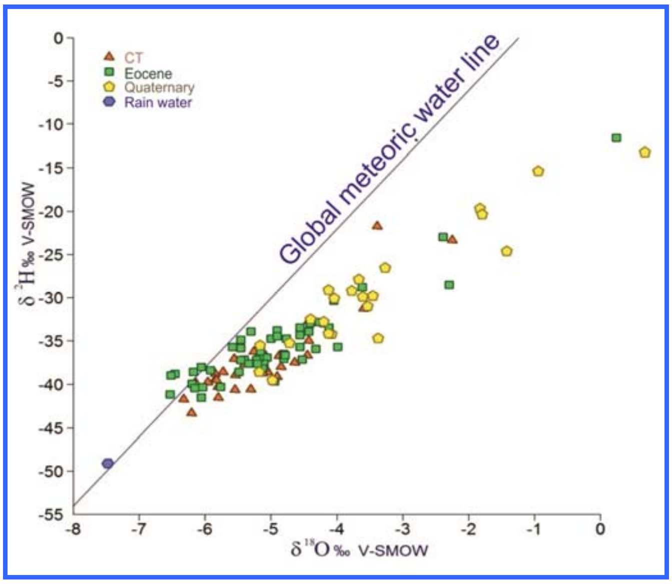


Figure 15: Stable isotope composition on plot $\delta^{18}O$ vs $\delta^{2}H$

Although Fig. 15 clearly indicates a significant influence of evaporative process, the plot Cl^- vs. $\delta^{18}O$ (Fig. 16), generally used for characterising salinization processes, does not clearly indicate a dominant evaporation role. Especially some CT points do not match considering the two diagrams. This will be discussed more in detail in the salinization paragraph especially using the Na^+/Cl^- ratio.

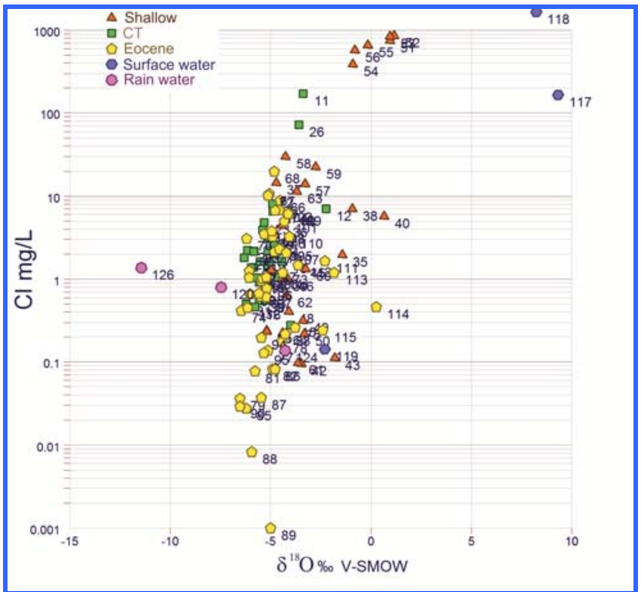


Figure 16: Relationship between $\delta^{18}O$ and Cl^- contents

Senegalese part of the basin

According to the to the well-known mineralisation process along the flow path (from the Western recharge zone) in the Maastrichtian aquifer (Travi, 1988; Faye, 1994), the water points evolve from water Ca^{2+}/ HCO_3^- dominated towards water Na^+/ HCO_3^- dominated and finally Na^+/Cl^- dominated (Fig. 17).

This chemical evolution reflects the cation exchange process (Ca/Na amplified by calcite saturation) and the presence of connate water in the western graben zone, where anionic mineralisation is strongly dominated by Cl^-. Some SO_4^{2-} water reflects the dissolution of evaporatic minerals discontinuously present in the Maastrichtian aquifer in the central part of the basin.

The two plots presented in figure 18, clearly confirm the hydro chemical evolution presented above, with a regular evolution from the Ca^{2+}/HCO_3^- type towards the Na^+/ HCO_3^- type and the significant shift to NaCl type.

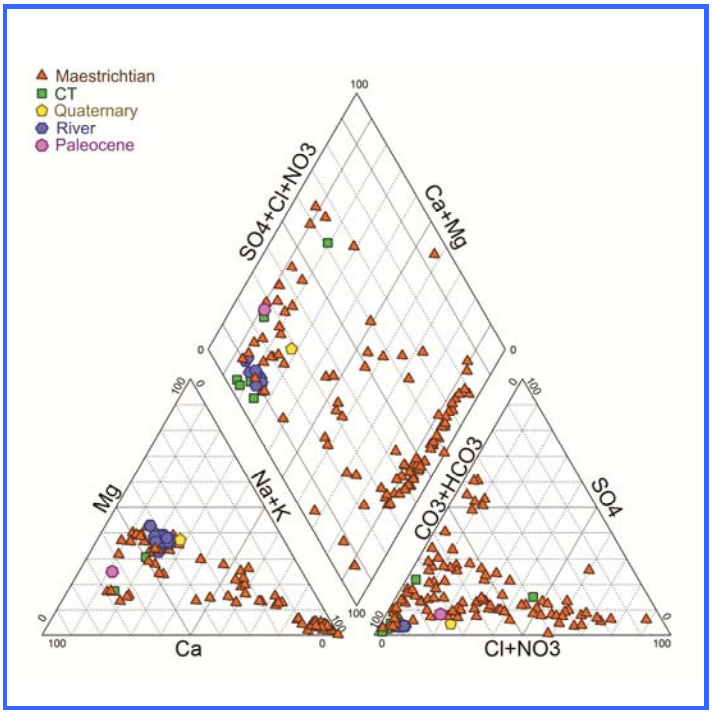


Figure 17: Piper diagram of Senegalese groundwaters (Mainly Maastrichtian aquifer)

The stable isotope data presented in Figs. 19 and 20 reveals that the $\delta^{18}O$ contents vary over a relative wide range. In addition, Fig. 19 shows a lack of relationship between the two parameters excluding a significant influence of evaporative process. The more enriched values corresponding to the eastern and Northern part of the basin seems display the Senegal River isotopic signature (slightly evaporated) of the flood period (Fig. 20).

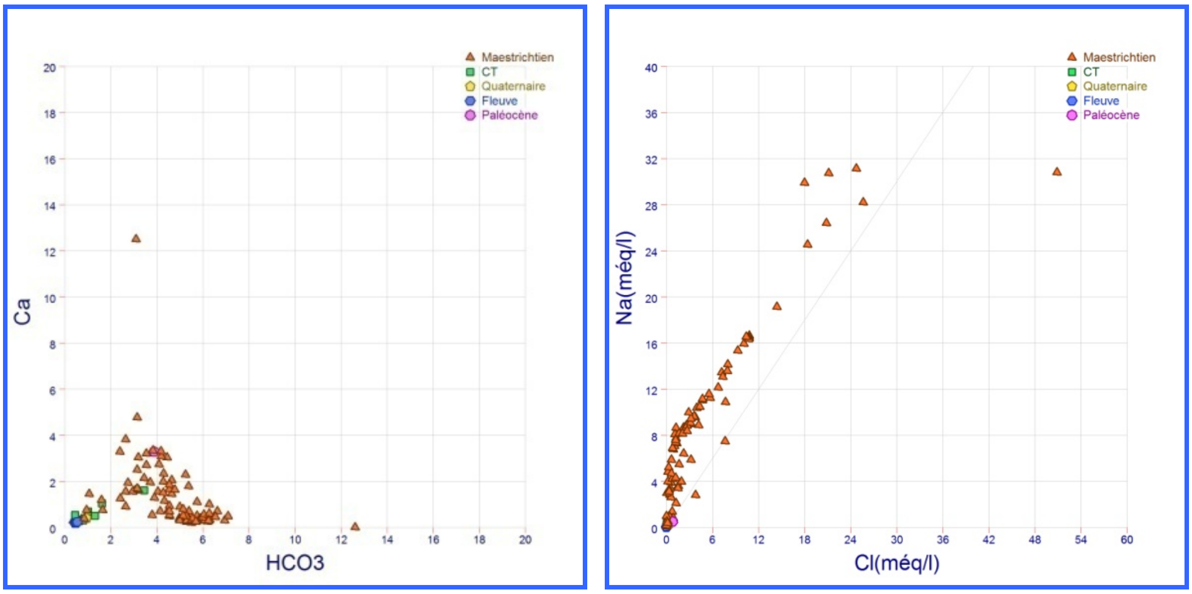


Figure 18: Relationship between Ca^{2+} and HCO_3^-, and Na^+ and Cl^-.

Groundwater samples in Central West part of the Basin lie on a trend line below the Meteoric Water Line, a feature which is typical of old ground water in the Northern part of Africa. Considering the CT samples position (green points), this graph also strongly suggests a recharge of the Continental Terminal aquifer by upward leakage from the Maastrichtian aquifer in the Central part of the basin.

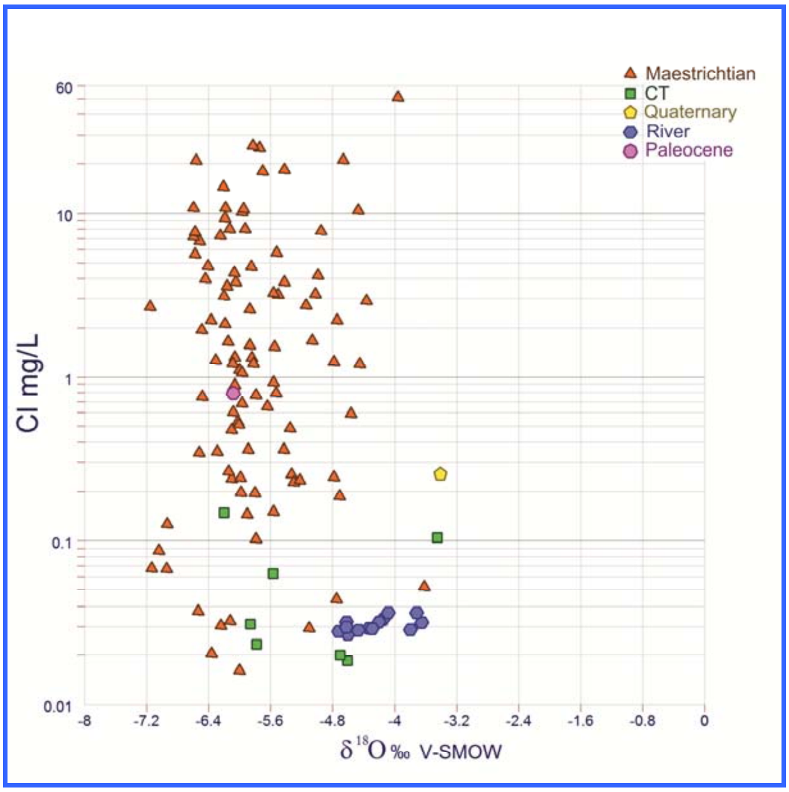


Figure 19: Relationships between $\delta^{18}O$ and Cl contents

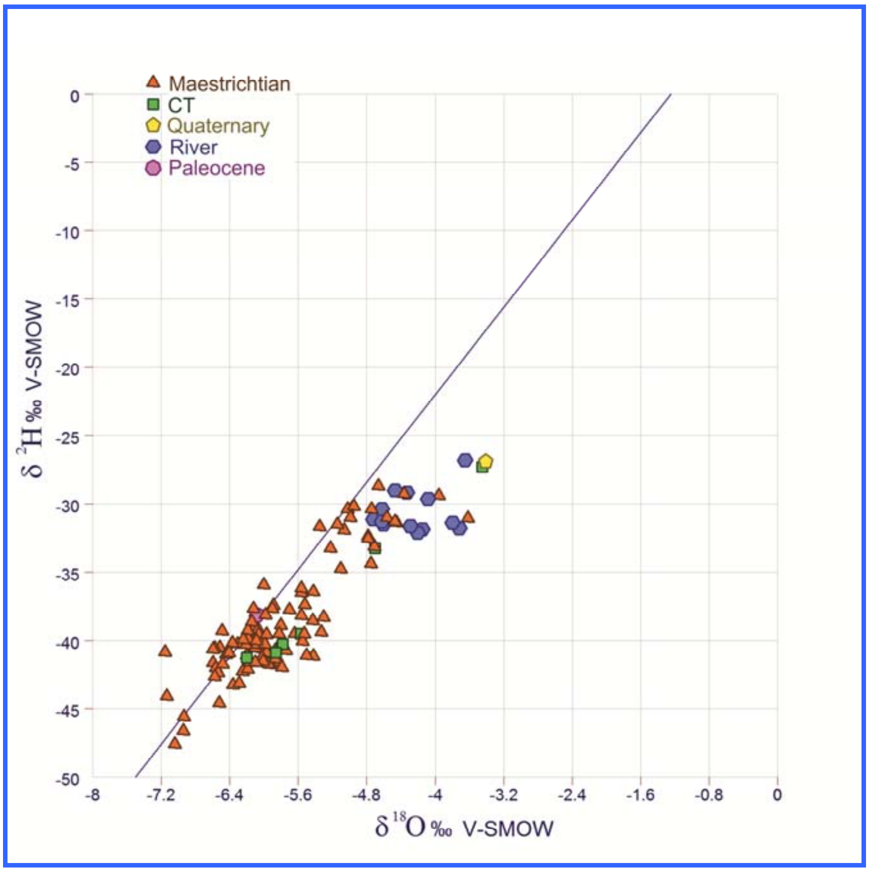


Figure 20: Stable isotope contents of the Senegalese part of the basin.

4.2. Recharge of the aquifer systems on the two sides of the Senegal River

The isotopic input signature

- The stable isotope composition of rainfall around the Senegal River has been measured in the past, e.g. in 1981 at Richard Toll (Travi et al., 1987) and in 2010 at Rosso and Idini (Mohamed, 2012) and some current data were acquired in the present project. At Idini (Central part of the Mauritanian basin), based on 5 rainfall events (August and September) the measured isotopic values range from – 5.93‰ to – 6.13‰ and -37,9‰ to -40.2‰ for $\delta\,^{18}O$ and $\delta\,^{2}H$ respectively. At Rosso (close to the Senegal River) based on 10 events (July, August and September) the measured isotopic values range from -0.49‰ to -7.99‰ and from -3.6 ‰ and -60.7 ‰ for ^{18}O and ^{2}H respectively. The $\delta\,^{18}O$ weighted mean value is -6‰ at Idini and -4.5‰ at Rosso. In 1981, at Richard Toll the $\delta\,^{18}O$ weighted mean values were -5.38‰ and -5.83‰ for July and August rainfall respectively.

- Stable isotopic composition of the Senegal River_has already been investigated in previous studies (Illy, 1972, Diagana, 1994) but often the sampling period is not known or this period is not representative as stable isotope contents display strong variations between dry and wet season. The aquifers recharge can occur essentially during flooding period. As a consequence, we only consider the data collected during and just after the rainy season. The Senegalese staffs involved in the project have sampled the Senegal River in November 2013 and at the end of June 2016 (see the sampling location in Figs. 11 and 12). The $\delta^{18}O$ contents range from -4.72‰ to -3.34‰, while the $\delta^{2}H$ contents range from 32.1‰ to 22.2‰.

Thus, to investigate possible ground water recharges from rainfall and/or from River Water, one must consider that rainfall stable isotopic signature is significantly more depleted compared to Senegal River signature. But we must keep in mind that paleo River water also could be more depleted compared to the present values, reflecting changes in the isotopic signature of regional rainfall during the late Pleistocene and early Holocene.

Tritium values have also been measured in the framework of the project. The tritium content of the Senegal River water sampled at the North east of Senegal basin ranges from 3.2 to 3.4 TU. Rainfall water collected at Kaedi in the same area varies between 2.7 and 6.3 TU.

Groundwater recharge on the Senegalese side of the Senegal River

If we exclude samples close to the Senegal River and the B-202 and B-040 samples, stable isotope signature does not correspond to the present signature of the Senegal River. It is worth noting that even the sample B-051 of actual age displays a present-day rainfall signature. The two samples B-202 and B-040 are of actual age. Their most enriched stable isotopic signature could be interpreted as a recent recharge from the “Lac de Guiers” probably enhanced since the commissioning of the Diama dam. This is also supported by a slight evaporated signature (Fig.21).

At the annual scale, no significant changes can be observed between the first sampling (November 2013) and the second sampling (June 2016) suggesting that the Senegal River does not supply significantly the Maastrichtian aquifer in this area (Fig.21).

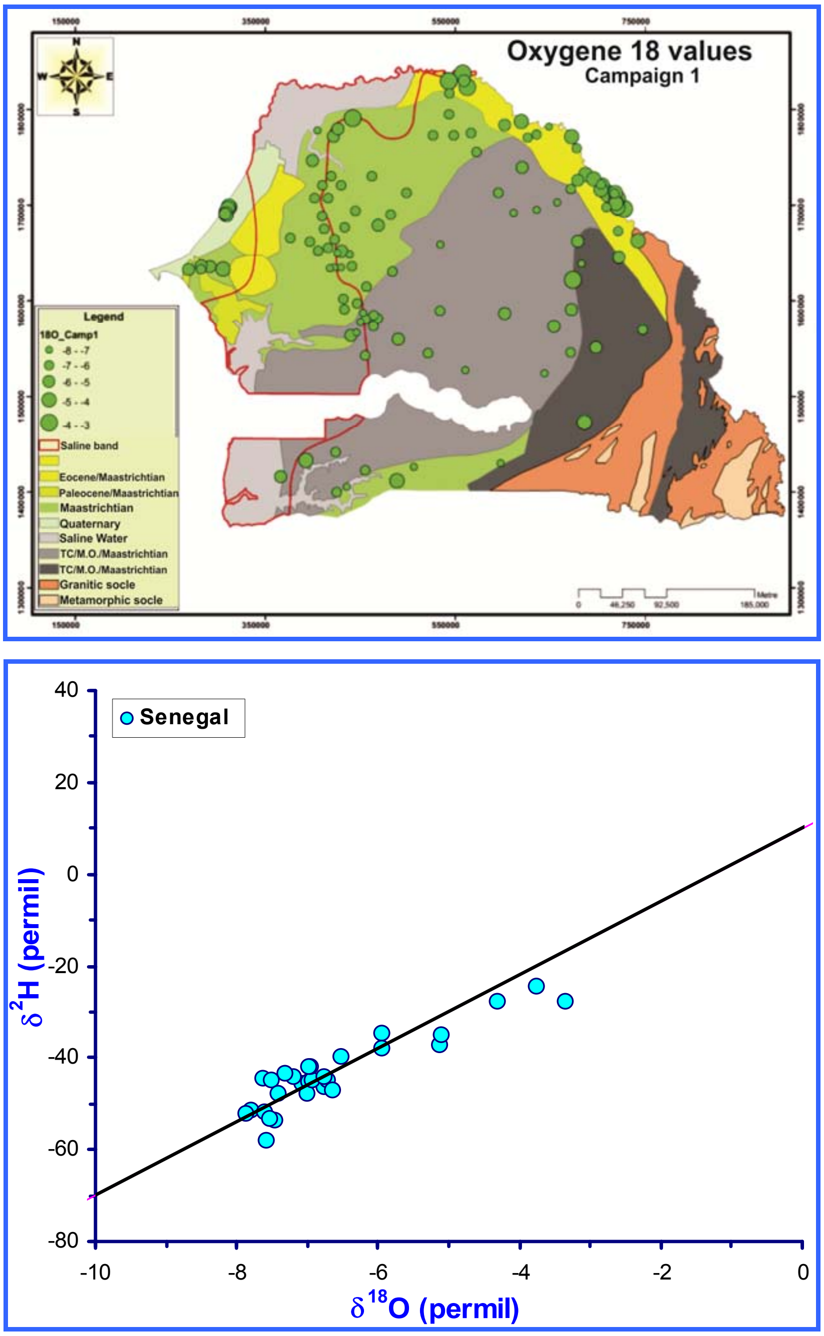


Figure 21: Spatial distribution of the $\delta^{18}O$ contents (campaign 1) and plot of $\delta^{18}O$ vs $\delta^{2}H$ for the 2nd campaign (North eastern side).

The interpretation of ^{14}C activities (Fontes & Garnier model) clearly indicates that almost all groundwater samples refer to Late Pleistocene recharge (transit time between 20,000 and 35,000 years) and a flow direction toward the North West. Holocene recharge from the Senegal River in 2 places, formerly suggested (Travi, 1988) probably exists, if we consider the age estimation of the first points of two profiles (13,000 and 18,000 years) which could correspond to a mixing between Pleistocene and more recent groundwater. The tritium contents, under the detection values, suggest a Holocene recharge, as observed in the Western border of the basin, in the “Horst de Ndiass” area” (Travi, 1988). Nevertheless this contribution is relatively few and the groundwater flow is mainly driven by the recharge in the South east along the “Senegal oriental” basement rocks.

The southernmost profile (B-068- B067) indicates present recharge and a Holocene recharge (5000 years, late Holocene). Based on this transit time and the distance of 25 km between the 2 boreholes, it is possible to estimate the ^{14}C velocity to be around 5m/y (Figs 22 and 23).

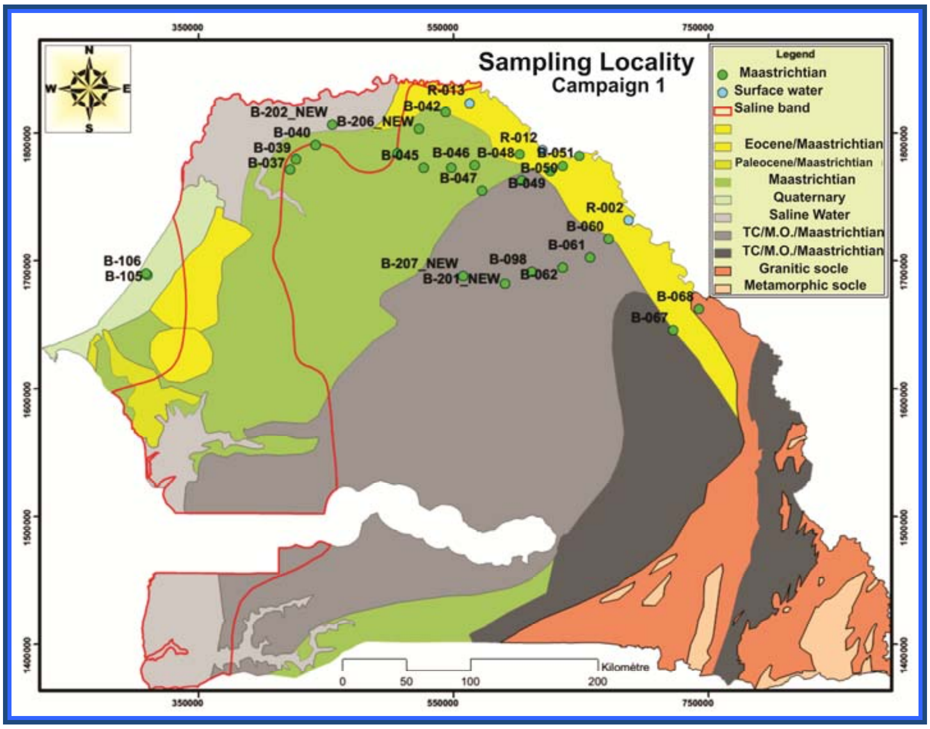


Figure 22: Sampling for ^{14}C dating along selected flow-paths.

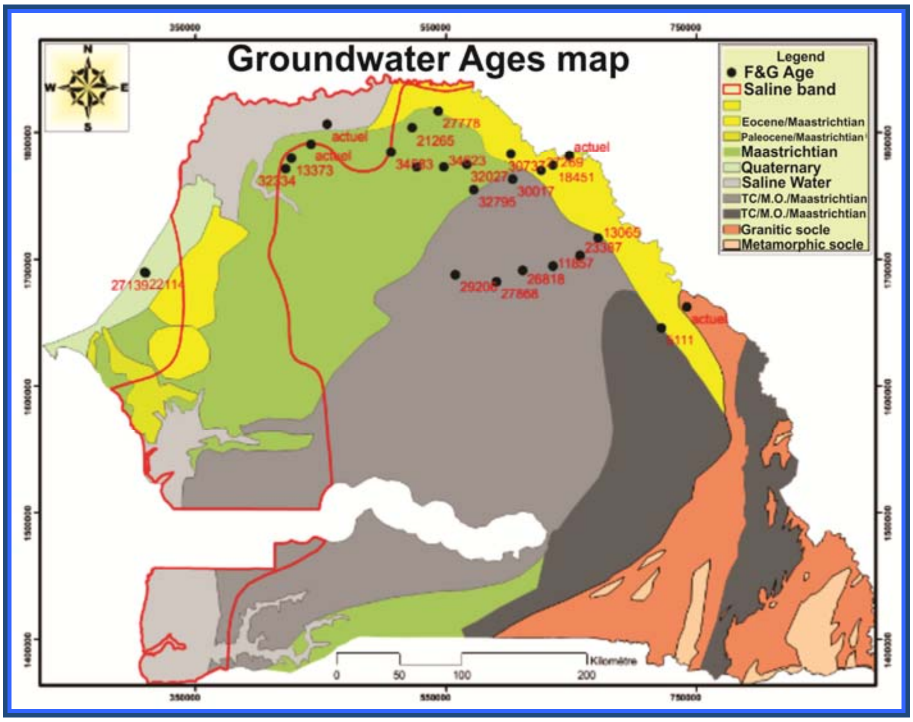


Figure 23: ^{14}C corrected transit times using the Fontes and Garnier model

Recharge on the Mauritanian side of the Senegal River

Stable isotopes show a large heterogeneity (Fig.15) and all the quaternary samples show more or less evaporated water. Some of CT and Eocene groundwater also display evaporative signature. This indicates infiltration from surface water (oued, lake, small senegal River tributaries or ponds).

Two evaporation lines seems to be distinguished and the stable isotope values observed on the plot ^{18}O vs ^{2}H allow, especially for the Eocene aquifer, two input signature to be considered. This suggest that all the groundwater could originate from rainfall or Senegal River. This is supported by the tritium contents which show an irregular decrease from the River towards the centre of the basin (Fig. 24). It is note worthing that the Quaternary aquifer and a part of the CT aquifer are recharged by present day rain fall or River water (Fig. 25). On the contrary, the deeper aquifer systems (CT and Eocene) are recharged by more ancient water. A rough calculation, using a "piston flow" model indicates that 44% of CT groundwater and 40% of Eocene groundwater have been recharged before 1961, while all the shallow groundwater (mainly Quaternary Aquifer) are later than 1961.

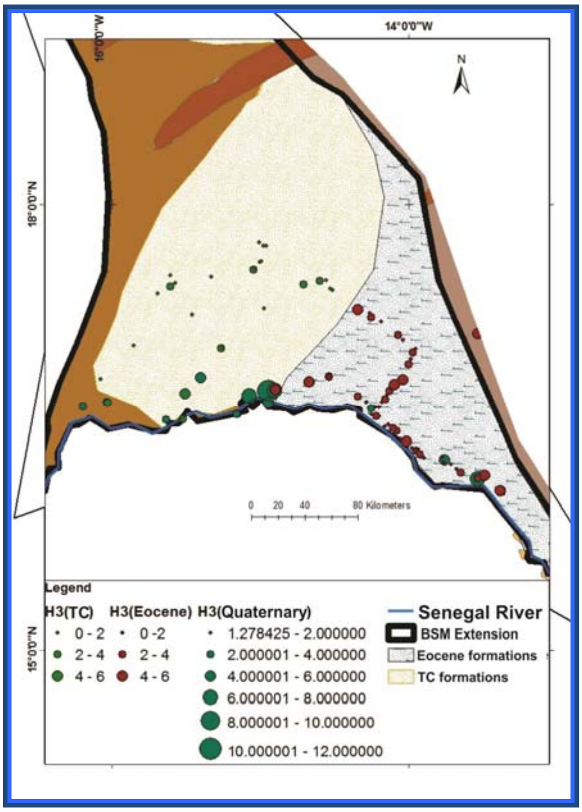


Figure 24: Tritium content evolution in the Mauritanian part of the SMB

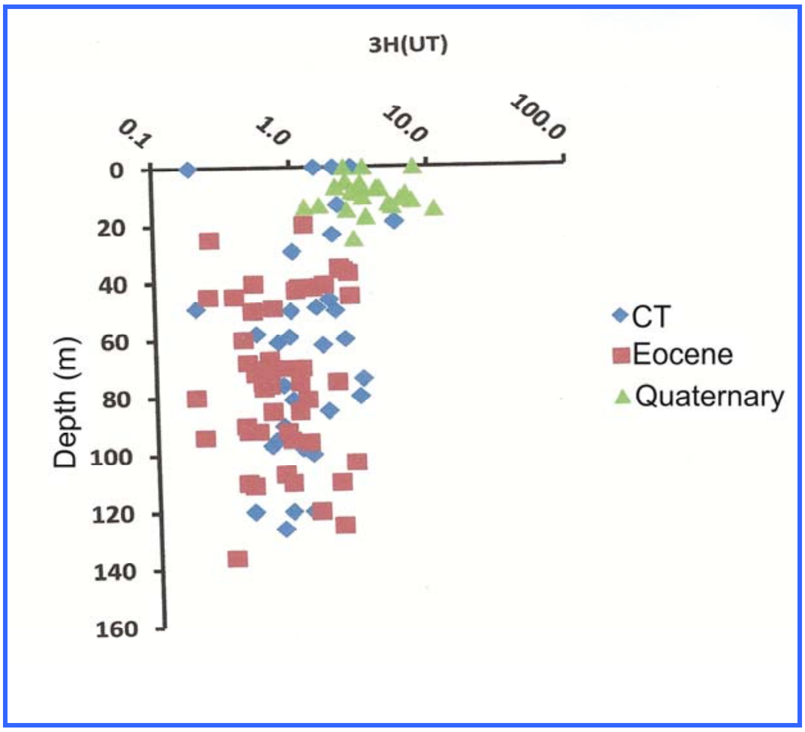


Figure 25: Tritium content vs groundwater depth

Nine radiocarbon measurements have been carried out. They give values between 56 and 76% modern carbon for CT and Quaternary aquifers (6 samples) and 25 and 52% modern carbon for Eocene aquifer (3 samples) and $\delta^{13}C$ values clearly indicate that carbon dilution has occurred. Corrected carbon activities, using the Fontes and Garnier model which seems the most adequate in these aquifer systems, indicate recent recharge except for 2 Eocene aquifer samples. Estimated groudnwater ages for these two samples are >100 yr and about 2,800 yr, showing that some ancient groundwater lies in the deeper part of the Eocene aquifer, recharged during the late Holocene humid period.

An attempt for calculating a recharge rate is by using the simple formula: recharge rate = porosity x depth / age. In this case, the formula provides very low values of recharge,which is consistent with other estimates; about 5% of the annual precipitation, Mohamed (2012), using water balance considerations and hydrodynamic approaches. This finding supports the hypothesis that an important source of the aquifer recharges is lateral infiltration from the Senegal River.

4.3. Salinization: general processes and location of the limit in the Maastrichtian aquifer

The plot $\delta^{18}O$ *vs* EC (Fig. 26) confirms the relatively large range of $\delta^{18}O$ values in the Central part of the aquifer, already observed before (Figs 19 and 20). In addition, the d-excess signature confirms the presence of very old groundwater. It may be noted that the stable isotope contents are relatively enriched compared with values observed in deep groundwaters of the eastern continental basins. This could be due to the proximity of the Atlantic Ocean and locally, to a possible mixing with connate water induced by excessive withdrawal.

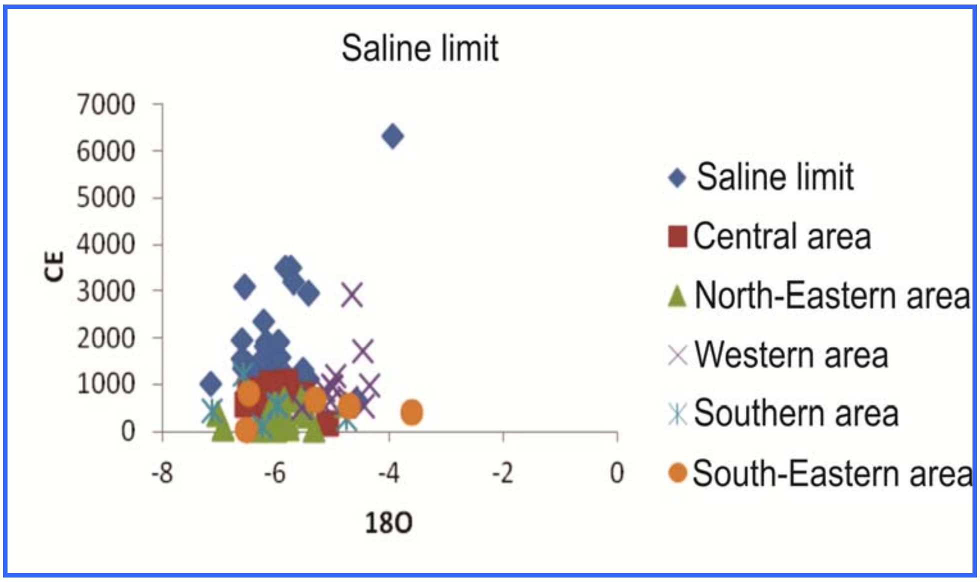


Figure 26: Plot of $\delta^{18}O$ vs EC in the Maastrichtian aquifer

Mapping of the new chemical data allows the limits of the western saline zone to be more clearly defined. However, Fig. 27 clearly demonstrate that the limit could be better defined and drawn using mainly chloride and bromide. Finally, boron and fluoride contents, often considered as good indicators, seem to be more associated, in this case, to marine clays sediments than the presence of saline groundwater (see map in Annex III).

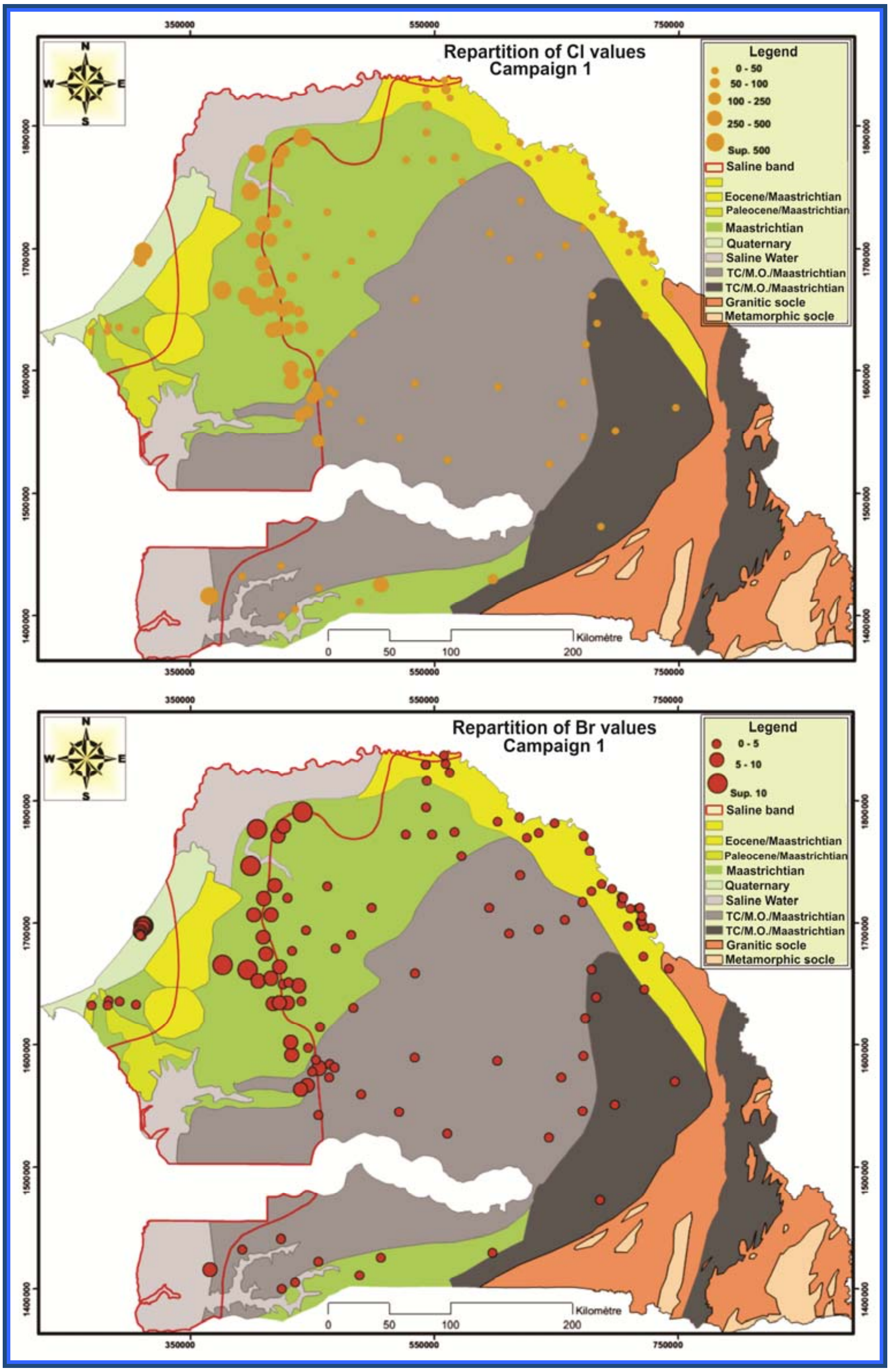


Figure 27: Chloride and bromide distribution maps of the Maastrichtian aquifer

In Mauritania, as already observed (Figs 15 and 16), the plot Cl^- vs. $\delta^{18}O$ clearly indicates a significant influence of evaporative process. But the $Cl^-/\delta^{18}O$ relationship, generally used for characterising salinization processes does not clearly indicate a dominant evaporation role. This is confirmed by comparing the total mineralization with different evaporating levels as shown in Fig. 28. From these graphs, it emerges that high concentrations are not mainly related to evaporative process, although evaporation on surface water before and during their infiltration has also strongly marked geochemical signature.

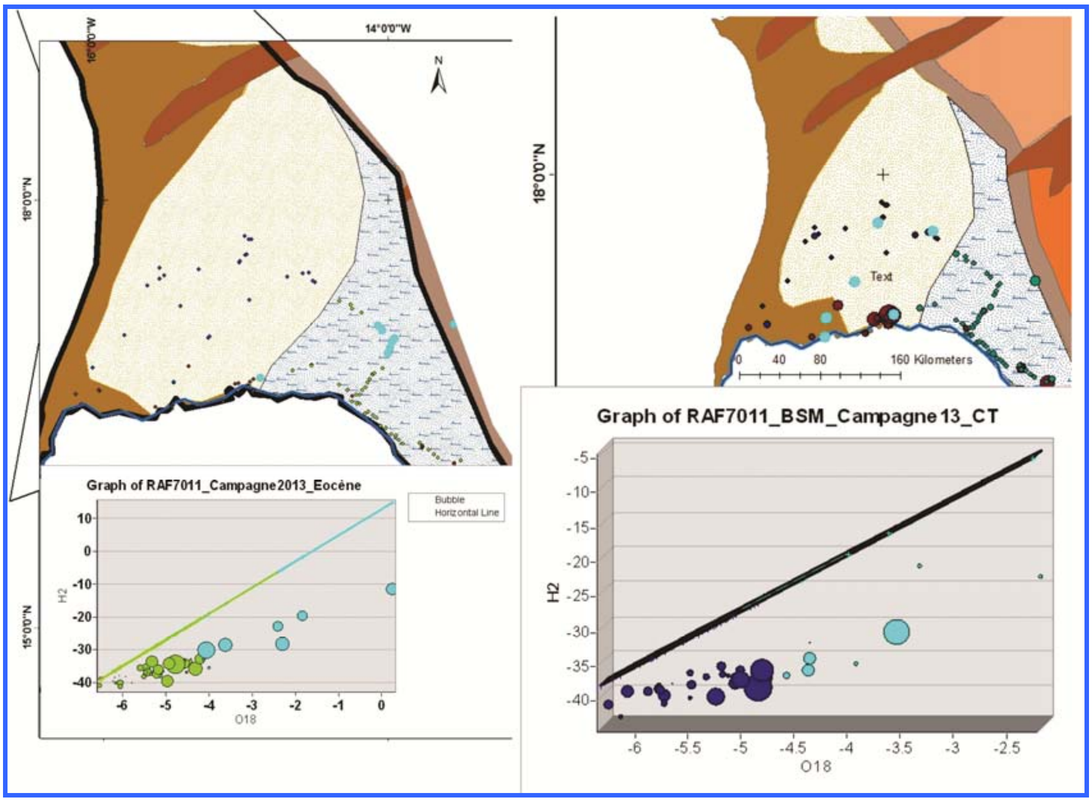


Figure 28: Evaporated water samples location and different evaporating levels compared with total mineralisation, in the CT and Eocene aquifers.

The mechanisms of such salinization are clearly identified through the ratio Na^+/Cl^- as shown in Fig. 29. Two ways, namely halite dissolution and mixing with sea water, clearly contribute to mineralisation increase.

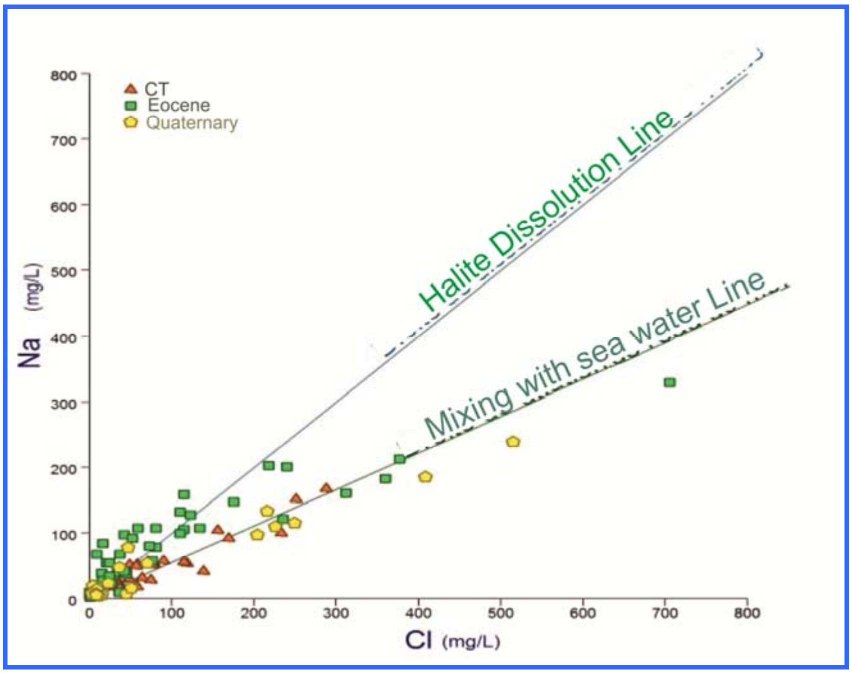


Figure 29: Relationship between Cl and Na in the Mauritanian aquifer system

In Mauritania, it is well known that groundwater quality is largely influenced by the residues of Quaternary transgressions. However, in the Eocene aquifer it is mainly due to dissolution of salt deposits rather than mixing with salt water. Thus, in the Quaternary and CT aquifer systems mixing with sea water is the dominant process, locally enhanced by evaporation. It is worth noting that such a mixing could regularly occur during marine intrusion along the Senegal River and its tributaries. This phenomenon has continued up to the present time and has probably been stopped by the Diama dam construction.

5. CONCLUSIONS

The two main themes addressed by the project were "recharge and salinization". The major findings provided by field and laboratory investigations using chemical and isotopic approaches, as well as interpretations described in this report, could be summarized as follow:

- New major information on recharge and palaeorecharge as well ground water flow in the Eastern and North Eastern part of the Maastrichtian aquifer, southern side of the Senegal River (Senegal). Despite a slight contribution during the late Holocene the Senegal River does not provide a significant recharge.

- New information on conditions and mechanisms of recharge in the shallower aquifers (Quaternary, CT and Eocene) Northern side of the Senegal River (Mauritania). Vertical recharge from rain fall and lateral from Senegal River are clearly differentiated.

- New information on the geographical limit of saline ground water in the Central part of the Maastrichtian Aquifer in Senegal, which has better been defined using Cl and Br-tracers. The connate origin of the salinization process is strongly suspected, but need to be more investigated.

- The two main ways of mineralization, namely evaporate dissolution and mixing with sea water, are clearly identified. Evaporation significantly enhances the process.

Equally important, the project allowed the chemical and isotopic database in Senegal and Mauritania to be significantly confirmed and completed. In Senegal, significant amount of isotopic data was already available, but the new investigation has covered two areas relatively poorly known:

i) At the East and North East of the basin, ground water of Late Pleistocene age have been identified proving the major role of rainfall recharge at the far South East limit of the basin, along the basement rocks boundary. Carbon-14 data also suggests a very limited recharge from the Senegal River (probably a slight contribution during the late Holocene);

ii) In the Centre West of the basin the saline limit has been clearly defined using Cl and Br tracing. Boron and Fluoride, which display significant concentrations in this area, are not directly linked to saline water but most probably to be related to the nature of the reservoir (marine clays).

In Mauritania, chemical and isotopic data are scarcer and the project allowed the density of the network, especially in the Trarza and Brakna aquifer systems to be expanded. Then, the knowledge base has been significantly improved in terms of recharge and salinization processes:

- i) Quaternary aquifer and a part of the CT aquifer are recharged from present day rainfall or from Senegal River. The deeper aquifer systems show relatively more ancient water and late Holocene water have been identified in the Eocene aquifer. Stable isotopes and radioisotopes suggested the predominant role of the Senegal River in affecting recharge.

- ii) Stable isotope data and chemical bivariate plots clearly indicated that the mineralization increase mainly originates from evaporates dissolution and/or mixing with sea water, often linked to Quaternary marine invasion. The important evaporative effect on surface water before and during their infiltration has a strongly marked geochemical signature.

Recommendations

In Senegal, expanding knowledge of the Maastricthian aquifer is the main challenge for water supply in the future. Its exploitation is significantly increasing without a sound management plan as available studies are relatively scattered and only give aquifer capacities in localized zones. There is an urgent need for modelling this aquifer as a whole, considering palaeohydrological aspects, to assure a suitable groundwater management in the future.

The IAEA-supported project RAF/7/011 project made a significant contribution, but to achieve this goal some complementary information is needed:

-Reliable information on the present-day aquifer recharge in the Northern limit around the “Lac de Guiers”, and in the Southern limit in Guinea Bissau.

-Exact nature and evolution of the Central West saline zone.

-Some complementary palaeohydrological information in the Central zone.

For this purpose, the following recommendations are suggested:

- Classical isotope methods (stable isotope, tritium and ^{14}C) should continue to be used for recharge problem around the "Lac de Guiers". This requires installing a piezometric network around the Lake, and to establish one (or two, if possible) sampling station on the Senegal River (IAEA GNIR Network?) for a better knowledge of the River isotopic signature.

- The Central zone should be more investigated using other radio isotopes which allow longer transit time to be determined as well as chemical trace elements (Bore and Lithium seems to be good indicators of the presence of connate water and could be more used to study upward leakage from the deep part of the system). Nevertheless, such studies should benefit from the new overall synthesis of all isotopic data provided, and often partially interpreted, through the numerous IAEA- supported projects and academic works.

- Finally, collaboration should be initiated with the Guinea Bissau Water Authorities in order to investigate (stable and radio isotopes) the Southernmost recharge zone of the Maastrichtian aquifer.

In Mauritania, quantification of the available resources of the Trarza and Brakna aquifers is fundamental requirement for ensuring a sustainable water supply. This implies modelling these aquifers after improving the knowledge of the recharge and the extension of saline water.

As for Senegal, the IAEA-supported project RAF/7/011 made a significant contribution to this purpose. It is recommended to continue the isotopic investigations, but only if such a study is associated with a reliable piezometric network since the maximum benefit will be gained when simultaneous isotope, geochemical and hydrodynamic data are incorporated.

Before starting new projects in the two countries a global assessment of groundwater resource is strongly recommended using the IWAVE approach.

6. REFERENCES

Audibert M. (1970) **:** Delta du fleuve Sénégal : Etude hydrogéologique. Projet hydroagricole du bassin du fleuve Sénégal. Tome III : Hydrogéologie. Tome IV : drainabilité, rapport projet AFR/REG-61. FAO/OERS.

Bellion Y. (1987). Histoire géodynamique post-paléozoïque de l'Afrique de l'Ouest d'après l'étude de quelques bassins sédimentaires (Sénégal, Taoudéni, Iullemmeden, Tchad). Thèse d'Etat sciences : Univ. d'Avignon et des pays du Vaucluse, 296 p., 126 Fig. et 213 Tab.

Bonkel A., 1989 : Etude de la répartition des paramètres hydrochimiques des eaux souterraines de l'aquifère alluvial situé en rive droite du fleuve Sénégal entre Keur-Macène et Dagana. Mémoire IST, UCAD, Dakar.

Diao S.M., 1992. - Etude des aquifères alluviaux de la vallée du fleuve Sénégal (Secteur Rosso - Dagana - Lac de Guiers) rapport de DEA Dépt. Géol., Fac. Sci.,Univ. C.ADIOP de Dakar 71 p.

Diagana A., 1994 : Etudes hydrogéologiques dans la vallée du fleuve Sénégal de Bakel à Podor : Relations eaux de surface/eaux souterraines. Thèse Doctorat 3ème cycle. FST-UCAD, 127p. et annexes.

Diaw M. (2008**)** Approche hydrochimique et isotopique de la relation eau de surface / nappe et du mode de recharge dans l'estuaire et la basse vallée du fleuve Sénégal, Thèse 3éme cycle, Université de Dakar. 210 p.

Dieng B., 1987 : Paléo hydrologie et hydrogéologie quantitative du Sénégal. Essai d'application des anomalies observées. Thèse Ecole des Mines de Paris, 168 p.

EQUESEN (1993). Environnement et qualité des eaux souterraines. Projet CEE TS 20198 F EDB - Rapport de synthèse Tome 4.

Faye A. (1983). Contribution à l'étude géologique et hydrogéologique du horst de Ndiass et de ses environs (Sénégal occidental). Thèse 3eme cycle Univ. Dakar. 160p, 74fig, 10 tab.

Faye A. (1994). Recharge et paléo recharge des aquifères profonds du bassin du Sénégal. Apport des isotopes stables et radioactifs de l'environnement et implication paléo hydrologique et paléo climatique. Thèse Doc. ès-Sciences, Université de Dakar, 185p.

Faye S. (2005). Apport des outils géochimiques et isotopiques à l'identification des sources de salinité et à l'évaluation du régime d'écoulement de la nappe du Saloum. Thèse de Doctorat d'Etat, és Sciences, Université Cheik Anta Diop, Dakar, p.

Gaye CB. (1980). Etude hydrogéologique hydrochimiques et isotopique de la nappe aquifère infra basaltique de la presqu'île du Cap-Vert (Sénégal). Thèse de 3éme cycle UCAD, 1980; 131p.

Gaye CB. (1990). Etude isotopique et géochimique du mode de recharge par les pluies, et de décharge évaporatoire des aquifères libres, sous climat semi – aride au nord du Sénégal. Thèse de doctorat d'état Dépt. Géol., Fac. Sci. Univ. C.ADIOP, Dakar, 243 p.

Illy P., 1973 : Etude Hydrogéologique de la Vallée du fleuve Sénégal. Projet hydro agricole du bassin du fleuve Sénégal. Rapport 65061, Dakar, OMVS, 58 p.

Madioune, D.H., 2012. Etude hydrogéologique du système aquifère du horst de Diass en condition d'exploitation intensive (bassin sédimentaire sénégalais): apport des techniques de télédétection,

modélisation, géochimie et isotopie. Thèse de doctorat en sciences de l'Ingénieur/Université de Liège/Faculté des Sciences Appliquées, 325p.
Madioune D.H., Mall I., Faye S., Crane E., Upton K., Ó Dochartaigh B.É. (2016). Africa Groundwater Atlas. Hydrogeology of Senegal.

Mohamed A.S. (2012): Approches hydrodynamiques et géochimique de la recharge de la nappe du Trarza, Sud-ouest de la Mauritanie. Thèse IRD/Université Paris Sud, 148 p. et annexes.

OMVS/USAID, 1990: Rapport de synthèse hydrogéologique du delta du fleuve Sénégal. Projet

OMVS/USAID 625-0958. Eaux souterraines. Rapport final. Dakar, Sénégal. Volume II, p. 63 et Annexes.

Saos J.L., Kane A., Carn M., Gac J.Y. (1984). Persistance de la sécheresse au Sahel : invasion marine exceptionnelle dans la vallée du Fleuve Sénégal. 10 ème réunion annuelle Sci. Terre, Bordeaux, p. 499.

Sarr, B. (2000). Contribution à l'étude hydrogéologique des aquifères de l'Ouest du bassin du Sénégal. Thèse Docteur 3éme cycle. Fac Sci. UCAD, 128p + annexes.

Semega B.M. (1999). Interaction physico-chimiques des eaux de la nappe côtière du Trarza à Idini et long du littoral sud (Thèse de doctorat). Université de Nice-Sophia Antipolis, 235 p.

Upton K., Ó Dochartaigh B.É. (2016). Africa Groundwater Atlas. Hydrogeology of Mauritania.

Touzi S. (1998). Formalisation des échanges fleuve-nappe en présence de zones d'inondation : Cas de la de la régularisation des crues du fleuve Sénégal. Mém. DEA « Sci. de l'Eau dans l'Environnement Continental », ENGREF, paris, 100 p.

Travi Y., Gac J. Y., Fontes J. C., Fritz B., 1987 : Reconnaissance chimique et isotopique des eaux de pluie au Sénégal. Géodynamique, 2 (1), 43-53.

Travi Y., 1988: Hydrogéologie et Hydrochimie des aquifères fluorés du Bassin du Sénégal. Origine et conditions de transport du fluor dans les eaux souterraines. Doctorat ès Sciences thesis. Paris Sud University, 190 p. « Hydrogéologie et Hydrochimie des aquifères du Sénégal, Hydrogéochimie du fluor dans les eaux souterraines », Mém. Sci. Géol., N°95, 1993, 155p.

ACRONYMS

CT: Continental Terminal

EC: Electrical Conductivity

ENIS: National Engineer School of Sfax

GNIR: Global Network of Isotopes in Rivers

IAEA: International Atomic Energy Agency

MAU: Mauritania

Q: Quaternary

SMB: Senegalo-Mauritanian Basin

TDS: Total dissolved salts

DGPRE : Direction de la Gestion et de la Planification des Ressources en Eau (DGPRE)

ANNEXES

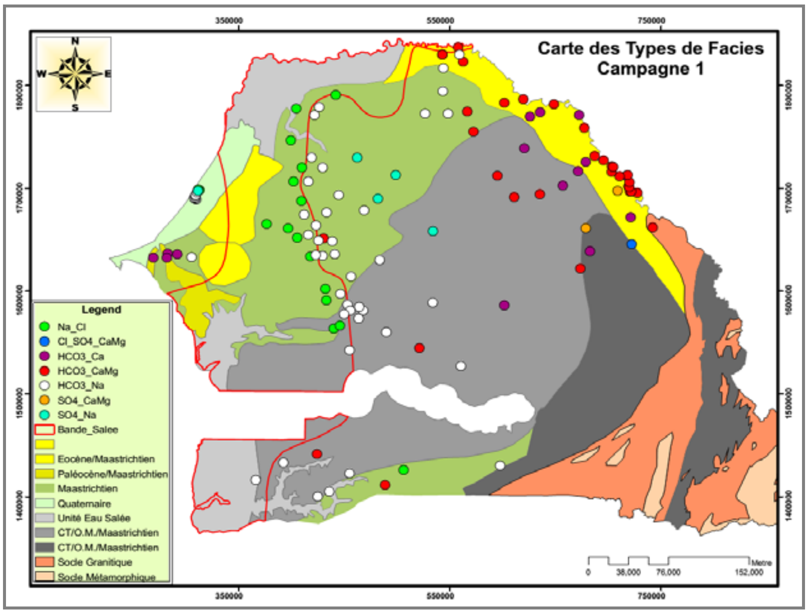
Annex I - Field, hydrochemical and isotope data generated in the framework of the IAEA-supported project RAF/7/011. A template with all the analytical results is separately provided

Annex II - ^{14}C-derived transit time calculation for the North Eastern part of the Senegalese Basin (Diagramme software)

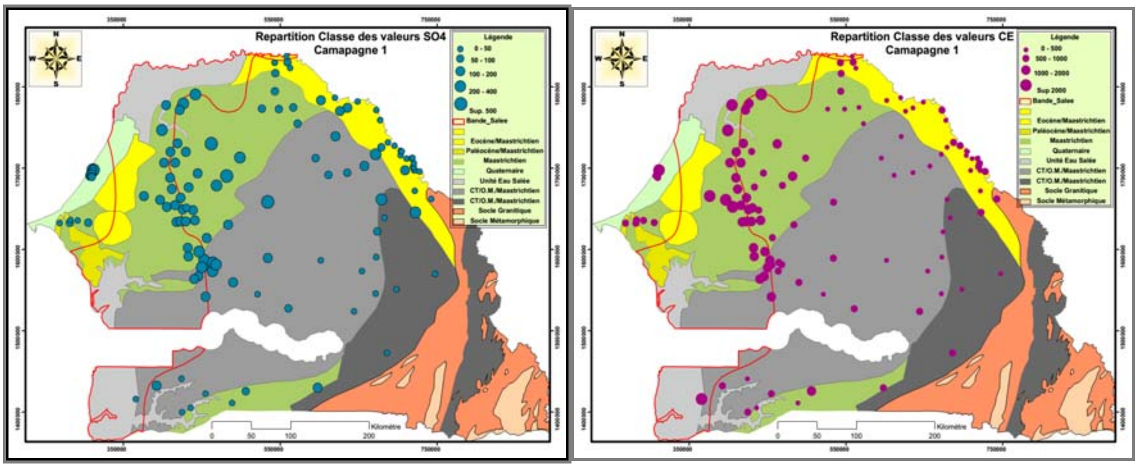
Nom	T°C	pH	TAC (meq/l)	$A^{14}C$	Erreur	$\delta^{13}C$	$\delta^{13}C$	$A^{14}C$	Matrice		brut	Tamers	Pearson	Mook	F & G	AIEA	Evans	Olive	eg_c	$d^{13}Ceq$	
									$\delta^{13}C$	$A^{14}C$											
B037	36,1	7,79	6,00	1,27	0,3	-11,250	-19	100	0	0	36095	30622	31762	35480	32334	35416	31291	29228	-8,9	-17,80	-12,49
B039	34,7	7,62	3,80	8,86	0,3	-8,590	-19	100	0	0	20036	14681	13473	17815	13373	17223	12667	13042	-9,1	-15,15	-12,46
B040	34,2	6,94	4,30	9,47	0,3	-2,040	-19	100	0	0	19486	15191	1038	9404	actuel	4822	actuel	11147	-9,1	-7,50	-13,54
B042	35,3	7,96	4,55	2,68	0,3	-12,870	-19	100	0	0	29921	24368	26701	30215	27778	30409	26387	23139	-9,0	-19,58	-12,35
B044	36,8	7,41	4,05	1,16		-12,990	-19	100	0	0	36844	31690	33700	36954	34623	37307	33379	29623	-8,8	-19,15	-12,85
B045	36,9	7,54	4,50	1,24		-13,620	-19	100	0	0	36293	31001	33541	36759	34655	37141	33266	29228	-8,8	-19,91	-12,73
B046	36,4	7,62	4,50	1,35		-11,490	-19	100	0	0	35590	30231	31432	35039	32027	35066	30981	28600	-8,9	-17,90	-12,62
B047	36,9	7,2	4,30	1,38		-12,690	-19	100	0	0	35408	30556	32072	35230	32795	35672	31725	27824	-8,8	-18,54	-13,16
B048	35,9	7,42	3,90	1,62		-11,780	-19	100	0	0	34083	28920	30131	33618	30737	33798	29716	26872	-8,9	-18,04	-12,76
B049	37,4	7,41	5,05	0,94		-5,250	-19	100	0	0	38582	33427	27949	33583	27269	31516	25895	31363	-8,8	-11,36	-12,91
B050	33,8	6,94	3,6	4,52		-8,230	-19	100	0	0	25600	21308	18683	22429	18451	22496	17839	17256	-9,2	-13,72	-13,51
B051	32,1	6,14	0,55	84,6		-4,110	-19	100	0	0	1386	actuel	actuel	actuel	actuel	actuel	actuel	actuel	-9,4	-6,37	-16,74
B060	36,1	7,24	3,9	8,98		-8,450	-19	100	0	0	19925	15010	13226	17301	13065	16880	12351	12419	-8,9	-14,43	-13,03
B061	37,9	6,9	3	3,18		-10,320	-19	100	0	0	28507	24286	23461	26639	23387	26995	22845	20059	-8,7	-15,40	-13,92
B062	37	6,6	2,6	9,18		-7,730	-19	100	0	0	19743	16397	12308	15378	11857	15901	11243	9778	-8,8	-11,85	-14,88
B067	39,3	6,34	2,1	32,6		-11,710	-19	100	0	0	9259	6738	5257	7120	5111	8700	4785	actuel	-8,5	-14,64	-16,07
B068	33,1	6,48	2,05	93,6		-12,850	-19	100	0	0	549	actuel	actuel	actuel	actuel	1178	actuel	actuel	-9,3	-16,65	-15,20

B098	37,3	6,9	3	2,1		-10,320	-19	100	0	0	31937	27720	26892	30081	26818	30465	26288	23483	-8,8	-15,45	-13,88
B105	43	8,11	4,7	0,89		-4,970	-19	100	0	0	39034	33426	27948	34084	27139	31158	25234	32309	-8,1	-10,99	-13,06
B106	42	8,25	5,15	1,37		-4,290	-19	100	0	0	35468	29827	23166	29945	22114	26437	19846	28777	-8,2	-10,44	-12,96
B201	37,4	6,69	2,6	1,97		-11,000	-19	100	0	0	32466	28836	27947	30663	27868	31514	27426	23040	-8,8	-15,44	-14,56
B202	32,4	6,81	4,3	51		-7,800	-19	100	0	0	5562	1626	actuel	1763	actuel	2113	actuel	actuel	-9,4	-12,98	-13,83
B203	36,9	7,7	3,1	1,27		-13,720	-19	100	0	0	36095	30676	33403	36659	34583	37004	33136	29170	-8,8	-20,14	-12,61
B204	37,4	7,24	3,1	1,88		-12,430	-19	100	0	0	32852	27932	29344	32551	30017	32911	28969	25353	-8,8	-18,30	-13,14
B205	34,3	7,64	4,55	5,49		-12,290	-19	100	0	0	23993	18623	20391	23966	21265	24169	20043	17015	-9,1	-18,91	-12,41
B206	37,4	6,86	3,3	1,8		-11,650	-19	100	0	0	33212	29097	29168	32083	29206	32735	28718	24600	-8,8	-16,65	-14,00

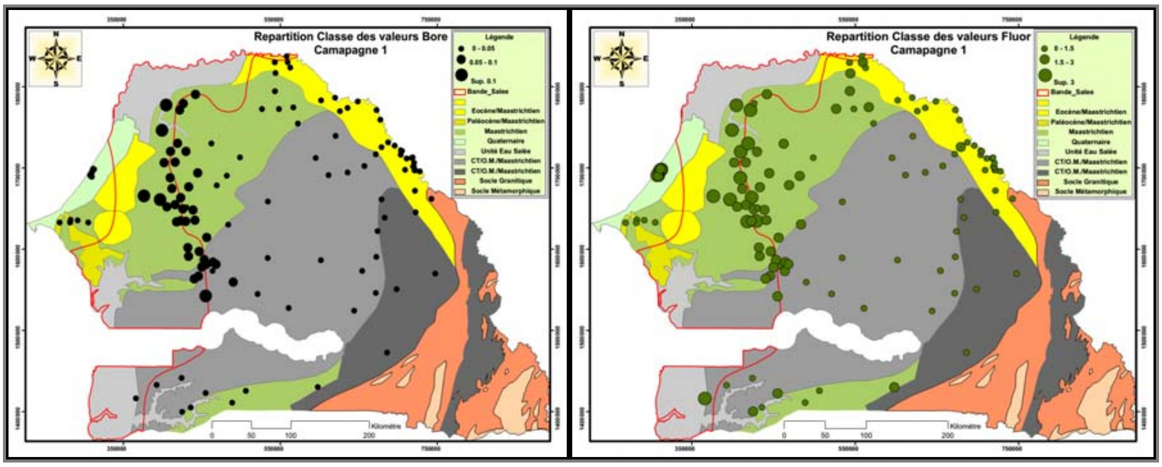
Annex III – Maps of spatial distribution of relevant hydrochemical-isotopic variables



Chemical facies in the Senegalese Maastrichtian aquifer



SO_4 and Electrical Conductivity maps along the saline limit in the Senegalese Maastrichtian aquifer



Boron and fluoride maps along the saline limit in the Maastrichtian aquifer