

Origin and distribution of saline groundwater in the Saloum (Senegal) coastal aquifer

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ABSTRACT

Seawater has entered the Saloum River system and encroached up to 100 km inland, contaminating surface water and the superficial groundwater resources. A hydrogeochemical study reveals four major water types occurring in the study area, namely Na-rich saline groundwater, Ca-Na-rich saline groundwater, Na-dominant fresh groundwater and Ca-dominant fresh groundwater. A hydrochemistry zonation model of the aquifer, based on the presence of different water types and on the groundwater flow, has led to the identification of the main processes controlling the groundwater chemistry. These are cation exchange, reverse cation exchange, dissolution of calcite, and to a lesser extent, gypsum dissolution. Results of $\delta^{18}\text{O}$ and δD analysis indicate that the groundwater has been partly affected by evaporation, as groundwater isotopic composition is lighter as depth of the water table increases. $\delta^{18}\text{O}$ and chloride data indicate sources of high salinity other than simple mixing between of modern seawater and native groundwater.

INTRODUCTION

The study area for this project is located in the mid-western part of Senegal and is characterized by a low lying estuary system bearing an important mangrove ecosystem, tidal wetlands and denuded saline soils.

The saltwater contamination constitutes a major environmental concern in this region agricultural land use is extensive and local residents rely solely on the groundwater and soil resources for economic development. In this paper we present the results of a study designed to characterize the current extent of the saline groundwater intrusion and identify the mixing mechanism for saline surface water, saline groundwater and fresh groundwater. We describe the chemical and isotopic composition of the groundwater as wells as the geochemical processes controlling the observed chemical patterns.

GEOLOGICAL FRAMEWORK

Beneath the study area are the Continental terminal (CT) formations that consist of interbedded sand, sandstone, sandy clay, silt, clay. The CT in the Senegalo-Mauritanian basin is a Cenozoic (Oligo-Miocene to Pliocene) formation of detrital sea origin, The CT shows evidence of an intense ferralitic alteration with formation of ferruginous concretions and crusting, and neo-formation of kaolinite and significant silica movements (Conrad & Lappartient, 1987). Horizontal and vertical facies changes are common, with locally indurate and clay veined sandstone bed, and permeable ferruginous crusting at the top formation. The CT sediments consist of

predominantly unsorted sand grain with a modal diameter of 0.125 mm. Fine grained sands are dominant and are mostly coated by a thin (10-20 μm) calcite mineral which develop to dimension of 100 μm at Nioro du Rip (Lappartient, 1985). Kaolinite is the dominant clay mineral and trace quantities of illite have been identified.

HYDROGEOLOGY

In the study area, the thickness of the CT aquifer ranges from about 10 m in the north-northwest to 80-100 m eastward where buried palaeochannels have been identified by geophysical investigations (Diluca, 1976). The CT unit is overlain by a thin (0-10 m) quaternary deposit of sand, sandy clay and clayey sand (Sarr, 1995). The Eocene impervious marl, limestone and clay constitute the basement of the CT aquifer, with a variable elevation between -20 to -100 m (Diluca, 1976).

The Saloum CT aquifer is under unconfined conditions and the potentiometric surface map indicates a radial flow pattern from the groundwater mound located in the south west of the study area (Figure 1). In the Northern part of the aquifer, groundwater flow is collected by a groundwater trench that also collects flow from the Saloum River hydraulically connected with the CT aquifer. Depth to groundwater was measured and ranges in depth from 2.87 to 38.25 m

The horizontal hydraulic conductivity of the aquifer (Diluca, 1976) ranges from 1.7×10^{-5} to 2.2×10^{-3} m/s, and transmissivity values range from 3×10^{-4} to 3.5×10^{-2} m^2/s . Recharge was estimated using chloride mass balance method in the unsaturated zone, an average value of 17.1 mm/yr represents the region as a whole (Edmunds, 1990).

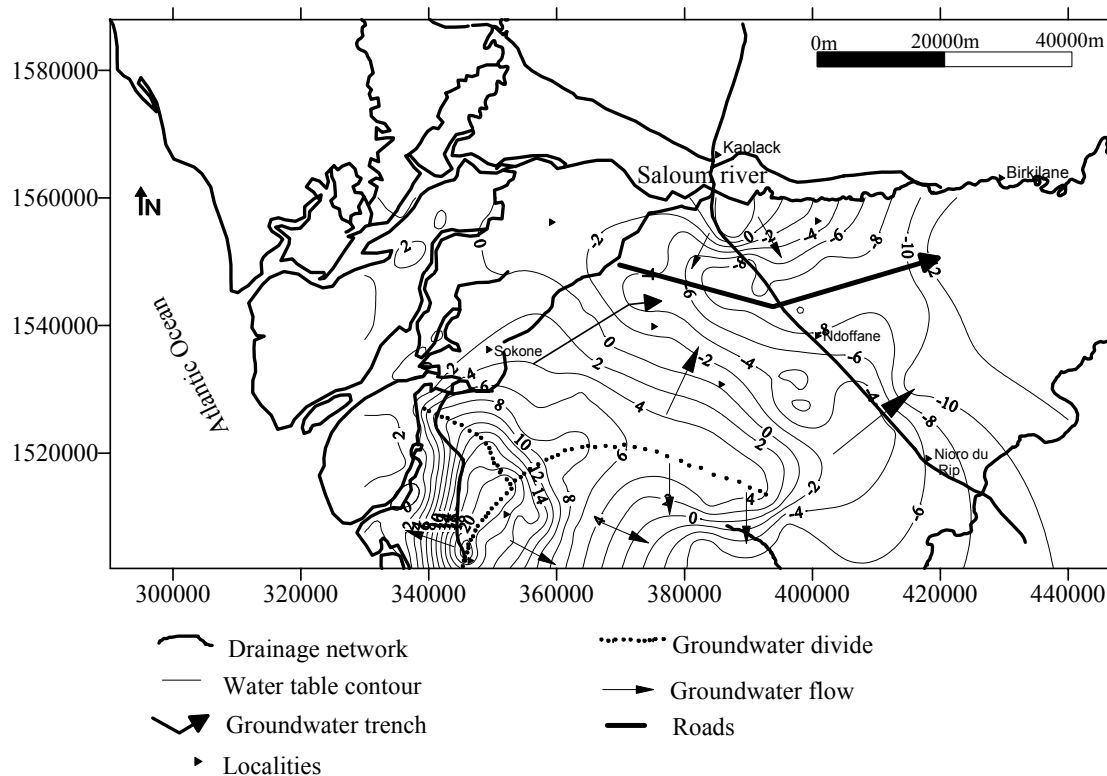


Figure 1. Potentiometric surface map

HYDROCHEMISTRY

Sampling and chemical analyses were performed in 71 wells during April 2000. The temperature, pH, electrical conductivity (EC), total dissolved solid (TDS), alkalinity (HCO_3^-) were measured in the field. Major ions (Ca^{2+} , Mg^{2+} , Na^+ , K^+ , NO_3^- , SO_4^- , Cl^-) were analyzed by ion chromatography. Fifteen selected wells were sampled and analyzed for stable isotopes ^{18}O and D.

Groundwater temperature ranges from 28 to 35 $^{\circ}\text{C}$, and pH of fresh water from 6 to 7. EC in the groundwater samples range from 19.8 $\mu\text{S}/\text{cm}$ in the recharge zone to 11,180 $\mu\text{S}/\text{cm}$ in the vicinity of the Saloum River (Figure 2).

Correspondingly elevated concentrations of sodium, chloride and sulfate occur in areas of high EC. Chloride concentrations in the fresh-water part of the aquifer range from 3.88 to 50 mg/L, and have concentrations as high as 3,195.9 mg/L in the saline part of the aquifer (Figure 3). In the recharge area (groundwater mound), very low concentrations of chloride (less than 10 mg/L) are observed indicating groundwater dilution by the infiltrating water. At two wells (19 and 31) located in the fresh water field of the aquifer, high chloride contents of 255.8 mg/L and 237.3 mg/L, respectively, have been measured. These high values seem to be related to anthropogenic local pollution since they are associated with high nitrate concentrations of 187.9 and 542.7 mg/L, respectively.

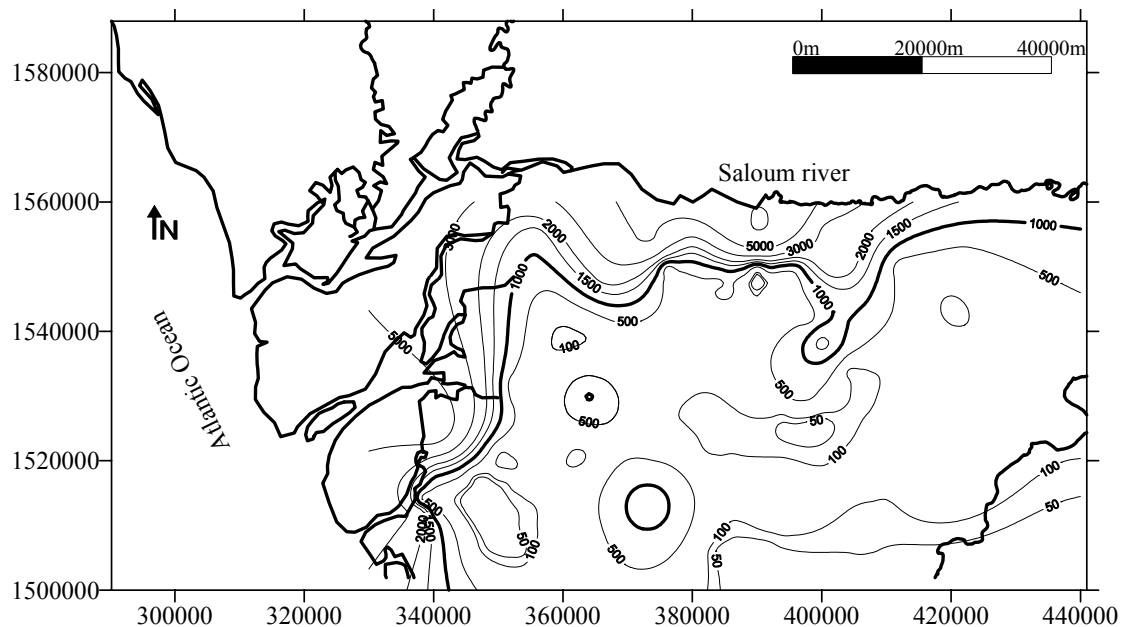


Figure 2 Distribution of EC ($\mu\text{S}/\text{cm}$) in the CT Saloum aquifer

Based on major cation and anion concentrations four distinct geochemical facies are differentiated (Figure 4), namely sodium bicarbonate (Na-HCO_3), calcium bicarbonate (Ca-HCO_3), calcium chloride (Ca-Cl) and sodium chloride (Na-Cl). One sample exhibits calcium sulfate (Ca-SO_4) water type.

The spatial changes in groundwater quality and pattern changes of the major ions in the Saloum CT aquifer are illustrated in Figure 4, where facies types are

grouped in five zones according to the TDS and the dominant cation of water samples:

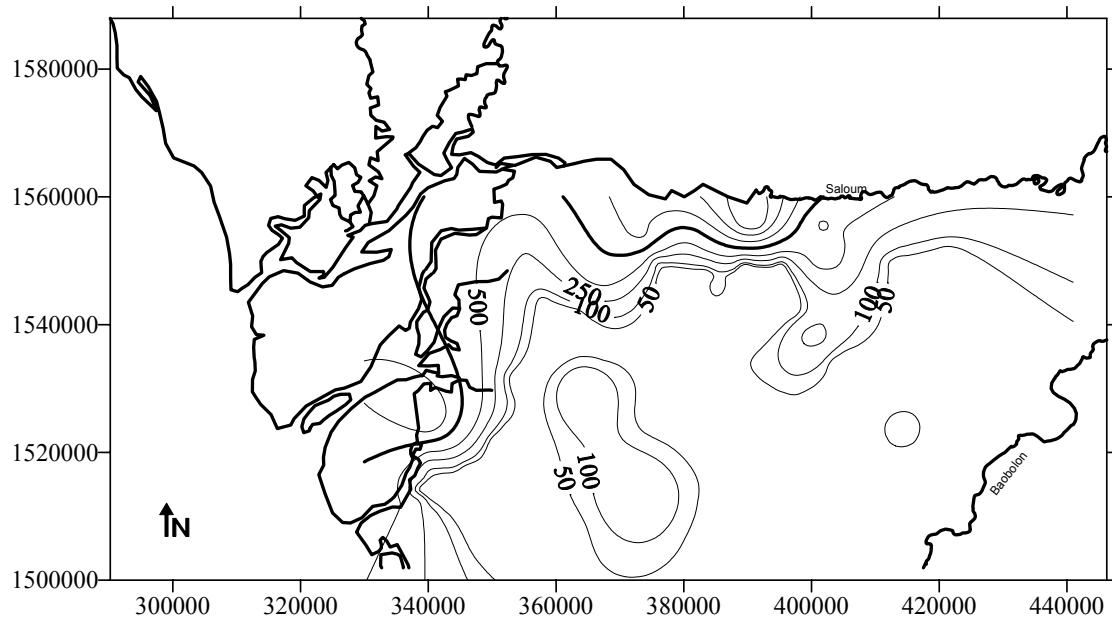


Figure 3 Distribution of Chloride (mg/L) in the CT Saloum aquifer

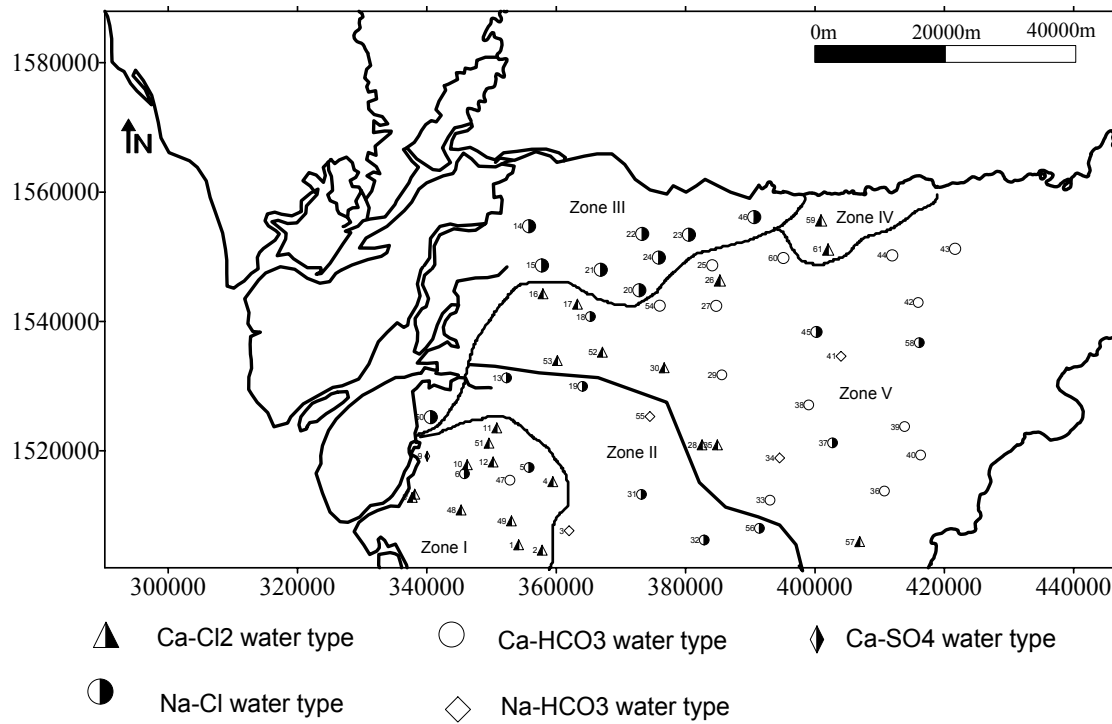


Figure 4 Spatial distribution of the water facies types

- Zone I represents mainly low TDS water samples, and Ca-Cl and Ca-HCO₃ water types encountered in the groundwater mound zone;
- Zone II represents low TDS water samples, and Na-Cl and Na-HCO₃ water types located down gradient in the vicinity of the groundwater mound zone;

- Zone III represents high TDS water samples and Na-Cl water type located north and north west of the study area;
- Zone IV represents high TDS water samples, and Ca-Cl water type located in the contaminated zone;
- Zone V represents low TDS water samples of the various water type encountered in the well samples located in the down gradient zone and eastern part of the study area.

Chemical data from the well samples plotted in the expanded Durov diagram (Faye et al, in press) have led to the identification of the hydrochemical processes in the aquifer in relation to the groundwater flow.

The well samples in Zone III are characterized by Na-Cl water type and high TDS values (greater 1000 mg/L). These are wells contaminated by mixing with the intruded hypersaline water from the river Saloum. Samples with low TDS values and Na-Cl water type, located in Zone II, are likely induced by exchange of Ca^{2+} for Na^+ in the aquifer matrix (kaolinite) resulting in an increase of Na^+ concentrations in groundwater. High values of TDS and Na-Cl water type observed in wells 19, 20 and 31 are associated with high nitrate contents ranging between 61 and 542 mg/L, and therefore, are subject to local contamination of the groundwater.

Zone V is characterized by samples with low TDS (49 to 236 mg/L) and Ca- HCO_3 water type derived from calcite mineral dissolution, as indicated by the Ca/ HCO_3 molar ratio is close to 0.5 and calcite minerals coating sand grains in the eastern part of the aquifer (Lappartient, 1985).

Low TDS (46 to 324 mg/L) Ca-Cl water type in Zone I exhibits variable concentrations of Ca^{2+} and Na^+ (in meq/L), and of Cl^- and HCO_3^- and therefore is related to recharging waters. The process controlling changes in the chemical composition is ion exchange reaction where Ca^{2+} from the solution is gradually replaced by Na^+ from the aquifer matrix.

The low TDS (40 to 66 mg/L) Na- HCO_3 / Ca/Na indiscriminate Cl water type samples in Zones I and II reveal ion exchange reactions.

Samples located in Zone IV with high TDS values show evidence of reverse ion exchange. When seawater intrudes into a fresh water aquifer, an exchange of cations occurs and sodium is taken up by the exchanger (clay), and calcium is released; thus water quality changes from Na-Cl rich to CaCl_2 rich water (Appelo and Postma, 1993). Magaritz and Luzier (1985) stated that groundwater samples containing less than 15% seawater are enriched in Na^+ , and as the percentage of seawater increases, the water becomes increasingly enriched in Ca^{2+} and Na^+ is depleted.

The Ca- SO_4 water type for well 9 seems to be related to gypsum mineral dissolution.

ISOTOPES

Fifteen wells were selected and sampled for stable isotopes ($\delta^{18}\text{O}$ and δD) analysis. Values of $\delta^{18}\text{O}$ and δD ranged from -4.47 to -6.08 ± 0.15 ‰ and -33.38 to -45.00 ± 2 ‰, respectively. Most of the water samples plot to the right of the local meteoric water line defined by Travy and others (1987) which indicates groundwater evaporation.

Water from wells located along the narrow strip parallel to the coastal wedge are isotopically heaviest ($\delta^{18}\text{O}$ values greater than -5 ‰ and δD values greater than -38 ‰). Intermediate $\delta^{18}\text{O}$ and δD values (-5.7 ‰ and -34 to -38 ‰) were found at wells close to the groundwater mound where water table depth is less than 15m. Water from wells sampled at greater depth (25 to 35m) exhibit lighter isotopic composition with value of $\delta^{18}\text{O}$ between -5.7 and -6.08 ‰ and δD value between -41 and -45 ‰. In these areas, evaporation seems to be attenuated as the depth to the water table increases (Figure 5).

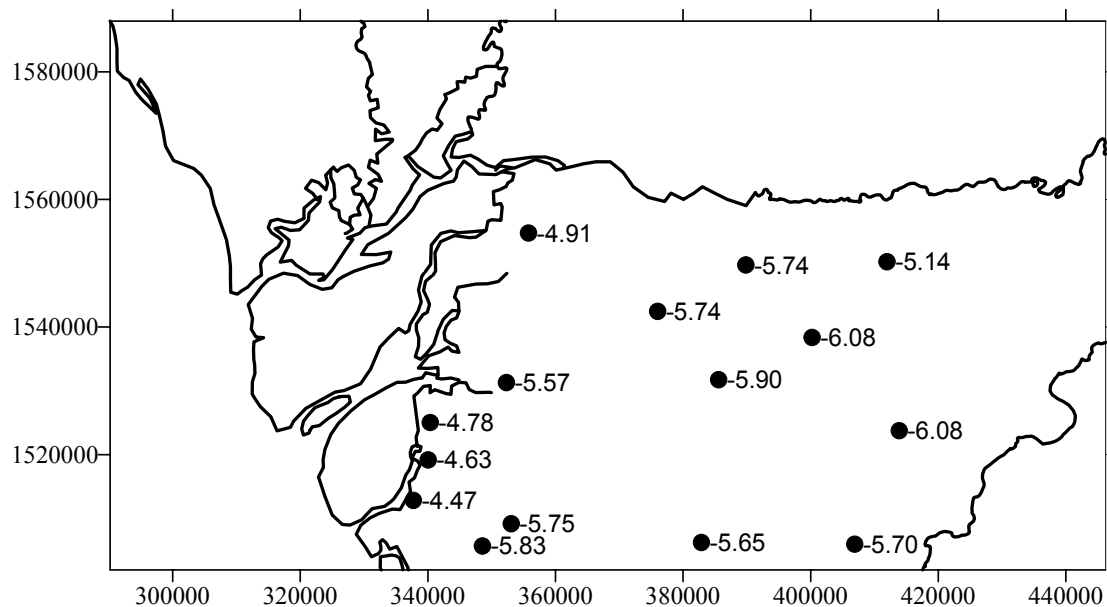


Figure 5. $\delta^{18}\text{O}$ values in the sampled wells

In order to explain change in the isotopic composition of the contaminated water in the Saloum CT aquifer, chloride concentrations were correlated with $\delta^{18}\text{O}$ (Figure 6). Similar results can be obtained using chloride and δD . When seawater intrudes and mixes with the native groundwater, the resulting mixture would have a chloride concentration and isotopic composition intermediate between the aquifer water and seawater and would plot along a line known as mixing line. In this study the position of the saline well samples do not fall on the line of mixing, indicating other processes rather than simple mixing with modern seawater alone (Figure 6). Sampled wells located along the Saloum hydrologic system with chloride concentration between 237.7 and 2047.8 mg/L seem to be invaded by hypersaline water isotopically different from the modern seawater. Moreover, the relatively shallow depth of the water table in this part of the aquifer (5 to 7m) and its consequence of direct evaporation of the groundwater will also contribute to lower concentration of lighter isotopes. As a result, increasing chloride in the saline water

field of the aquifer may be from a three part mixture of native groundwater, recharging water, hypersaline water accompanied with evaporation. A sample from well 45, located 20 km south of the Saloum river, had a chloride concentration of 366.4 mg/L and lighter isotopic composition ($\delta^{18}\text{O} = -6,08\text{‰}$ and $\delta\text{D} = -40.59\text{‰}$) which may result from the same processes.

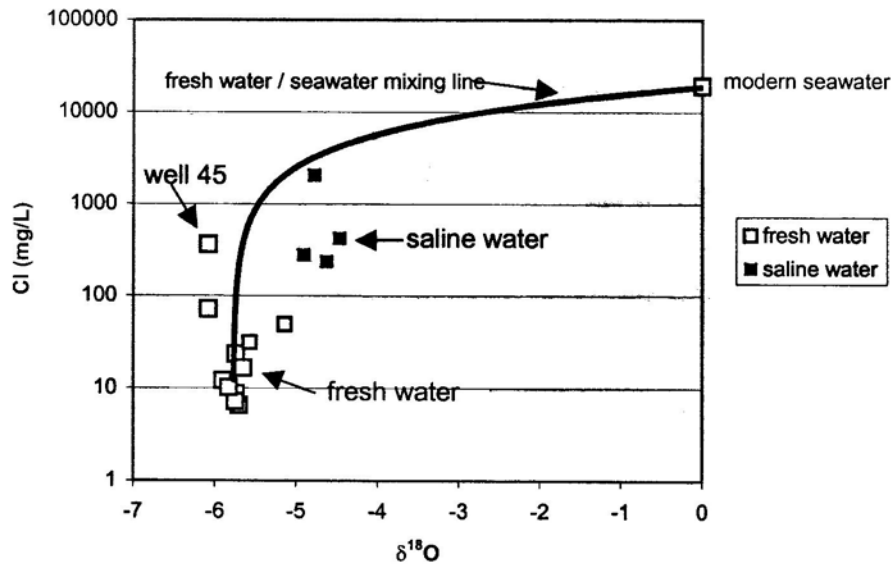


Figure 6 Relationship between $\delta^{18}\text{O}$ and chloride

CONCLUSIONS

The results of this study provide information that can be useful for the management of the groundwater resources in the Saloum region, especially with respect to areas impacted by saltwater intrusion. Results indicate that hypersaline water in the Saloum hydrologic system is the main source of contamination of the groundwater in the CT aquifer and in the uncontaminated part of the aquifer, the groundwater is characterized by a generally low electrical conductivity. The hydrochemical investigation indicates that the Saloum CT aquifer water is significantly modified as groundwater moves from the recharge to discharge areas and the main geochemical processes are cation exchange reactions on the kaolinite clay mineral, calcite dissolution, reverse cation exchange reactions in the saline contaminated band, and to a lesser extent a gypsum dissolution. Use of $\delta^{18}\text{O}$, δD and chloride data reveal evaporation process of the groundwater and salinity increase in the saline water field of the aquifer resulting from a three part mixture of native groundwater, recharging water, hypersaline water accompanied with evaporation.

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