International Journal of Water Resources and Environmental Engineering Vol. 5(2), pp. 77-93, February 2013
Available online at http://www.academicjournals.org/IJWREE
DOI: 10.5897/IJWREE12.078
ISSN 1991-637X ©2013 Academic Journals

Full Length Research Paper

Use of multivariate statistical and geographic information system (GIS)-based approach to evaluate ground water quality in the irrigated plain of Tadla (Morocco)

Naima EL Hammoumi[1,2]*, M. Sinan[2], B. Lekhlif[2] and M. Lakhdar[1]

[1]Laboratory of Catalysis and Environment, Faculty of Science, University Hassan II Ain Chock- km 8 Road of El Jadida P. O. BOX 5366, Casablanca Morocco.
[2]Research Team of Hydrogeology, Treatment and Purification of Water and Climate Change, Department of Hydraulics, Hassania School of Public Works, km 8 Road of El Jadida P. O. BOX 8108, Casablanca Morocco.

Accepted 5 December, 2012

Twenty five chemical, physical and bacteriological features of water samples from 25 wells were analyzed by multivariate statistical tools to provide the characterization of the ground water distribution in the basin of Tadla province (Morocco). The 25 parameters determined include: temperature, pH, conductivity, IP (permanganate index), dry residue (RS), total hardness, total iron (FeT), several bacteriological residues (faecal, total coliforms and faecal streptococcus) and several cations and anions (Ca^{2+}, Na^+, K^+, Mg^{2+}, SO_4^{2-}, Mn^{2+}, NH_4^+, NO_3, HCO^-_3 , NO^-_2, Cl^-). All sampling was performed in the period between December 2007 and February 2007(rain season). Principal Component Analysis together with the GIS approach (kriging methods) which provided a description of the area investigated with respect to the characteristics of the ground water was used. It is demonstrated that the water, quality in this region is critical. Nitrate levels are situated between 11.3 and 100 mg/L, with 73% of the observations exceeding the critical level of 50 mg/L fixed by the standards of the World Health Organization (WHO) for drinking water. However, bacteriological residues (faecal, total coliforms, and faecal streptococcus) are retrieved in nearly all water samples. Principal Component Analysis indicates that Bacteriological contamination is merely correlated with nitrite and ammonia amount rather than with nitrate amount, indicating a possible contribution of local pollution sources to ground water deterioration. The variability of the nitrate and bacteriological pollution is important and spatially correlated. A significant difference in water composition has been highlighted between water table of Beni Amir and water table of Beni Moussa and also a difference between ground water near cities (with a probable human polluting effect) and zones far from the built-up areas. Cluster analysis was also performed in order to evaluate the different wells similarity and to confirm the results obtained by Principal Component Analysis.

Key words: Morocco, ground water quality, Kriging methods, principal component analysis, geographic information system (GIS), multivariate analysis.

INTRODUCTION

Water resources in Morocco are currently under serious pressure. National averaged available water resources are estimated to be equal to 740 m^3/habitant/ year (Second National Communication of Climate Change of Morocco, 2010). Morocco thereby ranks on the 155th position on a scale of 180 countries, measuring the pressure that is exerted on available fresh water resources (Food and Agriculture Organization (FAO), 2002). The volume of available groundwater in Morocco is estimated

*Corresponding author. E-mail: hammoumi_naima@yahoo.fr. Tel: +212 0664634850. Fax: 00 212 522 23 06 74.

to be equal to approximatively 4 × 10^9 m^3/year. Groundwater resources are distributed within 32 profound and 46 superficial major groundwater bodies (Khattabi, 2003). Groundwater is a resource that should appropriately be protected.

Irrigated agriculture is responsible for 93% of the total water demand in Morocco. Irrigated agriculture is also the principal driver for ensuring food security and economical development (Bouchama and Benchakroun, 1991). Yet, the irrigated agriculture in Morocco is also reported to have negative impacts on groundwater quality (Abouzaid, 1980; Lhadi et al., 1993). Laftouhi et al. (2003) for instance observed high nitrate contamination of groundwater in the central Moroccan Essaouira basin and explained this contamination by an intensifying agricultural activity. Berdaı¨ et al. (2004) studied the groundwater quality in the Tadla plain for the period of August 1996 until April 1998. He reported that nitrate contamination levels vary between 3 and 228 mg/L for the Beni Amir part in the north of the plain and between 6 and 152 mg/L for the Beni Moussa part in the south of this plain.

Literature shows the permanent increasing potentiality of chemometric methods in obtaining useful information from environmental data, which could be otherwise correlated and interpreted. In particular, many examples of the application of multivariate analysis to sets of variables collected for surface and ground waters can be found. Pattern recognition methods were applied in the treatment of well waters in Vulture mount (Basilicata, Italy) to suggest the origin of mineral water samples (Caselli et al., 1998). A study based on Principal Component Analysis (PCA) and Kohonen neural networks, has been devoted to assess the quality of the waters of Mura River in Slovenia and evidenced the improvement of the quality of the waters along the 9 years of the project (Brodnjak-Vonin et al., 2002). Studies concerning the Suquia River in Cordoba (Argentina) making use of the Factor Analysis (FA) and PCA techniques, as well as cluster and discriminant analysis permitted to evaluate the sources of variability and the pattern of some variables in a graphical analysis were carried out. The results were correlated with seasonal variations, urban run-off and pollution sources (Wunderlin et al., 2001).

By robust cluster analysis and multivariate treatments freshwaters from wells in Friuli and karsic freshwaters of pollution were studied and the temporal evolution of the pattern was evaluated for the different sampling sites (Barbieri et al., 2001; Reisenhofer et al., 1998).

Vega et al. (1998) applied Principal Component Analysis and cluster analysis, to collect information from environmental data in lagoon waters and to discriminate the possible sources of spatial and temporal variations that can affect the quality of water.

Groundwater samples collected from wells located down gradient from the potential nuclear waste repository at Yucca Mountain (Nevada) were treated with PCA and QFA (Q-model factor analysis) to evaluate possible contamination (Farnham et al., 2003). Multivariate analysis techniques were employed to study the possibility that livestock slurries used as fertilizers in rural areas in Spain could influence the quality of drinkable water (Vidal et al., 2000). These techniques have been also used to investigate the possible interactions of India river waters and adjacent groundwater or mixing of different ground waters (Reghunath et al., 2002). A study based on 3-way PCA in addition to multivariate analysis techniques was used to collect information on the similarities and differences between ion amount / ion composition of underground waters with the aim to improve the criteria of water resource management in Sicily (Librando et al., 1998).

Unfortunately, most of the previous studies in this region focused only on one singular groundwater quality parameter, typical nitrate or total salinity. Previous studies did not allow to assess the overall water quality in holistic way, encompassing thereby physico-chemical, organic and microbiological quality criteria. The potential correlation which may exist between quality parameters is further rarely explored, in as much as their space-time dynamics.

The mapping of groundwater quality is therefore often subjected to a lot of uncertainty, which complicates the assessment of the overall quality of the groundwater body itself. We also observe that only few studies have been reported illustrating these problems for the aquifers in Morocco such us the management of regional aquifers using a combined procedure based on geostatistical and geographic information system (GIS) tools (Haouz groundwater of Marrakekech) (Sinan and Razack, 2005, 2008).

This paper is focused on the analysis of the distribution of ground water in the Tadla plain (Morocco). Water samples from 25 wells were characterized by 25 parameters, including: air and water temperature, pH, conductivity, permanganate Index, dry residue , TH , TAC, total hardness, Total iron (FeT), several cations and anions (NH_4^+, Ca^{2+}, Na^+, K^+, Mg^{2+}, Mn^{2+} , Ca^{2+}, Cl^-, NO_3^-, NO_2^-, SO_4^{2-}) and microbiological quality criteria (total streptococcus bacteria, Fecal streptococcus bacteria and fecal coliforms bacteria)**.**

The analysis was devoted to illustrate the influence of possible sources (irrigated agriculture, the domestic and factories activities) on as well physico-chemical and bacteriological groundwater quality parameters for the Tadla aquifer. This aquifer is a major groundwater body of the Oum R'bia catchment, situated in central part of Morocco. The study focuses on nutrient related and bacteriological quality parameters of the groundwater body. The latter parameters are further closely linked to health and sanitation problems, and it was carried out by means of multivariate statistical tools: Principal Component Analysis, cluster analysis and kriging

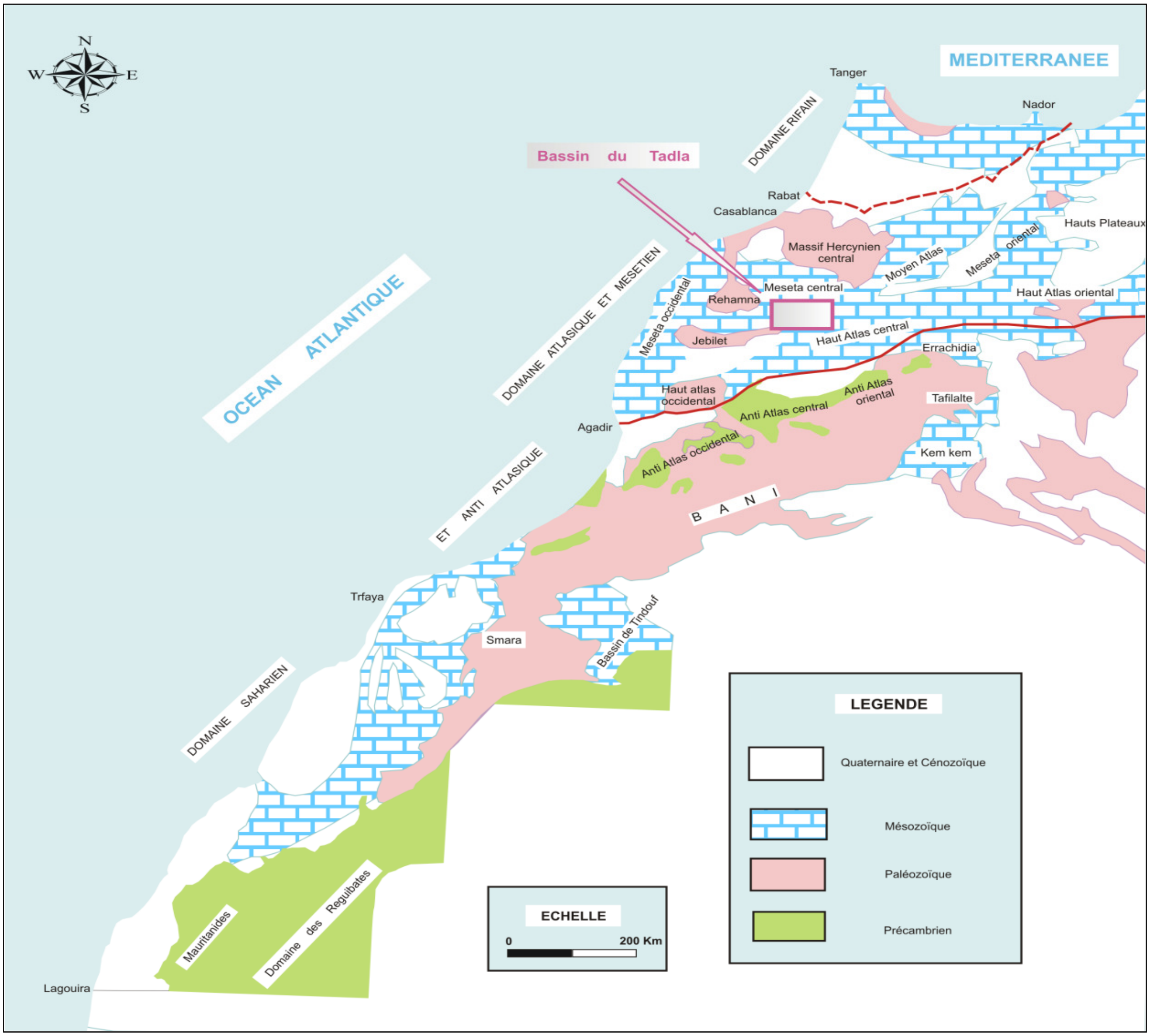

Figure 1. Map showing the location and geology of the case study area.

methods, for an improvement of management and protection of its water resources.

The research deals with both the analysis of the water samples and the chemometric treatment.

MATERIALS AND METHODS

The case study region

The plain of Tadla is a vast synclinal located in central Morocco. It spreads in ENE–WSW direction between the phosphate plateau and the High Atlas of Beni-Mellal in the basin of the Oum R'bia River approximately 270 Km of Rabat (capital of Morocco) which covers a surface of 3600 km approximately (Figure 1). It presents a slope varying from 1 to 3% and is traversed by approximately 160 Km of the Oum R'bia River which divides it into two large perimeters irrigated with different hydraulic characters: Beni Amir in the North and Beni Moussa in the South whose irrigated surfaces are respectively 33 000 ha and 69 500 ha. At the beginning of the XXe century, the population counted approximately 95 000 rural inhabitants with an average density of about 26 habitants/Km^2 practising extensive cereal crop primarily. The installation of the hydro farming infrastructure was accompanied:

(a) With a spectacular growth of the population, counting approximately 420 000 in 1982, 560 000 in 1994 including 440 000 rural and 571.000 inhabitants in 2004, of whom 65% were rural.

(b) With a development of the economic activities.

Thus the intensive agriculture is based primarily on the culture of cereals, sugar beet, market garden, fodder, cotton and arboriculture (olive-trees and citrus fruits), and on the breeding. Several agro-industrial units were installed in the perimeter, especially sugar refineries (3 units of which only one is functional), oil mills (461 units with 7 modern 195 semi-modern and 259 traditional) and three dairies.

The plain of Tadla has a semi-arid climate with a cold winter pluviometry spends an interval of 275 to 1025 mm over the period of 1935 to 1980 with an interval 175 to 625 mm over the period 1980 to 2008. It will be retained that this area knew an average degradation of the annual pluviometry of 70 mm (20%) over this period. It is thus undeniable that the zone regularly knows from now on more marked periods of dryness (PDAIRE, 2008).

From a geological point of view, the basin of Tadla is attached at the Mesetian domain of central Morocco, more particularly, at the synclinal zone "Bahira-Tadla". It is presented in the form of a synclinal basin filled by the sedimentary sequence from which the age extends from Permo-Trias to the Quaternary. In the whole of the basin, the quaternary coverings mask completely subjacent grounds, so that geological information available (FAO, 2002; BRGM, 1993) come from some major drillings. The results of these drillings reveal the existence of four great lithostratigraphic sets:

(i) A thick paleozoic base, of Cambrien to the Carboniferous one;
(ii) Triassic and Jurassic formations localised in the central edge of the basin;
(iii) Cretaceous marine transgressive deposits with Eocene;
(iv) An unmatched filling Neocene and quaternary mainly continental (Figure 2).

From hydrogeologic point of view: the ground water walks on in a Plio-Quaternary complex primarily made up of francs limestones, of marno-limestones and clays.

This aquifer shows a groundwater flow from the north to the southwest:

In Beni Amir, the transmissivity coefficients of the aquifer are situated between 1.10^{-3} and 1.10^{-1} m^2/s while the storage coefficient generally oscillate between 0.01 and 0.1. The Least low transmissivity meet along Oum R'bia and apart from the irrigated perimeters.

In Beni Moussa, the transmissivity coefficients aquifer situated between 1.10^{-3} and 5.10^{-1} m^2/s, and the storage coefficient between 0.06 and 1 (BRGM, 1993).

Sampling strategy and water analysis

Twenty-five groundwater sampling locations were selected in the study region (Figure 3). The sampling points were distributed all over the study area to ensure appropriate spatial coverage of the entire aquifer. Most of the sampling points were pumped wells.

All sampling was performed in the period between December 2007 and February 2007 (rain season), period during which contamination of groundwater is highest because of the infiltration of surface water (rain water and water of river).

The physicochemical and bacteriological analyses enter within the framework of the monitoring of the Oum R'bia basins water quality. A complete network of groundwater analyses is put by the Hydraulic Agency of Oum R'bia (ABHEOR) in collaboration with the Public Laboratory of the Studies and Tests (LPEE) in Casablanca.

Pumped groundwater samples were collected in polyethylene bottles of 1 L. Before sampling, the recipient was cleaned several times using the pumped water. Flushing allowed also to clean the adductions and tubing within the well and pumping system. Recipients were gradually filled to avoid turbulences and aeration during the sampling. To avoid sampling artifacts and analytical artifacts, in particular the gain of dissolved gas and microbiological activity, water samples were immediately cooled at 4°C using portable icebox. Analysis was further performed as fast as possible and this within 24 h after sampling.

The analytical method for NH_4^+ -N dosage is the method of Solorzano and Koroleff (cited in Afnor T90-015) which is a very sensitive method for low NH_4^+ -N content in the liquid phase. NO_2^- -N was determined through the diazotation with sulfanilamide (Afnor T90-013), NO_3^- -N with the method based on sodium salicylate (Afnor T90-012). For the determination of PO_4 -P, use was made of the colorimetric method (Afnor T90- 023). Other mineralogical properties have been determined following the French system of normalisation (Afnor): chloride (Afnor T90-014), sulfates (Afnor T90-009), the total toughness of water (Afnor T90-003), the calcium (Afnor T90-016), sodium (Afnor T90-019), and potassium (Afnor T90-020). The electric conductivity is measured with a conductivity meter (COND 330i, LUTRONTM). The pH is measured directly in water by a pH-meter (WTW530, LUTRONTM).

The bacteriological analysis for total streptococcus bacteria, fecal streptococcus bacteria and sulfito-reducing bacteria were determined by Rodier's method (Rodier, 1984).

Methods of analysis

The statistical and geostatistical methods were selected because of the strong capacity to characterize the special variation for different parameters from the quality of the groundwater.

Statistical modelling

Principal component analysis (PCA) (Box et al., 1978; Massart et al., 1988) was used to analyze the correlation structure between the set of groundwater quality parameters collected during the survey. The PCA adopted in this paper is based on normalized and standardized data and exploits the correlation matrix between groundwater quality parameters rather than the covariance matrix. The PCA analysis was performed using the statistical toolbox available in MATLAB7^{TM}.

Cluster analysis

Cluster analysis (CA) encompasses a number of different methods which organize objects (observations) into groups called clusters without explanation or interpretation. Objects within the same clusters are similar whereas objects in different clusters are dissimilar. This exploratory method is used to discover the data structure not only among observations, but also among variables, arranged into a tree diagram, usually called a dendrogram. The utilized methods, algorithms, and similarity/dissimilarity measures are described elsewhere in the literature (Everitt, 2001). In this study, the commonly applied average group and the Ward's clustering methods were used. The Euclidean distance was used as a similarity measure. The cluster analysis was performed using the software XLSTAT 2009.

Kriging method

Kriging methods are interpolation methods firstly proposed by Krige (Isaaks, 1990; Krige, 1978; Sinan, 2000) that allow taking into consideration the spatial continuity of the points. These methods are based on the minimisation of the variance of the estimation

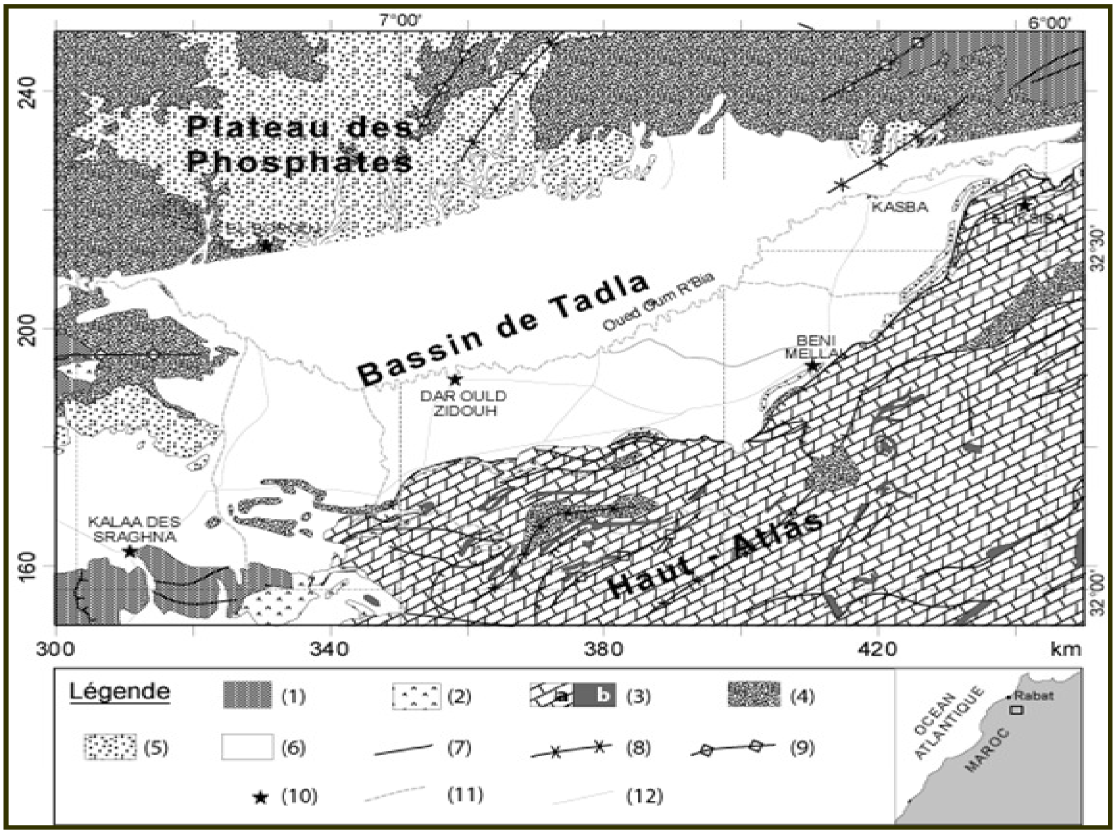

Figure 2. Geological map of the Tadla basin. (**1**) Palaeozoic (schist and quartzite). (**2**) Trias (red clay and basalt). (**3**) Jurassic (**a**, limestone and dolomites; **b**, diorite, gabbro). (**4**) Cretaceous (red detritic facies). (**5**) Tertiary (limestone, marls and phosphatic sands). (**6**) Quaternary (alluvium). (**7**) Fault. (**8**) Synclinal axis. (**9**) Anticlinal axis. (**10**) City. (**11**) River. (**12**) Road.

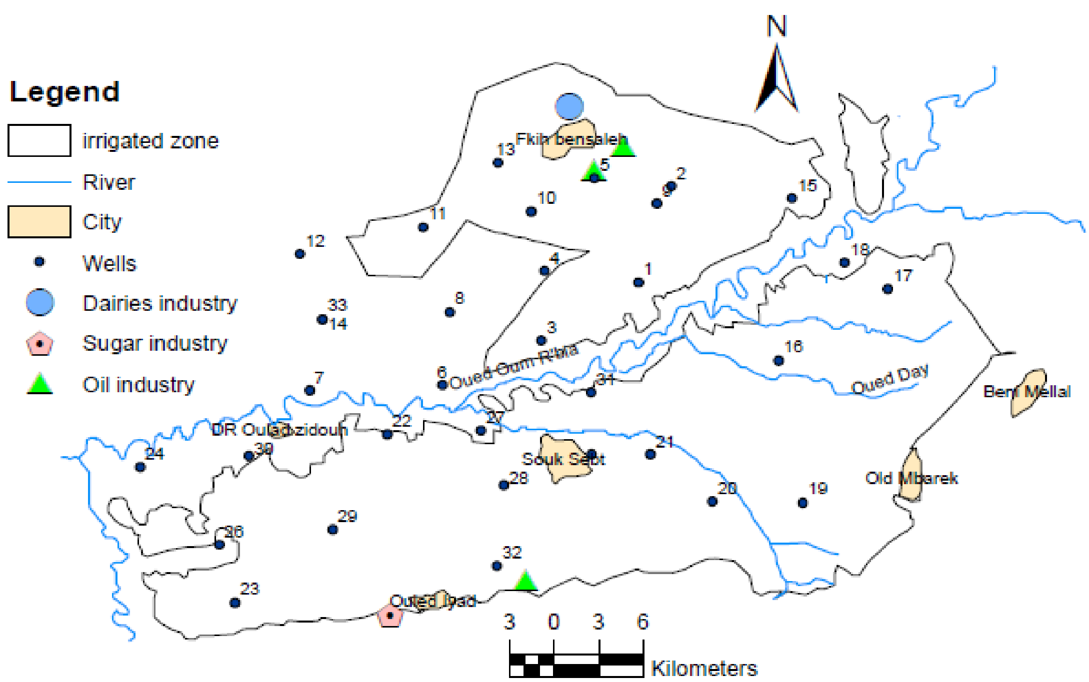

Figure 3. Map of the Tadla plain with the numbered sampling sites.

error, through a weighted linear combination of the available points. Different variants have been proposed but ordinary Kriging is certainly the most exploited method (Massart et al., 1997). The paper map of the region study was digitilized to north Morocco degree coordinate system.

The development of the map of distribution of each variable and the kriging of each axis were performed using the kriging approach integrated in the Geographic Information System (GIS) by the software ArcGIS 9.2 version.

RESULTS AND DISCUSSION

Data pre-treatment

Table 1 reports the average, minimum and maximum values calculated for each variable obtained in groundwater sample from wells in Tadla plain in comparison with WHO standards.

The pH of water varied between 3.85 and 6.08. The pH represents the intensity of acidity or alkalinity and measures the concentration in ions hydronium in water. The interval values of pH recommended by the O.M.S are 6.5 to 8.5. PH of analyzed water was in all the cases smaller than the limit recommended by the WHO. What shows the neutral character of this water.

As well anthropogenic, natural processes determine nitrogen release in soil and soil organic matter turn-over produces mineral N from the organic pool while biologically and chemically mediated processes sustain nitrogen transformation. Within the soil mineral N pool, nitrate-N receives particular attention as it is dissolved within the soil solution and therefore extremely mobile. It can easily be incorporated in the plant biomass, but also leach from the root zone of the crops and as such contaminate groundwater. Nitrate levels in the Tadla aquifer are situated between 11.4 and 99.4 mg/L.

Nitrite concentration in all wells never exceeds the drinking water norms proposed by the WHO. Observed values situate between 0 and 0.48 mg/L. This is in agreement with the study of Kholtei (2002) who analysed the nitrite quality of the Berrechid aquifer in the central part of Morocco and who observed nitrite contamination levels situated between 0.0014 and 0.066 mg/L. Ammonium is far less mobile than nitrite and nitrate.

Under normal pH conditions, ammonium will be protonated and retained in the soil by cation's exchange. Within the wells, the ammonium values never exceeded the drinking water norm proposed by the WHO.

The electric conductivity which is a measurement of the capacity of an aqueous solution to lead, it electrical current varied between 730 and 10800 µS/cm. All water of the wells had an electric conductivity higher than the limit recommended by the WHO which is of 2700 µS/cm, except the wells numbers 6, 13, 14, 15, 16, 17, 21, 23 and 25 which had an electric conductivity less than the value recommended by the WHO.

The results of the analysis indicate the calcium values range between 82.2 and 825 mg/L. This shows that the values exceeded the desirable limits set by WHO standards except the well number 12 and 22.

The results of the analysis indicated that the sodium values range between 7.68 and 1152 mg/L and exceeded the desirable limits set by WHO standards.

The results of the analysis indicated that the chloride values ranged between 57.6 and 3763 mg/L. This shows that the values exceeded the desirable limits set by WHO standards except wells number 6, 13, 14, 15, 16, 17, 21, 23 and 25.

The total hardness of water (THt) is attached mainly to the quantity of calcium and magnesium in water. In the water samples, THt varied between 38 and 429 mg/L of $CaCO_3$ For all the points of water studied, THt was higher than the value guides WHO which is of 200 mg/L of $CaCO_3$ for the majority of water except the wells numbers 5, 7, 10, 20, 21. According to the classification of Durfor and Becker (1964), the analyzed groundwater is hard.

Human activities at the land surface may cause groundwater contamination by bacterial pathogens. In general, the microbiological quality of groundwater will be better than that of surface water, since pathogens will be filtered by the soil and subsoil during the recharge process (Maier et al., 2000). Leaking waste water evacuation systems, leaking septic tanks, slurry and organic waste deposits, buried biomass, including animal cadavers may be responsible for pathogen contamination of groundwater (EPA, 2000). Contamination pathways of groundwater include pathogen transport through the soil matrix and fractures and preferential transport along pumping wells and boreholes. Viability of bacterial pathogens in the soil–groundwater system is determined as well by the soil–groundwater properties as by the properties of the bacteria themselves (Harvey and Harmas, 2002).

The results of the bacteriological survey show that 88% of the sampled wells exhibit a total bacteriological contamination which exceeds the norms. The total coliform, the faecal coliform and faecal streptococcus content exceeds at least once the norm of respectively 10, 1 and 1 count per 100 ml of sampled water. Total coliform, faecal coliform and faecal streptococcus content varies respectively between 0 and 80 000, 0 and 1200, and 0 and 18000 counts per 100 ml (WHO, 2000) Values range between 2 and 192 counts per 20 ml. These types of bacteria are indicative of the vulnerability of the aquifer system or the poor maintenance of the pumping and distribution systems.

Principal Component Analysis

In the aim of investigating the role of each variable and to simplify the original data structure, the first step of our analysis was the extraction of principal components from the original data set. The Principal Component Analysis was applied to a matrix of 25 observations and 25 variables. Four components explaining 69.76% of the

Table 1. Summary statistics of groundwater samples.

Variable	Acronym	Unit of measurement	Min	Max	Average	STD	The maximum permissible limits prescribed by WHO for drinking purposes
Air Température	Ta	°C	10.5	22.5	18.0	3.2	-
Water Température	Tea	°C	14.5	22.5	19.5	1.7	25
pH	pH		6.9	7.4	7.1	0.2	9.6
Conductivity	Cond	µS/cm	730.0	10800.0	4092.4	2962.9	2700
permanganate Index (COD)	IP	mg/L	0.3	13.1	4.3	2.9	-
Ammonuim	NH_4^+	mg/L	0.0	0.3	0.1	0.1	0.5
Sodium	Na^+	mg/L	7.7	1152.0	408.9	361.3	100
Potassium	K^+	mg/L	0.6	5.0	2.3	1.2	-
Calcium	Ca^{2+}	mg/L	82.2	825.0	260.6	194.8	100
Magnésium	Mg^{2+}	mg/L	28.6	649.0	176.6	165.8	50
Manganèse	Mn^{2+}	mg/L	0.0	0.1	0.0	0.0	0.5
Chloride	Cl^-	mg/L	57.6	3967.0	1204.4	1164.3	750
Nitrites	NO_2^-	mg/L	0.0	0.5	0.1	0.1	0.5
Nitrates	NO_3^-	mg/L	11.4	99.4	44.0	24.8	50
Hydrocarbonates	HCO_3^-	mg/L	183.0	494.1	380.7	81.2	-
Sulfates	SO_4^{2-}	mg/L	15.4	1076.0	179.3	295.0	200
Complete Alkalinity Titration	TAC	(°F)	15.0	40.5	31.2	6.7	-
Titre Hydrotimétrique (hardness)	TH	°F	37.9	429.0	137.4	110.3	200
Résidu Sec à 105°C (dry residue)	RS	mg/L	542.0	7685.0	3083.9	2249.9	1500
Fer Total (total iron)	FeT	mg/L	0.0	0.3	0.1	0.1	0.3
Faecal Coliforms	CF	/100ml	0.0	12000.0	1624.4	3002.8	-
Total coliforms	CT	/100ml	0.0	80000.0	10642.0	19098.6	-
Faecal Streptococcus	SF	/100ml	0.0	18000.0	1789.0	3934.9	-

total variance were retained for further analysis. The results obtained from the principal component decomposition of the original data set show a high correlation between the variables (Table 2); the total variance being highly partitioned over many components (the first five PCs hardly exceed 76.9%).

The loading and the score plots for the first four PCs are represented in Figures 4 and 5 respectively. From the analysis of these figures it is possible to argue about some particular relationships between observations and variables, as follows:

(1) The first Principal Component mainly discriminates well waters having large conductivity, due to the higher concentration of chlorides, hardness (including calcium and magnesium), hydrocarbonates, permanganate index, larger amount of some metal ions as Na^+, Ca^{2+}, Mg^{2+}, K^+, NH^{4+}, and dry residue, (large negative loadings). In the corresponding score plot, the first PC clearly extracts wells 21, 19 and 24 from all the others, and also, even if at a minor extent, wells 16. These samples are characterised by large amount of conductivity, chlorides, hardness and large values of some metal ions.

PC1 can be considered as the salt component because it is mainly saturated with conductivity and hardness (including calcium).

(2) The second Principal Component discriminates well waters having a larger amount of nitrate, nitrite, bacteriological contamination (CF, CT, SF) and Potassium. The score plot of PC2 versus PC1 allows to point out some particular samples: well 24 showing a large amount of conductivity, chlorides, hardness, Permanganate Index and large values of some metal ions: a large amount of potassium and NH^+ and a small amount of SO_4^-. Wells 3, 11, 14, 16 and 20 show a large amount of nitrite, bacteriological contamination (CF, CT, SF), potassium and NH^+ and a small amount of SO_4 for what regards PC2, but they are characterised by a small amount of conductivity, chlorides, hardness, Permanganate Index, dry residue and large values of some metal ions (negative values on PC1).

At positive values on PC2, it is possible to point out: wells 1, 2, 4, 5, 6, 9, 10, 12, 13, 18, 21, 22, 23 and 25 characterised by large amount of nitrate and large amount of Nitrite and Bacteriological residues (CF, CT, SF) (negative values on PC2) for what regards PC2 but a small conductivity, chlorides, hardness, Permanganate Index and large values of some metal ions as Na^+, Ca^{2+}, Mg^{2+} , FeT and dry residue, (negative values on PC1).

The PCA analysis did not allow identifying a strong

Table 2. Principal component weights.

Parameter	First principal component (PC1)	Second principal component (PC2)	Third principal component (PC3)	Fourth principal component (PC4)
Ta	0.2606	-0.0327	-0.3274	0.2078
pH	0.3361	-0.2229	**0.4220**	**-0.4438**
CE	**-0.9377**	0.0131	-0.2804	-0.0306
IP	**-0.7242**	-0.0151	0.2077	-0.0128
NH	-0.5706	-0.2278	0.1095	**0.4726**
Na	-0.6330	-0.0010	**-0.5452**	0.2004
K+	-0.6534	**-0.4433**	0.1557	0.2765
Ca	**-0.9105**	-0.0226	0.0396	-0.1813
Mg	**-0.8802**	0.0766	-0.1519	-0.2335
Mn	0.0010	-0.2620	0.0906	**0.7623**
Cl	**-0.9364**	-0.0160	-0.2150	0.0278
NO_2	-0.1224	**-0.7950**	0.3423	-0.0869
NO_3	0.2183	**0.4756**	0.2281	0.1983
HCO	0.6946	-0.0603	**-0.5503**	0.2390
SO_4	-0.0703	0.1074	-0.3784	-0.3012
TH	**-0.9450**	0.0373	-0.0764	-0.2241
TAC	0.6944	-0.0605	**-0.5503**	0.2393
RS	**-0.9428**	0.0042	-0.2758	-0.0640
FeT	-0.3807	-0.1699	0.2417	**0.5030**
CT	0.1955	**-0.4468**	-0.5689	0.0115
CF	0.2205	**-0.7803**	-0.2691	-0.1292
SF	0.2254	**-0.8708**	0.0501	-0.2857
Eigenvalue	8.3152	2.8488	2.2765	1.9082
% Total variance	37.7963	12.9493	10.3476	8.6737
% Cumulative variance	37.7963	50.7456	61.0932	69.7668

positive correlation between nitrate amount and bacteriological quality. However, rather a strong negative correlation exists between the nitrite and bacteriological contamination. Weak positive correlations are observed between nitrite/ammonia amount on the one hand and pathogenic pressure on the other hand.

Explaining this weak but significant correlation may be indicative of recently generated groundwater pollution from a rather local pollution source, such as a leaking farmyard stock or septic tank, local contamination by human wastewater and local contamination by livestock excrements around wells used to watering animals aggravated by the absence of proper protection of the wells. Indeed, in case of a local and close by pollution source, high amounts of fresh dissolved organic matter will be released likely together with a set of pathogenic bacteria.

This release will stimulate the oxygen consumption during the degradation of the fresh organic matter and the oxidation of organic N. The degradation of organic N will further result in a release of ammonia, which oxidizes fast to nitrite. The further oxidation of nitrite to nitrate may be impeded by a limited amount of oxygen during this first stage of the mineralization process. The partial mineralization of the fresh organic matter released from such local pollution sources may therefore explain a weak but positive correlation between bacteriological quality and nitrite/ammonia amount on the one hand, and a weak, but negative, correlation with oxygen and nitrate amount on the other hand. The PCA graph further shows that the nutrient and bacteriological related parameters are poorly correlated with the basic mineralogical parameters of the groundwater body. This confirms that external anthropogenic sources are most likely contributing to the pollution of the groundwater body. Similar observation of correlation between nutrient and bacteriological parameters of aquifers in morocco were in irrigated plain of Triffa (Fetouani et al., 2008).

(3) The third principal component mainly explains the differences to the amount of pH (positive loadings on PC3), to the alkalinity, hydrocarbonates, total coliforms and sodium (negative loadings on PC3). The score plot points out wells 1, 2, 4, 5, 6, 9, 12, and 13 at large positive values on PC3 with a small amount of Na^+ and a small conductivity (negative values on PC1). Wells 3, 8 and 11 are characterised by similar behaviour to wells 14 and 16 for what regards the variables weighing on PC3 but they show a small conductivity, Cl^-, dry residue, Mg

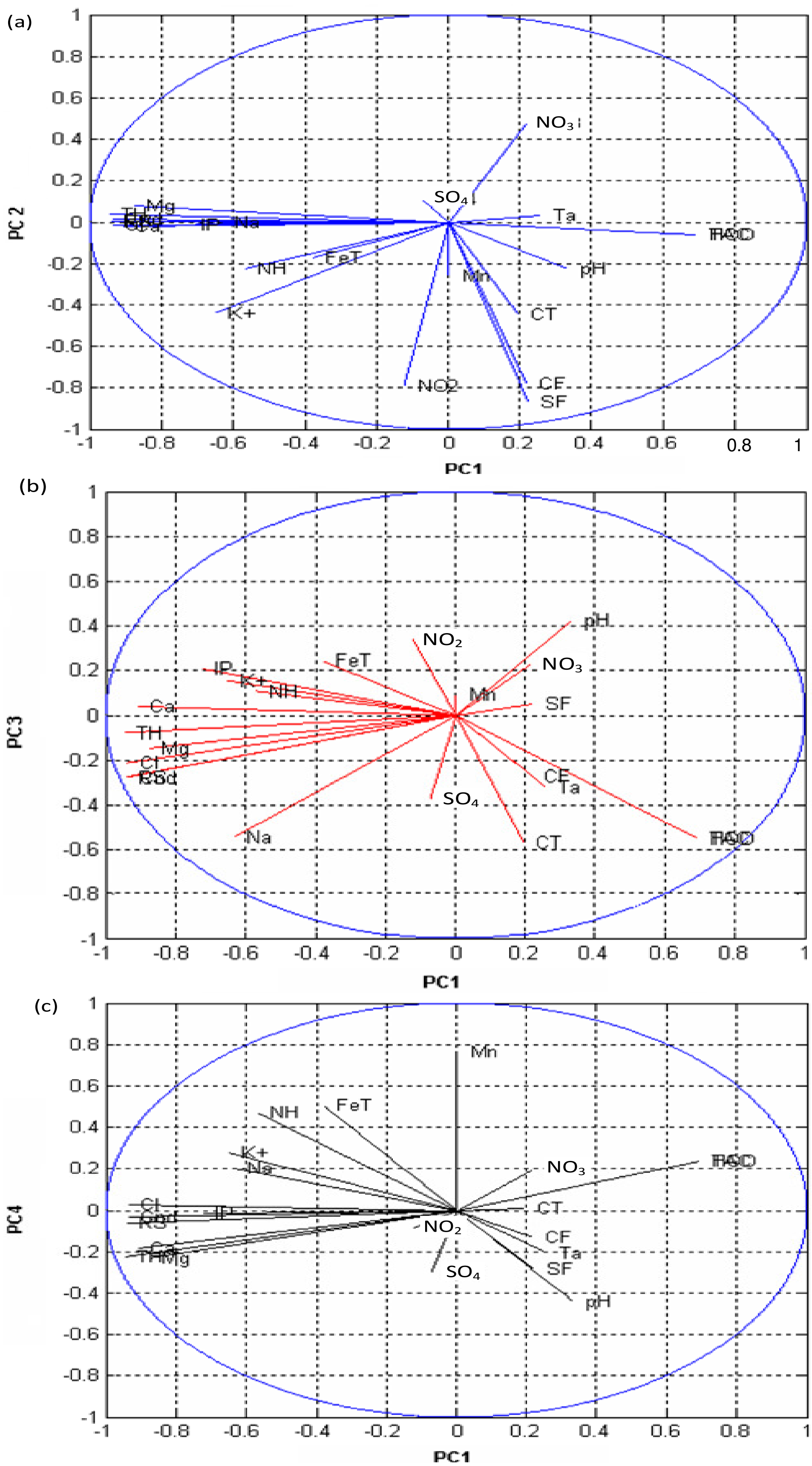

Figure 4. Loading plots: (a) PC1 versus PC2 (b) PC1 versus PC3, (c) PC1 versus PC4.

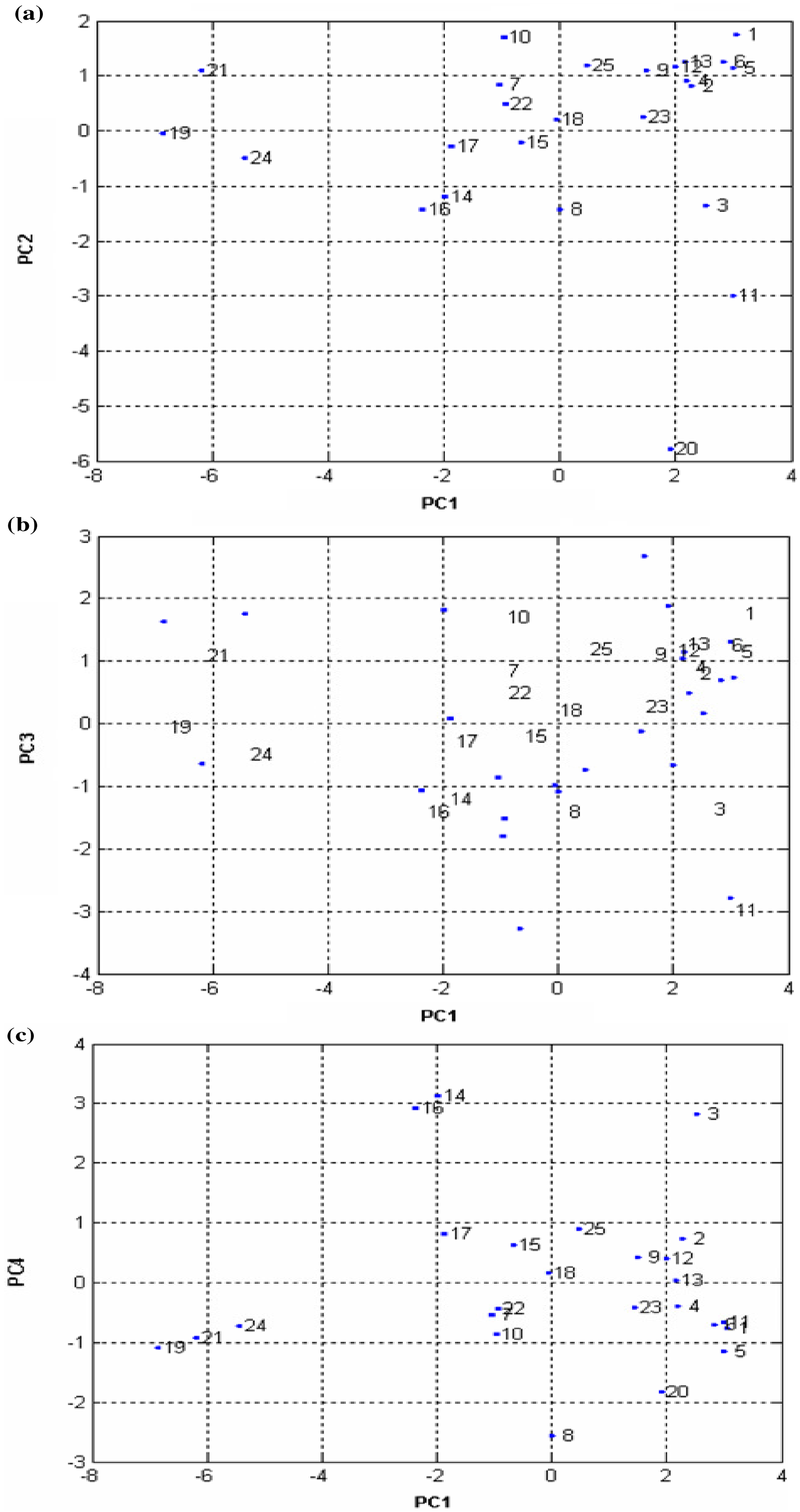

Figure 5. Score plots: (a) PC1 versus PC2, (b) PC1 versus PC3 (c) PC1 versus PC4.

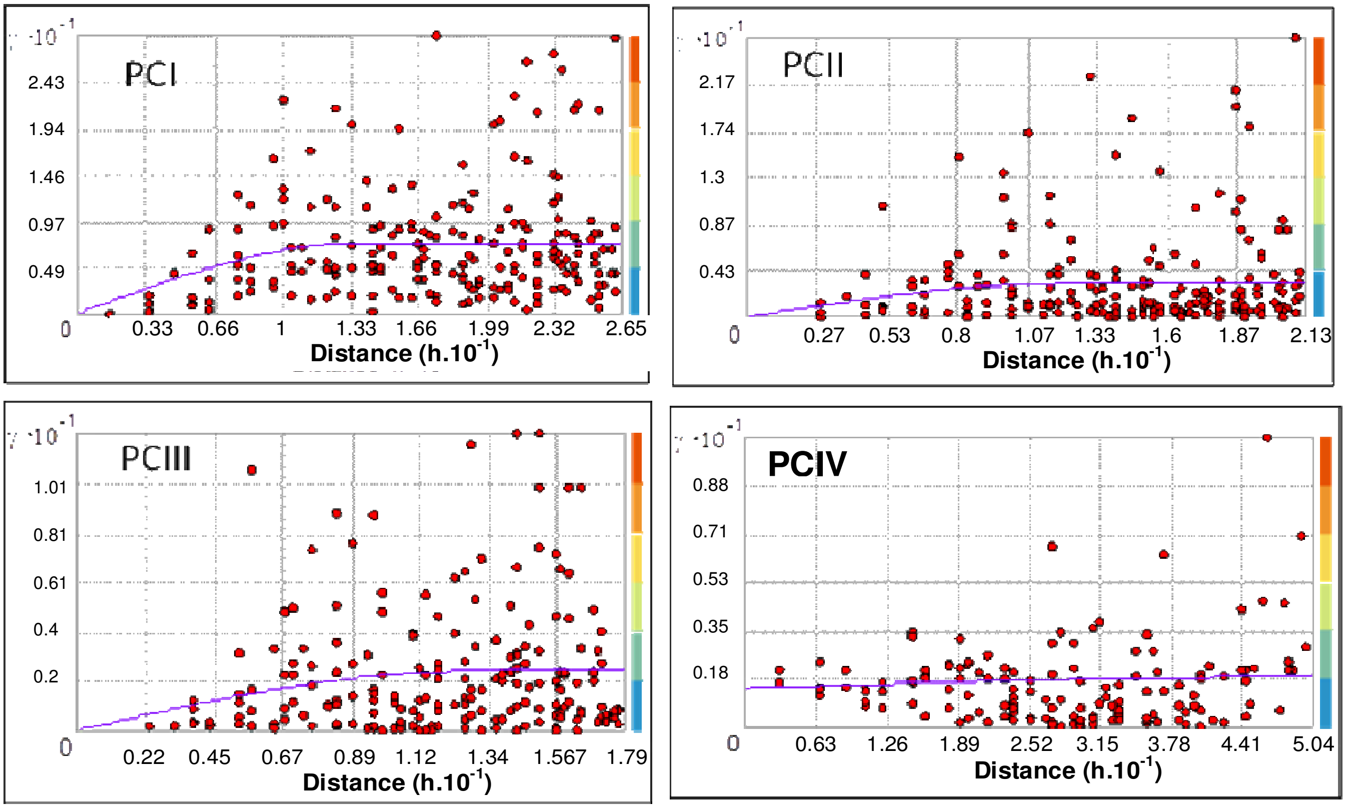

Figure 6. Observed and modelled semi-variograms of PC1 semi-variogram model is spherical, with range 13,99 km and sill 7,54. – Observed and modelled semi-variograms of PC2 semi-variogram model is spherical, with range. 12,45 km and sill 3,134 . – Observed and modelled semi-variograms of PC3 semi-variogram model is spherical, with range 12,87 km and sill 2,431. – Observed and modelled semi-variograms of PC4 semi-variogram model is spherical, with range 49,810 km and sill 0,405399.

and TH (positive values on PC1). At negative values on PC3 (large hydrocarbonates, alkalinity, total coliforms and sodium) we can distinguish well 24 and 16 (large conductivity) from wells 3, 8 and 11 (small conductivity).

(4) The fourth principal component discriminates the samples according to their amount of total iron (FeT), NH^+, pH and Mn. This PC discriminates wells 14, 15, 16, 17 (large amount of total iron (FeT), NH^+, pH and Mn) from well 7, 10, 22 (small values of the above mentioned variables) and in a minor way well 8. These samples are further separated according to their conductivity, chlorides, hardness, Permanganate Index and large values of some metal ions as Na^+, Ca^{2+}, $Mg^{2+}$and dry residue,: well 19, 21, 24 being characterised by large values of these variables and wells 8 by small values.

The geostatistical study

The geostatistical study includes two main phases:

i) The first is the characterization of the spatial structure of the regionalized variable; development of variogramme.
ii) The second is to estimate this variable using an interpolation tool by kriging method.

Variogram modeling

Once the experimental variogram established, he must calibrate a model that suits best, it is not always easy to find the theoretical model that corresponds to it. four models are proposed, namely linear, spherical, Gaussian and exponential.

The empirical semi-variogram for de PC4 illustrates that observed parameters concentrations are characterized by a significant spatial dependence up to a distance of 49.81 Km.

The nugget effect is relatively high and may be explained by the coarse sampling network, the lack of short distance data pairs within the experimental data set, and the expected short range variability of nitrate contamination within the groundwater body. In our case, the adjustment is done graphically. We opted for the spherical variogram for the four principal components (Figure 6).

Kriging method

Ordinary kriging was used to make the spatial predictions. It assumes a constant but unknown mean.

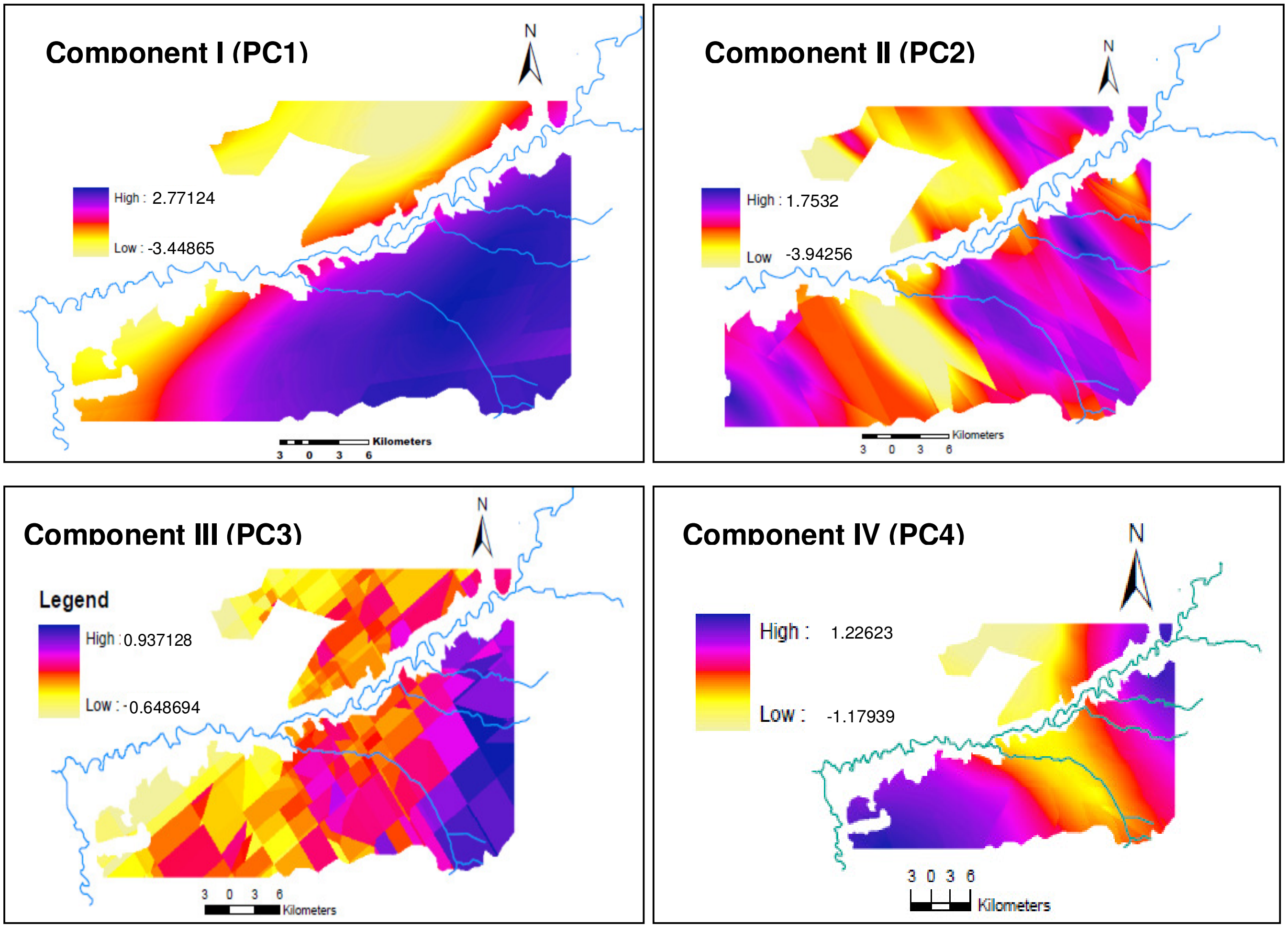

Figure 7. Geographical representation of PC1, PC2, PC3 and PC4 by the ordinary Kriging method.

Given the known geographic localisation of each sample, it is possible to use mapping techniques to efficiently analyse the relationships between geographic position and sample characteristics.

This was performed by using kriging mapping technique (Davis, 1986) representing each individual PC, whose information amount has been described on a thermographic scale. The results of such visualizations are reported in (Figure 7). The wells are represented on a color scale from light to dark blue (increasing positive score) and from light to dark red light (increasing negative score).

The first map describes the behaviour of the scores of PC1 with respect to the geographical co-ordinates: the map shows the clear presence of a hot spot (yellow to red color zone), identifying samples with large negative scores on PC1; these samples are characterised by large values of conductibility, chlorides, hardness (including calcium and magnesium), hydrocarbonates, permanganate index(larger amount of some metal ions as Na+, Ca^{2+}, Mg^{2+}, K^{+} NH^{4+}, and dry residue, located in the area of Beni Amir especially around the city of "Fkih Ben Saleh" which are characterised by many factories like oil industry and the dairies industry and minor entity of western Beni Moussa. The other areas present samples with positive or slightly negative scores on PC1: this is particularly true for the middle and eastern zone of Beni Moussa. The composition of waters by hydrocarbonates, TAC, conductivity and Na^{+} is explained by the leaching of geological red detritic facies in the north of the plain and the calcaire levels of the haut atlas in the south of the plain (limestone and dolomites).

The map of PC2 shows the same hot spot zones corresponding to large negative scores. These samples are rich in nitrite, bacteriological contamination (CF, CT, SF) and Potassium around the Souk Sebt city. Similar characteristics, even if of minor entity, can be detected in the samples collected nearby the city of Ouled Ayad, in the Beni Moussa area and Fkih Ben Saleh (yellow to red colour zones). There is also a large zone clearly detectable at the map, characterised by samples with large positive scores on PC2 and are rich in nitrate.

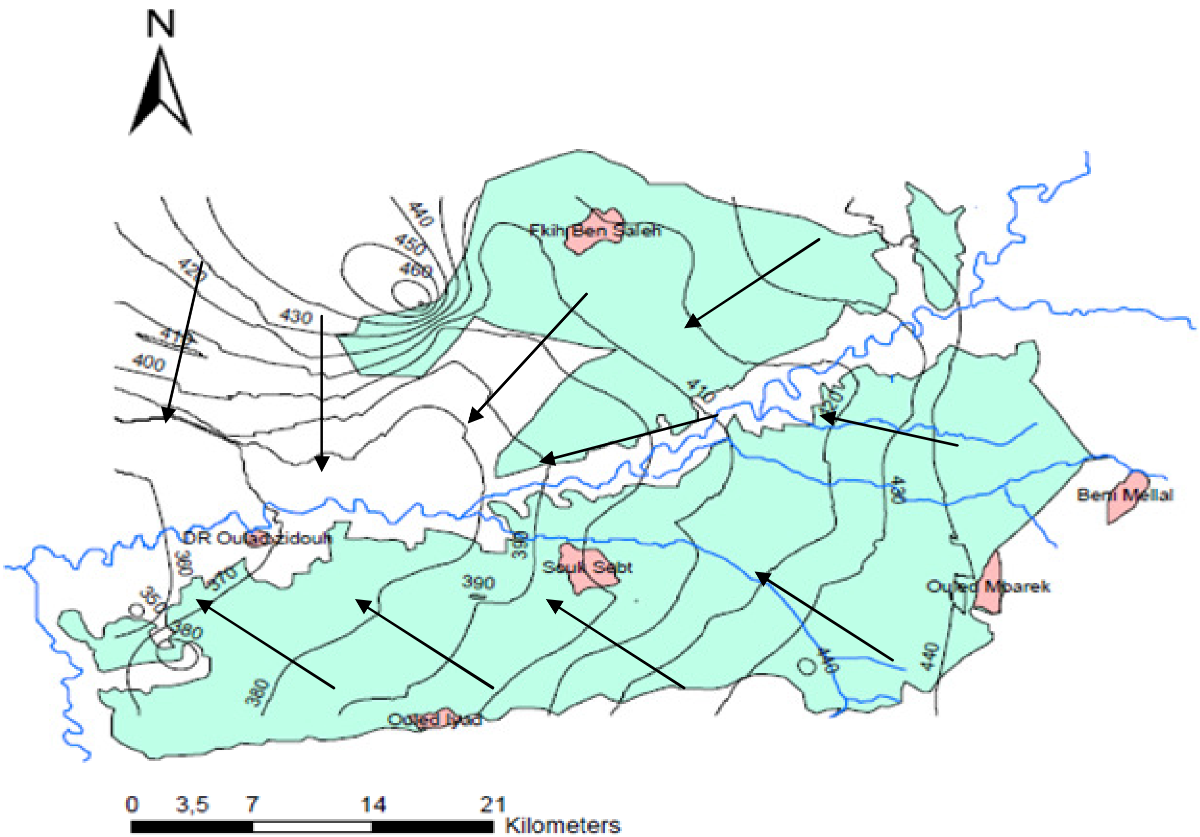

Figure 8. Piezometric map (m), Tadla plain, Morocco (2007).

These samples are collected in the area of Beni Amir and Beni Moussa which are characterised by intensive agriculture releasing a large amount of nitrate exceeding 50 mg/L (Berdai et al., 2004). Comparing the nitrate contamination map with the piezometric map (Figure 8) suggests also that the nitrate contamination occurs mainly in areas of shallow water depths (that is, piezometric heights 5 to 10 m below surface level) or in areas where the soil is permeable.

The map of the third PC shows the presence of a zone with large negative scores (red colour zone) near factories in Beni Moussa area and Beni Amir which are characterised by an intensive agriculture, characterised by waters with large amount of sodium, hydrocarbonates, TAC and total coliforms. Similar characteristics are detected for the Beni Moussa areas. The blue areas present large positive scores on PC3, characterised especially by the pH. These zones correspond to the eastern area of Beni Moussa and the area between Ouled Ayad and Souk Sebt.

In the map of the fourth PC the red colour areas indicate negative scores on PC4 (that is, samples with a small amount of pH). This representation indicates that built-up zones are mainly characterised by large positive values (blue areas), indicating a large amount of total iron (FeT), NH^{+} and Mn^{2+}.

Cluster analysis

The obtained diversity-based hierarchical dendrograms for variables and wells are depicted in Figure 8. The analysis of the diversities among variables could be done extracting two main groups of variables, applying a horizontal cut at 80% of diversity (Figure 9a). Considering the loading plots of the first four PCs, group A identified in the dendrogram mainly gathers the variables with negative loadings on PC1: conductibility is therefore related to chlorides, Na^{+}, dry residue (RS), Mg^{2+}, TH, Ca^{2+}, IP, total iron (FeT), NH^{+}, K^{+}, and Mn^{2+} ions are also present in the same group. The analysis of the dendrogram built on variables confirms the conclusions already drawn by PCA, pointing out a group of variables connected with conductibility that show a large negative weight on the first PC.

The dendrogram built on the wells (Figure 9b) shows two main groups with a horizontal cut at 80% of diversity. Group A contains the samples showing particularly large values of some of the variables identified by group A in the corresponding dendrogram: this group is characterised by large negative scores on PC1, showing therefore a large amount of chlorides, Na^{+}, conductibility, and dry residue. The second group can be further divided in groups B and C, even if this subdivision takes place at

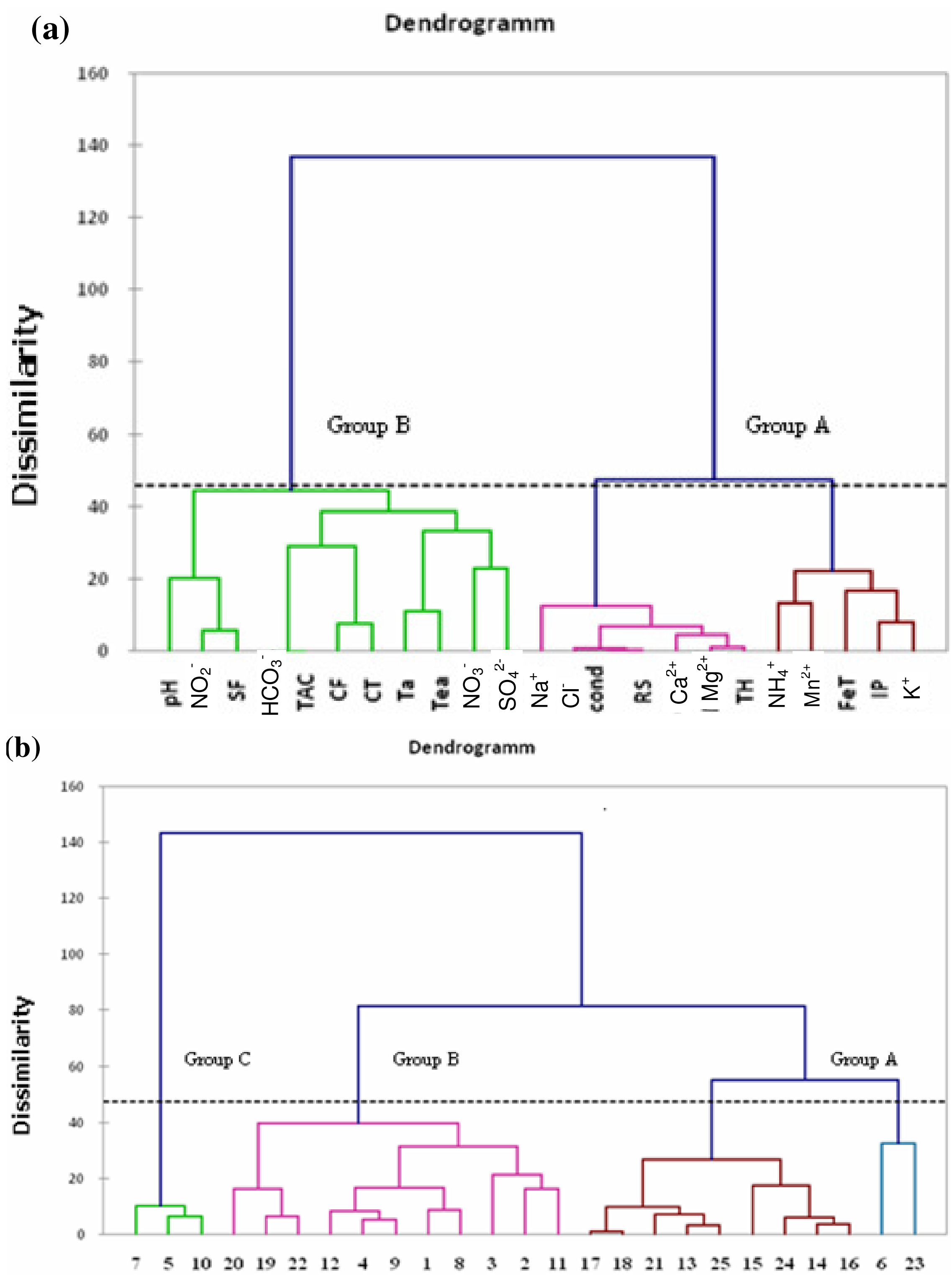

Figure 9. Cluster analysis: (a) grouping original variables (b) grouping wells described by their original variable.

a level of diversity of only 48%. Group B represents samples showing small values for all the variables considered, therefore characterised by no particular behaviour. Group C instead represents a middle course between the anomalous behaviour of samples belonging to group A and the flat behaviour of samples from group B. This analysis therefore confirms the conclusions on wells similarities already pointed out by PCA.

Implications for ground water monitoring

The results of the sampling campaign presented in this paper allow confirming that the groundwater body in the Tadla plain enters in a critical state. The high concentration that has been observed for the nutrient related parameters corroborates with the observed increase of fertilizer use in this area. However, agriculture should not be considered as the single contributor to the observed pollution. Indeed, the water sanitation infrastructure in this region is generally poor. Leakage of nutrients from poorly performing waste water collection systems, the factories installed in the region (sugar, oil and dairy) and waste disposal sites should not be excluded. Similar cautionary remarks were formulated by Laftouhi et al. (2003) for the pollution observed in the Essaouira aquifer in the centre part of Morocco. These authors suspected the presence of different point sources to contribute to the nitrate pollution.

In order to improve the diagnosis of the observed pollution and to quantify the role of agriculture in this pollution, different strategies can be followed. First, the time resolution of the survey could be improved.

A regional survey of the groundwater body was only performed twice campaign per year by the Hydraulic Basin Agency of Oum R'bia in Beni Mellal for all nutrient. and three times per year by the regional office of the agricultural development of Tadla (O.R.M.V.A.T) for salinity and nitrate only.

Comparing the results of both surveys (results not shown) demonstrates that the reaction time of this groundwater body is rather fast. In such cases, more regular surveying is needed to understand the time dynamics of the pollution problem and to alert agriculture and water managers when the groundwater body enters in a critical state. In addition, when time series of pollution would become available, analysis of the time dynamics of the pollution would allow to better assess the origin of the pollution, as agricultural pollution will most likely be determined by seasonal dynamics, in contrast to point pollution which will be more constant in time. A plea is therefore made to repeat the presented survey on a regular time basis and to implement a continuous monitoring of the ground water body. Second, the space resolution of sampling in the survey could be improved.

The observed large nugget effect on the calculated variograms for the components (for example, the PC IV in Figure 6) showed that quite some variability cannot be explained with the adopted sampling density.

Third, other parameters could be analysed during the survey. In the present study, most attention was devoted to basic mineralogical, nutrient and bacteriological related parameters. The correlation analysis between the nutrient and bacteriological parameters on the one hand, and the basic mineralogical parameters on the other hand, did not allow to discriminate between agricultural and non-agricultural pollution sources, as both sources are suspected to give similar signature in the observed pollution of the ground water body.

However other parameters could be added in the future monitoring programmes. It may be suggested to analyse the ground water body at least for residues of plant protection products, and the heavy metals as these parameters would allow to identify more efficiently the origin of the observed pollution. Alternatively, isotope analysis could be proposed to discriminate between the agricultural and non-agricultural pollution.

Fourth, the current knowledge of the agricultural practices in this area is poorly documented. The presented survey, allows to screen the area and to identify sub-regions where the pollution is most problematic. A more detailed analysis of the nutrient balance in those areas by means of advanced agro-ecological models would definitely allow to elucidate clearly the role of agriculture in the observed contamination. This latter strategy is currently followed in an ongoing study.

CONCLUSION AND RECOMMENDATIONS

The results obtained by the application of the different pattern recognition methods proved to be in agreement with each other. From PCA, groups of variables and samples were pointed out, stressing the existence of areas showing particular behaviours with respect to the amount of some of the investigated parameters. The analysis was then refined through the construction of termographic maps of the first relevant PCs.

The maps showed the existence of a yellow to hot and red spots, located in the area of Beni Amir. This area proved to be peculiar from different points of view (it was identified as peculiar from the analysis of all the PCs considered, showing each an independent source of variation): a further geological study analysis showed that this zone is characterised by a thickening north towards the south, of the aquiferous system of Tadla observed on both sides of Oum R' Bia river.

In the Beni Moussa area it was possible to point out even similar contributions due to the presence of cities (with a probable human and industrial polluting effect). The results obtained were further confirmed by cluster analysis.

In the plain, contamination by nutrients may therefore be indicative for bacteriological contamination of groundwater. Wells contaminated by nutrients should therefore receive particular attention in the groundwater monitoring programme. Nutrient contamination may therefore also guide the design and implementation of sanitation operations needed to reduce environmental and health risks.

Different strategies could be developed to reduce the pollution. A first, but elementary, step hereby would consist in diffusing the relevant information about the observed pollution and associated risk to the local actors, that is, the farmers, the local population, the communes and the different administrations dealing with water and agricultural management. Indeed, mitigation strategies will only be effective if local actors are motivated to implement the mitigation strategies. In case agriculture would play a key role, than farmers must correctly be informed about the pollution problem, the role of agricultural sector in this problem and their responsibility.

Hence, extension services of the O.R.M.V.A.T will probably play a key role in this first step. In a second step, mitigation strategies could be implemented. Different fertilizer management options could be presented such as reducing the total fertilizer dose, adapting the fertilizer dose in terms of the actual crop demand and available residue in soil, modifying the timing of the fertilizer dressing, modifying the spatial application in particular for the fruit tree exploitation in the area, and finally using covering crops and catch crops.

ACKNOWLEDGMENTS

The authors sincerely thank the Hydraulic Basin Agency of Oum R'bia in Beni Mellal (Morocco) for their help in providing necessary data.

REFERENCES

Abouzaid H (1980). Qualité des eaux et orientation de la recherche applique´e a` l'office national de l'eau potable pendant le plan quinquennal 1980–1985. CNCPRST. Rabat. 173:72-80.

Barbieri P, Adami G, Favretto A, Lutman A, Avoscan W, Reisenhofer E (2001). Robust cluster analysis for detecting physico-chemical typologies of freshwater from wells of the plain of Friuli (northeastern Italy). Anal. Chem. Acta 440(2):161-170.

Berdaı¨H, Soudi B, Bellouti A (2004). Contribution a` l'étude de la pollution nitrique des eaux souterraines en zones irriguées: Cas du Tadla, Projet INCO-WADEMED, Actes du Séminaire, Modernisation de l'Agriculture Irriguée, Rabat, du 19 au 23 avril 2004, p. 28.

Box GEP, Hunter WG, Hunter JS, Hunter WG, Hunter JS (1978). Statistics for Experimenters: An Introduction to Design, Data Analysis, and Model Building, Wiley-Interscience, New York, ISBN 0471093157.

Bureau De Recherches Géologiques Et Minières (BRGM) (1993). Etude du système multicouche de la plaine de Tadla. Description des aquifères et analyse du système multicouche. Maroc. Rapport R35610 4S/Eau- 92:129.

Brodnjak-Vonina D, Dobnik D, Novi M, Zupan J (2002). Chemometrics characterisation of the quality of river water. Anal. Chem. Acta. 462(1):87-100.

Caselli M, De Giglio A, Mangone A, Traini A (1998). Characterisation of mineral waters by pattern recognition methods. J. Sci. Food Agric. 76(4):533-536.

Durfor CN, Becker E (1964) «Public water supplies of the 100 largest cities in the US». US-Geological Survey Water Supply Paper, 1812, 364.

Davis JC (1986). Statistics and Data Analysis in Geology, John Wiley & Sons, New York, ISBN 0471080799.

Everitt B (2001). Cluster Analysis (4th edn). Hodder Arnold, London.

Food and Agriculture Organization (FAO) (2002). The State of Food Insecurity in the World. Rome [http://www.fao.org/ DOCREP/003/YO1500E/Y1500E00. HTM], April 2002.

Farnham IM, Johannesson KH, Singh AK, Hodge VF, Stetzenbach KJ (2003). Factor analytical approaches for evaluating groundwater trace element chemistry data. Anal. Chem. Acta 490(1):123-138.

Fetouani S, Sbaa M, Vanclooster M, Bendra B (2008). Assessing ground water quality in the irrigated plain of Triffa (north-east Morocco). Agric. Water Manage. 95(13):3-142.

Harvey RW, Harmas H (2002). Transport on micro organisms in the terrestrial subsurface: in situ and laboratory methods. In: Dans: Manual of Environmental Microbiology, 2ème edition. ASM Press, Washington, DC.

Isaaks EH, Srivastava RM (1990). An Introduction to Applied Geostatistics, Oxford University Press, Oxford ISBN: 0195050134.

Khattabi A (2003). Diagnostic socio-économique: Beni Snassen. Rapp. Inédit, projet MedWetCoast-Maroc, PNUE/Secr. Etat Envir. /Départ. Eaux & Forêts, Maroc, p. 82.

Kholtei S (2002). Caractéristiques physico-chimiques des eaux usées des villes de Settat et de Berrechid et évaluation de leur impact sur la qualité des eaux souterraines. Thèse. Doctoral p. 146.

Krige DG (1978). Lognormal-de Wijsian Geostatistics for Ore Evaluation (Geostatistics), South African Institute of Mining and Metallurgy, Johannesburg, ISBN: 0620030062.

Laftouhi N, Vanclooster M, Jalal M (2003). Groundwater nitrate pollution in the Essaouira Basin (Morocco). CR Geosci. 335:307-317.

Lhadi EK, Mountadar M, Younsi (1993). Contamination des eaux souterraines par les sels et les nitrates de la zone littorale entre Azemour et Bir Jdid. Se´minaire de recherche nationale dans le domaine: Eaux et Environnement, LPEE, Casablanca (Maroc).

Librando V, Drava G, Forina M (1998). 3-way principal component analysis applied to the evaluation of water quality of underground waters in the area of Siracusa. Ann. Chem.-Rome 88(11-12):867-878.

Maier RM, Pepper IL, Gerba CP (2000). Environmental Microbiology. Academic Press, San Diego, CA.

Massart DL, Vandeginste BG, Buydens LM, Lewi PJ, Smeyers-Verbeke J (1997). Handbook of Chemometrics and Qualimetrics: Part A, Elsevier Science Ed., Amsterdam, ISBN: 0444897240.

Massart DL, Vandeginste BGM, Deming SN, Michotte Y, Kaufman L (1988). Chemometrics: A Textbook (Data Handling in Science and Technology), Elsevier Ed., Amsterdam ISBN: 0444426604.

PDAIRE (Plan Directeur d'Aménagement Intégré des ressources en Eau) (2008). Etude d'actualisation du PDAIRE de la zone d'action de l'Agence de l'OER. Mission I, ETAT DES LIEUX ET PERSPECTIVES D'EVOLUTION. Rapport définitif, Royaume du Maroc, p. 4.

Reghunath R, Sreedhara Murthy TR, Raghavan BR (2002). The utility of multivariate statistical techniques in hydrogeochemical studies: An example from Karnataka, India. Water Res. 36(10):2437-2442.

Reisenhofer E, Adami G, Barbieri P (1998). Using chemical and physical parameters to define the quality of karstic freshwaters (Timavo River, North- Eastern Italy): A Chemometric Approach. Water Res. 32(4):1193-1203.

Rodier J (1984). L'analyse de l'eau, eaux naturelles, eaux résiduaires, eau de mer, 7ème édition. Dunod, Paris p. 1353.

Sinan M (2000). Méthodologie d'identification, d'évaluation et de protection des ressources en eau des aquifères régionaux par la combinaison des SIG, de la géophysique et de la géostatistique. Application à l'aquifère du Haouz de Marrakech (Maroc), thèse d'état, université Mohamed V de Rabat, Maroc.

Sinan M, Razack M (2008). An extension to the DRASTIC model to assess groundwater vulnerability to pollution. Application to the Haouz groundwater of Marrakech (Morocco). Revue Environmental Geology. DOI 10.1007/s00254-008-1304-2 (Allemagne).

Sinan M, Razack M (2005). Management of regional aquifers using a combined procedure based on geostatistical and GIS tools (Haouz groundwater of Marrakekech, Morocco). Proceeding de la 6ème Conférence Internationale de l'European Water Resources Association : EWRA 2005 (7 au 10 septembre 2005), Menton, France.

USEPA (2000). CFR title, sous-partie S, parties 141 et 142, RIN 2040-aa97 National Prinking Water Regulation, Ground Water Rule.

Vega M, Pardo R, Barrado E, Debán L (1998). Assessment of seasonal and polluting effects on the quality of river water by exploratory data analysis. Water Res. 32(12):3581–3592.

Vidal M, López A, Santoalla MC, Valles V (2000). Factor analysis for the study of water resources contamination due to the use of livestock slurries as fertilizer. Agric. Water Manage. 45(1):1-15.
World Health Organization (WHO) (2000). Global Water Supply and Sanitation Assessment 2000 report. OMS, UNICEF p. 77.
Wunderlin DA, Díaz MP, Amé MV, Pesce SF, Hued AC, Bistoni MA (2001). Pattern recognition techniques for the evaluation of spatial and temporal variations in water quality. A case study: Suquía River Basin (Córdoba Argentina). Water Res. 35(12):2881-2894.