Environmental Research Journal 3 (3): 92-100, 2009
ISSN: 1994-5396

Nitrate Contamination of Groundwater in Irrigated Perimeters under Arid Climate (The Case of Souss-Massa Aquifer, Morocco)

[1]Tarik Tagma, [1]Youssef Hsissou, [1]Lhoussaine Bouchaou, [2]Latifa Bouragba and [1]Said Boutaleb
[1]Laboratory of Hydrogeology and Geo-Environment, Department of Applied Geology, Faculty of Sciences, University of Ibn Zohr, P.O. Box 8106, 80060 Agadir, Morocco
[2]Department of Geoscience, Faculty of Sciences, University of Franche-Comte, 16 Route de Gray, 25030 Besancon Cedex, France

Abstract: The objective of this study was to clarify, the current status of alluvial aquifer in the Souss-Massa basin, where, the nitric pollution of groundwater is being increasing along the last decades. A multi-approach methodology using hydrogeology, nitrate concentrations, irrigation mode and Oxygen-18 and Deuterium isotopes data, was carried out to identify the sources of this pollution. According to the spatial distribution of nitrate contents, nitric pollution occurs mainly in the Chtouka-Massa plain. More than 36% of the sampled wells exceed the value of 50 mg L^{-1} which, constitutes the threshold value of nitrate concentrations for drinking water Moroccan standards. The groundwater in Souss plain is less polluted comparing to Chtouka-Massa. Only 7% of wells exceed the permitted level. The widespread distribution of high nitrate contents agrees with the distribution of irrigated areas, which can explain the major origin from agricultural fertilizers. High nitrate levels are associated with high $\delta^{18}O$ values, clearly indicating that significant quantities of evaporated (isotopically enriched) irrigation water infiltrate along with fertilizer nitrate to the groundwater system. Different $\delta^{18}O$-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, isotopes, agricultural fertilizers, irrigation water infiltration, evaporation, recharge, Morocco

INTRODUCTION

Groundwater nitric 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 compromises the socio-economic development of the country (Colleen, 1993; Aghzar *et al*., 2002; Berdai *et al*., 2002). Such situations may become worse in arid and semi-arid areas where, water resources are scarce and poorly or even non renewable.

Many studies have shown that anthropogenic activities, involving nitrogenous compounds, are the major factor leading to the increase of nitric pollution (Power and Schepers, 1989; Kacaroglu and Gunay, 1997; Guimera, 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 on early fruits and vegetables productions and contributes about 60% of national exports. During the three last decades, the region has witnessed deep changes in agricultural production systems. Thus, thousands of hectares have been developed for irrigation, fertilizers have largely replaced animal manure as a source of nitrogen and monocultures have often replaced diversified cropping systems. Consequently, the demand for water has increased. Indeed, about 90-95% of water is used for irrigation, of which 71% is provided by groundwater resources. These drastic improvements have had an impact on the environment and specifically, on groundwater 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 discussed (Boutaleb *et al*., 2000; Hsissou *et al*., 2002; Ahkouk *et al*., 2003; Dindane *et al*., 2003; Krimissa *et al*., 2004; Bouchaou *et al*., 2005). However, none of these studies has emphasized groundwater degradation caused by nitric pollution.

Corresponding Author: Tarik Tagma, Laboratory of Hydrogeology and Geo-Environment, Department of Applied Geology, Faculty of Sciences, University of Ibn Zohr, P.O. Box 8106, 80060 Agadir, Morocco

The present study aims, therefore, to establish the nitric pollution status in Souss-Massa basin, identify the sources of this contamination and indicate the vulnerable parts of the unconfined aquifer in the basin. The information would be useful for the subsequent elaboration of strategies for current and future groundwater management in the region.

MATERIALS AND METHODS

Study area settings: The present study is conducted in Souss-Massa basin, Southwest of Morocco (Fig. 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 km^2. 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 is ranging 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, with a range of high temperature of 48°C. From a hydrogeological point of view, the Souss-Massa basin contains a shallow unconfined aquifer, which constitutes the major groundwater's resource in the region. It is made up essentially by plioquaternary deposits. These deposits interlay, in the Souss plain, with marine deposits of Pliocene and Moghrebian age in the west and by continental deposits of fluvio-lacustrin calcareous marls and conglomerates of Plio-Villafranchian age towards the east forming thus, the Souss formation. The whole sediments were underlain by an heterogeneous substratum of diverse lithology and age (Georgian shales, Albian marls and calcareous and marls of upper Cretaceous) (Dijon, 1969). The Chtouka-Massa plain constitutes a natural extension of Souss plain towards the south; it comprises sand, sandstones, conglomerate and lacustrin limestone considered to be mainly of Plio-Quaternary age. The lower boundaries were made of calcareous and marls of Cretaceous age to the north and by shales dating back to Acadian and Ordovician age in the south part of the plain (Bernert and El-Hebil, 1977). The soils of Souss-Massa plain are diversified. Several groups, dominated by the sandy-loam soils with little humus, are highlighted (Ghanem, 1974). They are characterised by a coarse texture with low content of clay and occur chiefly in the Chtouka-Massa region and in Atlas foothills surrounding the Souss plain. The heterocalcareous soils, xeric, brown-to-black, clayey-sand texture with moderate amounts of clay are frequent in Souss upstream as well as in Ouled Teima and El Guerdane areas. Finally, fersialitic xeric soil, halomorphic soil, hydromorphic soil and calcimagnesic soil are poorly represented in the study area.

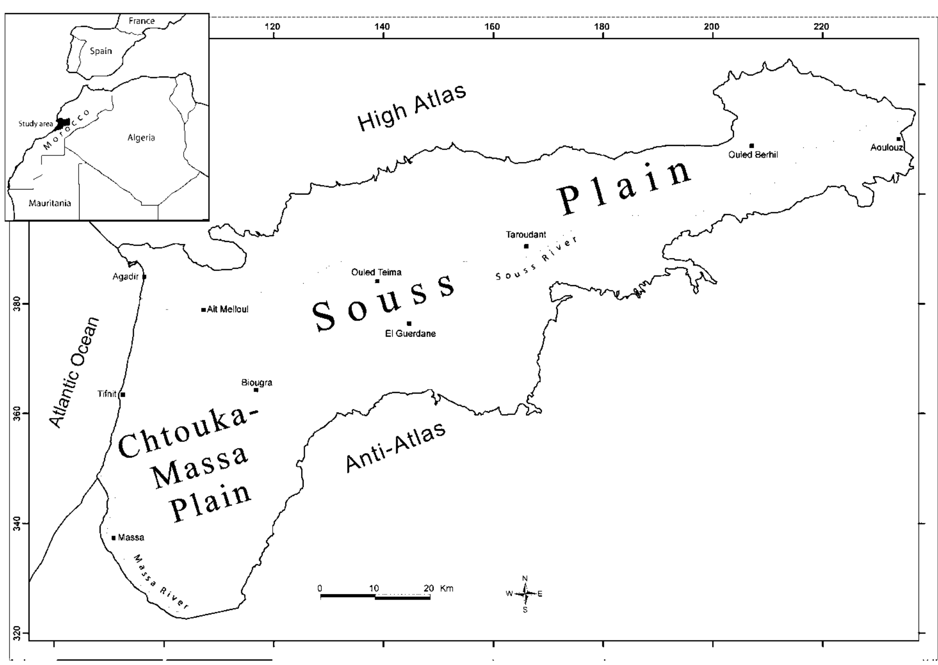

Fig. 1: Location map of study area

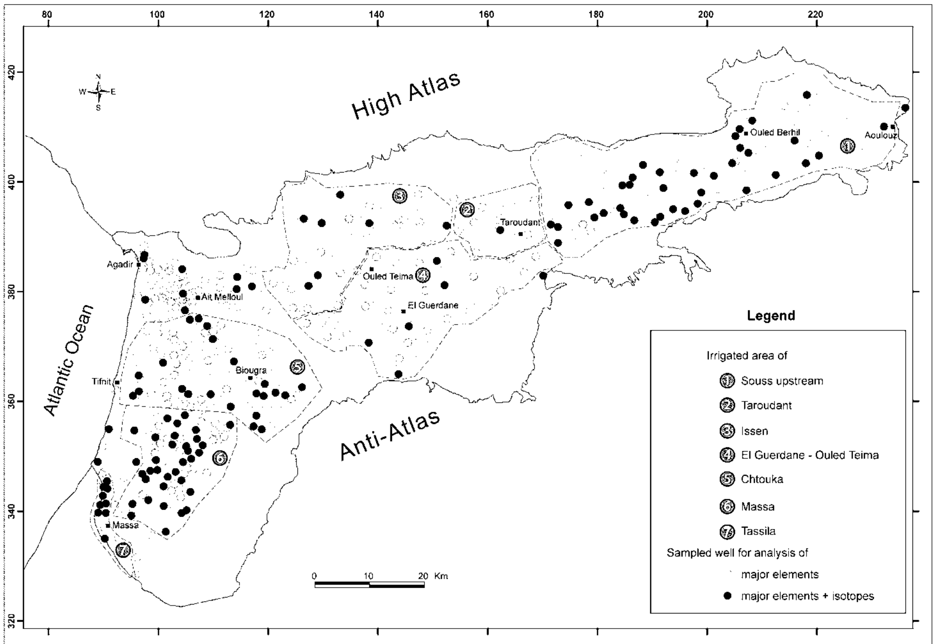

Fig. 2: Sampling network and the major irrigated areas. Empty circles represent samples for which only the major elements have been analyzed. The full circles represent samples for which ^{18}O, ^{2}H and the major elements have been analyzed

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

Lithology	T (10^{-2} m^2 sec^{-1})	K (10^{-4} m sec^{-1})	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

The Souss-Massa plain contains the major unconfined aquifer in the South of Morocco. The aquifer is heterogeneous regarding the spatial distribution of hydrodynamic parameters (Table 1). The Transmissivity (T) fluctuates between 0.1 10^{-2} and 7 10^{-2} m^2 sec^{-1}. The high t-values of 3-7.10^{-2} m^2 sec^{-1} are found in sandstones and limestones near Agadir city. The general groundwater flow direction is from east to west. The Souss-Massa aquifer is recharged from the surrounding Atlas Mountains chiefly from the High Atlas one particularly along the Souss eastern part (Bouchaou *et al*., 2005).

The plain of Souss-Massa includes several irrigated areas (Fig. 2); representing an area of 123140 ha. These irrigated areas constitute the first early crops zone of production in citrus and market gardening in the overall Moroccan national horticultural production: 60% of the bananas, 15-20% of the open field and greenhouse tomatoes, 5% of the potatoes, 14% of the other market garden products and around 47% of the citrus.

The data concerning the groundwater nitric 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 the year 2004.

The dataset used in this study included hydrogeology and nitrate concentrations in 283 wells spreading over the study area. Within the sampled wells, 117 were chosen for an isotopic investigation of oxygen-18 (^{18}O) and deuterium (^{2}H). These wells were selected within the irrigated areas in order to assess the effect of irrigation water on groundwater quality (Fig. 2). Groundwater samples were taken directly from wells after enough pumping time. Temperature, pH and electrical conductivity were measured *in-situ*. 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 isotope were analysed in the National Center of Energy, Sciences and Nuclear Techniques of Morocco. ^{18}O and ^{2}H 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 $^{2}H/^{1}H$ ratio of the sample and R_{SMOW} is either the $^{18}O/^{16}O$ or the $^{2}H/^{1}H$ ratio of Standard Mean Ocean Water (SMOW) (Craig, 1961).

RESULTS AND DISCUSSION

Nitric pollution status of Souss-Massa groundwater: The nitrate contents of the groundwater samples range between 0 and 300 mg L^{-1} with an average of 33 mg L^{-1}. Table 2 lists some elementary statistics parameters of nitrate data in Souss-Massa aquifer. The frequency distribution of the whole sampled wells onto nitrate concentration classes (Fig. 3) indicates that about 20.3% of samples exceed the maximum permissible limit of 50 mg L^{-1} in drinking water Moroccan standards set on World Health Organization (WHO) standards and 47.1% of these samples crossed the recommended limit of 25 mg L^{-1}.

The spatial distribution of nitrate concentrations in the study area is shown in Fig. 4. The examination of this map shows that the highest nitrate concentrations are observed in the western and southwestern parts of the study area, especially in Chtouka-Massa region. The upstream part of Souss-Massa aquifer seemed to be spared by nitric contamination. Also, this map demonstrates clearly that very high levels of nitrate (e.g., >100 mg L^{-1}) are situated within the irrigated areas where, agricultural activities involving nitrogen compounds are intensively used. In other respects, some localized spots of nitric 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 $\delta^{2}H$ values are plotted and compared to the World Meteoric Line (Rozanski *et al.*, 1993), which the equation is $\delta^{2}H = 8\ \delta^{18}O + 10$. The points from Souss and Chtouka-Massa regions are shown by different legends for identification only (Fig. 5).

According to this Fig. 5, the data are situated on the both sides of the WML, so they can stand in two distinct groups: 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 Fig. 5 shows that points corresponding to wells sampled in Chtouka-Massa region are $\delta^{18}O$-enriched than those of

Table 2: Elementary statistics of nitrate contents in groundwater in Souss and Chtouka-Massa areas

Statistics	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^{-1}	7%	36%	18%

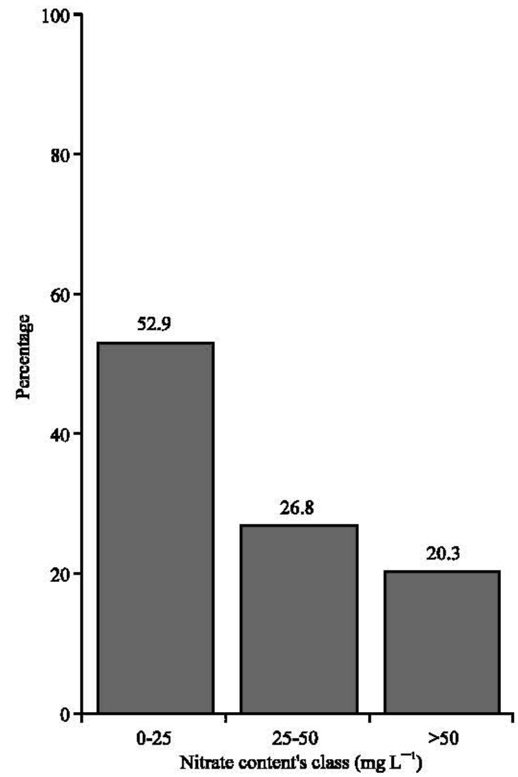

Fig. 3: Frequency distribution of NO_3 contents

Souss region and they are plotted under the WML. These waters have undergone evaporation process with variable degrees. Therefore, an evaporation trend can be delineated (Fig. 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 >1 of rain waters collected in the surrounding mountains and also the aquifer in Chtouka-Massa area is rather recharged directly from local and/or oceanic rainwater where as in the Souss area, this aquifer is recharged by lateral flows coming from High and Anti-Atlas mountains rather than direct infiltration of rain water.

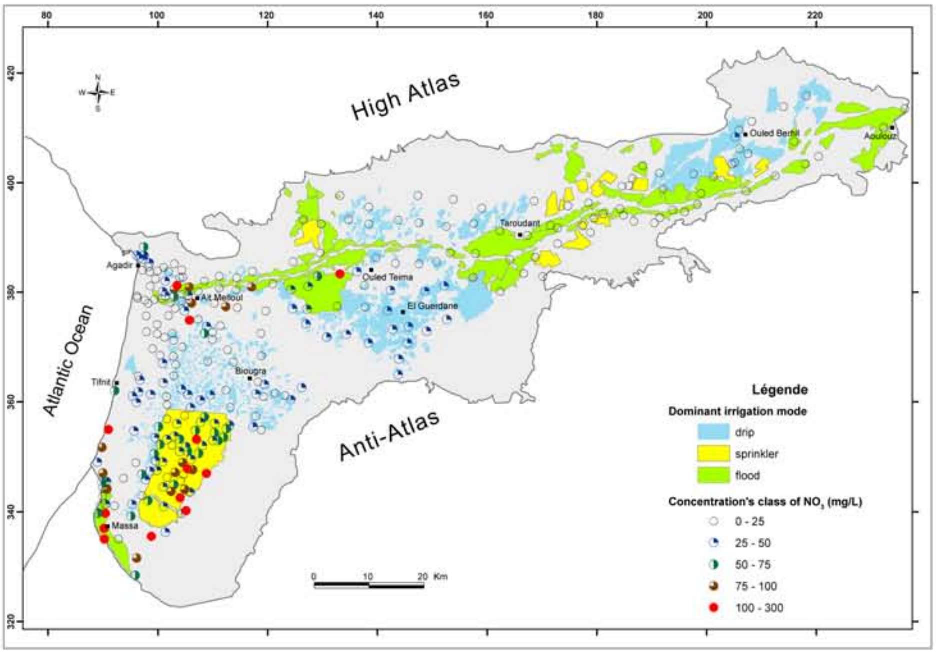

Fig. 4: Spatial distribution of NO_3 contents overlaid to the irrigation mode used in Souss-Massa region

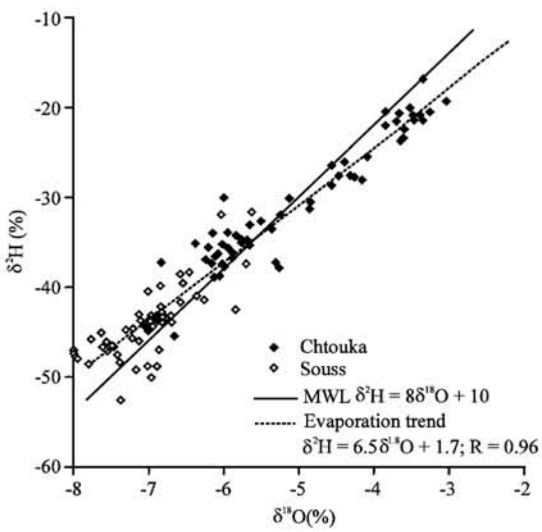

Fig. 5: Water isotopic composition in the Souss-Massa groundwater. The heavy line represents the WML with of slope of 8.0 and the dashed line represents the evaporation trend with a slope of approximately 6.5

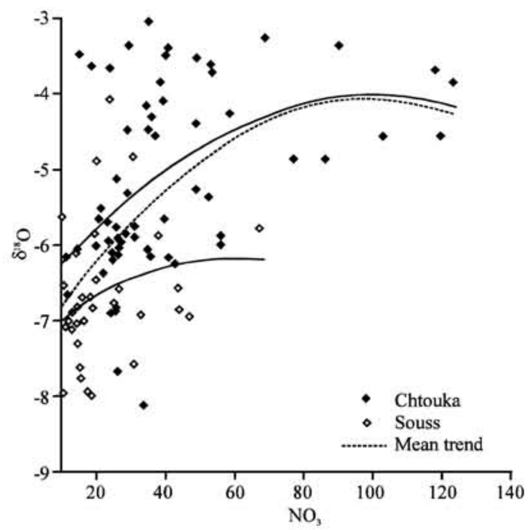

Fig. 6: Scatter diagram of $\delta^{18}O$ vs. NO_3 in the groundwater of Souss-Massa aquifer. The heavy line represents the mean trend of the $\delta^{18}O$-NO_3 correlation

On the other hand, considering the data points as a single grouping and barring the groundwater samples with low nitrate content (<10 mg L^{-1}), the high nitrate levels in groundwater are associated with high ^{18}O (isotopically enriched) water (Fig. 6).

Thus, the Fig. 6 indicates that 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, 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 $\delta^{18}O$ (Fig. 6) also suggests that the groundwater originates from two or more isotopically distinct non-point sources, which vary spatially as well as temporarily, 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 nitric pollution in Souss-Massa: In Souss-Massa, nitric pollution splits up, according to its geographical extension, into two categories: diffuse pollution and sporadic pollution. Diffuse pollution is associated with farmers' agricultural practices. Market gardening in Massa (tomatoes, bananas and green bean) and arboriculture in Souss (citrus and olive trees) remain the primary types of crops grown in the region. To increase yields, farmers have recourse to fertilization techniques though they sometimes exceed the required levels. 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 Ait Lhaj, 2006), have shown that the amount of mineral fertilizers used are extremely high, especially for market gardening products. By way of example, the doses in question range between 610 and 850 kg N ha^{-1} for tomatoes, while, the maximum dose required is 580 kg N ha^{-1} for an average output of 166 t ha^{-1}. 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 (Bohlke 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 >60% of sand and a low percentage of clay. Such a composition would favour groundwater pollution by nitrates and this accounts for the high rate of nitrates in groundwater in this region.

To these factors can be added the irrigation mode used. In Souss-Massa plain, flood-irrigated areas represent 54% of total irrigated areas whereas, drip and sprinkler irrigation cover only 31 and 15%, respectively. Figure 4 displays the irrigation mode mainly used overall the study area. According to this map, drip irrigation mode 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 region. 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; Bohlke *et al.*, 2007) have proved that the technique of 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 the groundwater altering its quality. The nitric anomalies identified in the study area are fitted with zones where flood irrigation mode is most used as is the case of Tassila and Issen 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 the 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 overexploitation of groundwater for irrigation purpose combined to an intensive use of mineral fertilizers.

In Chtouka and Massa irrigated areas, although the most irrigation mode used is sprinkler and drip, this sector displays sometimes high concentrations of nitrates. This can be related to the existence of an intensive agricultural activity over a long period of the year and to the sandy nature of soils as well. The high values of nitrate contents, which can reach 300 mg L^{-1}, found in some wells within this sector may be explained by a sporadic pollution, due probably to septic tanks, which can be added to a non-point pollution caused by overfertilization.

According to interpretation provided above, the main origin of nitrate is coming from agricultural fertilizers. Soil texture, irrigation return flows, irrigation mode and water table depth are as many factors, which contribute effectively in the pollution process of groundwater by nitrates. However, the punctual anomalies of nitrates in the vicinities of Ait Melloul and Ouled Teima towns

(Fig. 4) might be explained by waste water effluents, since liquid and solid wastes of these towns are discharged directly into the rivers without any preliminary treatment.

CONCLUSION

This study presents, the results of hydrogeological, nitrates and isotopic tools to better represent and explain the state of nitric 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 in the Souss-Massa aquifer system. The aquifer in Chtouka-Massa region is the most contaminated, 36% of wells exceed the regulatory threshold of potability of 50 mg L^{-1} of nitrates. In the Souss region, it is relatively less affected; 7% of wells crossed 50 mg L^{-1} with an average of composition of 22 mg L^{-1}. The irrigated areas seem to be the most affected by nitric pollution. The generalized character of this pollution would favour a pollution of agricultural origins linked to the excessive use of water and nitric fertilizers. Infiltration/recycling of irrigation water to the groundwater system, as reflected by the high nitrate concentration (up to 50 mg L^{-1}) and high $\delta^{18}O$ values, is the main process of pollution origin. However, agriculture cannot be held the only responsible for the contamination by nitrates of groundwater in Souss-Massa; there are many other factors, which can contribute to this pollution. Obviously, continued water utilisation and agricultural fertilizers without any rationalisation 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.

ACKNOWLEDGEMENTS

We gratefully acknowledge the help provide by Hydraulic Agency of Souss-Massa basin (ABHSM) and Agricultural department of Souss-Massa (ORMVASM). Our thanks go also to Dr. Ghislaine Demarsily for his insightful remarks and constructive comments on an earlier version of this manuscript.

REFERENCES

Aghzar, N., H. Berdai, A. Bellouti and B. Soudi, 2002. Groundwater nitrate pollution in Tadla (Morocco). J. Water Sci., 15: 495-492. http://www.rse.inrs.ca/art/volume15/v15n2_459.pdf.

Ahkouk, S., Y. Hsissou, L. Bouchaou, M. Krimissa and J. Mania, 2003. Impact of agricultural fertilizers on groundwater quality (the case of Chtouka plain, Souss-Massa basin, Morocco). Afr. Geosci. Rev., 9:355-364.http://www.geoscafr.com/vol10num4.html.

Bausch, W.C. and J.A. Delgado, 2005. Impact of residual soil nitrate on In-Season nitrogen applications to irrigated corn based on remotely sensed assessments of crop Nitrogen Status. Preci. Agric. 6: 509-519. DOI: 10.1007/s11119-005-5641-9. http://www.springerlink.com/content/p734rh34l27w3k60/fulltext.pdf.

Berdai, H., N. Aghzar, F.Z. Cherkaoui and B. Soudi, 2002. Residual mineral nitrogen and its evolution during summer in relation with previous crops in mediterranean area. Soil. Study Manage., 9: 7-23. www.inra.fr/internet/Hebergement/afes/pdf/EGS_9_1_berdai.pdf.

Bernert, G. and A. El-Hebil, 1977. The Chtouka plain. In: Water Resources of Morocco, Tome 3. Atlasic and South-Atlasic Domaines. Notes. Mem. Geol. Serv. Morocco, pp: 202-233.

Bohlke, J.K. and J.M. Denver, 1995. Combined use of groundwater dating, chemical and isotopic analyses to resolve the history and fate of nitrate contamination in two agricultural watersheds Atlantic coastal plain, Maryland. Water Ressour. Res., 31: 2319-2339. DOI: 10.1029/95WR01584. http://www.agu.org/pubs/crossref/1995/95WR01584.shtml.

Bohlke, J.K., I.M. Verstraeten and T.F. Kraemer, 2007. Effects of surface-water irrigation on sources, fluxes and residence times of water, nitrate and uranium in an alluvial aquifer. Applied Geochem., 22: 152-174. DOI: 10.1016/j.apgeochem.2006.08.019. http://www.sciencedirect.com/science/article/B6VDG-4MFJJ6P-1/2/d01cc36ea1f971e85b2986a2e3aacbef.

Bouchaou, L., Y. Hsissou, M. Krimissa, S. Krimissa and J. Mudry, 2005. ^{2}H and ^{18}O Isotopic Study of Groundwaters under a Semi-Arid Climate. In: Lichtfouse, E., J. Schwarzbauer and D. Robert (Eds.). Environ. Chem., Green Chemistry and Pollution in Ecosystems, Springer, Berlin, pp: 57-64. ISBN: 978-3-540-22860-8 (print) 978-3-540-26531-3 (electronic). DOI: 10.1007/3-540-26531-7_6. http://www.springerlink.com/content/l181856455483v42/fulltext.pdf.

Boutaleb, S., L. Bouchaou, J. Mudry, Y. Hsissou and P. Chauve, 2000. Effects of lithology on quality of water resources. The case of oued Issen (Western upper Atlas, Morocco). Hydrogeol. J., 8: 230-238. DOI: 10.1007/s100400050009. http://www.springerlink.com/content/kwcqhqw179j8qa1w/fulltext.pdf.

Coleman, M.L., T.J. Sheperd, J.J. Durham, J.E. Rouse and G.R. Moore, 1982. Reduction of water with zinc for hydrogen isotope analysis. Anal. Chem., 54: 993-995. DOI: 10.1021/ac00243a035. http://pubs.acs.org/doi/pdf/10.1021/ac00243a035.

Colleen, S., 1993. The effect of nitrate, nitrite and N-nitrosocompounds on human health. Rev. Vet. Hum. Toxicol., 35: 521-538.

Cosserat, M., J. Decau, H. Patacq-Crontzet and B. Pujol, 1990. Fertigation in Coarse-Textured Soil. Consequences on Production and Nitrate Pollution. In: Calvet, R. (Ed.). Nitrate-Agriculture-Eau, INRA, Paris, France, pp: 257-262. ISBN: 2-7380-0284-6 (print).

Craig, H., 1961. Standard for reporting concentrations of deuterium and oxygen-18 in natural waters. Science, 133: 1833-1834. DOI: 10.1126/science.133.3467.1833. http://www.sciencemag.org/cgi/reprint/133/3467/1833.pdf.

Criss, R.E. and M.L. Davisson, 1996. Isotope imaging of surface water/groundwater interactions, Sacramento Valley, California. J. Hydrol., 178: 205-222. DOI: 10.1016/0022-1694(96)83733-4. http://www.sciencedirect com/science?_ob=MImg&_imagekey=B6V6C-3VW297J-1C-4&_cdi=5811&_user=3444726&_orig=search&_coverDate=04%2F15%2F1996&_sk=998219998&view=c&wchp=dGLbVzz-zSkWb&md5=462fbb250cc04e28afd10728acec7c68&ie=/sdarticle.pdf.

Davisson, M.L. and R.E. Criss, 1993. Stable isotope imaging of a dynamic groundwater system in the southwestern Sacramento valley, California (USA). J. Hydrol., 144: 213-246. DOI: 10.1016/0022-1694(93)90173-7. http://www.sciencedirect.com/science?_ob=MImg&_imagekey=B6V6C-487FG0F-27X-3&_cdi=5811&_user=3444726&_orig=search&_coverDate=04%2F30%2F1993&_sk=998559998&view=c&wchp=dGLbVtz-zSkWz&md5=c33af65d29b41431 68eafb9a22ac8eda&ie=/sdarticle.pdf.

Di, H.J., K.C. Cameron, S. Moore and N.P. Smith, 1998. Nitrate leaching and pasture yields following the application of dairy shed effluent or ammonium fertilizer under spray or flood irrigation: Results of a lysimeter study. Soil Use Manage., 14: 209-214. DOI:10.1111/j.1475-2743.1998.tb00152.x.http://www3.interscience.wiley.com/user/accessdenied?ID=119118968&Act=2138&Code=4719&Page=/cgi-bin/fulltext/119118968/PDFSTART.

Dijon, R., 1969. Hydrogeological Study and Water Resources Assessment in Souss valley. 216th Edn. Notes. Rep. Geol. Serv. Morocco, 299: 19-35.

Dindane, K., L. Bouchaou, Y. Hsissou and M. Krimissa, 2003. Groundwater in the Souss upstream basin, southwestern Morocco: Evidences to its chemical evolution and origin. J. Afr. Earth Sci., 36: 315-327. DOI: 10.1016/S0899-5362(03)00050-2. http://www.sciencedirect.com/science?_ob=MImg&_imagekey=B6VDT-4956611-1-Y&_cdi=5991&_user=3444726&_orig=search&_coverDate=05%2F31%2F2003&_sk=999639995&view=c&wchp=dGLbVlz-zSkzk&md5=50eee8972363436459f3580fd019c29f&ie=/sdarticle.pdf.

Epstein, S. and T.K. Mayeda, 1953. Variation of O18 content of waters from natural sources. Geochim. Cosmochim. Acta, 4: 213-224. DOI: 10.1016/0016-7037(53)90051-9. http://www.sciencedirect.com/science?_ob=MImg&_imagekey=B6V66-489SJ76-47-2&_cdi=5806&_user=5835995&_orig=search&_coverDate=11%2F30%2F1953&_sk=999959994&view=c&wchp=dGLbVtb-zSkzk&md5=72ccd89b83b690920908a5d0e4d1b1e3&ie=/sdarticle.pdf.

Feng, Z.Z., X.K. Wang and Z.W. Feng, 2005. Soil N and salinity leaching after the autumn irrigation and its impact on groundwater in Hetao Irrigation District, China. Agric. Water Manage., 71: 131-143. DOI: 10.1016/j.agwat.2004.07.001. http://www.sciencedirect.com/science?_ob=MImg&_imagekey=B6T3X-4DBCFXV-1-1&_cdi=4958&_user=3444726&_orig=search&_coverDate=02%2F02%2F2005&_sk=999289997&view=c&wchp=dGLbVlW-zSkzS&md5=d82447e7b353d6d5249ac7a5518a6a46&ie=/sdarticle.pdf.

Ghanem, H., 1974. Pedological Monograph of Souss Plain. Ecol. Research. Serv. Dep. Agron. Res., pp: 101.

Guimera, J., 1998. Anomalously high nitrate concentrations in groundwater. Ground Water, 36: 275-282. DOI: 10.1111/j.1745-6584.1998.tb01093.x. http://www3.interscience.wiley.com/user/accessdenied?ID=119106718&Act=2138&Code=4719&Page=/cgi-bin/fulltext/119106718/PDFSTART.

Hsissou, Y., J. Mudry, L. Bouchaou, P. Chauve and J. Mania, 2002. Use of chemical tracy to study acquisition modality of mineralization and behaviour of unconfined groundwater under semi-arid climate: The case study of the Souss plain (Morocco). Environ. Geol., 42: 672-680. DOI: 10.1007/s00254-002-0576-1. http://www.springerlink.com/content/rykr2agvb40twrmp/fulltext.pdf.

Kacaroglu, F. and G. Gunay, 1997. Impacts of Human Activities on Groundwater Quality of an Alluvial Aquifer: A Case Study of the Eskisehir Plain, Turkey. Hydrogeol. J., 5: 60-70. DOI: 10.1007/s100400050257. http://www.springerlink.com/content/3kpl4h9jlgemtlvd/fulltext.pdf.

Kim, J.G., C.M. Chon and J.S. Lee, 2004. Effect of structure and texture on infiltration flow pattern during flood irrigation. Environ. Geol., 46: 962-969. DOI: 10.1007/s00254-004-1108-y. http://www.springerlink.com/content/x809qfucw8fjupg8/fulltext.pdf.

Krimissa, S., J.L. Michelot, L. Bouchaou, J. Mudry and Y. Hsissou, 2004. About the origin of chloride in groundwater from a coastal aquifer under semi-arid climate (Chtouka-Massa, Morocco). C.R. Geosci., 336: 1363-1369. DOI: 10.1016/j.crte.2004.08.003. http://www.sciencedirect.com/science?_ob=MImg&_imagekey=B6T3X-4DBCFXV-1-1&_cdi=4958&_user=3444726&_orig=search&_coverDate=02%2F02%2F2005&_sk=999289997&view=c&wchp=dGLbVlb-zSkzk&md5=d82447e7b353d6d5249ac7a5518a6a46&ie=/sdarticle.pdf.

Lake, I.R., A.A. Lovett, K.M. Hiscock, M. Betson, A. Foley, G. Sunnenberg, S. Evers and S. Fletcher, 2003. Evaluating factors influencing groundwater vulnerability to nitrate pollution: Developing the potential of GIS. J. Environ. Manag., 68: 315-328. DOI: 10.1016/S0301-4797(03)00095-1. http://www.sciencedirect.com/science?_ob=MImg&_imagekey=B6WJ7-48TM8CD-1-J&_cdi=6871&_user=3444726&_orig=search&_coverDate=07%2F31%2F2003&_sk=999319996&view=c&wchp=dGLbVlz-zSkWz&md5=87305b4f2cd3ac78dccf554af3fc1f76&ie=/sdarticle.pdf

Liu, A., J. Ming and R.O. Ankumah, 2005. Nitrate contamination in private wells in rural Alabama, United States. Sci. Total Environ., 346: 112-120. DOI: 10.1016/j.scitotenv.2004.11.019. http://www.sciencedirect.com/science?_ob=MImg&_imagekey=B6V78-4FC8V3D-1-9&_cdi=5836&_user=3444726&_orig=search&_Date=06%2F15%2F2005&_sk=996539998&view=c&wchp=dGLbVlW-zSkzk&md5=aceee91223a426ca354dd443572a09ab&ie=/sdarticle.pdf.

Mimouni, A. and A. Aît-Lhaj, 2006. Fertilization practices in Souss-Massa region and its consequences on groundwater nitrate pollution. Paper presented at the First International Congress Integrated Water Resource Management and Challenges of the Sustainable Development, Marrakech, 23-25 May Faculty of Sciences of Semlalia, Marrakech, Morocco, pp: 48-51.

Peterson, J.M. and Y. Ding, 2005. Economic Adjustements to Groundwater Depletion in the High Plains: Do Water-Saving Irrigation Systems Save Water? Am. J. Agric. Econ., 80: 147-159. DOI: 10.1111/j.0002-9092.2005.00708.x. http://www3.interscience.wiley.com/cgi-bin/fulltext/118681447/PDFSTART.

Pixie, A.H. and R.H. Dennis, 1995. Effects of agriculture on groundwater quality in five regions of the United States. Ground Water, 33: 217-226. DOI: 10.1111/j.1745-6584.1995.tb00276.x. http://www3.interscience.wiley.com/cgi-bin/fulltext/119236178/PDFSTART.

Power, J.F. and J.S. Schepers, 1989. Nitrate Contamination of Groundwater in North America. Agric. Ecosyst. Environ., 26: 165-187. DOI: 10.1016/0167-8809(89)90012-1. http://www.sciencedirect.com/science?_ob=MImg&_imagekey=B6T3Y-4914VJG-77-1&_cdi=4959&_user=3444726&_orig=search&_coverDate=10%2F31%2F1989&_sk=999739996&view=c&wchp=dGLbVzz-zSkWb&md5=ff958420130903092e8549b02ad226df&ie=/sdarticle.pdf.

Rao, N.S., 2006. Nitrate pollution and its distribution in the groundwater of Srikakulam district andhra Pradesh, India. Environ. Geol., 51: 631-645. DOI: 10.1007/s00254-006-0358-2. http://www.springerlink.com/content/uk272319hhv22807/fulltext.pdf.

Rozanski, K., L. Araguas-Araguas and R. Gonfiantini, 1993. Isotopic Patterns in Modern Global Precipitation. In: Swart, P.K., K.L. Lohmann, J. McKenzie and S. Savin (Eds.). Climate Change in Continental Isotopic Records, Geophysical Monography. AGU, Washington DC, 78: 1-36.

Sharmasarkar, F.C., S. Sharmasarkar, S.D. Miller, G.F. Vance and R. Zhang, 2001. Assessment of drip and flood irrigation on water and fertilizer use efficiencies for sugarbeets. Agric. Water Manage., 46: 241-251. DOI: 10.1016/S0378-3774(00)00090-1. http://www.sciencedirect.com/science?_ob=MImg&_imagekey=B6T3X-41XM99C-4-5&_cdi=4958&_user=3444726&_orig=search&_coverDate=01%2F31%2F2001&_sk=999539996&view=c&wchp=dGLbVzW-zSkzV&md5=3989b26119c75f7759799368bf504712&ie=/sdarticle.pdf.

Vinten, A.J.A., B.J. Vivian, F. Wright and R.S. Howard, 1994. A comparative study of nitrate leaching from soils of differing textures under similar climatic and cropping conditions. J. Hydrol., 159: 197-213. DOI: 10.1016/0022-1694(94)90256-9. http://www.sciencedirect com/science?_ob=MImg&_imagekey=B6V6C-487DTBV-V-1&_cdi=5811&_user=3444726&_orig=search&_coverDate=07%2F31%2F1994&_sk=998409998&view=c&wchp=dGLbVtb-zSkzk&md5=fdc1205d75858579cc864af1b93c446f&ie=/sdarticle.pdf.

Widory, D., W. Kloppmann, L. Chery, J. Bonnin, H. Rochdi and J.L. Guinamant, 2004. Nitrate in groundwater: an isotopic multi-tracer approach. J. Contam. Hydrol., 72: 165-188. DOI: 10.1016/j.jconhyd.2003.10.010. PMID: 15240171. http://www.sciencedirect.com/science?_ob=MImg&_imagekey=B6V94-4CGMB19-1-R&_cdi=5888&_user=3444726&_orig=search&_coverDate=08%2F31%2F2004&_sk=999279998&view=c&wchp=dGLbVzz-zSkzV&md5=228cd21a20af31527d222c2af4870a10&ie=/sdarticle.pdf.