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Full Length Research Paper

Groundwater nitrate pollution in Souss-Massa basin (south-west Morocco)

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The objective of our study was to determine the current status of alluvial aquifer in the Souss-Massa basin, where the nitrate pollution of groundwater is being increasing along the last decades. A multi-approach methodology using hydrogeology, nitrate concentrations, irrigation type and oxygen-18 and deuterium data, was carried out to identify the sources of this pollution. According to the spatial distribution of nitrate contents, nitrate pollution occurs mainly in Chtouka-Massa plain. More than 36% of the sampled wells exceed the value of 50 mg/L as NO_3^-. Groundwater in Souss plain is less polluted comparing it to Chtouka-Massa; only 7% of wells exceed the permitted level. Agricultural practices in the study sites are the main cause of serious nitrate pollution given the superimposition of high nitrate concentrations with the distribution of irrigated perimeters. High nitrate levels are associated with high $\delta^{18}O$ values, clearly indicating that significant quantities of evaporated irrigation waters infiltrate along with fertilizer nitrate to groundwater system. Different $\delta^{18}O\text{-}NO_3^-$ trends suggest isotopically distinct, non-point source origins which vary spatially and temporally, due to different degrees of evaporation/recharge and amounts of fertilizer applied.

Key words: Groundwater, contamination, nitrate, water isotopes, agricultural fertilizers, Morocco.

INTRODUCTION

Groundwater nitrate pollution has become a widespread problem which affects all countries regardless of their development level. It reduces the potential of available freshwater resources, generates sanitation problems, especially in rural areas and jeopardizes the socio-economic development of the country (Colleen, 1993; Aghzar et al., 2002; Berdaï et al., 2002). Such situations may become worse in arid and semi-arid areas where water resources are recharged slowly, irrigation returns are re-used intensively and evaporation rates are high.

Many studies have shown that anthropogenic activities, involving nitrogenous compounds such as mineral fertilizers and products of organic compounds from agriculture, septic systems and cattle manure, are the major factor leading to the increase of nitrate pollution (Power and Schepers, 1989; Kaçaroglu and Gunay, 1997; Guimerà, 1998; Lake et al., 2003; Widory et al., 2004; Liu et al., 2005; Rao, 2006).

The Souss-Massa basin is one of Morocco's most important economic regions. It has significant agricultural activities based mainly early fruit and vegetable production and contributes about 60% of national exports. During the last three decades, the region has undergone large changes in agricultural production. Thus, thousands of hectares have been developed for irrigation, inorganic fertilizers have largely replaced animal manure as a source of nitrogen and monocultures have often replaced diversified cropping systems. Consequently, water demand has increased. Indeed, about 90 to 95% of water is used for irrigation of which 71% is provided by groundwater resources. These drastic improvements have impacted groundwater supply and quality. In previous studies conducted in Souss-Massa, the qualitative aspects of groundwater in relation to their natural and anthropogenic environment have been widely proved and

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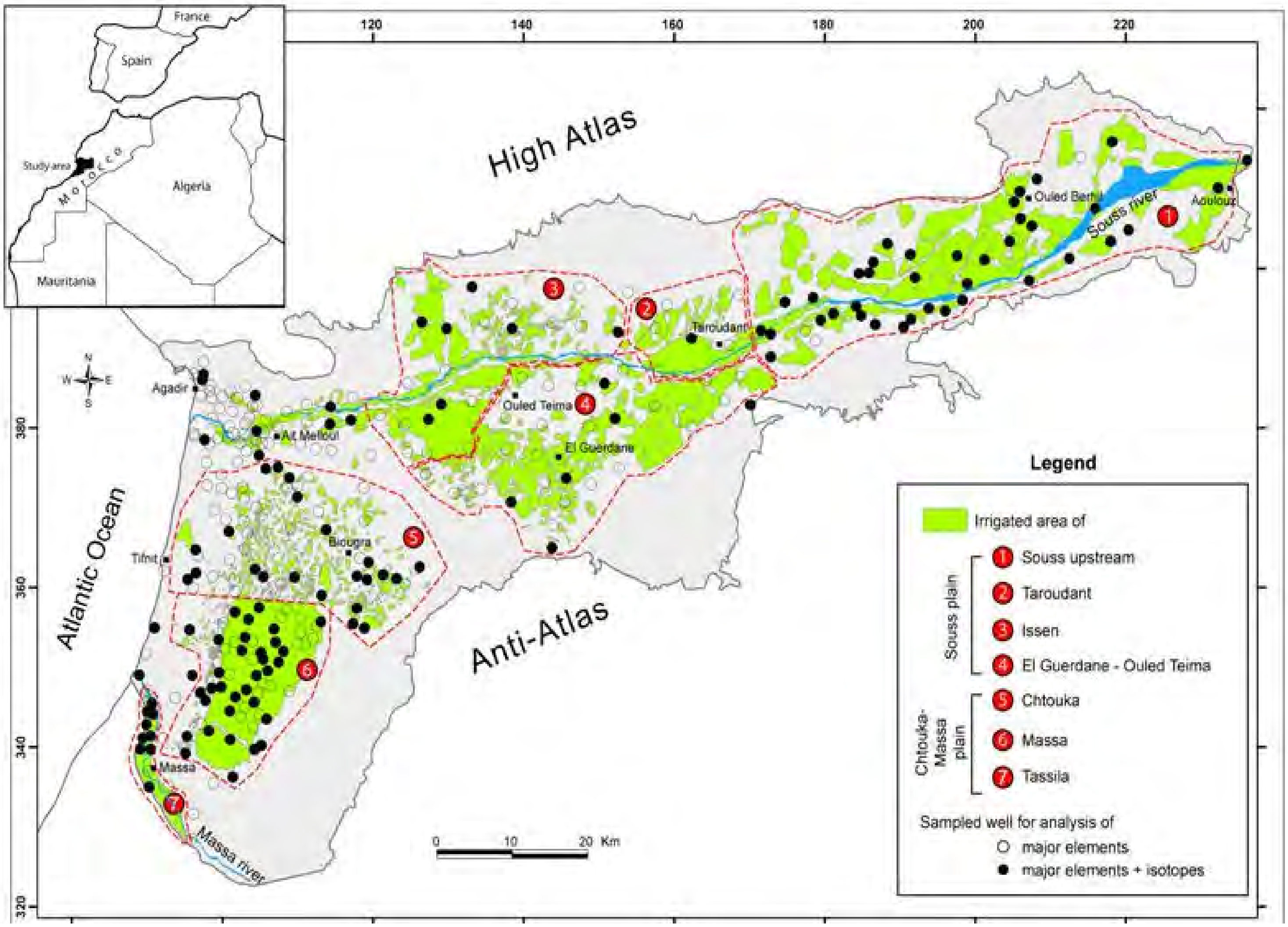

Figure 1. Location map of the irrigated areas and the sampling network. Empty circles represent samples for which only the major elements have been analyzed. The full circles represent samples for which ^{18}O, ^{2}H and the major elements have been analyzed.

discussed (Boutaleb et al., 2000; Hsissou et al., 2002; Ahkouk et al., 2003; Dindane et al., 2003; Krimissa et al., 2004; Bouchaou et al., 2008). However, none of these studies has emphasized groundwater degradation caused by nitrate pollution. The present paper aims, therefore, to establish the nitrate pollution status in Souss-Massa basin and to identify the sources of this contamination. The information would be useful for the subsequent elaboration of strategies for current and future groundwater management in the region.

MATERIALS AND ME THODS

Study area settings

The present study is conducted in Souss-Massa basin, southwest Morocco (Figure 1). It is bounded to the North by the High Atlas Mountains, to the South by the Anti-Atlas Mountains, to the East by the junction of these two mountain chains and to the West by the Atlantic Ocean. The study area covers a surface extent of 5700 km². The climate is semi-arid to arid, characterized by a mild littoral component in the West and a warm semi-continental component in the East. Annual rainfall average ranges from 250 mm in the plain to 600 mm in the mountains. The annual average temperature ranges between 14 and 20°C in the High Atlas and in the Anti-Atlas, respectively.

From a hydrogeological point of view, Souss-Massa basin contains a shallow unconfined aquifer which constitutes the major groundwater resource in the region. It is made up essentially by sedimentary deposits (Figure 2). In the Souss plain, these deposits interlay with marine deposits in the West and with continental deposits of fluvio-lacustrine calcareous marls and conglomerates towards the East constituting thus the Souss formation. The entire sediments are underlain by a heterogeneous substratum of diverse lithology (schists, marls and marly limestone) (Dijon, 1969). The Chtouka-Massa plain constitutes a natural extension of the Souss plain towards the South. It comprises sand, sandstones, conglomerate and lacustrine limestone. The lower boundaries are made of calcareous and marls to the North and by schists in the south part

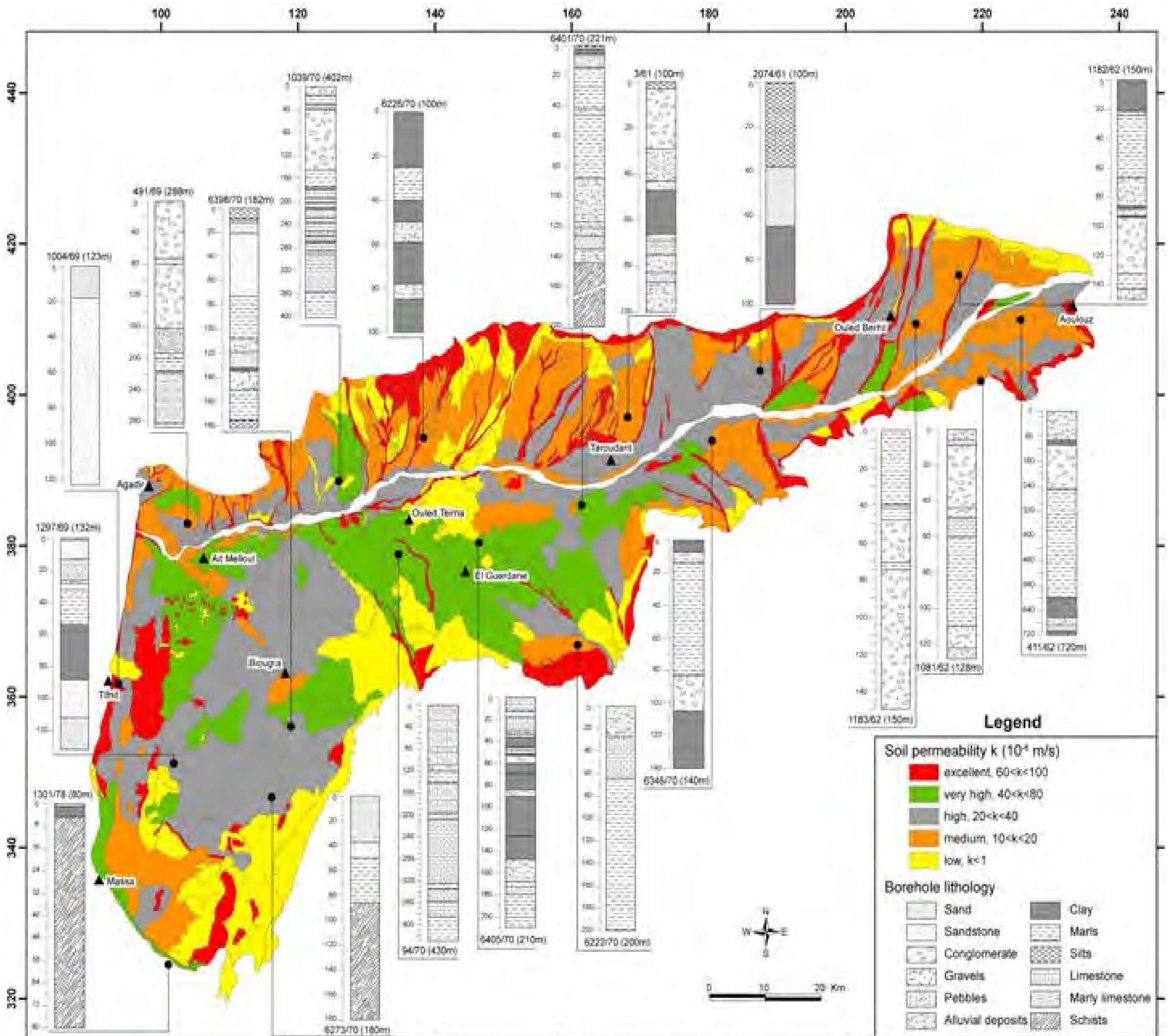

Figure 2. Soil permeability and lithology logs of boreholes in Souss-Massa plain.

of the plain (Bernert and El-Hebil, 1977).

The soils of Souss-Massa plain are diversified (Ghanem, 1974). Several groups can be delineated (Figure 2). The sandy-loam soils with little humus, characterized by a coarse texture with low content of clay, occur chiefly in the Chtouka-Massa region and in the Atlas foothills surrounding the Souss plain. They have high permeability (k), varying from 40 to 80 10^{-6}m/s and have a coefficient of retention varying between 13 and 18%. The heterocalcareous soils, xeric brown-to-black, sandy-clay texture with moderate amounts of clay are frequent in Souss upstream as well as in Ouled Teima and El Guerdane areas. These soils are also of high permeability. The alluvial soils with very high permeability (k varying between 60 to 100 10^{-6} m/s, coefficient of retention less than 12%) are developed along the mean streams coming from the High Atlas. The colluvial soils are common in the piedmont of the High Atlas in the North-western of Taroudant and in Aoulouz area as well. They are characterized by moderate to low permeability (k between 1 and 40 10^{-6} m/s, coefficient of retention between 20 and 25%). Finally, fersialitic xeric soil, halomorphic soil, hydromorphic soil and calcimagnesic soil are poorly represented in the study area.

Souss-Massa aquifer is heterogeneous regarding the spatial distribution of hydrodynamic parameters (Table 1). The general groundwater flow direction is from east to west and the aquifer is recharged from the surrounding Atlas Mountains, particularly along

Table 1. Summary of hydrodynamic parameters of Souss-Massa aquifer.

Lithology	T (10^{-2} m²/s)	K (10^{-4} m/s)	S (10^{-2})
Fossil bed	2 – 6	8	3 – 10
Marine clay	0.2 – 7	1 – 10	–
Souss formation	1 – 6	1 – 10	1 – 5
Chtouka-Massa	0.1 – 5	1 – 10	–

T: transmissivity; K: permeability; S: coefficient of storage.

Table 2. Elementary statistics of nitrate contents (mg/L) in groundwater in Souss and Chtouka-Massa areas.

	Souss	*Chtouka-Massa*	*Souss-Massa*
Minimum	0	4	0
Maximum	145	300	300
Mean	21	52	33
Standard deviation	22	44	36
NO_3^- > 50 mg/L	7%	36%	18%

along the eastern Souss valley (Bouchaou et al., 2005).

The Souss-Massa plain includes several irrigated areas (Figure 1), representing an area of 123140 ha (ORMVA-SM, 2004).

Methodology

Data concerning groundwater nitrate pollution in Souss-Massa aquifer were obtained from a regional database set up by the Applied Geology and Geo-Environment Laboratory of Ibn Zohr University in Agadir, within the framework of studies relative to the isotopic and hydrochemical characterization of water resources in the South of Morocco. These studies were carried out in different part of Souss-Massa plain during 2004.

Data used in this study included hydrogeology and nitrate concentrations in 283 wells within the study area. Within the sampled wells, 117 were chosen for an isotopic investigation of oxygen-18 (^{18}O) and deuterium (^2H). These wells were selected inside the irrigated areas in order to assess the effect of irrigation water on groundwater quality (Figure 2). Groundwater samples were taken directly from wells after enough pumping time. Temperature, pH and electrical conductivity were measured in the field. Chemical analyses were carried out as soon as the samples reached the laboratory. Nitrate ion concentration was measured following the Na-salicylic method with a UV-VIS spectrophotometer. Hydrogen and oxygen isotopes were analysed in the National Center of Energy, Sciences and Nuclear Techniques of Morocco. ^{18}O and ^2H isotope analyses were made by, respectively, employing the standard CO_2 equilibration (Epstein and Mayeda, 1953) or the zinc-reduction techniques (Coleman et al., 1982), followed by analysis on an isotope ratio mass spectrometer. All oxygen and hydrogen isotope analyses are reported in the usual δ notation relative to the standard mean ocean water (SMOW), where $\delta = (R/R_{SMOW}-1).1000$, R represents either the $^{18}O/^{16}O$ or the $^2H/^1H$ ratio of the sample, and R_{SMOW} is either the $^{18}O/^{16}O$ or the $^2H/^1H$ ratio of standard mean ocean water (SMOW) (Craig, 1961).

RESULTS AND DISCUSSION

Nitrate pollution status of Souss-Massa groundwater

The nitrate contents of groundwater samples, presented throughout this paper as NO_3^-, range between 0 and 300 mg/L with an average of 33 mg/L. Table 2 lists some elementary statistical parameters of nitrate data in the Souss-Massa aquifer. The frequency distribution of the entire sampled wells onto nitrate concentration classes (Figure 3) indicates that about 20.3% of samples exceed the maximum permissible limit of 50 mg/L in drinking water Moroccan standards based on World Health

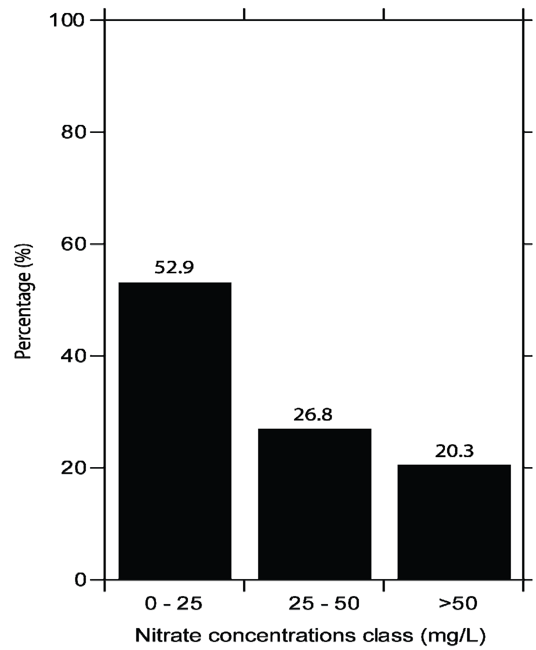

Figure 3. Frequency distribution of NO_3 contents.

Organization (WHO) standards and 47.1% of these samples crossed the recommended limit of 25 mg/L.

The examination of the spatial distribution of nitrate concentrations (Figure 4) shows that the highest nitrate concentrations are observed in the western and south-western parts of the study area, especially in Chtouka-Massa region. The upstream part of Souss–Massa aquifer seemed to be spared by nitrate contamination. Also, this map demonstrates clearly that very high levels of nitrate (e.g. > 100 mg/L) are situated within the irrigated areas where agricultural activities involving nitrogen compounds are intensively used. In other respects, some localized spots of nitrate pollution spread out in the vicinity of towns as the case is of Ait Melloul and Ouled Teima city.

Isotopic composition of Souss-Massa groundwater

The $\delta^{18}O$ and δ^2H values are plotted and compared to the World Meteoric Line (WML, Rozanski et al., 1993) which

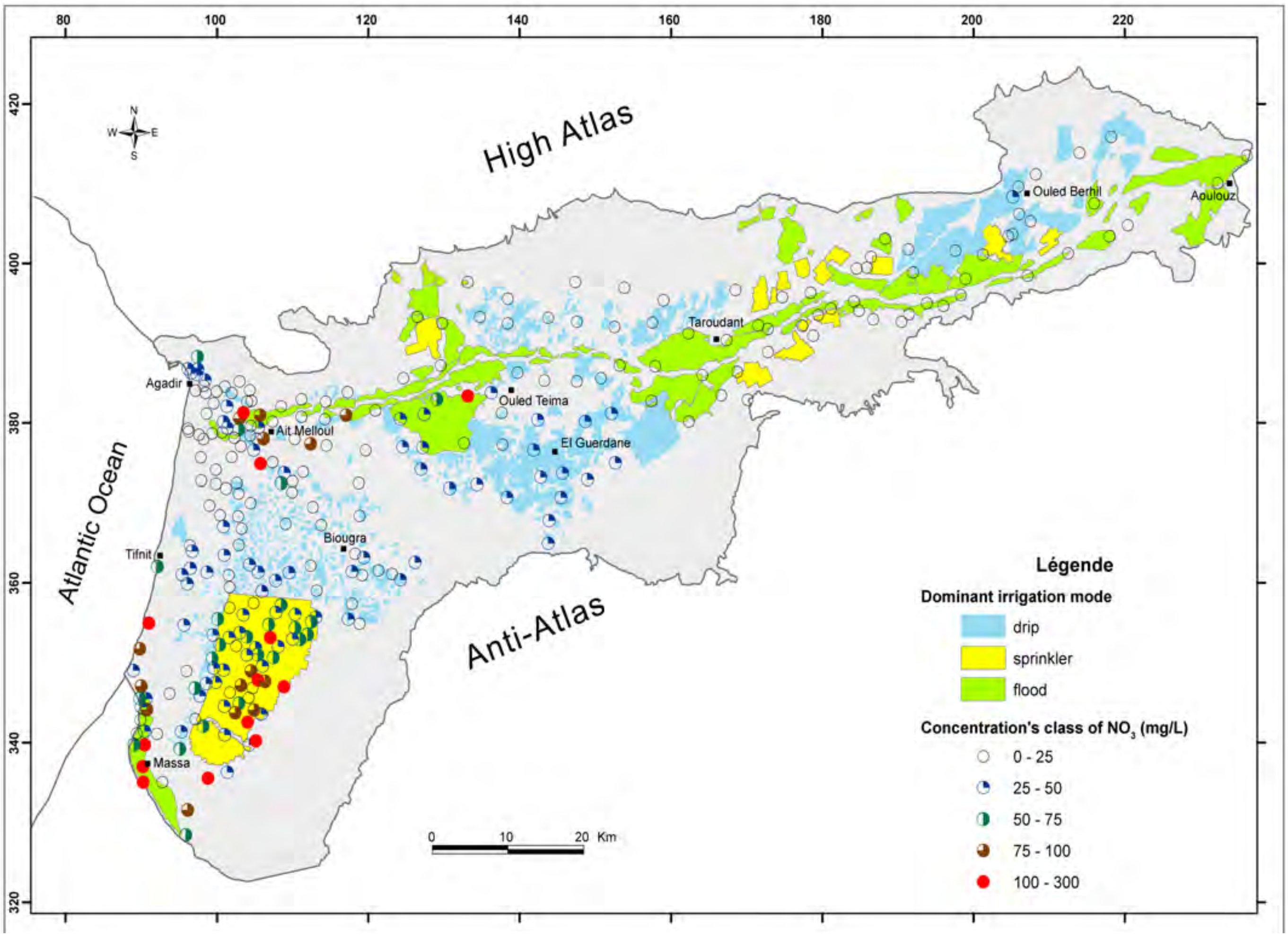

Figure 4. Spatial distribution of NO_3 contents overlaid to the irrigation type used in Souss-Massa region.

the equation is $\delta^2H = 8\ \delta^{18}O + 10$ (Figure 5).

According to this Figure, data are situated on the both sides of the WML and can stand in two distinct groups: one first group contains points plotted slightly above the WML of which $\delta^{18}O$ contents range between -8 and -5‰ and a second group plotted under the WML with $\delta^{18}O$ contents varying from -5 to -3‰. Also, the Figure shows that points corresponding to wells sampled in Chtouka-Massa region are $\delta^{18}O$-enriched relative to those of Souss region and they are plotted under the WML. These waters have undergone evaporation process to varying degrees. Therefore, an evaporation trend can be delineated (Figure 5) and presents a slope of 6.5, distinctly less than the slope of the WML.

The observed isotopic enrichment of $\delta^{18}O$ that concerns groundwater in Chtouka-Massa area can be attributed to a local supply by waters with high contents of $\delta^{18}O$. Bouchaou et al. (2005) has demonstrated that rain waters collected in Souss-Massa plain are characterized by $\delta^{18}O$ significantly higher than that of rain waters collected in the surrounding mountains. In addition, the aquifer in Chtouka-Massa area is recharged directly from local and/or oceanic rainwater where as in the Souss area, this aquifer is recharged by lateral flows coming from the High and Anti-Atlas mountains rather than direct infiltration of rain water.

On the other hand, considering the data points as a single group and barring groundwater samples with low nitrate content (< 10 mg/L), the high nitrate levels in groundwater are associated with high ^{18}O content (Figure 6).

Thus, significant quantities of evaporated (isotopically enriched) irrigation water infiltrate along with fertilizer nitrate to the groundwater system. Investigations carried out in Sacramento Valley, California, USA also observed similar features (Davisson and Criss, 1993; Criss and Davisson, 1996). Indeed, a combination of nitrate concentration and oxygen and hydrogen isotope data of Sacramento Valley indicates that isotopically enriched, evaporated, nitrogen fertilized irrigation water is recharging the aquifer. This further indicates that there is an imbalance between plant uptake and nitrate availability

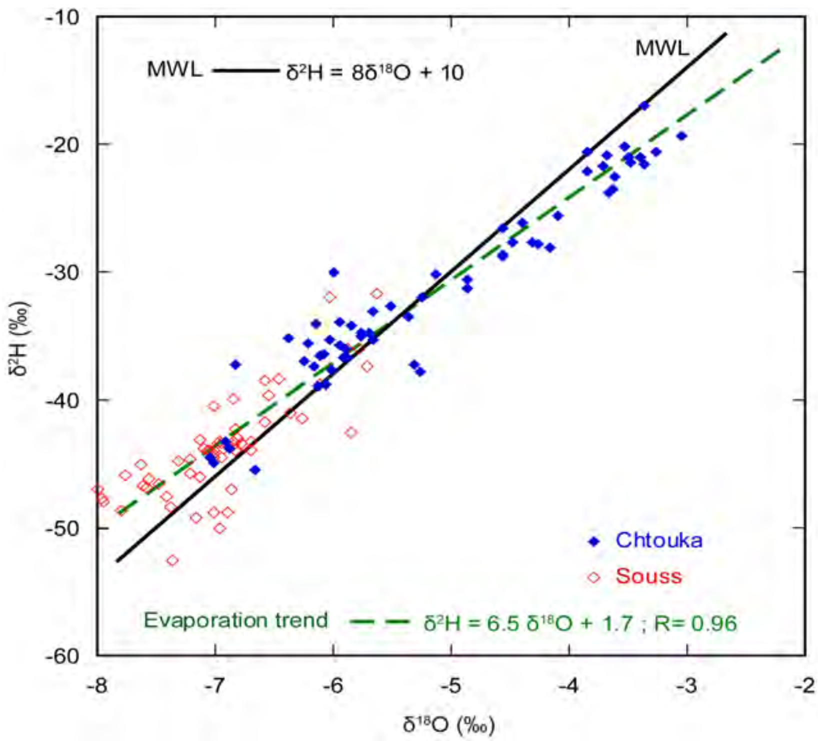

Figure 5. Water isotopic composition in Souss-Massa groundwater. The heavy line represents the WML with of slope of 8.0 and the dashed line represents the evaporation trend with a slope of approximately 6.5. The points from Souss and Chtouka-Massa regions are shown by different legends for identification only.

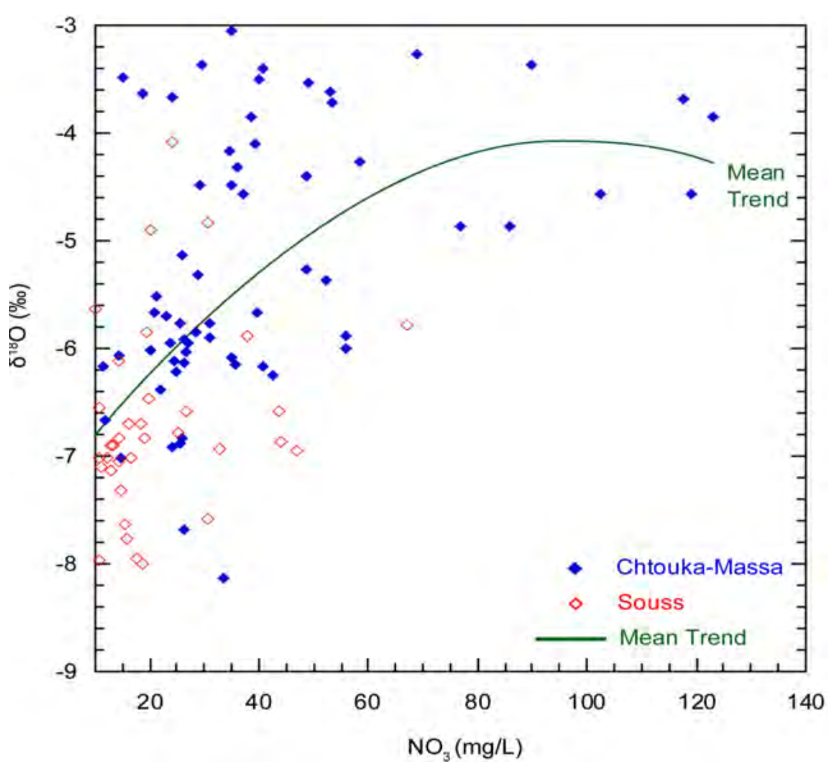

Figure 6. Scatter diagram of δ18O vs. NO3 in Souss-Massa groundwater. The heavy line represents the mean trend of the δ18O-NO3 correlation.

for example, due to application of fertilizer at a time when it cannot be taken up by plants. Alternatively, the plant density is too low to fully utilize the nitrate produced naturally in the soil. The positive relationship between NO_3 and $\delta^{18}O$ (Figure 6) also suggests that groundwater originates from two or more isotopically distinct non-point sources, which vary spatially as well as temporally, due to different degrees of evaporation/recharge and different amounts of fertilizer applied and thus show deviation of points from the main central trend.

Sources of nitrate pollution in Souss-Massa

In Souss-Massa, nitrate pollution can be separated into two categories: diffuse pollution and point pollution. Diffuse pollution is associated with farmers' agricultural practices. Market gardening in Massa (tomatoes, bananas and green beans) and arboriculture in Souss (citrus and olive trees) remain the primary types of crops grown in the region. To increase yields, farmers sometimes exceed required fertilizer application. There are no available data relative to quantities or types of nitrogen fertilizer's loading in the region, but some local studies conducted at small scale (Mimouni and Aït Lhaj, 2006), have shown that the amount of mineral fertilizers used is extremely high, especially for market gardening products. By way of example, the doses in question range between 610 and 850 kg N/ha for tomatoes, while the maximum dose required is 580 kg N/ha for an average output of 166 t/ha. Moreover, this fertilization, as it is used, dismisses manuring, agricultural waste and soil's natural components. Thus, it would generate considerable amounts of residual inorganic nitrogen, mainly in nitric forms, which might be leached deep into the soil by rainwater and irrigation water flows. The risk increases particularly in the beginning of the cropping season when the soils are still bare and crops require low amounts of nitrogen (Böhlke and Denver, 1995; Di et al., 1998; Bausch and Delgado, 2005; Feng et al., 2005). This leaching process increases in magnitude when the soil's texture is coarse and not very deep (Cosserat et al., 1990; Vinten et al., 1994; Pixie and Dennis, 1995; Kim et al., 2004). As is the case in Chtouka-Massa sector, the soil is made up of more than 60% of sand and a low percentage of clay. Such a composition would favour groundwater pollution by nitrate and this accounts for the high concentrations of nitrates in groundwater in this region.

To these factors can be added the irrigation type used. In Souss-Massa plain, flood-irrigated areas represent 54% of the total irrigated areas whereas drip and sprinkler irrigation cover only 31 and 15%, respectively. Figure 4 displays the irrigation types used within the study area. According to this map, drip irrigation is basically localized in private irrigated areas scattered around Biougra, El Guerdane and Ouled Berhil. The flood irrigation is used in traditional irrigated areas of Tassila, Issen, Taroudant and in some of Souss upstream sector. Finally, sprinkler irrigation is practiced in public irrigated areas such as in Massa perimeter. A number of studies (Sharmasarkar et al., 2001; Peterson and Ding, 2005; Böhlke et al., 2007) have proved that flood irrigation, given its low efficiency, does not offer groundwater enough protection against pollution even when mastered. Consequently, significant amounts of nitrates may be drained to groundwater altering its quality. The nitrate anomalies identified in the study area are fitted with zones where flood irrigation type is most used as is the case of Tassila irrigated areas. This finding is supported by NO_3^- and $\delta^{18}O$ of the sampled water wells. High nitrate levels in groundwater are associated with high ^{18}O values (isotopically enriched), clearly indicating that significant quantities of evaporated irrigation water infiltrate along with fertilizer nitrate to groundwater system. The percolation of water with high NO_3^- contents has entailed to an increase of $\delta^{18}O$ from -6.5 to -3‰ and from -8 to -5.5‰ in Chtouka-Massa area and Souss area respectively. This association has allowed considering that a recharge process takes place inside the irrigated perimeters by the infiltration of irrigation water and by their recycling. This later is due to an over-exploitation of groundwater for irrigation purpose combined to an intensive use of mineral fertilizers and to the evaporation phenomenon.

The other irrigated areas (Issen, Taroudant and Souss upstream), they do not exhibit high nitrate contents although flood irrigation type is used. This may be explained by the fact that olive and citrus trees are the common crops grown inside of these irrigated areas and these crops do not require important amounts of fertilizers.

In the Chtouka and Massa areas, high nitrate concentrations are sometimes present although the most common types of irrigation are sprinkler and drip. This can be related to the existence of intensive agricultural activity (market gardening) over several months of the year and to the sandy nature of soils as well.

According to the interpretation provided above, the main origin of nitrate is agricultural fertilizers. Soil texture, irrigation type and irrigation return flows are as many factors which contribute effectively in the pollution process of groundwater by nitrates. However, the localized anomalies of nitrates in the vicinities of Ait Melloul and Ouled Teima towns (Figure 4) might be explained by waste water effluents, since liquid and solid wastes of these towns are discharged directly into "wadis" (dried streams) without primary treatment.

Conclusion

This study presents the results of hydrogeologic data, nitrate concentrations and isotopic tools to better represent and explain the state of nitrate pollution of groundwater in Souss-Massa aquifer. Identification of factors that control the origins of nitrate in groundwater is of a paramount concern for predicting the long-term variations in groundwater quality and for improving management strategies. The aquifer in Chtouka-Massa region is the most severely contaminated; 36% of wells exceed the regulatory threshold of potability of 50 mg/L nitrate. In the Souss region, it is relatively less affected; 7% of wells crossed 50 mg/L with an average composition of 22 mg/L. The irrigated areas seem to be the most affected by nitrate pollution. The generalized distribution of this pollution would favour a pollution of agricultural origin linked to the excessive use of water and nitric fertilizers and to the infiltration/recycling of irrigation water to groundwater system, as reflected by the high nitrate concentrations (up to 50 mg/L) and high $\delta^{18}O$ values. However, agriculture cannot be held solely responsible for the contamination by nitrates of ground-water in Souss-Massa; there are many other factors (septic tanks, poultry and cattle manure) which can contribute to this pollution. Obviously, continued water utilisation and agricultural fertilizers without any rationalization would further increase the degradation of groundwater quality by nitrates. Therefore, the information provided in this study would be useful for the subsequent elaboration of strategies for current and future groundwater management in the region.

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