Water quality decline in coastal aquifers under anthropic pressure: the case of a suburban area of Dakar (Senegal)

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Abstract. In recent years, the unregulated increase of the population in coastal areas of developing countries has become source of concern for both water supply and quality control.

In the region of Dakar (Senegal) approximately 80% of water resources come from groundwater reservoirs, which are increasingly affected by anthropogenic pressures. The identification of the main sources of pollution, and thus the aquifer vulnerability, is essential to provide a sound basis for the implementation of long term geochemically based water management plans in this sub-saharian area.

Whit this aim a hydrochemical and isotopic survey on 26 wells was performed in the so called Peninsula of Cap-Vert. Results show that sea water intrusion represents the main process affecting groundwater chemical characteristics. Nitrates often exceed the WHO drinking water limits: stable isotopes of dissolved nitrate ($\delta^{15}N$ and $\delta^{18}O$) indicate urban sewage and fertilizers as a major source of contamination. Results depict a complex situation in which groundwater is affected by direct and indirect infiltration of effluents, mixing with seawater and freshening processes from below. Beside the relevance of the investigation at a regional level, it represents a basis for decision making processes in an integrated water resources management, and in the planning of similar monitoring strategies for other urban coastal regions.

Keywords: Urban and coastal aquifers, groundwater quality, hydrochemistry, environmental isotopes.

INTRODUCTION

Water shortages, droughts and groundwater pollution due to human activities are increasingly becoming a worldwide source of concern.

Although the world is not yet experiencing a global water shortage, more than 1.2 billion people live under conditions of physical water scarcity, which occurs when more than 75 per cent of the river flows are withdrawn (WHO/UNICEF, 2006). Another 1.6 billion people live in areas of economic water scarcity, where human, institutional and financial capital limits access to water. These conditions are prevalent in much of sub-Saharan Africa, and at continental level there is an alarming trend in artificially-created scarcity, even in areas where water is apparently abundant (IWMI, 2006). During the past century, water use has increased at double rate if compared to the one of population growth (IWMI, 2006), with consequent impacts in water availability and contamination. Symptoms often include lack of adequate water infrastructure, high vulnerability to short and long-term drought, and difficult access to reliable water supplies, especially for rural people.

This is why groundwater resources have been increasingly used to rectify the supply backlogs and many urban areas rely on groundwater as fundamental part of the drinking water supply (Xu and Usher, 2006).

As many African urban and rural areas present the aforementioned lack of adequate and accurate information on both quality and quantity of water resources (Showers, 2002), and as the demands on freshwater resources is rapidly growing, there is an urgent need to link research with improved water management. Provision of safe water, access to water and sustainable water use need to be assessed in order to avoid the water crisis, and this should be achieved only applying science based long term management projects.

Better monitoring, assessment, and forecasting of water resources will help allocate water more efficiently among competing needs. Without protection there is a serious risk if an irreversible decline of water, with a severe impact on ecosystems and human health.

However, under need to rapidly develop new water supplies, there is rarely adequate attention to, and investment in, the maintenance, protection and longer-term sustainability of groundwater.

Groundwater use is dominated by three features: depletion due to overexploitation; salinization and water logging due mostly to inadequate drainage and insufficient conjunctive use or to seawater intrusion linked to the costal aquifer overdraft; and pollution due to agricultural, industrial and other human activities.

The three aforementioned points summarize three key areas: water scarcity, water quality and water-related disasters, linked reciprocally, which often create serious and irreversible problems to underground resources in many coastal areas (Abramovitz 2001).

The region of Dakar (Senegal), collectively called Peninsula of Cap-Vert, is a classical example of these problems. As several other African cities, the Peninsula has seen a rapid population growth increased by movements of refugees from nearby countries in conflict (Deme et al., 2006). This fast population growth has resulted in an increase in water requirements and is putting even more pressure on already insufficient sanitation infrastructures. Moreover as many other coastal African cities (Showers, 2002) Dakar's water supply depends upon groundwater for its daily function, and population use pit latrines and dump waste resources already threatened by seawater intrusion.

These peculiarities make the studied area a classical example of several key problems, and can be used as a reference case study representative for groundwater management in urban and coastal areas in both developed and developing countries.

At present the urban population of Dakar and its suburb zone accounts for 23% of the total population of Senegal and only 0.3% of the surface area. As a consequence many informal settlements are present in marginal land with lack of both control and sanitation measures. The lack of use and diffusion of sewage drainage infrastructures can be considered as one of the main sources of groundwater pollution in this area, as in most developing countries. These considerations are not limited to Dakar and its outskirts but can be applied to all cities and villages in the peninsula. Thiaroye, Pikine, Yeumbeul, Keur Massar are only few examples of cities in which most houses are equipped with improper septic tanks, seeping from below into the groundwater (Cissé et al., 2004).

In addition to this social situation, 90% of the local industries located in this region (including agribusiness, textile and fertilizer production) are recognized as the main drivers of the severe groundwater pollution by nitrate in the region (Collin and Salem 1989, Tandia et al., 1999).

In this area, both point and non-point sources of chemical contamination contribute to groundwater quality decline for this reason the apportioning of the relative loads in groundwater, with a focus on anthropogenic inputs of nitrogen and occurrence of saline water intrusion is required.

Despite of the rising awareness and attention to such problems (SONES 1986; Diop and Tandia 1997; Cissé et al., 2004; Faye et al., 2005, Deme et al., 2006) the region is still strongly affected by nitrogenous pollution, and the quality of the water has diminished over the last few years with a considerable increase in nitrate content. Concentrations close to 300 mg/L have been measured while the WHO recommends 50 mg/L as a limit for the drinking water supply. In fact, the deterioration in groundwater quality can be primarily explained by the proximity of confirmed sources of pollution to the wells (Cissé et al., 2004). In the region of Dakar, the presence of different sources of chemical pollutants is widely recognized. Hence it has become a primary objective to discriminate the contribution of different loads in drainage waters.

The continuous overexploitation of coastal aquifers increases the groundwater mineralization and produces a decline in the water quality, with important drawbacks on agricultural development and on the population's health. Groundwater salinization is a common problem for both developing and developed countries (Ghassemi et al., 1995; Foster and Chilton 2003).

The use of isotopic tracers has been recognized to be useful in terms of providing new insights into hydrologic processes (Girard and Hillaire-Marcel 1997; Kellman and Hillaire-Marcel 2002; Fukada et al., 2004). In fact, tracers permit to encompass the small-scale variability and provide a description of catchment-scale processes (McDonnell and Kendall 1992). The development of effective management strategies to preserve water quality, and remediation plans for sites with suspected contamination, requires the identification of the pollutant sources and understanding of the effective processes affecting local nitrate concentrations (Kendall 1998). An integrated, holistic approach is therefore required to tackle the big challenge of sustainable water management. In order to implement and integrate equitable policies and projects a sound knowledge of both the natural and human induced phenomena occurring in the aquifer is required.

This work tries to deal with the need for the development of an integrated management, concerning both groundwater and wastewater, by providing a sound data basis related to the major processes occurring in shallow aquifers of the Dakar region.

Moreover the present study has to be considered not only for its relevance at local level, as a basis for decision making processes in integrated water resources management, but also for the value of the used of approach for broad applications to similar urban coastal areas in Africa.

This work can contribute at the provision of geochemical and isotopic data in the framework of the assessment of groundwater quality at regional level and as a basis for constructing geochemical and isotopic based programs for water management and international level.

1. SITE DESCRIPTION

The region of Dakar is located in the mid-western part of Senegal between the 14° 24’ and 15° 5’ North and between the 16° 55’ and 17° 32’ West (Fig. 1). It is characterized by a rocky headland, the peninsula of Cap-Vert, and is linked to the continent by the isthmus of Thiaroye. The morphology of the peninsula is formed by two units: the extreme westward unit, characterised by an uplift of the sedimentary deposits in relation to the Dakar quaternary volcanism, and the eastward depression zone located in the Thiaroye suburban area (Hébrard and Elouard 1976).

here Fig.1

In this area it is possible to distinguish:

- The northern coast, where the dune zone is separated from the Ocean by a continuous littoral strip. The Quaternary sand dunes are oriented SW–NE while the ‘‘Niayes’’ constitute the main surface features along the ocean facade. In this zone, some lakes occur beside the dune deposits; most of them are dry except for the hypersaline Lake Retba (Seck 1988).
- The southern coast, where the pre-Quaternary basement, essentially marly, outcrops in Rufisque and Bargny as a plateau relief of 30 m high.

Dakar climate is controlled by the dual influence of oceanic and continental processes forced by the relative position of the Azores anticyclone, the North African anticyclone, the Saharan thermal low and the Saint Helena anticyclone (Fall et al., 2006). It is governed by the position of the Inter-Tropical Front (ITF), which regulates the rainfall mechanism in this region (Lebel and Le Barbé 1997). As a consequence, in the region of Dakar the dry season (October-June) occurs when the InterTropical Convergence Zone (ITCZ) migrates southward and the area is out of reach from the moist monsoonal flow. The migration of the ITCZ determines the duration of the wet season (June–July), also called *hivernage* (Fontaine 1991; Leroux 2001).

The mean annual rainfall rate is 480 mm/year (mean 1961–1990), although it was reduced in 1970-1998 to 342 mm (Dasylva et al., 2004). The mean annual air temperature (1971-1988) is 24°C, the annual potential evapotranspiration, (Turc's method) is 1830 mm/yr. The relative humidity varies little during the day or in the course of the year. It stays higher than 70% and reaches 98% in June. The real evapotranspiration is estimated at about 700 mm/yr. The present-day infiltration rate is assumed to vary from year to year between 40 and 60 mm with a mean value of 48 mm per year (Travi et al., 1987; Travi et al., 1991; Tandia 2000).

The Geology of Dakar is mainly dominated by Tertiary igneous rocks, and overlying Quaternary sediments. The geology of this region is characterized by a long period of volcanic activity from Tertiary (southern horst) to Quaternary (northern horst) and by cycles of transgression/regression of the Atlantic Ocean. The southern horst forms the Dakar plateau, some 50 m above sea level, which consists mainly of Tertiary volcanic products. The northern horst reaches a height of 105 m and is mainly formed of Quaternary volcanic deposits. From the Mesozoic to the Quaternary, the general evolution of the area is marked by deep faults (Bellion 1980; Bellion 1987) which delimit two horsts, the Dakar and Ndiass horsts, and the Rufisque graben. The effect of this tectonic control is highlighted by the presence of only Tertiary sediments: marls and limestones from the Eocene, karstic limestones from the Paleocene and sandstones and limestones from the Maestrichtian periods. The entire area is covered by eolian sands dating from the Quaternary.

Quaternary phreatic aquifer is composed of unconsolidated sands. The sediments consist largely of fine and medium grained sands with a porosity value of about 20%. The aquifer overlies Palaeocene and Maestrichtian limestone aquifers (Martin 1970).

Recharge to the phreatic aquifer is yearly provided by direct rainfall infiltration. Outflows are due to evaporation, occurring during the dry season in the Niayes, direct flow into the sea and, in recent years, human exploitation through wells (Audibert 1971).

The flows are usually from South-East to North-West, hence from the sea to inner zones (Forkasiewicz 1982; Cissé 2001).

The presence of two piezometric domes (the first located at North-East, among Mbawane lake and Tanma lake, and the second sited in South-West in proximity of the Niayes of Pikine) allowed the isolation of the studied reservoir as an independent hydrodynamic system.

The western zone is marked by the catchment basin of Thiaroye, characterized by a depression generated from its exploitation. East of this basin the hydraulic gradient is generally important, with an order of 1-3%.

Aquifers in the Cap Vert peninsula have been over-exploited since 1952, when they first started being used in response to Dakar's water demand (SONES 1986). This has resulted in some encroachment of salt water (Faye et al., 2005). It appears that the encroachment of the salt water is continuing, albeit slowly, in the Southern area. The chloride contents of some piezometers have increased considerably since 1985 (increasing from 35 to 300 mg/L) (Cissé 2001). Therefore, the groundwater is still slightly over-exploited and maintaining the current level of chloride. However, it should be observed that the quality of the water has degraded over the last few years with a considerable increase in nitrate content up to 300 mg/L (Diop and Tandia 1997; Cissé et al., 2004).

2. Materials and methods

In order to discriminate between different sources of contamination in the region of Dakar, groundwater has been sampled in 26 wells (13 drilled wells and 13 dug wells) spread across the Quaternary aquifer. Water sampling was conducted during the dry season (March and April 2006) in an area of approximately 300 km^2 in the Cap Vert Peninsula, from Dakar Yoff to Kayar (Fig. 1).

Different isotopic techniques associated with the hydrochemistry of major and trace elements have been applied in order to investigate the pollution sources affecting groundwater quality.

The hydrochemistry of minor elements, namely boron (B), strontium (Sr) and bromide (Br) together with the environmental stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) and the major-ion chemistry (chloride, sodium and calcium) has been used to restrict the sources and the processes of salinization in the Quaternary sand aquifer. Stable isotopes of oxygen-18 and deuterium are commonly used in regional groundwater studies to identify flow regimes mixing and sources of recharge (Fritz and Fontes 1980). In addition, the use of $\delta^{13}C$ in DIC (Dissolved Organic Carbon) can be important to trace carbon sources in groundwater (Clark and Fritz 1997).

The basis for the identification of NO_3^- is the use of a natural abundance of $\delta^{15}N$. since it allows to distinguish between synthetic and natural fertilizers (Clark and Fritz 1997). The analysis of nitrogen isotope composition permits the identification of the occurrence of contamination by septic effluents apart from agricultural sources and to verify the expected correlation between groundwater pollution and land use. The $\delta^{18}O$ composition of nitrate provides further information on the processes affecting NO_3^-, namely on the occurrence of nitrification and denitrification phenomena.

Sampling was performed by pumping water from wells until electrical conductivity became constant. Pumping was performed using a GRUNDFOS pump, BMP/MPI-230 V, with an output flux of 0.4 L/s.

During the sampling phase chemical-physical parameters were measured: water level, temperature, pH, EC and Eh using 340/SET-WTW while dissolved oxygen was measured with an electrode Eh (Sentix ORP).

Samples for major ion analysis were collected in polyethylene bottles, filtered in the laboratory through 0.45 µm cellulose nitrate membrane filter papers, stored in 500 ml PE bottles, preserved with $HgCl_2$ except those for Cl^- analysis. These samples were analysed at the Département de Géologie (UCAD, Dakar) by ion chromatography. Alkalinity was determined by titration immediately after the sampling campaign. All reported values have ionic balance within 5%.

Trace elements analyses (B, Li, Sr) were performed at the Dipartimento di Scienze della Terra (Università di Pavia), using an ICP-AES. Br analyses were performed at the IGG-CNR (Pisa) using ionic chromatography (Dionex 100) with an accuracy of 3%.

Samples for stable isotope analysis were collected according to the procedures described by Clark and Fritz (1997). Hydrogen isotope composition was measured by water reduction over metallic zinc (Coleman et al.. 1982), while $\delta^{18}O$ was analyzed by water-CO_2 equilibration at 25 °C (Epstein and Mayeda 1953); both results are expressed in V-SMOW (Gonfiantini 1978; Gonfiantini et al., 1995). The analytical errors are ±1 and ±0.1 ‰ respectively. The $\delta^{13}C$ of DIC was analysed by direct acidification of the water sample with phosphoric acid (Kroopnick 1974) and the released CO_2 recuperated in vacuum line for further analysis through the dual inlet of the mass spectrometer. Results are expressed in ‰ V-PDB (Gonfiantini 1978; Gonfiantini et al., 1995). Analytical errors are ±0.3. $\delta^{15}N_{NO3}$ and $\delta^{18}O_{NO3}$ of dissolved nitrate were analysed following the procedures described by Kendall and Grim (1990) and by Silva et al., (2000) and refer to V-AIR (Gonfiantini et al., 1995). The analytical error is ±0.5‰ and ±1‰ respectively. All gases were analysed on a Finnigan MAT 250 Mass Spectrometer at ISO4 s.s., (Pavia, Italy).

3. RESULTS

Water temperature varies between 27°C and 31°C, with an average of 28.4 °C. pH has a mean value of 6.9 and a standard deviation of 1.2 (Table 1). Waters from wells number 16 (Darou Mbayakh) and number 17 (Mbayakh) are strongly acidic (4.1 and 4.2, respectively), and are located in the eastern part of the Cap-Vert peninsula; on the contrary, waters from well 11-Malika are very basic (pH of 9.9).

here Table 1

Eh and dissolved oxygen (Table 2) varies significantly between drilled wells (with a mean of +0.33 V and 5.8 mg/L respectively) and dug wells (+0.44 V and 11 mg/L). Electrical conductivity suggests the presence of exceedingly mineralized waters, with an average of 1,325 µS/cm, and a maximum of 4,150 µS/cm in well 24 (Bambilor).

Dominant major ions are sodium-chloride. Mineralization processes are relevant and concern areas where farming and rural or urban life can affect groundwater quality. Data indicate high cation content and low alkalinity values, together with an increase in dissolved nitrate and chloride. The abundance of major ions, especially of nitrate, chloride and sulphate suggest an elevated undesirable evolution of physical-chemical properties of fresh water resources, and thus an increased risk for public health.

In particular, the content of nitrate is very high, and, for 50% of wells, the concentrations exceed the WHO regulatory limit of 50 mg/L, with a maximum value of 790 mg/L in dug well 24. Lithium is the least abundant, with an average concentration of 11 µg/L, and only two wells (20 and 22) reach Strontium concentrations exceeding 1 mg/L. Boron concentration, higher than 1 mg/L, is significant only in well number 7, drilled near Retba Lake.

here Table 2

The $\delta^{15}N_{\text{-NO3}}$ values (Table 3) range from approximately +7 to +19 ‰, and are in the range of signatures for manure and septic systems (Kendall 1998). $\delta^{18}O_{\text{-NO3}}$ varies between +10 to +16 ‰, while the mean value for $\delta\ ^{13}C$ of DIC is -12 ‰. Mean $\delta^{18}O$ and $\delta^{2}H$ are -4.8 and -33.5 respectively, corresponding to expected values for meteoric waters in the region (Travi 1988).

here Table 3

4. DISCUSSION

The extreme pH values observed in groundwater could be controlled both by the aquifer mineralogical matrix, and by the dissociation of dissolved carbon dioxide mostly originated in the soil (Tandia 2000). In the case of acidic pH, the hydrosystem might be considered hydrologically phreatic and geochemically open to the atmosphere. On the contrary, waters with higher pH values circulate in a confined aquifer and thus, in a geochemically closed system, where CO_2 is consumed by the active interaction with aquifer matrix. These waters are limited to the basaltic aquifer located dominantly in the western part.

In the Eh-pH diagram (Fig. 2) waters define a trend progressively leading from an open hydrosystem (dug wells), characterized by a more oxidising environment, to a closed hydrosystem (drilled wells) where the environment is more reducing.

here Fig.2

These observations are in agreement with the significant levels of DO relatively more present in waters from shallower wells, either from phreatic or confined aquifers, than in the waters from deeper wells (Fig. 3).

here Fig.3

On the basis of the anion distribution (Fig. 4) it is possible to recognize two main trends: on the one hand a progressive enrichment in chloride, associated with very low nitrate concentrations, on the other a significant enrichment in nitrate affecting both drilled and dug wells.

These two trends could be considered as the major processes controlling groundwater decline, in the region of Dakar: sea water intrusion and anthropogenic pollution.

here Fig.4

The coexistence of these two sources of contamination adds complexity to the system, in which direct and indirect infiltration of effluent, and saline or fresh water flushing, work together, limiting the detection of representative end members for each phenomenon.

4.1 Salinization

The hydrochemistry of trace elements boron (B), strontium (Sr), lithium (Li) and bromide (Br), environmental isotopes of water molecule (^{2}H and ^{18}O) together with major ion chemistry (mainly Na and Cl) has been used to investigate the occurrence of saline water encroachment.

Plots of dissolved species versus chloride can be used to investigate mixing processes between groundwater, whose composition is determined by water-rock interaction, and saline water (Faye et al., 2005). Thus, waters with low salinity (i.e. less than 100 mg/L of chloride) were assumed as representative of fresh groundwater or more diluted salty waters.

By plotting Na versus Cl (Fig.5a) it is possible to point out the process of progressive mixing with saline water.

here Fig. 5

Some wells (7, 15 and 24) show an excess in Na: in particular, well number 7 is characterized by a great enrichment, due to its location in respect to the hypersaline Retba Lake, mainly composed of sodium carbonate. This enrichment in sodium, with respect to calcium, is dominant in this part of the aquifer, as groundwater flows from the Retba Lake south-eastward.

Nevertheless, in the Na/Cl ratio versus Cl (Fig. 5b) diagram, evidence of depletion or enrichment of Na appears which seem to result from other processes rather than mixing with saline water.

Waters with a Na/Cl weight ratio higher than the reference seawater value (0.858) may be derived by the mixing of fresh waters, whose chemical composition is close the one of deep groundwater, and seawater. Indeed, according to Faye *et al.*, (2005), deep groundwater flowing throughout sandstones shows a Na/Cl ratio of 1.6, due to the presence of Quaternary evaporitic deposits mainly composed of Na_2CO_3 (Garnier 1978) or of glauberite-rich sediments ($Na_2Ca(SO_4)_2$). On the other hand, enrichment in chloride suggests a possible contribution from anthropogenic sources, in association to nitrate (Fig. 4).

The detection of traces of dissolved carbonates in wells 7, 15 and 24 is supported by the enrichment of strontium (Fig. 5c and 6). In general, the increase in the Sr concentration, parallel to that of Cl, is largely due to the saltwater intrusion processes (Faye et al., 2005).

here Fig.6

Fig. 6 shows enrichment in Sr indicative of carbonate dissolution. In fact, the incongruent dissolution of carbonates readily increases the Sr concentration of the solution because the large Sr^{2+} ions are rejected from recrystallized calcite (Hem, 1985; Edmunds et al., 1987; Chou et al., 1989; Drever 1997). This typically occurs in the presence of paleo-lacustrine systems in warm regions, where the alternation of clays, carbonate-clays and clays-carbonates is dominant (Mees 1999).

The trend of progressive mixing with saline waters can also be pointed out considering boron distribution respect to chloride (Fig. 5d).

Apart from sea-water mixing, boron in groundwater can be derived by the leaching of clay minerals (Vengosh et al., 2004; Bouchaou et al.. 2008), as possibly in the case of well number 7. The high B concentrations of wells 20 and 21 however, may derive from fertilizers and detergents, due to the location of these wells (orchard and barnyard).

The analysis of bromine content in groundwater has been used to distinguish between salinization and anthropogenic pollution (Barros et al., 2008). Fig.. 7 shows that, although the Br concentration is partly controlled by sea water intrusion, as already evidenced by Faye et al., (2005), an enrichment of chloride can be observed. This confirms an anthropogenic input of chloride.

here Fig.7

The carbon isotopic composition for the samples range from approximately -7 to -15 ‰ indicating a significant difference in the $\delta^{13}C$ values of Dissolved Inorganic Carbon (DIC). The most negative $\delta^{13}C$ values correspond to water in shallow sandy aquifers (open system conditions), and are controlled by the isotopic composition of soil CO_2 and microbial activity affecting OM, which is usually quite negative (-15 to -22 ‰; Clark and Fritz 1997). The shift in $\delta^{13}C$ composition of DIC toward more negative values is indicative of an involvement of an isotopically light carbon into the DIC phase, which may be derived from the oxidation of organic carbon to carbon dioxide.

Comparing the Cl/Br ratio with $\delta^{13}C$ (Fig. 8), a negative correlation between these two parameters appears. Water characterized by high values of Cl/Br (800-600) and by highly negative carbon isotope ratios (−12 - −16‰) may be representative of an organic matter rich environment with an preferential uptake of Br (Gerritse and George 1988). The progressive lowering of Cl/Br ratio and the isotopic enrichment indicates the above mentioned mixing process with saline waters. Two wells (6 and 12) give different results, which could be due to the complete oxidation of the original organic matter content in an open system.

here Fig. 8

The same results can be found if comparing the Cl/Br ratio with the nitrate content (Fig. 9). By applying the range proposed by Vengosh and Pankratov (1998) for sewage and seawater in particular, and by considering the complete oxidation of organic matter in an oxidising environment, it is possible to use Cl/Br ratio to distinguish between different sources of pollution affecting groundwater of the studied system: domestic waste waters (sewage), seawater intrusion and organic matter degradation. In particular it is important to underline the increase of NO_3^- associated with the first group. The origin and the fate of nitrate pollution is investigated in the following section.

here Fig.9

Finally, in addition to these minor elements, environmental isotopes (^{18}O and ^{2}H) were also used for supporting evidence of the mixing processes (Fig. 10).

here Fig.10

The groundwater isotope composition falls below the LMWL (Travi et al., 1987), which appears to be very close to the Global Meteoric Water Line (Craig 1961; Gonfiantini 1998). Deviations from this line reflect an enrichment of heavy isotope concentration, with a slope of 5.49, confirming once more the mixing process with seawater.

4.2 Nitrogen pollution

Intensive anthropic activity in this area results in nitrate concentrations in groundwater often exceeding drinking water standards. In order to identify the different sources of nitrate and the processes affecting its concentration in groundwater (nitrification and denitrification), the isotopic composition of nitrogen and oxygen in dissolved nitrates was investigated.

Most of the samples lay within the range consistent with an origin from animal wastes, manure and septic system effluents ($\delta^{15}N_{-NO3}$ = + 10 - +15‰); this result is consistent with the position and the social situation of the region of Dakar (Fig. 11). In fact, in both rural areas and sub urban areas the main impact on groundwater is represented by organic fertilizers and septic effluents.

The second registered trend involves three wells (11, 14 and 23), all located in areas of intensive agriculture (Niayes), and is compatible with the signature of soil organic matter (δ15N-NO3 = +4 - +9‰), therefore indicating that nitrates are derived from soil organic nitrogen by mineralization and nitrification (Clark and Fritz 1997)

here Fig.11

In other words, on one side nitrates are directly derived from septic effluents (point source), and on the other infiltration of organic matter spread on soils provide an additional non-point source input. In the latter case groundwater takes the same $\delta^{15}N_{-NO3}$ composition of soil organic matter, as a consequence of mixing effects (Kendall 1998). Both direct and indirect inputs cause the processes of oxidation or nitrification in sandy media, as found in the shallow drilled and dug wells (Reynaud and Roger 1981).

On the other hand, denitrification is observed in the deepest wells, specifically where they drain water from aquifers located underneath clay layers in closed system conditions. Both the extent and rate of denitrification vary depending on the groundwater flow path. While little or no denitrification occurs in much of the upland portions of the aquifer, a gradual redox gradient is observed as aerobic upland groundwater moves deeper in the aquifer (Fig. 2).

A loss of nitrate provides evidence that denitrification occurs as groundwater enters deep layers. Electron and mass balance calculations suggest that organic matter oxidation is the primary source of electrons for denitrification. Therefore the major presence of anthropic contributions to the shallow systems and the presence of iron and aluminium species in a confined aquifer explain these observations (Fall 1986). Indeed, the removal rate of dissolved oxygen is strongly dependent on the presence of electron donors such as dissolved organic matter or Fe^{+2} (Clark and Fritz 1997; Edmunds and Shand 2008)

This is also confirmed by the $\delta^{15}N$ and $\delta^{18}O$ diagram (Fig. 12).

here Fig.12

Indeed, the oxygen isotope composition of dissolved nitrates is not governed by the relative proportions of atmospheric and groundwater oxygen (Clark and Fritz 1997), but is related to the electron donors involved in the oxidation processes affecting the organic products. This is more evident in samples collected from sand-point wells, more vulnerable to septic-waste contamination spread at the surface. Results also indicate that groundwater under clayey soil or close to septic drain fields are clearly affected by denitrification processes as indicated by the trend observed in $\delta^{18}O$ vs $\delta^{15}N$.

5. CONCLUSION

Dakar, as well as other African coastal capitals like Abidjan, Lomè, Lagos or Dar Es Salaam is characterized by an increase of nitrates and other contaminants in groundwater (Abiodun, 1997; Showers, 2002 ; Oga et al., 2007; Akouvi et al., 2008), strongly associated with seawater intrusion processes..

This underlines the fact that problems associated with rapid urbanization, inadequate sanitation, lack of alternative water supplies and lack of public awareness and implementation requires urgent addressing. In particular no action is longer possible without a clear understanding on the physical and geochemical processes occurring in natural groundwater.

Anthropogenic inputs of nitrogen from human activities are a central concern in urban watershed management. However, identifying the locations of these inputs, in particular if represented by improperly functioning or ill-maintained septic tanks or from leaking sewer lines is difficult (Steffy and Kilham 2004).

The hydrochemistry of major and trace elements, coupled with environmental isotopes shed new light on the geochemical processes affecting groundwater quality in the suburban area of Dakar. They have shown that groundwater from drilled and dug wells in near-coastal aquifers are characterized by relatively high chloride content, due to the seawater intrusion related to the overexploitation of the aquifer. The high nitrate concentration is evidence of the presence of several point and non-point pollution sources, principally linked to sewage and septic effluents. This type of pollution provides a supplementary input of chloride.

These two phenomena affecting water quality are not separated but representative of a complex situation in which groundwater is affected by both direct and indirect infiltration of contaminants, mixing with seawater and the freshening process from below.

All these processes have significant consequences on groundwater quality and pose serious threats to the health conditions of the inhabitants in the region of Dakar (Gaye et al., 1998; Tandia, 1997; Cissè, 2001). In addition to the mentioned pollutants, other substances strictly connected with human activities, i.e. bacteria, parasites and heavy metals, which are liable to deteriorate groundwater quality, should be taken into account and be actively monitored in the future.

To better understand the aquifer vulnerability, and to provide a sound basis for the implementation of groundwater and wastewater management plans in this coastal and urban area, it is important to distinguish:

- Geochemically and hydrologically closed systems, laying underneath clay strata, often affected by denitrification processes controlled by the organic matter degradation.
- Systems which are geochemically and hydrologically open to deep inputs, affected by groundwater freshening and dissolution of carbonates.
- Systems which are geochemically and hydrologically open to surface inputs, affected by the direct infiltration of pollutants.

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