
Groundwater salinization of the Sfax superficial aquifer, Tunisia

Rouaida Trabelsi · Moncef Zairi · Hamed Ben Dhia

Abstract Groundwater salinization has become a crucial environmental problem worldwide and is considered the most widespread form of groundwater contamination. The origin of salinity in the coastal aquifer of the Sfax Basin, Tunisia was investigated by means of chemical analyses of groundwater samples from 65 wells. The groundwater samples present a clear gradation from calcium sulphate salinization to that of sodium chloride. The saturation indices for calcite and gypsum, and binary diagrams of different ions, together with multivariate analysis, indicate the existence of various salinization processes such as: dissolution of gypsum and calcite dispersed through the reservoir rock; ion exchange; intensive agricultural practices that produce effluents that infiltrate to the saturated zone; and sea-water intrusion, enhanced by excessive withdrawal of groundwater.

Résumé La salinisation de l'eau souterraine est devenue un problème environnemental crucial dans le monde entier et est considérée comme la contamination de l'eau souterraine la plus étendue. L'origine de la salinité dans l'aquifère côtier du bassin de Sfax en Tunisie, a été étudiée grâce à des analyses chimiques d'échantillons d'eau souterraine de 65 puits. Les échantillons d'eau souterraine présentent un gradient net allant de la salinisation calco-sulphatée à la salinisation chloro-sodique. Les indices de saturation de la calcite et du gypse, et les diagrammes binaires de différents ions, ainsi que plusieurs analyses multivariées, indiquent l'existence de processus variés de salinisation comme : la dissolution du

gypse et de la calcite, dispersés à travers la roche-réservoir; l'échange d'ions; des pratiques agricoles intensives produisant des effluents qui s'infiltreront vers la zone saturée; et l'intrusion d'eau de mer, accentuée par l'exploitation excessive de l'eau souterraine.

Resumen La salinización de Agua subterránea se ha vuelto un problema medioambiental crucial de escala mundial y se le ha considerado la forma más extendida de contaminación del agua subterránea. El origen de salinidad en el acuífero costero de la Cuenca de Sfax, Túnez, se investigó por medio de los análisis químicos de muestras del agua subterránea de 65 pozos. Las muestras de agua subterránea presentan una gradación clara desde la salinidad de sulfato de calcio a la del cloruro de sodio. Los índices de saturación para la calcita y el yeso, y los diagramas binarios de iones diferentes, junto con el análisis multivariado, indican la existencia de varios procesos de salinización como: la disolución de yeso y calcita, dispersada a través de la roca-reservorio; el intercambio iónico; prácticas agrícolas intensivas que producen efluentes que se infiltran a la zona saturada e intrusión de agua marina, reforzada por una extracción excesiva de agua subterránea.

Keywords Coastal aquifers · Salinization · Hydrochemistry · Tunisia

Introduction

Water is a finite resource and it is becoming a scarce commodity in many parts of the world. Competition amongst agriculture, industry, and domestic uses for limited water supplies is a constraining factor for economic development in countries with scarce water resources. These undesirable effects are expected to become more serious as climatic changes cause more desertification, greater erosion in watersheds, and sea-level elevation in coastal areas.

In the last 20 years, groundwater salinization has become an urgent environmental problem worldwide and constitutes one of the most widespread forms of water contamination. The problem is particularly serious in

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coastal areas, where rapid population growth and intensive economic activity has increased the need for fresh-water supplies. This need is mainly being satisfied by pumping groundwater from coastal aquifer systems. However, in coastal regions, groundwater quality patterns are complex because of the input from many different water sources. These include precipitation (possibly polluted or saline due to strong evaporation), seawater, ascending deep groundwater, and anthropogenic sources such as wastewater or irrigation return flow (Steinich et al. 1998).

Problems in coastal areas are typically connected to contamination of fresh water resources by saltwater and include well field salinization, crop damage, and surface water quality deterioration (Karro et al. 2004). Proper management of available groundwater reserves is impossible without knowledge of the spatial distribution of fresh and saline groundwater and the processes that determine their evolution (Glynn and Plummer 2005). Understanding the spatial variations in chemical composition of groundwater that result from different types of input is extremely difficult, especially if concentrations have varied over time or if boundary conditions have changed (Hussein 2004). Descriptions of the processes and factors that control saline water evolution over time is an academic challenge, but of important practical use for water resource evaluation and seawater intrusion studies (Post 2004). Processes and chemical reactions associated with saltwater intrusion in coastal aquifers have been investigated by several authors. Richter and Kreitler (1993) used geochemical techniques to identify sources of groundwater salinization. Petalas and Diamantis (1999) describe the origin and distribution of saline groundwater in the coastal area of Rhodope, Greece, using several hydrochemical diagrams. Chadha (1999) proposes a new hydrochemical diagram for classification of natural waters and identification of hydrochemical processes. Manzano et al. (2002) used chemical and environmental isotope evolution studies in the Inca-Sa Pobla aquifer, Balearic Islands, Spain, and found mostly unconfined flow along the main flow path. Gaaloul and Cheng (2003) explained hydrogeological and hydrochemical evolution of coastal aquifers in Tunisia by anthropogenic activities. Cardona et al. (2004) examined groundwater quality in the Santo Domingo irrigation district in Baja California Sur, Mexico, and identified various salinization processes, and Post (2005) recently described the problem of fresh and saline groundwater interaction in coastal aquifers through characterization methods and possible solutions.

Many authors (Calvache and Pulido-Bosch 1994; Oude Essink 1998; Sakr 1999; Pucci 1999; Bear et al. 2001; Das and Datta 2001; Oude Essink 2001; Grube et al. 2002; Martínez and Bocanegra 2002) have attempted to explain the occurrence of saline groundwater in coastal aquifers and have used numerical techniques to study the processes through which seawater can enter the aquifers.

The Tunisian shoreline extends for 1,300 km, with the coastal zone width ranging from 20 to 60 km and a total area of approximately 40,000 km² (Gaaloul and Cheng 2003). The dry climate conditions in this zone and the

heavily irrigated agriculture have led to intensive groundwater exploitation. Consequently, the coastal aquifers are at great risk of saltwater intrusion.

The purpose of this study is to characterize the hydrogeological and hydrochemical changes of the coastal area in the north part of the Sfax Basin, Tunisia, to analyze the relationships between these changes and the groundwater chemical composition of the area, and to characterize the processes and chemical reactions involved. This is achieved by using chemical inorganic indicators as major, minor, and trace elements.

Study area

The Sfax Basin (Fig. 1) in eastern Tunisia, is bounded to the east by the Mediterranean Sea, the N–S Axis mountain chain to the west, the Korj, Bouthadi, Chorbane, Zeramidine and Djemmel Hills to the north and Mezzouna Mountain to the south. A number of *sebkhas* (salt plain) are distributed in the west. The study area is characterized by an arid climate with mean annual precipitation of about 250 mm. The population of the area is growing along with economic development.

The geology of the area has been described by Castany (1953), Burollet (1956), Zebidi (1989), and Maliki (1994). The lithology includes the Souar formation, considered to be of Eocene age and composed of sediments deposited in a marine environment. The Oligocene sediments are composed of a lower marine unit and an upper continental sandy one.

The Miocene presents an important thickness with alternating clay, sand and sandstone units. It is divided into three units, including the Ain Ghrab formation (Burdigalian) that mainly consists of limestone interlayered in the lower part with gypsum, the Oum Douil formation (Langian to Tortonian) consisting of a variable proportion of silt and clay and the Segui formation (Messinian) composed of continental sand, silt, and clay alternations.

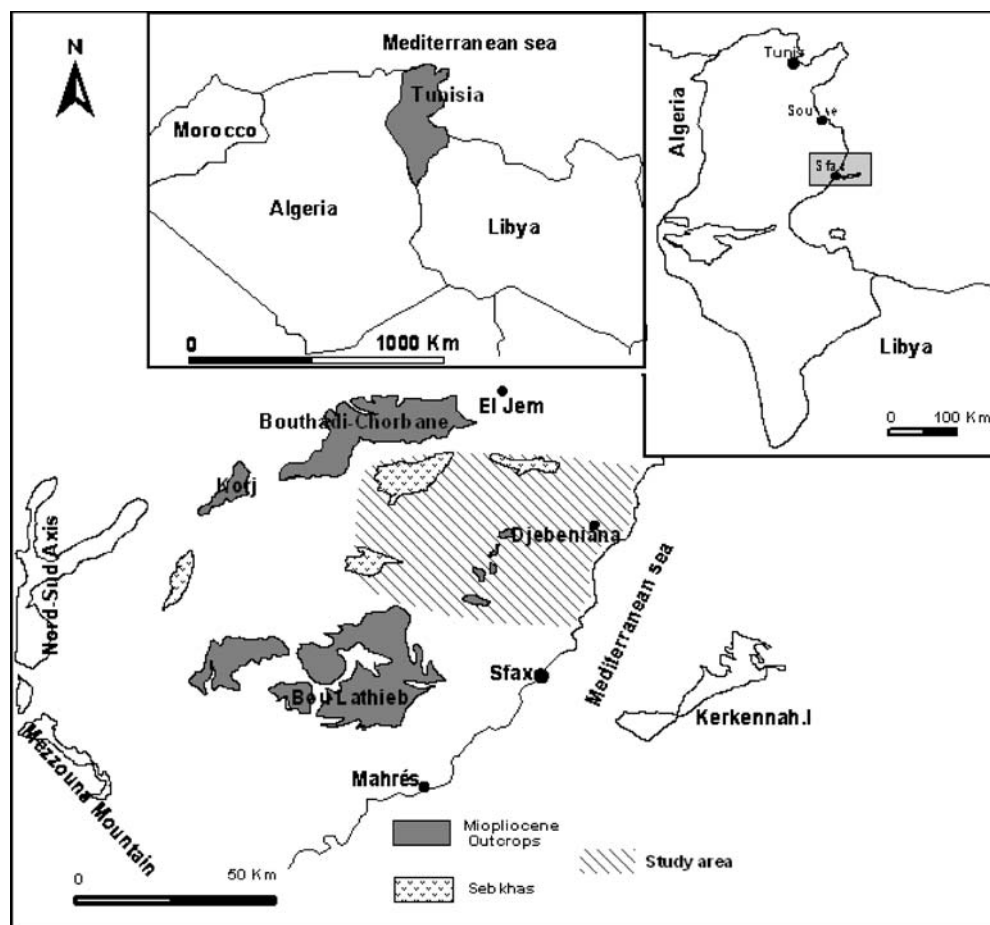
The Pliocene deposits overlie discordantly to older formations and consist of marl units. The Pleistocene is divided into two units: the lower is characterized by calcareous sand and the upper of silt and gypsum. The Holocene age is characterized by granular materials of various origin overlying clayey formations.

The upper Miocene, Pliocene and Quaternary sand and silty clay deposits constitute the reservoir of the superficial aquifers of the region. These deposits present several productive layers separated by semi-permeable layers.

Materials and methods

Representative groundwater samples were obtained from 65 pumping wells selected on the basis of geographical distribution. Most of the selected wells are used for irrigation and their depths ranged from 5 to 120 m.

Fig. 1 Location of the study area



The electrical conductivity, temperature, and pH were measured in situ and laboratory chemical analyses for the major elements (Na, Ca, Mg, HCO_3 , Cl, SO_4) and minor elements (K, NO_3) and boron (B) were carried out. Field measurements of pH were made using a pH-meter. Electrical conductivity was measured by means of a conductivity meter. Electrode calibration was made using a standard solution at different concentrations. The analyses of K and SO_4 were undertaken by a gravimetric method, those of HCO_3 , Cl, NO_3 , and Ca by the titrimetry method, B by the spectrophotometry method, and Mg and Na were analyzed by spectrometry of atomic adsorption (SAA).

Differences between potential salinization sources were investigated by analyzing the major elements (HCO_3 , Cl, SO_4 , Na, Ca, and Mg), the minor elements (NO_3 and K) and the trace element (B). The effect of irrigation return flow on groundwater was identified on the basis of the concentrations of SO_4 , NO_3 , and B. Available information regarding the historical characteristics of groundwater in the study area consisted of annual records from several head monitoring wells. The reported data by the local water management authorities were used to establish the evolution of the groundwater head and the salinity trends.

Piezometry and salinity of groundwater

Figure 2a shows the piezometric head contour map overlying the geologic outcrops in the region. The recharge area of the superficial aquifer is situated upstream from the Médasse Sidi Salah and Blettech regions. The discharge fields are situated in the seashore and the sebkhias of El Jem and El Ghorra. Groundwater occurs at an average depth of 20–30 m below ground surface. The flow system is controlled by the topography and involves multidirectional flow with the dominant flow from the higher topographic area in the west toward the area of lower topography in the east. Variations in the hydraulic gradient are related to the spatial characteristics of the aquifer and the presence of well fields.

The available water-level records of selected wells (Fig. 2b,c) cover the time period from 1970 to 2002 with interruptions in both time and space. Most hydrographs of the four upgradient wells indicate unchanging or steady-state water level when viewed over several years, corresponding to a local groundwater recharge in balance with groundwater discharge (Fig. 2b). However, in the Djebeniana region, the monitoring wells show lower or declining water level over the period of record (Fig. 2c). A detailed follow-up of piezometric levels in this coastal

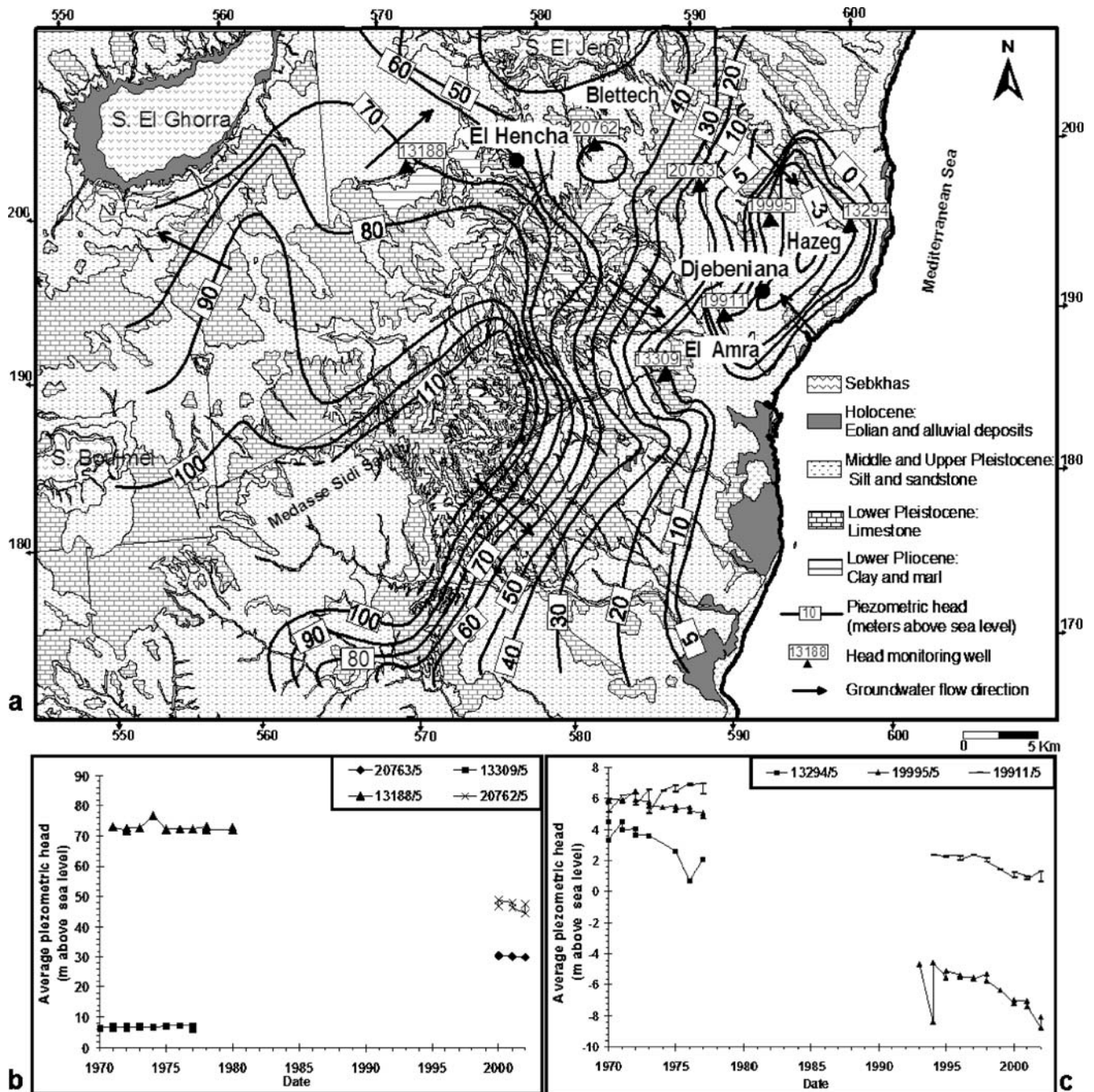


Fig. 2 a Geologic outcrops and piezometric head of the study area with b hydrographs of upgradient wells and c downgradient wells. The base geologic map is also used in Figs. 4, 6 and 7

zone, where the greatest decrease occurs, was undertaken. The spatial distributions of the piezometric heads measured in 1970, 1980, 1991, and 2002 are presented in Fig. 3. The latter reveals that water level in the eastern part of the Djebeniana region declined at least 8 m during the 32-year period due to intensive pumping of groundwater; a permanent regional cone of depression has been formed and is increasing in size from year to year. This has resulted in seawater intrusion into the aquifer system from the eastern boundary of the study area.

Salinity is the total amount of inorganic solid material dissolved in any natural water and is normally expressed in terms of total dissolved solids (TDS). A lot of classification methods have been developed to differentiate freshwater from saltwater and to define the degree of salinity of the water (Smith 2003; Barlow 2003). These somewhat arbitrary classifications of freshwater, brackish water and brines are based on the suitability of the water for human consumption and usage.

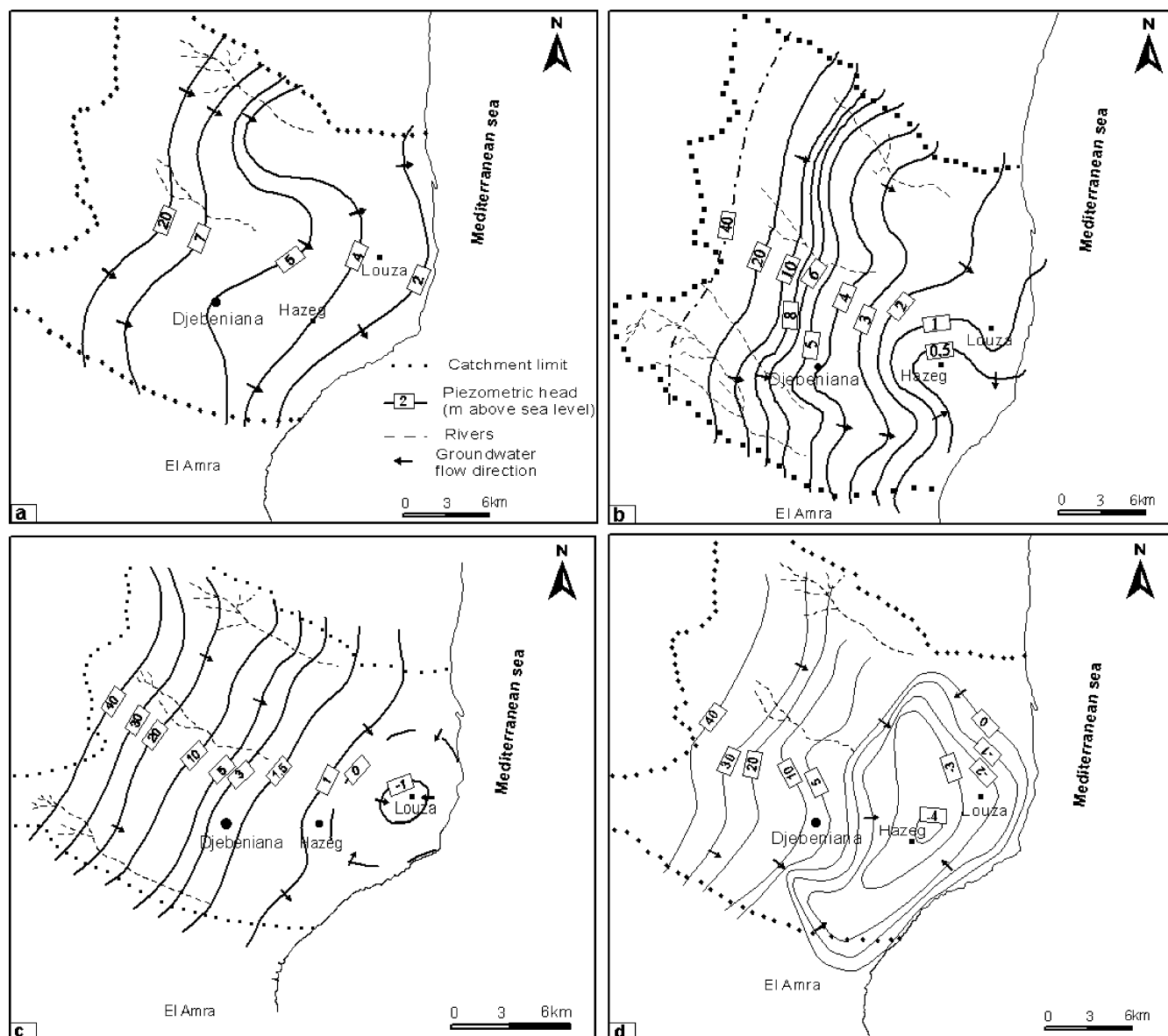


Fig. 3 Piezometric head (in meters above mean sea level) contour maps in the Djebeniana region for: **a** 1970 (Hajjem 1980), **b** 1980 (Hajjem 1980), **c** 1992 (Amouri 1993), and **d** 2002 (this study)

The salinity map drawn from a representative set of 65 groundwater samples is shown in Fig. 4. In the north part of the Sfax Basin, the phreatic aquifer generally contains brackish water with 71% of the total samples having salinity between 2,000 and 6,000 mg/l, and an average TDS of 4,100 mg/l. These waters are mainly used for agricultural irrigation.

The low salinity waters, with a TDS less than 2,000 mg/l (13% of the total samples), are mainly located at the preferential recharge zones of Blettech and Medasse Sidi Salah regions and a major temporary stream (wadi). This low salinity can be explained by the short lifetime of the groundwater in the reservoir before it is pumped.

Groundwater with TDS greater than 6,000 mg/l is observed mainly in the regions of El Jem sebkha, the northwestern part of Medasse Sidi Salah, and in the south

of the study area. The important mineralization near such areas is probably related to the local processes and the contamination by anthropogenic activities.

To the east of the Djebeniana region, TDS values varied between 9,000 and 12,000 mg/l and are associated with the piezometric depression there. The distributions of salinity for waters recovered in 1980, 1994, 1998, and 2002 in this region are presented in Fig. 5. In 1980, TDS values of less than 4,000 mg/l were identified in most parts of the region with a maximum as high as 7,000 mg/l observed in the coastal area.

By 2002, regions with TDS less than 4,000 mg/l comprised only 20% of the total area and TDS values greater than 11,000 mg/l are frequently found in the coastal area. This indicates a serious deterioration in the chemical quality and a sharp increase in the salinity of

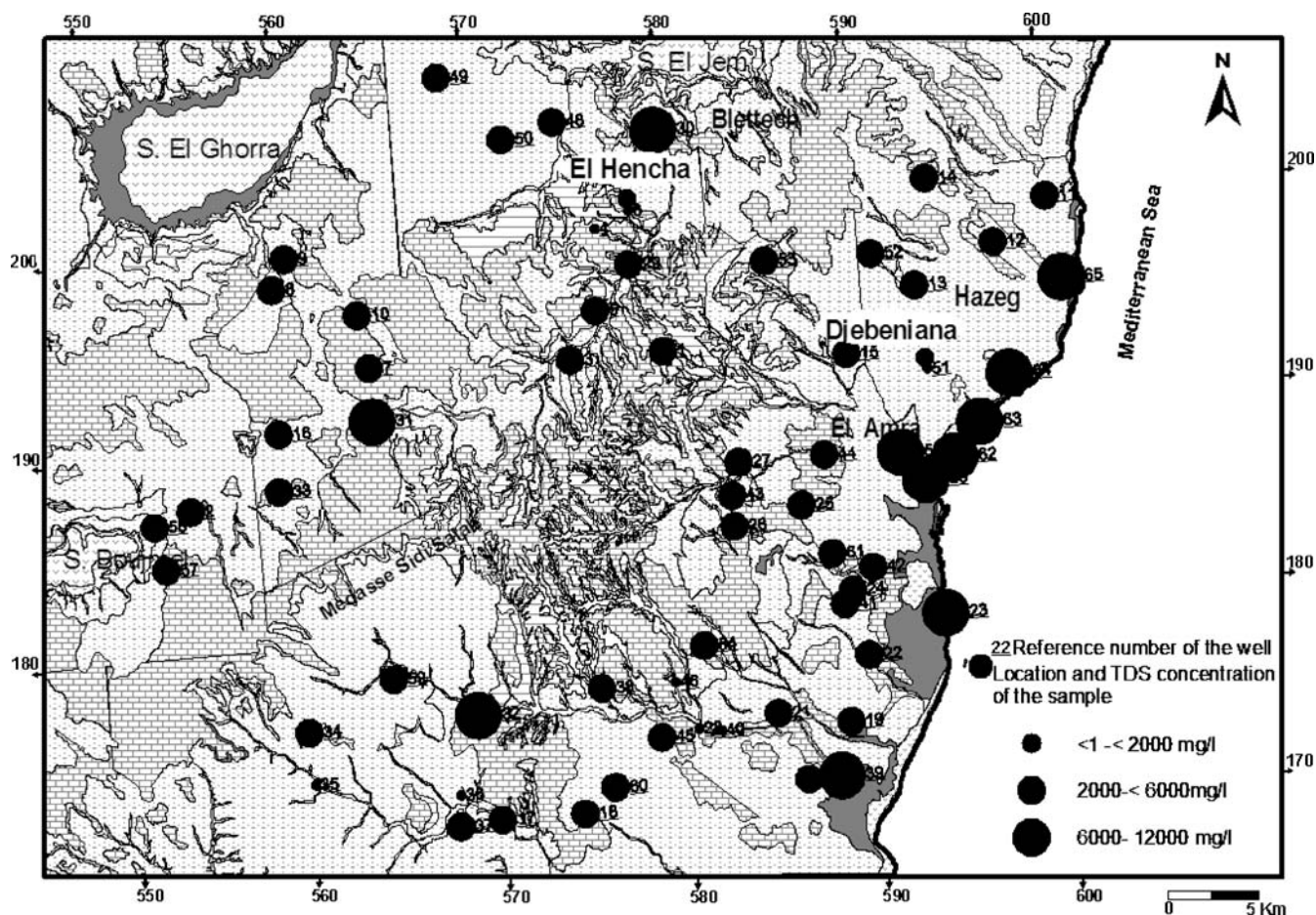


Fig. 4 Spatial distribution of the total dissolved solids (TDS) in groundwater samples

the groundwater from TDS of 7,000–12,000 mg/l during a period of 22 years.

Groundwater quality

The chemical analyses of the groundwater show large variations in groundwater chemical composition with high salinity of some samples (see chemical analysis results, [Electronic supplementary material](#)). The standard deviations for chloride and nitrate are greater than their averages due to the large groundwater concentration variations for these two ions. The electrical conductivity and pH show large spatial variations. The former vary between 1,315 and 17,125 $\mu\text{S}/\text{cm}$, while the latter range from 6.7 to 8.2.

Spatial distributions of major elements

The spatial distribution of the major elements depend on the distance from the shoreline, topography, geology, groundwater flow direction, and other sources of contamination (Kim et al. 2002). Figure 6 shows the distribution of the four identified groundwater facies within the study area. The sulfate-sodium facies charac-

terizes the northeastern and southeastern zones of the region and presents the most important percentage (45%) of the water types. The abundance of the sodium is probably due to cation exchange processes and pollution by human activities. In fact, the chemical processes that influence the concentration of the sodium ion in groundwater as it flows from the recharge area towards the sea are the dissolution of silicate minerals, cation exchange (which is the most important chemical process affecting its concentration), and pollution from wastewater and from seawater (Post 2002).

The sulfate-calcium facies water was encountered in the northwestern part of the study region where the groundwater composition probably results from the dissolution of the gypsum, anhydrite, and calcite dispersed within the aquifer materials. The chloride-calcium facies and the chloride-sodium facies waters principally occupy the coastal band which is proposed to be the part of the aquifer affected by seawater intrusion.

The superficial aquifer in the northern part of the Sfax Basin supports extensive irrigation activity and is therefore subject to contamination by nitrate (NO_3). Nitrate values range from 0.4 to 378 mg/l and only 26% of the samples present a nitrate concentration less than 20 mg/l (Fig. 7 shows nitrate contours). Because those sites are

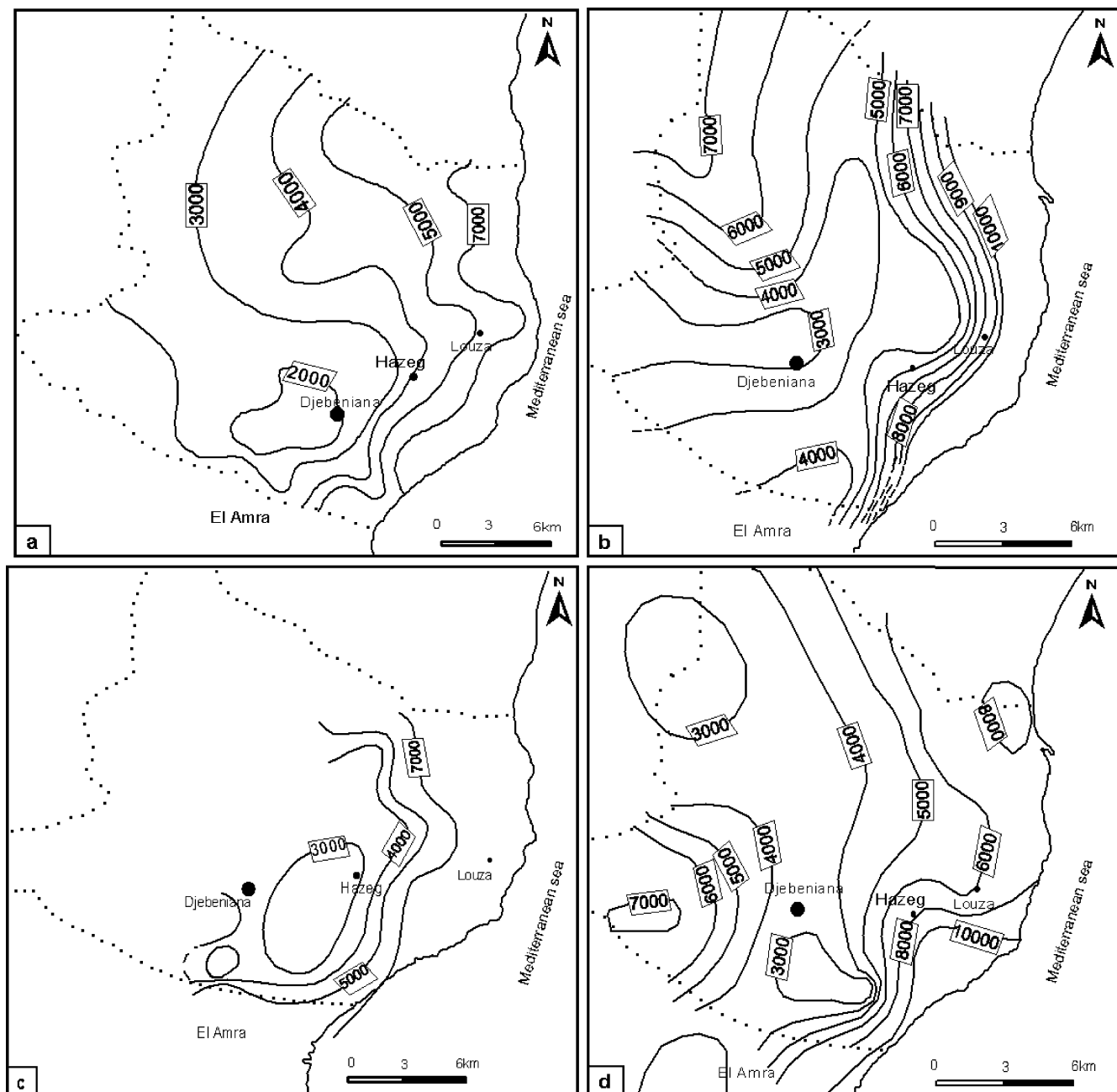


Fig. 5 Groundwater salinity measured as TDS (mg/l) for: **a** 1980 (Hajjem 1980); **b** 1994 (Maliki 1994); **c** 1998 (Ben Marzouk 2001) and **d** 2002 (this study)

distributed throughout the study area, this value is considered to represent a background concentration. Samples with concentrations of NO_3^- between 20 and 50 mg/l present 48% of the total number of wells.

Samples with noticeably high concentrations of NO_3^- (between 50 and 378 mg/l) present 26% of sampled wells and occur in: (1) the area south of Sebkhass El Jem; (2) a central zone near Medasse Sidi Salah hills; and (3) a coastal band of the study area. The high NO_3^- concentration in the groundwater is probably related to the injection, in the aquifer, of the raw sewage (untreated domestic effluents) particularly in the populated zones of

Djebeniana, El Amra, Hazeg, Blettech, and El Hencha, together with the infiltration of fertilizers used in irrigation perimeters.

Groundwater salinization origins

Generally, rocks that are most soluble include limestone (CaCO_3), dolomite (CaMgCO_3), gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), halite (NaCl), and sylvite (KCl); these also serve as the principal source for Ca, Mg, Na, K, CO_3 , SO_4 , and Cl in groundwater. Silicates and other so-called “insoluble

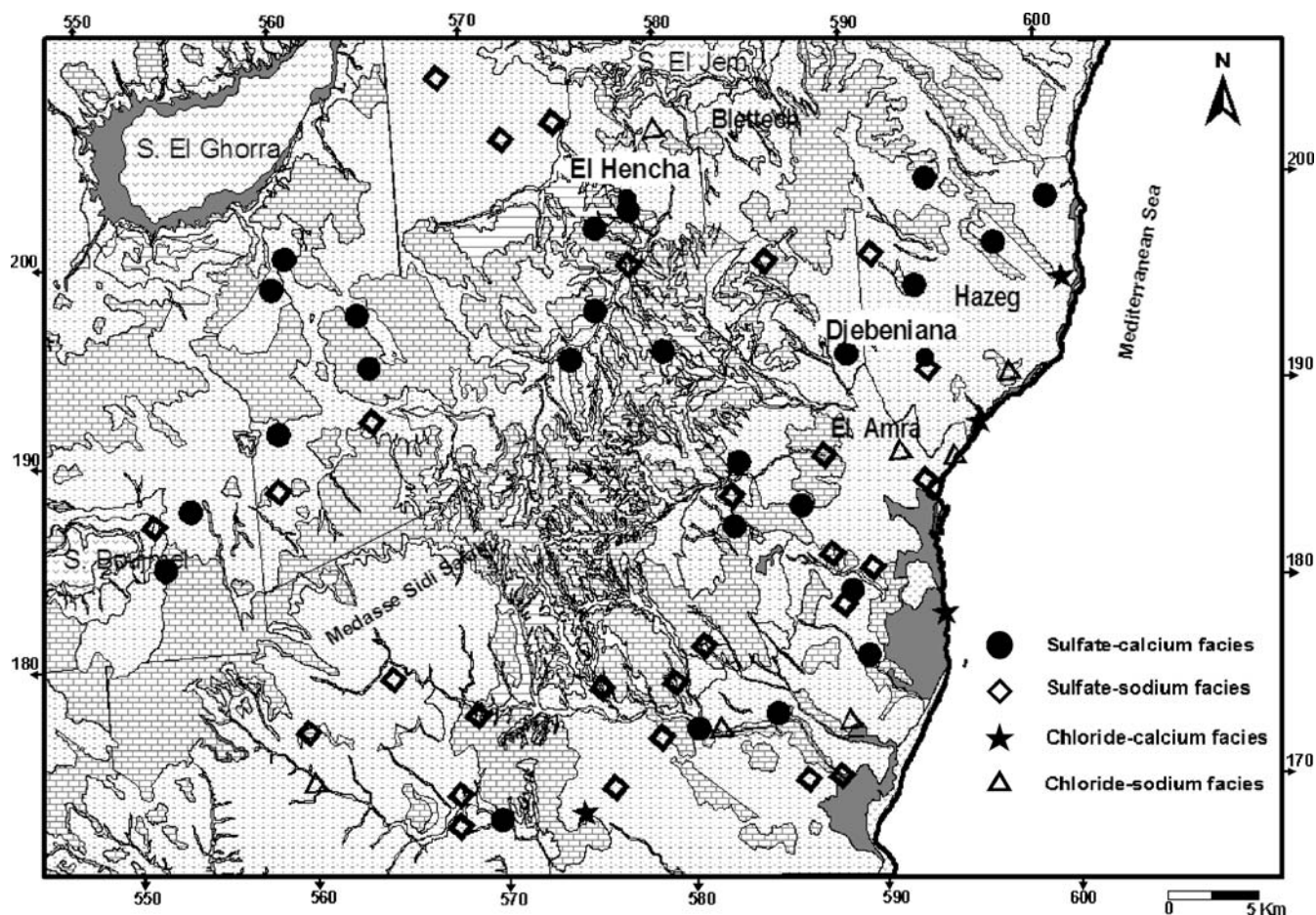


Fig. 6 Groundwater facies distribution in the study area

rocks” also are soluble to some degree under certain chemical conditions and yield the minor constituents or trace constituents in groundwater (Tóth 1999).

In this study, effects of water-rock interactions were investigated by calculating calcite, and gypsum saturation indices for groundwater samples using the PHREEQC geochemical code (Parkhurst and Appelo 1999).

The mean water temperature of the superficial aquifer of Sfax Basin is 20°C which coincides with the mean annual atmospheric temperature. The average pH is 7.4, the maximum is 8.2, and the minimum is 6.5 with no clear pattern in the regional distribution. These waters show variable saturation indices: -0.649 – 0.142 for gypsum and -1.033 – 1.170 for calcite (Fig. 8). The 34% of the samples are subsaturated to calcite, while 25% of them are subsaturated to gypsum.

Waters are in equilibrium with carbonate minerals for the major part of the samples (57%). The recharge regions of Medasse Sidi Salah, Blettech and the temporary streams show unsaturated waters in these minerals. Waters of the aquifer are in equilibrium with evaporitic minerals as 70% of the total samples present a saturation index between 0.1 and -0.1 . However, a number of samples (25%) show a negative value of saturation index in the recharge area cited above.

Figure 9a shows the concentration of Na as a function of Cl in the groundwater samples. The Cl has conservative behavior, and deviations from conservative mixing that result from solubility or redox controls are not feasible (El Achheb et al. 2001). Consequently, the high Na concentrations for the majority of samples suggest a strong water-aquifer interaction related to direct cation exchange between groundwater and the clay fraction of the aquifer material particularly for the samples of the sulfate-sodium facies (Petalas and Lambrakis 2005).

A look at the evolution of Ca relative to Na (Fig. 9b) shows a mixing trend between fresh water from the recharge zone (samples 6, 15, 23, 33, 34, 35, 36, 37, 38, 45, and 57) and brackish groundwater to the northeast of Djebeniana (samples 62, 63, 64, and 65).

The concentrations of Mg in the Mg–Cl diagram (Fig. 9c) occur in significant amounts for all the groups with different amplitude, mainly resulting from clay mineral alteration. The most important boron species in natural waters are anions or load-free complexes, meaning that they are probably not significantly adsorbed onto the mineral surfaces. Therefore, the study of the boron content compared with those of Cl, SO_4 , and NO_3 ions enables the determination of its origin (Cardona et al. 2004; Molina et al. 2003). As shown in Fig. 9d, the groundwater samples

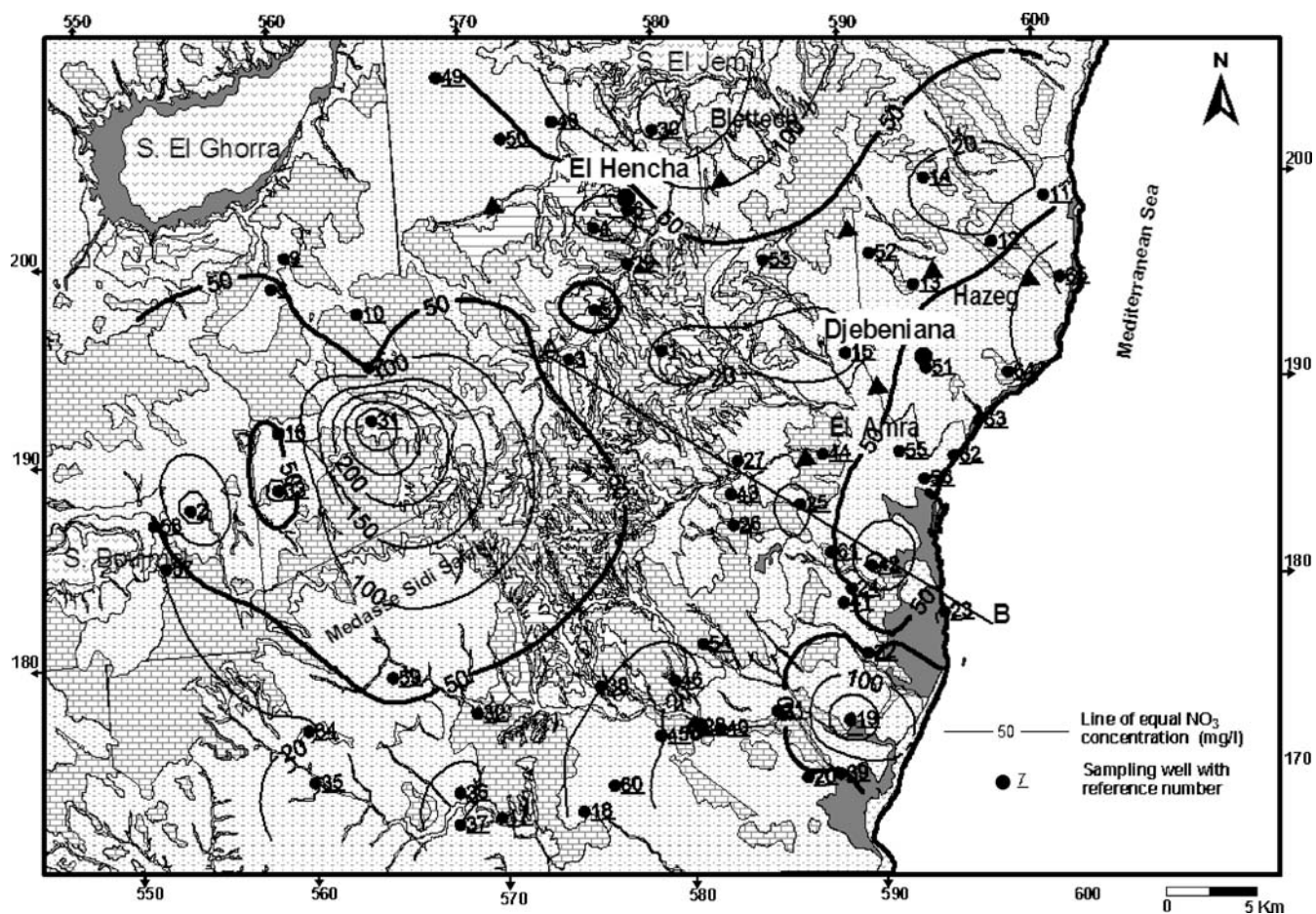


Fig. 7 Contour map of nitrate concentration in groundwater. The cross section AB is shown in Fig. 11

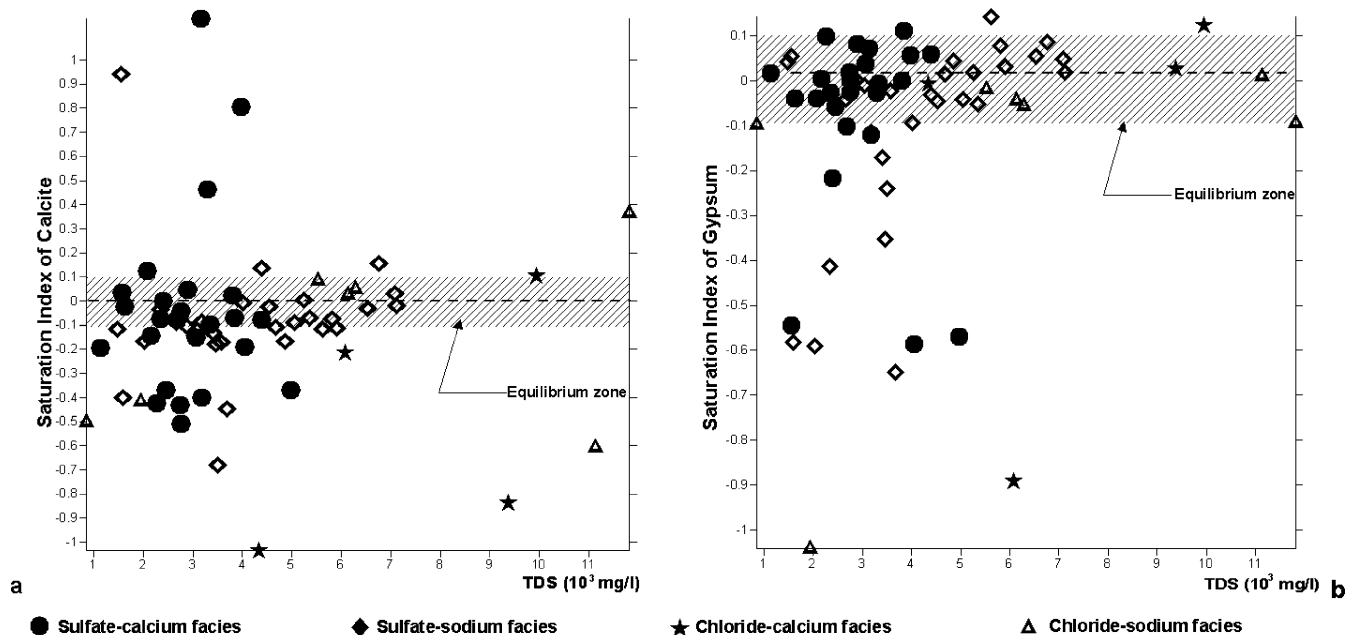


Fig. 8 Saturation indices vs. TDS for samples of the Sfax superficial aquifer for a calcite, and b gypsum

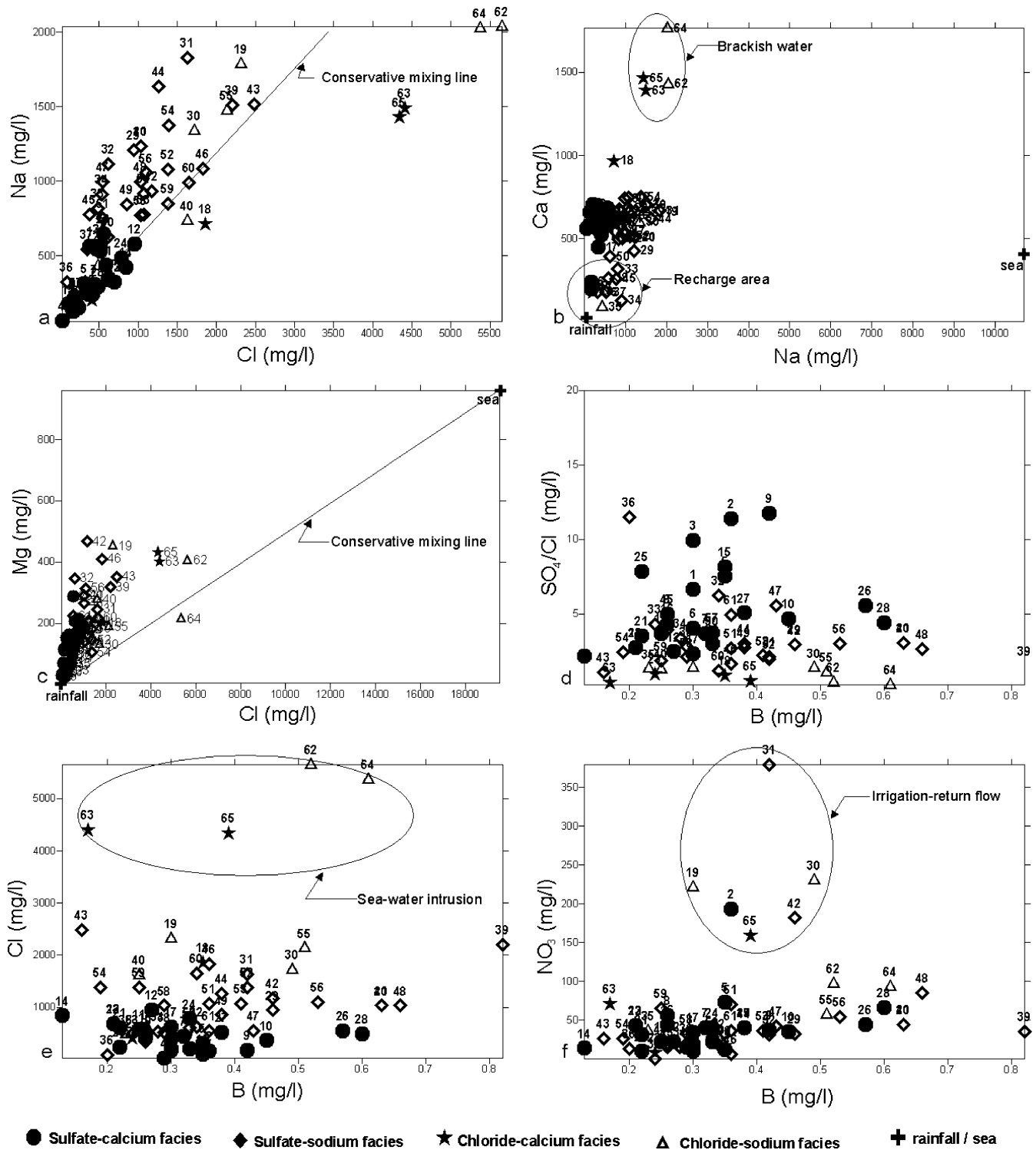


Fig. 9 a Evolution of Cl vs. Na (A), b evolution of Na vs. Ca, c evolution of Cl vs. Mg, d evolution of B vs. SO_4/Cl ratio, e evolution of B vs. Cl, f evolution of B vs. NO_3

indicate moderate values of the ratio SO_4/Cl and B concentration confirming the dissolution of evaporites disseminated in fine-grained aquifer material.

The B vs. Cl rates increase with the proportion of seawater introduced into the fresh water (Fig. 9e). The

samples with the highest concentrations (62, 63, 64, and 65) are indicative of seawater origin. Figure 9f shows that wells 2, 19, 30, 31, 42, and 65 have high B and NO_3 concentrations revealing an anthropogenic pollution of the groundwater.

Multivariate analysis

Generally, hydrological and geochemical processes are difficult to understand on account of their complexity; based on hydrochemical composition, multivariate statistical analysis can show the correlations between them (Kim et al. 2002; Helena et al. 2000). In this study, the statistical approach was used to define the origin of the chemical elements by identifying hydrochemical processes.

The 2.0 version of the KyPlot program, developed by Koichi Yoshioka (2001), was used to carry out calculations. The method used for initial factor extraction was the principal component analysis and for the factor rotation the Varimax method was used. Table 1 shows the Varimax factor loadings matrix, communalities for each variable and the proportion and the cumulative proportion of variance.

The choice of six factors is based on the proportion of variance accumulated which present a percentage superior to 85%. The factor analysis is considered successful, as the communalities for all variables are close to 1 (Ruiz et al. 1990). An absolute value of the loading of a chemical variable superior to 0.5 is an indicator of its participation in the factors (Table 1).

Factor 1 is contributed by electrical conductivity, Cl, Na, Ca, Mg, and K, whose concentrations in seawater are much greater than that in continental fresh water. Figure 10a shows the scores for the area distributions for factor 1 and it can be seen that the coastal band of the study area are characterized by high scores (>0.5), particularly in the zone of Djebeniana where the piezometric depression cone is detected. Therefore factor 1 can be associated with the seawater intrusion into the aquifer, which is considered to be an important contamination process affecting the quality of groundwater. This factor accounts for 33.24% of the variance of the concentrations of samples and it presents the highest percentage in relation to the other factors.

Factor 2 explains 16.52% of the variance and mainly associated with SO_4 , Mg, and Na. These are constituents resulting from the dissolution of evaporate minerals within the aquifer. Figure 10b shows the factor 2 scores in the study area using dashed areas for zones with a

score superior to 0.5, located in the south of the region and corresponding to the maximum dissolution of the gypsum.

Factor 3 (11% of the variance) includes HCO_3 , which is the result of dissolution of CO_2 in the water and gives an idea of the recharge areas located essentially in the regions of Hencha-Blettech, Medasse Sidi Salah hills, and the principal temporary streams as indicated by the dashed zones in Fig. 10c.

Factor 4 includes mainly NO_3 , and the area distribution of these factor scores (Fig. 10d) does not show areas characterized by particularly high values but it presents a local distribution in some wells. Furthermore, since the aquifer surface is used for agricultural proposes as recognized by Ruiz et al. (1990), the NO_3 may be associated mainly with surface runoff of NO_3 fertilizers.

Factor 5 (9.20% of the variance) includes the pH, which presents an important role in the geochemistry of carbonates and is probably associated with dissolution of carbonate minerals (Fig. 10e). Factor 6 (9.16% of the variance) is associated with the trace element B. It presents maximum factor loadings in the northwestern and eastern zones of the region (Fig. 10f). As it follows the groundwater flow path, it is possible that it is related to ion exchange processes.

Discussion

Considering the numerous sources and processes that influence solute concentrations, investigators that attempt to study their chemistry are faced with an almost overwhelming complexity. However, the distinction between sources and the classification of samples into groups are necessary to discern regional trends and to identify chemical processes (Stuyfzand 1999).

In this study zone, natural recharge is extremely limited, and is probably associated with exceptional wet periods with intense precipitation, mainly in the regions of Hencha, Blettech, Medasse Sidi Salah hills, and the principal temporary streams in the south of the zone. Runoff infiltration dominates particularly for samples 6, 15, 17, 23, 33, 34, 35, 36, 37, 38, 45, and 57; this group of

Table 1 Varimax factor loading matrix, communalities for each variable analyzed the variance and cumulative proportion of variance of each factor

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Communality
EC	0.851135	0.103894	0.17193	0.22318	-0.04066	0.111355	0.828647
pH	-0.05357	-0.05737	-0.10203	-0.01382	0.979823	0.0684	0.981493
HCO_3	-0.00102	0.011214	0.967384	0.033319	-0.1043	0.071333	0.953035
Cl	0.969955	0.101398	-0.0364	0.064002	-0.03932	0.04199	0.959825
SO_4	0.076252	0.937835	-0.02707	0.146821	-0.04777	0.159696	0.935423
NO_3	0.239953	0.169688	0.028284	0.941459	-0.01725	0.075148	0.979462
Na	0.718073	0.490629	0.2493	0.179275	-0.06143	0.114433	0.867504
K	0.599589	0.316069	0.049483	0.250651	0.127343	-0.47933	0.770659
Ca	0.840486	0.115261	-0.39683	0.078898	-0.01588	0.107138	0.895135
Mg	0.543999	0.66786	0.01286	0.065929	-0.03713	0.063301	0.751869
B	0.219555	0.291929	0.097167	0.135746	0.119802	0.833784	0.870843
Variance %	33.2473	16.5271	11.0031	9.8825	9.2062	09.1693	
Cumulative %	33.2473	49.7744	60.7775	70.6599	79.8661	89.0354	

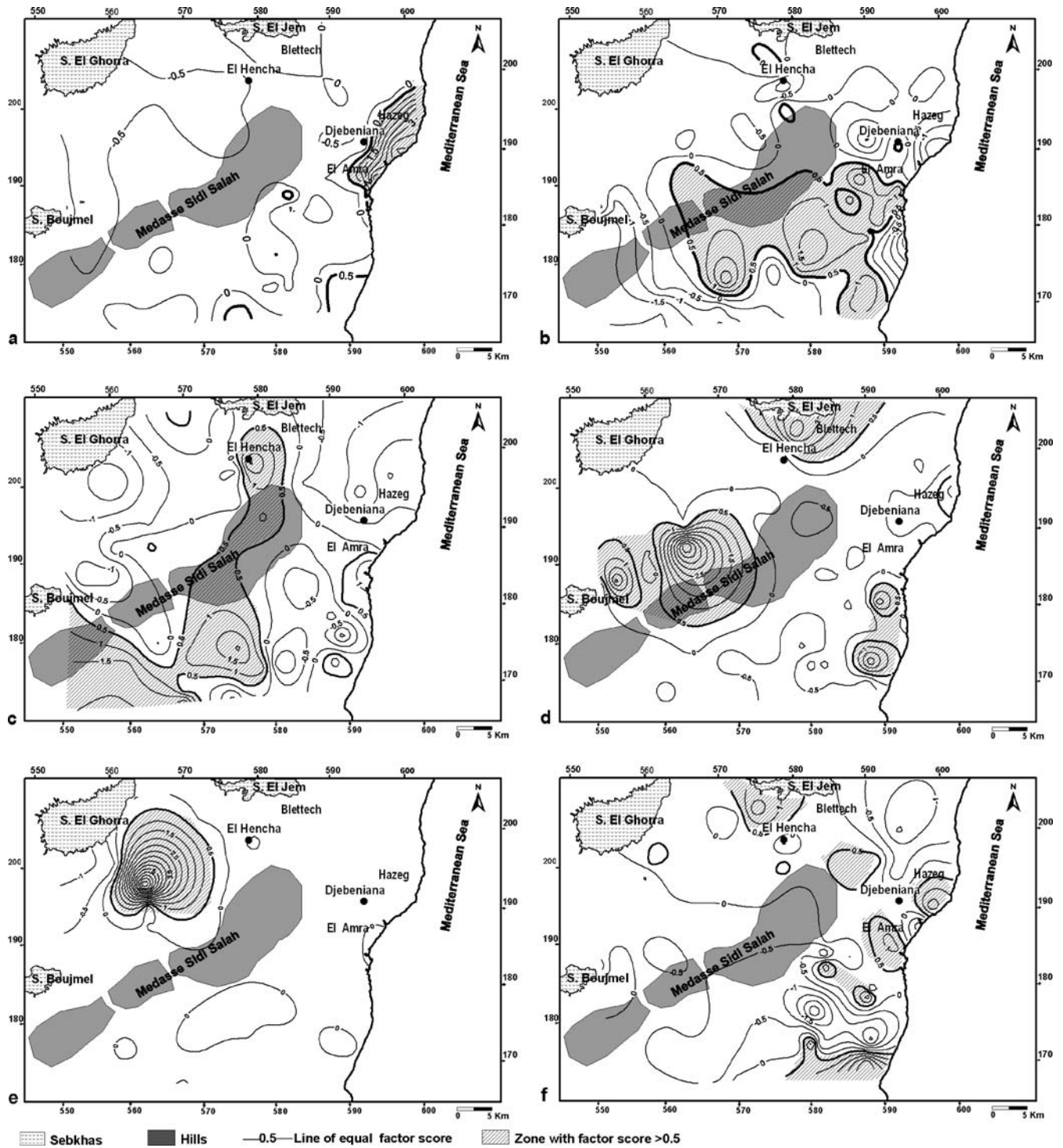


Fig. 10 Distribution of factor scores for **a** factor 1, **b** factor 2, **c** factor 3, **d** factor 4, **e** factor 5 and **f** factor 6 on the superficial aquifer of Sfax Basin

wells presents high values for HCO_3^- (and factor 3) but low values for Na, Ca and low saturation indices for gypsum and calcite. The identification of these recharge zones is important when recommending sites for artificial recharge facilities because, in such zones, natural recharge flow is quickly and easily infiltrated (Scanlon et al. 2002; Cardona et al. 2004).

Most of the groundwater samples (71%) present salinity between 2,000 and 6,000 mg/l, and their compositions are affected by natural material dissolution and direct cation exchange reactions. The presence of sulfate-calcium facies, the values of gypsum saturation index, and discrimination of the factor 2 by statistical analysis suggests dissolution of evaporates within the

aquifer. On the other hand, the saturation index of calcareous materials with factor 5 confirms a significant contribution from calcite dissolution in the water.

Appelo and Postma (1993) explained that mineral dissolution and precipitation is a well-known category of chemical reactions that can have an important impact on solute concentrations. A long residence time of the groundwater in an aquifer leads to greater dissolution of the gypsum and calcite present in the aquifer and consequently influences their saturation indices.

The direct cation exchange reaction was the principal factor driving the sodium facies formation. In fresh groundwater, Ca is usually the dominant cation; the release of Na from the aquifer matrix in return for Ca or Mg present in the aquifer waters contributes to the difference in composition between the matrix material and the groundwater Na/Ca ratio (Glover 1959). The cation-exchange capacity can be related to the clay fraction, clay minerals, organic matter, and oxy-hydroxides of iron, all of which can be found in aquifer formations (Beekman 1991; Glynn and Plummer 2005).

The infiltration of irrigation return waters associated with farming practices was identified in regions with high concentrations of NO_3 (Fig. 7), corresponding to the

regions with a high score of factor 4 (Fig. 10d). Their local influence was detected mainly in the chemical composition of samples 2, 19, 30, 31, and 42.

In the northern coastal fringe, the groundwater of samples 62, 63, 64, and 65 present a salinity greater than 9,000 mg/l and a chloride facies with high values of Ca, Na, Mg, and Cl. For this group, the effect of seawater intrusion is detected through chemical facies, saturation index calculations, correlation between Cl and B, and factor analysis (factor 1 accounts for 33.24% of the variance).

The geological and hydrochemical cross section (Fig. 11) attempts to present a conceptual model to explain the relation between the geochemistry and the hydrogeological behavior of the systems. It also includes TDS, facies families, saturation indices, and the factor from the multivariate analysis.

The groundwater recharge to the aquifer mainly occurs from surface water flow from the Medasse Sidi Salah hills. Well 3 was drilled on the western border of the section in the recharge area and shows a low value of salinity (freshwater) and belongs to factor 3.

For wells 26, 27 and 43, the high values of TDS correlate with the positive saturation index of gypsum. In

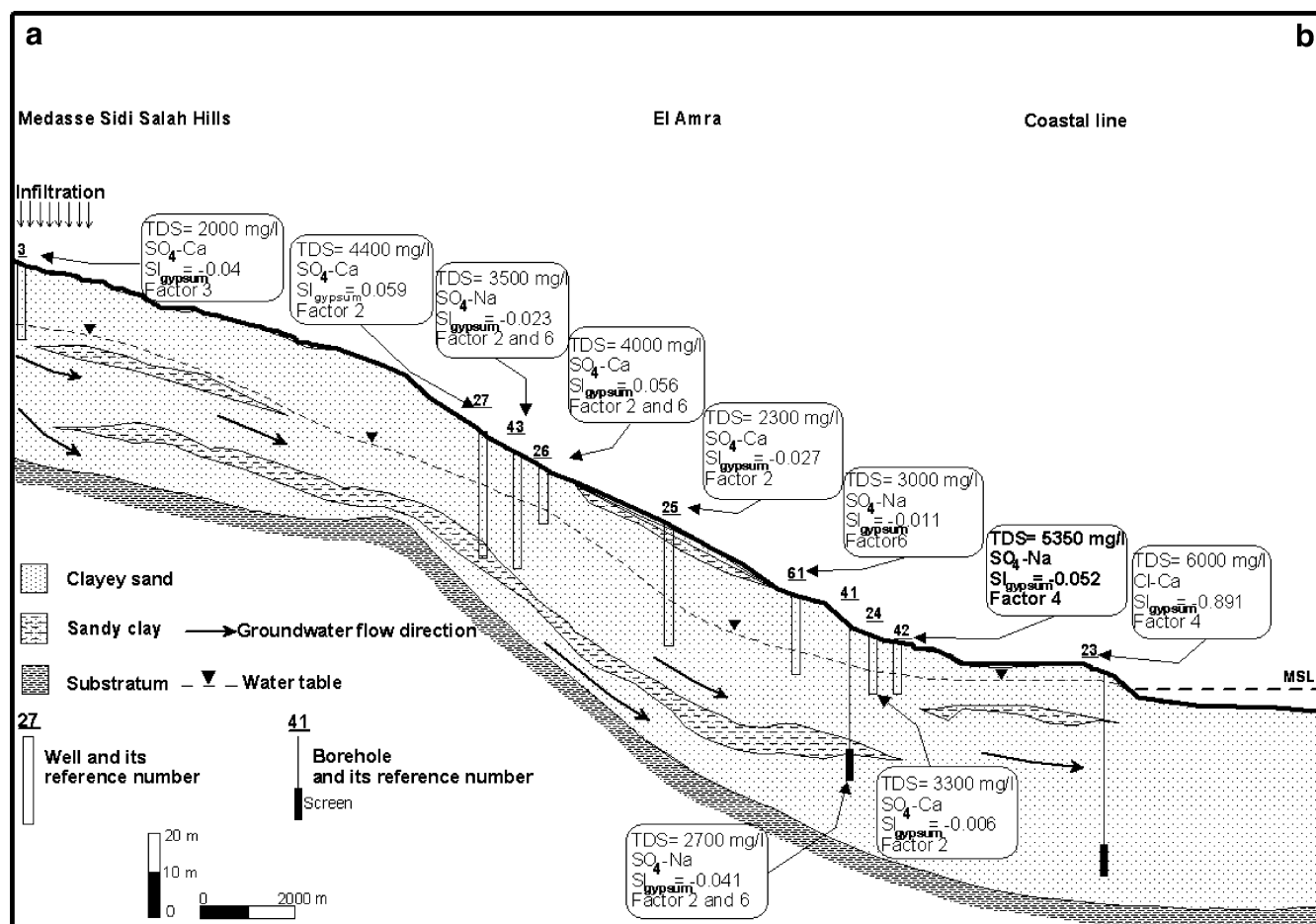


Fig. 11 Hydrogeological cross section in the study area (a–b in Fig. 7), including TDS (mg/l), chemical facies, saturation indices (SI), and factor analysis of groundwater

this location, salinization resulted mainly from evaporitic materials dissolution. Wells 42 and 23 stand out with elevated values of TDS. The sample from well 42 belongs to factor 4 of the multivariate analysis, which is related to high NO_3 values in the groundwater; the infiltration of fertilizers used in the irrigation district probably caused the high salinity in this sample. Well 23, screened at a depth of 40 m, presents a high value of salinity with chloride facies as it was located in the natural interface zone between groundwater and seawater in the coastal band.

Natural recharge in the study area is extremely limited, and is identified in the regions of Hencha-Blettech, Medasse Sidi Salah hills, and the principal temporary streams present in the south. Effects of water–rock interaction on natural water in the aquifer are evident due to the change of the water's character, confirmed by salinity value rise and chemical facies variation, as a consequence of the dissolution of the aquifer material and direct cation exchange reactions between groundwater and the clay fraction; the latter of which influences the magnitude of the process. NO_3 concentration is important in parts of this superficial aquifer, suggesting the possibility of pollution linked to agricultural activity.

In the Djebeniana region, in the northeastern part of the study area, over-exploitation during the last 20 years has resulted in the development of a drawdown cone and in the lowering of the water table to as much as 5 m below mean sea level, inducing seawater intrusion and facilitating evolution of the chemical facies to a chloride type.

Low rainfall and high groundwater withdrawal, currently associated with a pumping well density of about 100–110 wells per km^2 (compared with 30–45 wells per km^2 in the 1970s), has increased the hydraulic gradients within the drawdown cone, producing groundwater–seawater mixing. This situation increases the concentration of the displacing solutions and consequently modifies the concentration of the bivalent cations Ca and Mg (Freeze and Cherry 1979).

In the coastal zone of Djebeniana, groundwater management could be more effective if the percentage of groundwater abstraction for irrigation is reduced. To achieve this, a total water volume of $2 \times 10^6 \text{ m}^3/\text{year}$ is estimated as being needed to recharge the aquifer system from direct rainfall infiltration, streambed infiltration via flood irrigation and lateral subsurface inflows. The annual abstraction at present is $16.5 \times 10^6 \text{ m}^3/\text{year}$, thus, groundwater abstraction exceeds groundwater recharge by $14.5 \times 10^6 \text{ m}^3/\text{year}$. In order to reduce the non-sustainable groundwater usage, in 1980, the groundwater authority implemented an interdiction perimeter for new wells creation. In view of the results from this study, the enlargement of this perimeter is urgent. In addition, the need for the installation of a monitoring network for the observation of piezometric head and water quality is high, and the capital investment will be well justified. The piezometers should be multistage so that water levels and salinity can be monitored at different depths. By continuously monitoring the head and the water quality, it will

be possible to detect long-term trends and thus to devise strategies to combat the loss of fresh-water resources. For more precise knowledge of future trends and the ability to simulate different water management scenarios, computer modeling will be necessary and on-going data acquisition will be needed to calibrate and validate the data set and any predictions.

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