Assessment of groundwater salinization using PEST and sensitivity analysis: case of Zeuss-Koutine and Mio-Plio-Quaternary aquifers

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Abstract

Groundwater is the main source of water in arid regions. In the Southeast of Tunisia, Zeuss-Koutine and Mio-Plio-Quaternary underflow aquifers of Jeffara plain are considered the main source of water supply for drinking, agriculture, and industry. The study area is characterized with several known groundwater pollution sources (industrial and wastewater effluents, domestic wastes, etc.). This paper explains how sensitivity analysis can be useful tools in risk assessment of groundwater salinization. The main concern is whether the contamination sources threaten the drinking and irrigation water wells of the area. The groundwater flow and transport model of salts is set up to answer this question using MODFLOW, MT3DMS, and PEST tools. The preliminary results of the model are associated with large uncertainty. Thus, the effect of boundary conditions, dispersivity and porosity, on the migration of pollutants was investigated to estimate this uncertainty and build confidence in the model results. All variables and parameters were given a value from a range of realistic values. The sensitivity analyses show that the model is more sensitive to the salinity of the infiltrated water and the dispersivity. The results showed that the salinization process affects the areas close to the Mediterranean Sea and the Sebkha of Oum Zessar. The recharge areas have the low salinity values ranging from 1 to 2.5 g/l. High salinity reaching 3 g/l in the southeast of the Zeuss-Koutine aquifer is due to the inflow from the Triassic aquifer through Tajra fault.

Keywords Groundwater modelling · MODFLOW · Salinity · Sensitivity analysis · Zeuss-Koutine aquifer · Mio-Plio-Quaternary underflow aquifer

Introduction

Groundwater is an important source of water supply for drinking, irrigation, and industry in coastal regions (Pazand et al. 2012). Specifically, in arid and semiarid regions, groundwater salinization in coastal aquifers becomes a serious problem.

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The groundwater is highly vulnerable to natural and anthropogenic contaminants (Huysmans et al. 2006; Zammouri et al. 2014; Jarray et al. 2017a, b). Indeed, groundwater salinization is enhanced through human activities due to the intensification of industrial and agricultural activities as well as the overexploitation of groundwater resources. However, the use of groundwater has been rising steadily in the last several decades (Lachaal et al. 2012).

Numerous methods and techniques are used to study groundwater issues. However, modelling tools are commonly used to predict groundwater flow and assess groundwater quantity and quality (Anderson and Woessner 1992; Shoemaker 2004; Zammouri et al. 2007). Yet, the lack of input data of the model parameters causes uncertainties on model results (Huysmans et al. 2006). Several approaches are available to deal with parameter uncertainties. The commonly known approach is sensitivity analysis. It consists of varying calibration parameters and calculating changes in model outputs (Allen et al. 2004; Mishra et al. 2009, Abdelaziz and Merkel 2015, Jarray 2018).
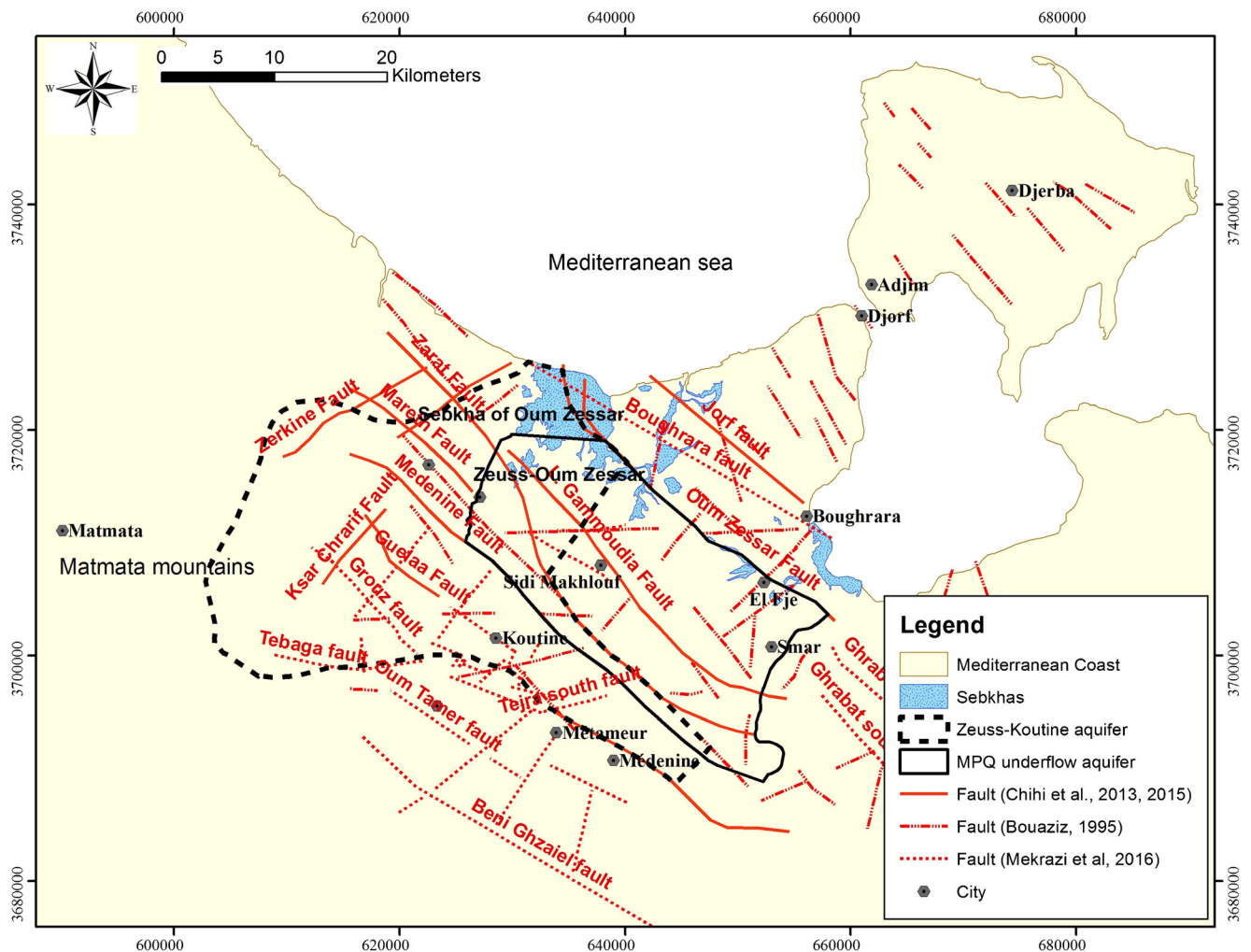
Fig. 1 Location of the study area where the black dash line for the ZK aquifer and the solid black line for MPQ aquifer (Projection: UTM WGS-84 Zone 32 N) (adapted from Bouaziz 1995; Chihi et al. 2013, 2014, 2015; Mekrazi et al. 2016)

During the last decades, the increased pumping of groundwater in the southeast of Tunisia causes many problems on both water quality and availability (Trabelsi et al. 2011; Hamzaoui-Azaza et al. 2011). In addition to the over-use, the limited resources are under the threat of seawater intrusion (Kharroubi et al. 2014) and contamination by domestic and industry wastewater effluents, and agricultural return flow, which are the potential sources of high salinities concentrations (Jarray 2018).

The study area, Zeuss-Koutine (ZK) and Mio-Plio-Quaternary (MPQ) underflow aquifers, are considered the main sources of drinking and irrigation water (Ben Baccar 1982; Gaubi 1988; Yahyaoui 2000, 2001; Hamzaoui-Azaza et al. 2011), respectively. This groundwater has changed, in terms of quantity and quality, due to the high water demand, increasing population, tourism, industry, and agriculture.

The aim of this paper is to assess groundwater salinization process using groundwater flow model and a transport model. Thus, the available hydrologic, hydrogeologic, and geologic database is analyzed for understanding the hydrodynamic and groundwater quality of the study area. MODFLOW (Anderson and Woessner 1992; Anderson et al. 1992) and MT3DMS (Zheng and Wang 1999) are used to perform objectives of this study. PEST is used to adjust the calibration parameters in the groundwater flow model.

Materials and methods

Study area overview

The study area (Fig. 1) is a part of the Jeffara plain. The climate is an arid Mediterranean type with rainfall characterized by low averages (about 200 mm/year), high irregularity in both time and space (average of 30 rainy days per year), and torrentiality (Derouiche 1997). The geology of southeast Tunisia is characterized by the presence of alternating marine and continental formations ranging from Permian to
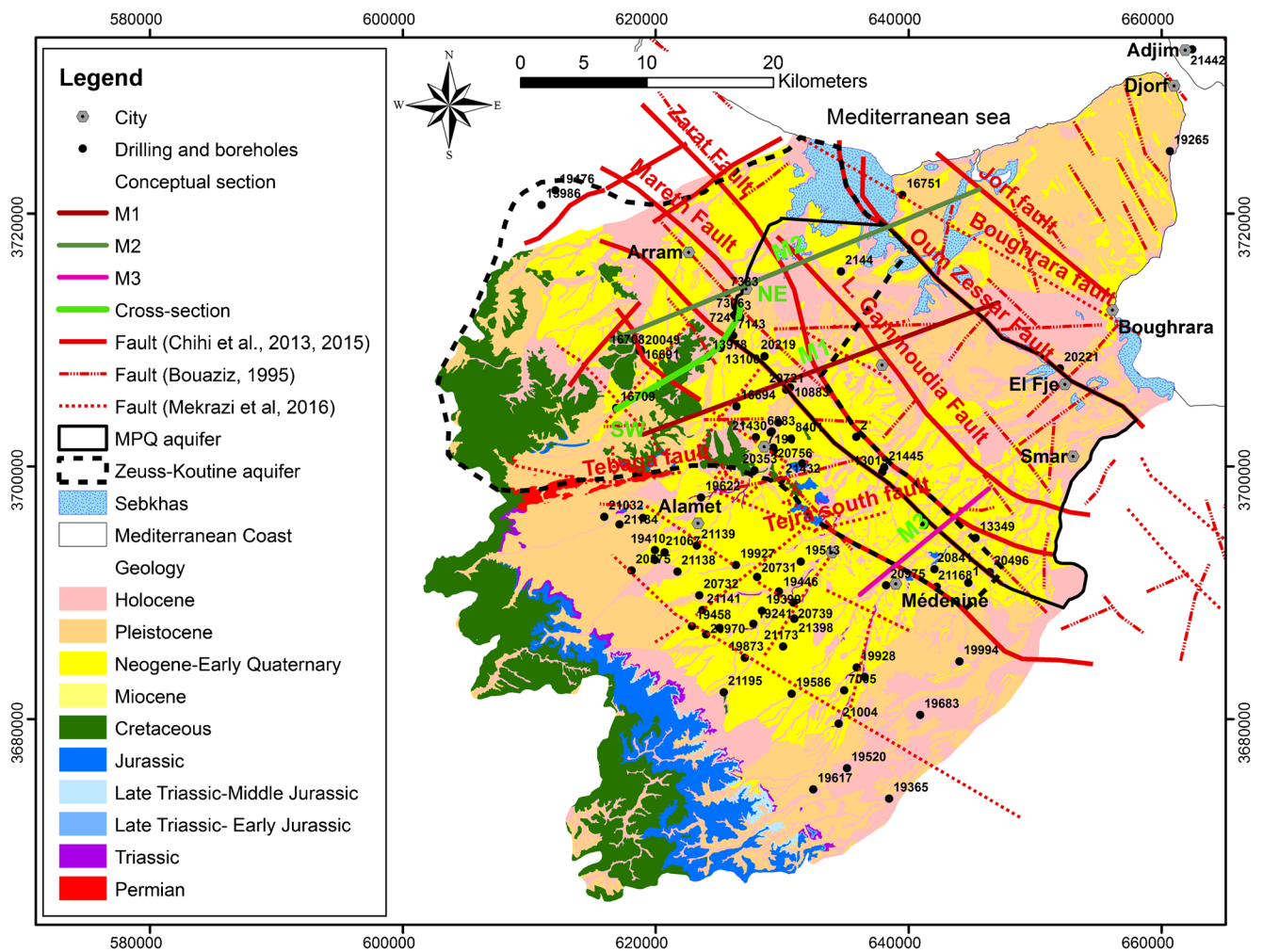
Fig. 2 Outcropping geology of the study area (Projection: UTM WGS-84 Zone 32 N) (adapted from ONM 1987, 1990, 1997; Bouaziz 1995; Chihi et al. 2013, 2014, 2015; Mekrazi et al. 2016)

Quaternary that are the consequence of marine transgressions and regressions throughout the geological history of the northern Sahara (Bouaziz 1986; Gabtni et al. 2009; Mamou 1990) (Fig. 2).

The main aquifers of the study area are the Zeuss-Koutine (ZK) aquifer and the Mio-Plio-Quaternary (MPQ) underflow aquifer.

The ZK aquifer constitutes a multilayered hydrogeological entity. The groundwater circulates throughout the Jurassic, Albo-Aptian, Turonian, and lower Senonian carbonate formations (Fig. 3) (Ben Baccar 1982; Gaubi 1988; Yahyaoui 2000, 2001). However, Jurassic is the main layer with a thickness reaching 120 m (Hamzaoui-Azaza et al. 2011). The hydraulic connection between different layers of the ZK aquifer is realized through faults of which the Medenine fault is the most important one (Ben Baccar 1982; Gaubi 1988). The ZK aquifer is bounded to the South by the Triassic sandstones through the Sidi Stout unconformity, the Grouz fault, and the Tajra fault (Yahyaoui 2007; Ben Baccar 1982). The Northern and

Northwestern limit is a hydrological limit on the watershed of wadi Zigzaou (Chihi et al. 2015). The ZK aquifer is limited to the east by the Miocene sands through several faults (Oum Zessar, Zarat, etc.) (Ben Baccar 1982).

The MPQ underflow aquifer covers maritime Jeffara of Tunisia and Libya. This aquifer is related to wadis. In this work, the studied MPQ underflow aquifer covers the downstream part of the wadis of Smar, El Fje, Sidi Makhlouf, and Zeuss-Oum Zessar (Eberentz 1976a, b; Yahyaoui 1998). It is accommodated in Mio-Plio-Quaternary filling (alluvium, sands and sandy clays of Zarzis formation) (Yahyaoui 1998). The west boundary of MPQ underflow aquifer is Medenine fault. The south and northwest boundary are the hydrological limits of watersheds of Smar and Zeuss-Oum Zessar, respectively. The northeast boundary is Oum Zessar fault separating the MPQ underflow aquifers from the Horst of Jorf (Mekrazi 1974 in Agoubi et al. 2013). This limit corresponds also to a line of Sebkha such as Oum Zessar and El Gourine.
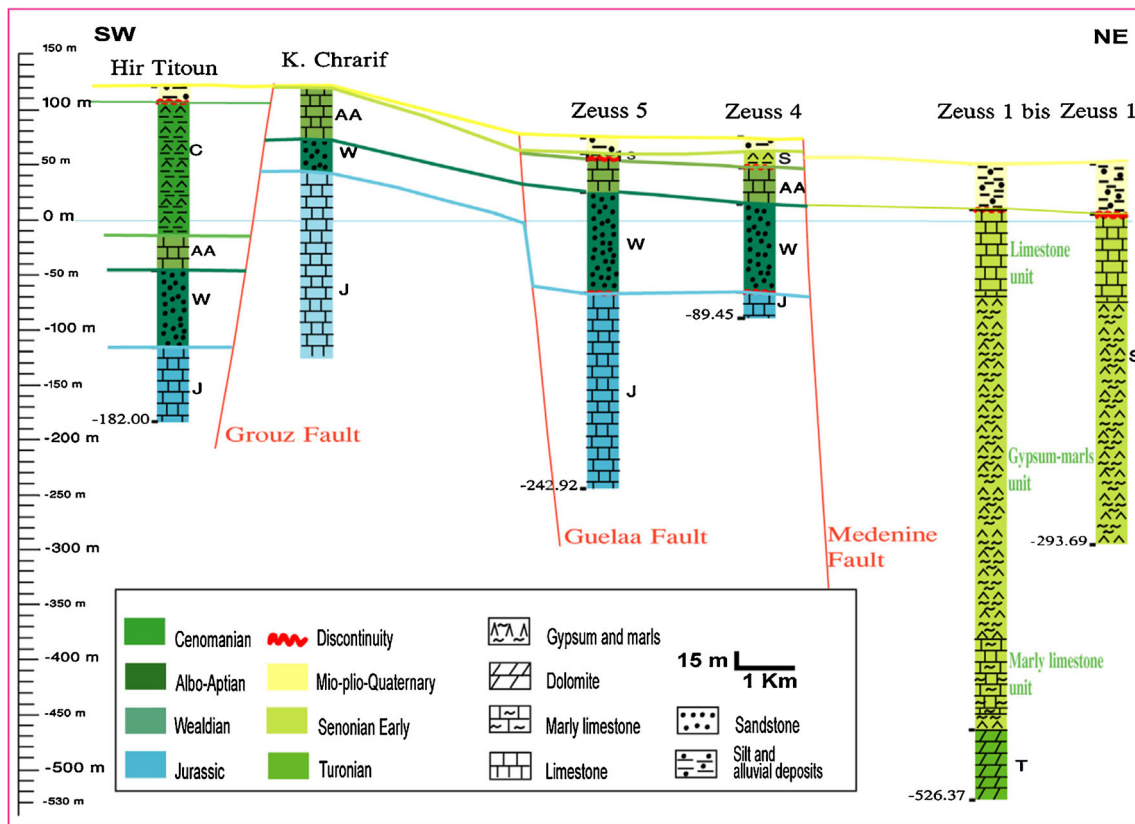
Fig. 3 Geological cross-section in the study area where the ZK aquifer is presented by the Jurassic limestone unit (blue) and the Senonian lime-stone unit (green) and the MPQ aquifer is presented by the alluvial deposits (yellow) in the NE of Medenine fault (adapted from Chihi et al. 2015) (see Fig. 2 for location)

The main sources of recharge of the ZK aquifer are the runoff from the Matmata mountains and local infiltration from several streams (Wadis of: Zigzaou, Oum Zessar, Zeuss, Sidi Makhlouf, El Morra) (Gaubi 1988; Mamou 1990; Ouessar et al. 2004). The aquifer transmissivity varies between 0.055 and 0.2 $m^2 s^{-1}$ (OSS 2005). Groundwater flow in the study area is towards the Sebkha Oum Zessar and the Mediterranean Sea (Hamzaoui-Azaza 2011). The ZK aquifer is exploited by several wells, providing water for drinking and agricultural uses. Since 1962, it contributes significantly to drinking water supply of Jerba Island and the major cities of Tataouine and Medenine' governorates. Its pumping has kept a gradual increase up to present; e.g., exploitation flow rates have increased from 206 l/s in 1977 to 277 l/s in 1987, 298 l/s in 1995, 339 l/s in 2004, 589 l/s in 2010, and 622 l/s in 2014. This resulted in a decline of the mean piezometric level and increase of water salinity in the ZK aquifer (Gaubi 1988; Haddad et al. 2013; Haddad 2015). Shallow MPQ groundwaters are often considered secondary aquifers because of their high salinity. Their contribution to the water resources of the region is relatively small. The MPQ aquifer is recharged by the direct infiltration through wadi beds (Yahyaoui 1998). In the study area, this shallow aquifer is tapped by several shallow wells used for irrigation. The evolution of the total exploitation since 1980 shows a continuous increase and reached 32 l/s in 2010 (Jarray et al. 2017b; Jarray 2018).

Groundwater modelling

In order to assess the risk of groundwater salinization, a three-dimensional finite-difference flow model was established using Processing MODFLOW (Besbes et al. 2004; McDonald and Harbaugh 1988; Chiang and Kinzelbach 1998; Harbaugh et al. 2000; Chiang and Kinzelbach 2001).

The reference year for the steady state is 1980. This choice can be justified by the availability of piezometric observations and the low groundwater abstraction in the study area.

The model domain is discretized into rectangular cells considering the full range of information collected from the study area. We have adopted a square mesh of 1000 m per side, identical throughout the whole area. It forms a grid of 59 columns and 38 rows. At each cell, we introduce the geometric and hydrodynamic parameters required for the simulation.

The structure of the hydrodynamic model includes two aquifer layers. It consists in several hydrogeological entities that are interconnected: Mio-Plio-Quaternary underflow aquifers of coastal Jeffara (Smar, El Fje, Sidi Makhlouf, and

Fig. 4 Conceptual model for the studied aquifers (ZK and Mio-Plio-Quaternary (MPQ) underflow aquifer) showing the hydraulic communication between adjacent aquifers (Triassic and Miocene sandstone); (**a**), (**b**), and (**c**) correspond to the conceptual section of M1, M2, and M3 on the location map, respectively
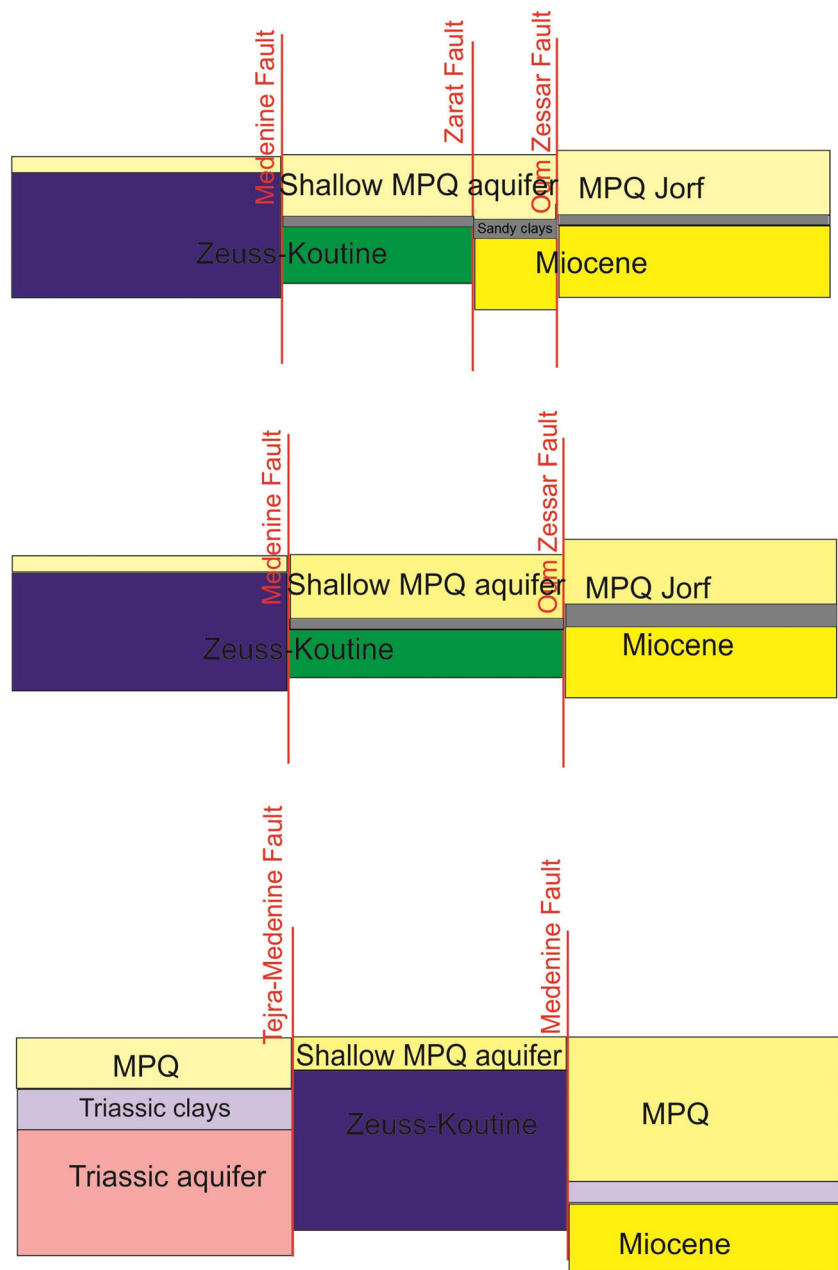
Zeuss-Oum Zessar) and the Jurassic, the Albo-Aptian, the Turonian, and Senonian aquifers of Zeuss-Koutine. The layers are separated by a semi-permeable level formed by sandy clays and marl of Miocene (Fig. 4). The thickness of the ZK aquifer is important (10 to 450 m). The thickness of MPQ underflow aquifer is from 10 to 50 m. MPQ underflow aquifer is contained in the alluvial fillings of wadis. It is unconfined over the whole surface. In addition, Zeuss-Koutine aquifer is unconfined over the whole area except in the southwest where the Jurassic layer is surmounted by a thick layer of Albo-Aptian gypsum (Fig. 2).

The MPQ underflow aquifer is recharged directly by rainfall infiltration through wadi beds (Yahyaoui 1998). The ZK aquifer is mainly recharged by infiltration of runoff from wadis Zigzaou, Zeuss, and Koutine-Oum Zessar and their tributaries and at Matmata piedmont. In addition, the groundwater flow from Triassic sandstone aquifer supplies the aquifer in the southern limit through the faults of Grouz and Sidi Stout on the front Koutine-Tejera-Medenine.

The reference piezometric map of MPQ aquifer (Fig. 5a) was performed using inverse distance weight interpolation on ArcGIS. It shows that the direction of flow is southwest to northeast. The main outlet of MPQ aquifer is the Mediterranean Sea. In addition, MPQ groundwater flows to the coastal Sebkha such as the Sebkha of Oum Zessar. The piezometric map was performed using universal kriging
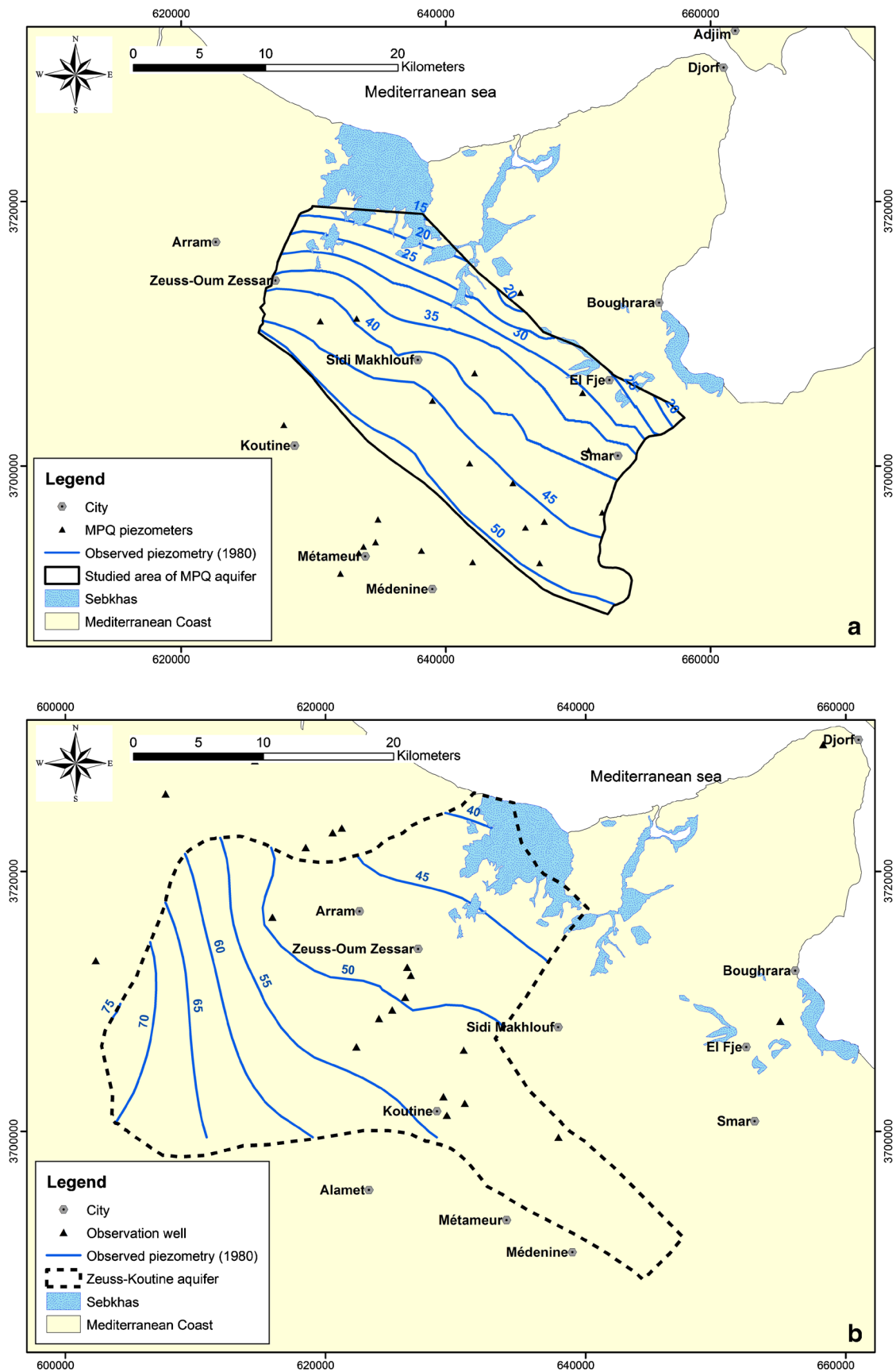
Fig. 5 Piezometric maps (meters a.s.l.) in 1980: **a** MPQ aquifer and **b** ZK aquifer

interpolation for the ZK aquifer. The experimental variogram was fitted by spherical model. The general groundwater flow is southwest to northeast (Fig. 5b). The Sebkha of Oum Zessar is the principal outlet of the ZK aquifer. An amount of groundwater of Zeuss-Koutine flows to the Miocene aquifer.

The hydrochemical surveys started in 1962 in the ZK aquifer for two wells. Nevertheless, regular observations were available since 1980s. Salinity reference maps for the study area were elaborated using inverse distance weight interpolation on ArcGIS. Maps show that the salinity increases from continent to the Sea. Zeuss-Koutine salinity map shows values ranging from 0.7 to 5.57 g/l. The high values are located at the Sebkha of Oum Zessar corresponding to the discharge area. The low values are recorded in the recharge area mainly in wadis, Koutine region and the western region. MPQ underflow aquifer shows values ranging from 2 to 6.43 g/l. The high values are observed in near the sea, which constitutes the outlet of the aquifer.

Vertically, the upper layer corresponds to the MPQ underflow aquifer. Therefore, the lower layer corresponds to the ZK aquifer.

In the first stage of the study, we proceed to the calibration of the model in the steady state. It consists of comparing the calculated piezometric results and the observed piezometry in the MPQ underflow and the ZK aquifers.

Calibration in the steady state would guarantee the consistency between the adopted transmissivity and boundary conditions. The calibration process was manual (trial and errors) and automatic using PEST (parameter estimation) (Doherty 1994, 2002, 2015; Young et al. 2010). PEST can adjust the parameters until it reduces differences between the relevant model-generated value and the corresponding field measurements (hydraulic head and salinity). PEST is integrated in Processing MODFLOW.

In the second step, the model is calibrated in transient state over the period 1981–2015. The observed piezometry is the calibration criterion. Horizontal transmissivities, storage coefficients, and leakage between MPQ underflow and the ZK aquifers are the calibration parameters. The spatial variability of transmissivity has a high influence on the dispersion of the contaminant (Zammouri et al. 2014). Accordingly, PEST was used to adjust the transmissivity and storage coefficient of the studied aquifers.

Generally, local measurements are scarce, unavailable, and irregularly distributed over the aquifers. Therefore, the interpolation between existing data was used to estimate initial parameters distribution. Transmissivity, storage coefficients, and specific yields of the ZK aquifer were extracted from pumping tests (Fig. 6). Transmissivity of MPQ aquifers were estimated from the geological data.
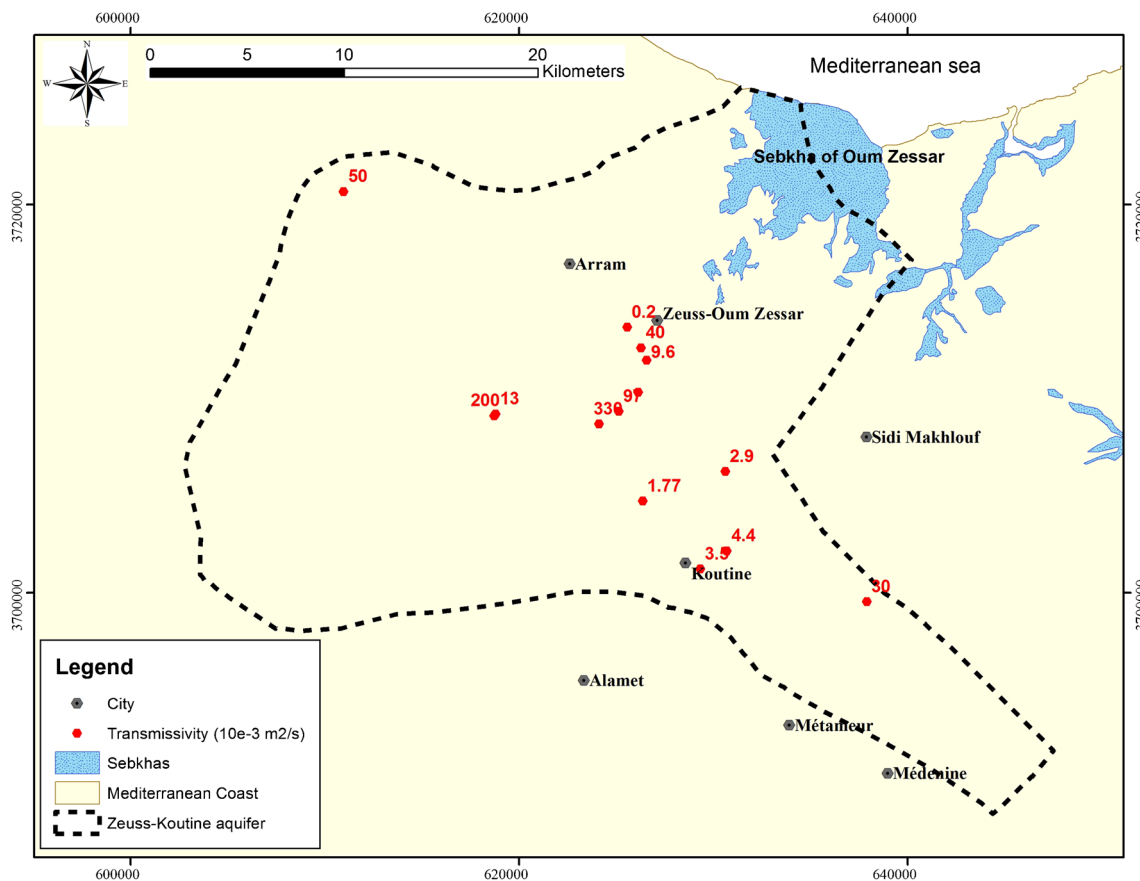

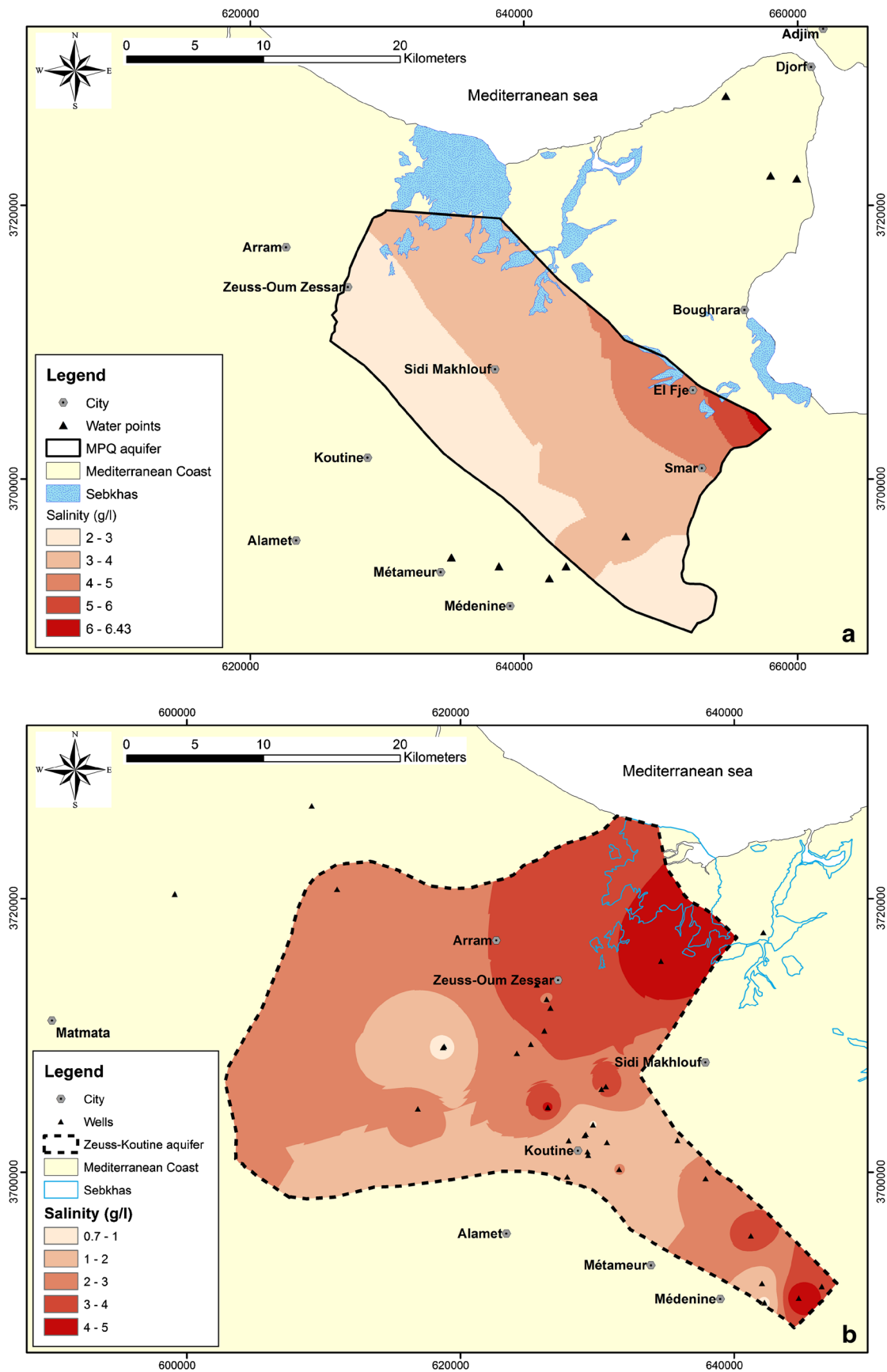Fig. 6 Distribution of transmissivity values extracted from pumping tests

Fig. 7 Distribution maps of salinity (g/l) in 1980: **a** MPQ underflow aquifer and **b** ZK aquifer

After the flow model calibration, the transport model was built by using the modular three-dimensional multi-species transport model MT3DMS (Freeze and Cherry 1979; Zheng and Wang 1999; Anderson and Woessner 1992).

The transport parameters, dispersivity and porosity, are usually derived from the permeability and lithological characteristics. These parameters are basic to calculate the effective velocity and consequently to specify the groundwater flow by convection and dispersion. Due to the lack of data, the dispersivity and the porosity are considered calibration parameters of the model. The initial salinity distribution of both aquifers in 1980 was based on available data. The MPQ underflow aquifer generally has poor quality of data. It has not benefited from significant investigations in terms of salinity measurements. The salinity measurements of the ZK aquifer around 21 values are distributed over a large part of the aquifer excluding the northeast and southwest limits. The inverse distance weight interpolation was used to produce the spatial distribution salinity maps of both layers (Fig. 7a,b). For the ZK aquifer, salinity values are reported from the drilling wells reports. The evolution of measured salinities are used to calibrate the transport model. The monitoring system includes 12 control points with three in the MPQ underflow aquifer and nine in the ZK aquifer.

The model boundaries (Fig. 8) with a drain condition correspond to the drainage by wadis and losses in Sebkha near coastal and border areas for the MPQ aquifer and the drainage by the Sebkha of Oum Zessar for the ZK aquifer. The specified flow (Neumann condition) represents direct infiltration of precipitation in permeable zones, infiltration of floods in the wadi beds, and pumping rates for MPQ underflow aquifer. Furthermore, it represents the direct recharge of precipitation in the ZK aquifer. It is adopted equivalent to 2.42% of precipitation (Pallas et al. 2005); this value is previously used for the Tunisian-Libyan Jeffara (Ould Baba Sy 2005). The direct recharge applied to Matmata, where permeable formations of Turono-Senonian Matmata are outcropping, corresponds to 35% of the rainfall received by the area (Haddad 2008). In

Table 1 Results of hydrodynamic calibration: observed and calculated hydraulic head (m)

Observation	Observed	Measured	Sensitivity	Aquifer
1	52.5	52.67948	− 0.17948	ZK
2	52.92	53.69443	− 0.77443	ZK
3	52.5	50.71021	1.78979	ZK
4	53.5	52.69199	0.80801	ZK
5	52.5	52.5431	− 4.31E−02	ZK
6	53.47	53.3856	8.44E−02	ZK
7	54.57	53.38442	1.18558	ZK
8	53.47	52.952	0.518	ZK
9	53.75	50.88683	2.86317	ZK
10	50.8	48.41336	2.38664	ZK
11	50	48.28358	1.71642	ZK
12	50	48.28474	1.71526	ZK
13	45.73	48.25008	− 2.52008	ZK
14	53.59	51.84437	1.74563	ZK
15	51	52.09256	− 1.09256	ZK
16	53.7	53.10638	0.59362	ZK
17	42.2	47.25928	− 5.05928	MPQ
18	49	49.0228	− 2.28E−02	MPQ
19	45	45.54773	− 0.54773	MPQ
20	46.5	47.22641	− 0.72641	MPQ
21	38.5	39.49604	− 0.99604	MPQ
22	45.2	46.38027	− 1.18027	MPQ
23	46.5	46.69515	− 0.19515	MPQ
24	47.5	47.55073	− 5.07E−02	MPQ

addition, the specified flow represents flood infiltration in wadis estimated to 30% of the runoff volume (Besbes 2010) and spread over some kilometers for wadi Zigzaou (22 cells), Zeuss (20 cells), Oum Zessar (26 cells), and Sidi Makhlouf (seven cells) (Besbes 2010). The pumping rates are represented as discharge wells. The general head boundary conditions represents the lateral inflow from southern boundary of MPQ underflow aquifer (Hezma aquifer), the lateral outflow, to the
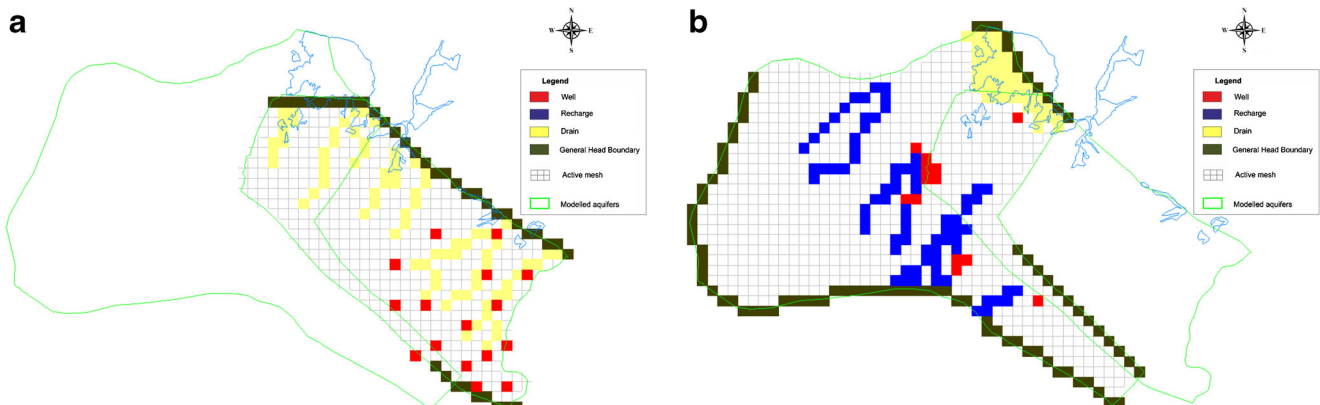
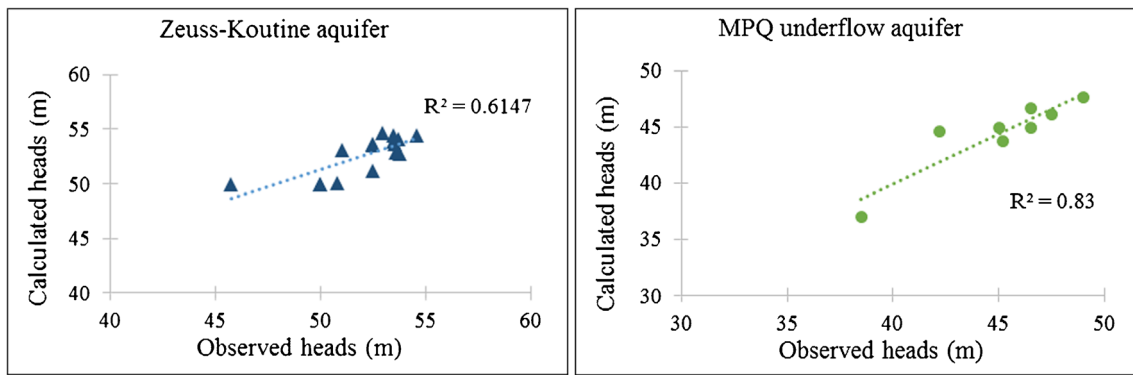**Fig. 8** Boundary conditions of **a** MPQ underflow and **b** ZK

Fig. 9 Correlation between the calculated and the measured piezometry (m) in steady state of the observation wells of both aquifers

northeastern boundary of MPQ underflow aquifer (Jorf aquifer). Additionally, the general head boundary conditions represent the lateral inflow to the ZK aquifer from the Triassic aquifer and the southern limit of Gabes aquifer, thanks to

Grouz, Tejera, and Medenine faults at the southern boundary of the modeled area.

Results and discussion

In order to calibrate the model in steady state, several simulations were performed by changing the transmissivity values manually. The modeled area was subdivided into several zones with uniform value based on geological setting for the MPQ aquifer and on extracted values from pumping tests for the ZK aquifer. The results in this stage are not coherent, and the reference piezometric map is not obtained for both aquifers. The calibration was performed using the PEST inverse modelling software package on PMWIN. The software performs many simulations during which it varies the calibration parameters to approach, by calculation, the values of the piezometric levels of the piezometers defined as references in PMWIN.

To do this, it is enough to indicate to the software the ranges of variation of the values of the calibration parameters. For the ZK aquifer, the minimum value is of 10^{-4} m²/s, and the maximum value corresponds to 0.3 m²/s. For MPQ underflow aquifer, the minimum value is of 10^{-4} m²/s, and the maximum value corresponds to 5×10^{-2} m²/s. The transmissivity values obtained from manual and automatic calibration vary from 10^{-5} to 0.5 m²/s for MPQ underflow aquifer and from 6×10^{-5} to 0.06 m²/s for the ZK aquifer.

Table 1 shows the differences between measured and calculated values simulated using PEST.

The comparison of the observed and calculated piezometric values in 1980 shows an acceptable model calibration with a correlation coefficient (R^2) of 0.61 and 0.83 (Fig. 9), respectively, for the MPQ underflow and the ZK aquifers, respectively. The root mean square error (RMSE) of ZK aquifer is 1.51 m, and the RMSE of MPQ aquifer is 1.89 m. The average of absolute residuals of ZK aquifer is 1.25, and the MAD of the MPQ aquifer is 1.1. Both aquifers have low RMSE and the average of absolute residuals, so we consider that the calibration is acceptable.

Table 2 The water balance calculated for 1980 and 2015 according to the flow model (l/s)

	1980	2015
Zeuss-Koutine		
Inflow (l/s)		
Recharge	63	63
Triassic aquifer supply	137	285
Gabes South aquifer supply	187	240
Exchange ZK	100	114
Reserves depletion	-	60
Total	487	762
Outflow (l/s)		
Exploitation	248	640
Drain	12	3
Outflow to Miocene and sea	80	64
Exchange ZK	144	20
Flow to MPQ aquifer	3	35
Total	487	762
MPQ underflow		
Inflow (l/s)		
Recharge	36	36
Flow from Hezma aquifer	108	141
Exchange MPQ	108	-
Reserves depletion	-	140
Total	252	317
Outflow (l/s)		
Exploitation	22	115
Drain	161	112
ET	4	4
Flow to Jorf aquifer	58	45
Exchange MPQ	7	41
Total	252	317
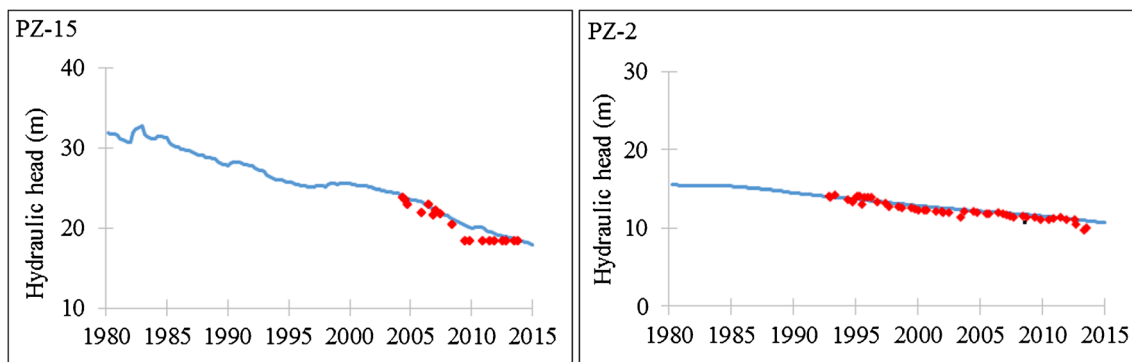
Fig. 10 Temporal reproduction of piezometry (1981–2015) in two selected observation wells of MPQ underflow aquifer. Straight line corresponds to calculated values, and measured values are marked by filled symbols

The calibration of storage coefficient values was performed using the PEST inverse modelling software package on PMWIN. For the ZK aquifer, the minimum value is 10^{-5}, and the maximum value is 0.5. For the MPQ underflow aquifer, the minimum value is 10^{-6}, and the maximum value is 0.006. In some cases, the results of calibration are not good to reproduce the piezometric fluctuations measured in observation wells. Consequently, we use manual calibration. The calculated piezometry values over the period 1981–2015 are well correlated to the observed ones for most piezometers (Figs. 10 and 11). The increase of pumping rates over the period 1981–2015 leads to a decrease in natural flows. Indeed, the flow to the Mediterranean Sea and the outflow to Miocene sands decrease from 80 l/s in 1980 to 64 l/s in 2015 (Table 2). Drainage by wadi and Sebkha is decreased from 12 l/s in 1980 to 3 l/s in 2015 for the ZK aquifer and from 161 l/s in 1980 to 112 l/s in 2015 for MPQ underflow aquifer (Table 2).

The groundwater model was used to assess the impact of long-term exploitation on groundwater piezometry. For this purpose, model simulation was extended to the year 2050 with various scenarios. In the first scenario, current abstraction was maintained in the study area. The drawdown will reach 7 m for MPQ underflow aquifer in 2050. The highest drawdown values are located near the urban area where the exploitation rates are relatively high. For ZK aquifer, the drawdown reaches 24 m in 2050 and it increases from the southwest to

the northeast of the aquifer. For the second scenario, regarding the water demand increase for domestic, agriculture and industrial use, we suppose that the exploitation will rise twice times each 20 years over the period 2015−2050. The MPQ layer drawdown will reach in 2050 a maximum of 9 m in Sidi Makhlouf area. The high ZK aquifer drawdown will reach 24 m near the Sebkha of Oum Zessar.

Concerning the transport modelling, the porosity was firstly assigned to 0.1 for both aquifers. The initial salinity values were introduced from interpolated salinity maps of 1980 (Fig. 7). Near the coastal limits, the salinity was adopted to 10 g/l corresponding to averaged observation values. Calculated longitudinal dispersivity varies between 200 m and 2000 m in the coast. The obtained initial concentration state over 100,000 years was not coherent with reference salinity maps.

The limited data availability and the several simplifications and assumptions about parameter values and boundary conditions has great consequences on the accuracy and the reliability of the model results. To check the impact of each calibration parameter, a sensitivity analysis is carried out for the effective porosity of both aquifers, the dispersivity values, the transverse dispersion coefficient α_T, the longitudinal dispersion coefficient α_L and the vertical dispersion coefficient α_V, and the salinity of recharge. It consists of varying input parameters and evaluating how model results change with values variations. The sensitivity analysis serves to understand
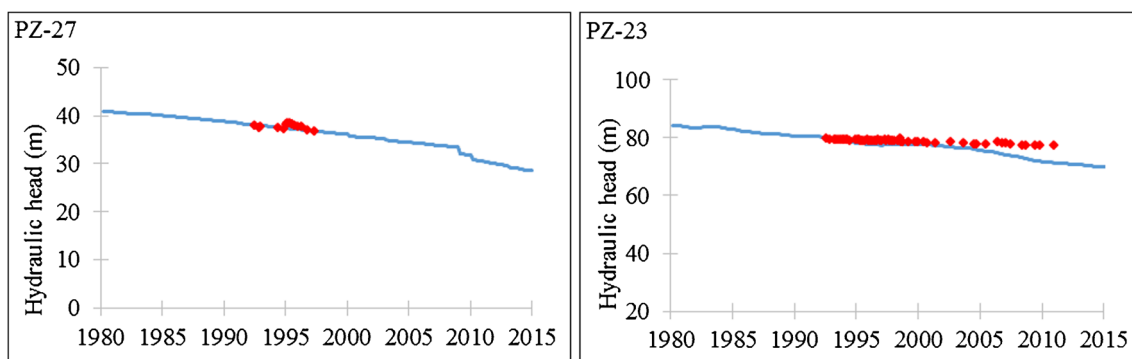
Fig. 11 Temporal reproduction of piezometry (1981–2015) in two selected observation wells of the ZK aquifer. Straight line corresponds to calculated values, and measured values are marked by filled symbols

Table 3 Parameter values during simulation performed for sensitivity analysis

| Parameters	Unit	Test 1		Test 2		Test 3		Test 4	
		MPQ aquifer	ZK aquifer	MPQ aquifer	ZK aquifer	MPQ aquifer	ZK aquifer	MPQ aquifer	ZK aquifer
ne	%	1	1	50	50	1	1	50	50
α_L	m	100	100	100	100	100	100	100	100
α_T	m	10	10	30	30	30	30	30	30
α_V	m	2.5	2.5	2.5	2.5	10	10	10	10
Dispersivity	m	200	200	200	200	2000	2000	2000	2000
Recharge (min)	g/l	1	1	1	1	1	1	1	1
Recharge (max)	g/l	8	8	8	8	8	8	8	8

the model implementation. The comparison of the obtained maps after simulation makes it possible to estimate the sensitivity of the model to the variation of each parameter. The values assigned to the parameters for each simulation are presented in the Table 3.

The analysis of the curves of equal concentrations shows that the variation of the parameters does not have the same influence on the evolution of the plume of salinity and therefore on the concentrations. Actually, the variation of α_T (test1/test 2) has no influence on the obtained concentrations. The salinity plumes of tests 1 and 2 have the same overall shape and concentration values. Also, for tests 3 and 4, we obtain the same results of calculated salinities. Therefore, the model is not sensitive to porosity parameter. The gradient is slightly larger for the maximum dispersion values, but the calculated salinity has slightly increased in the direction of flow than in the case of minimum values. The variation of the salinity of the recharge gives the greatest difference in the form and extension of the plume. These results are observed between all

tests corresponding to the values of the strongest and weakest dispersivities. The higher value of the salinity of recharge reflects the greater impact to the overall model output. For example, for test 2, the model results are highly affected by the salinity of recharge (Fig. 12 and 13).

Therefore, the dispersion and salinity of the recharge parameters have a predominant role in the evolution of the salinity plume. It would be very interesting to carry out field measurements in order to better constrain the model and to improve its prediction of salinity. Six control points were selected to monitor aquifers salinities over the period of 1981–2015 (Fig. 14).

Figures 15 and 16 show the obtained salinities in the selected control points over the period 1981–2015. The transport model shows that the natural salinization processes close to the Mediterranean Sea and the Sebkha of Oum Zessar. The salinity reaches 7 g/l in the Sebkha of Oum Zessar. The recharge areas of the aquifers (the mountainous area of Beni Khedache, wadi beds) have the lowest salinity values.
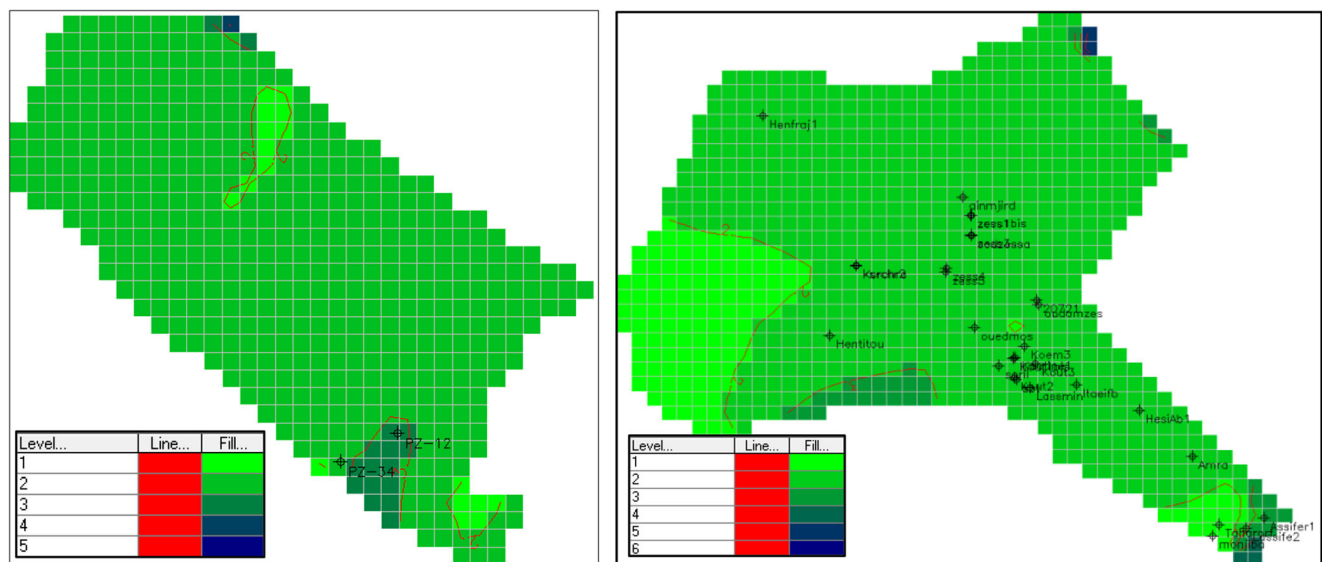
Fig. 12 Distribution map of salinity corresponding to test 2 (salinity of recharge min) for the studied aquifers
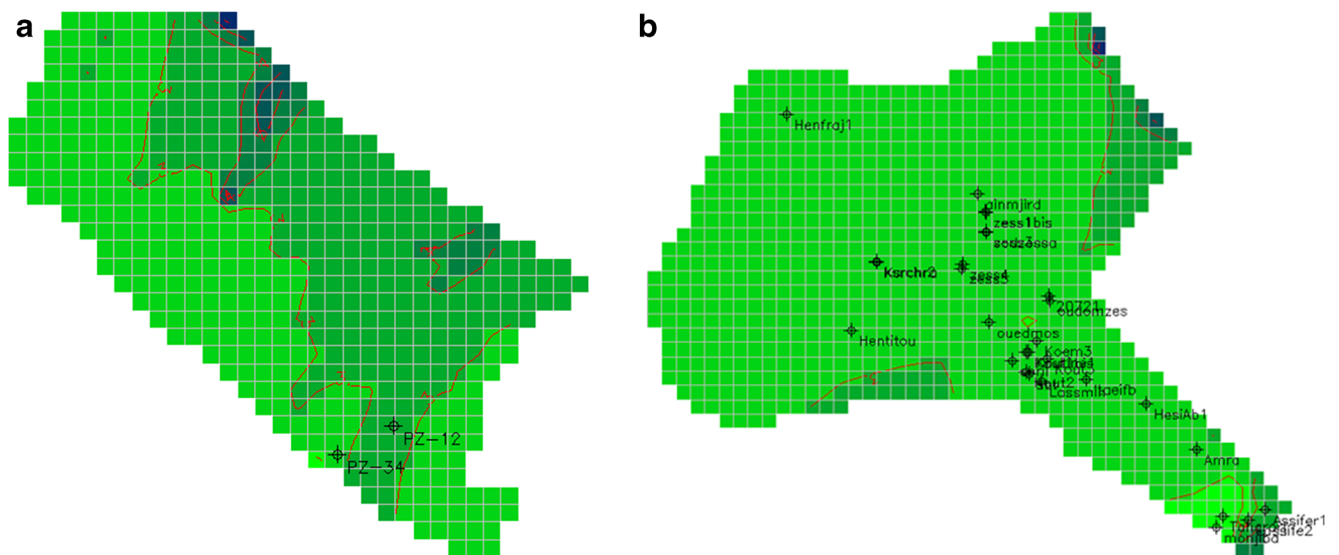
Fig. 13 Distribution map of salinity corresponding to test 2 (salinity of recharge max) for the studied aquifers

Conclusions

The exploitation in the ZK and MPQ underflow aquifers had hugely increased between 1980 and 2015. A groundwater flow model and transport model were installed, using the coupling of MODFLOW and MT3DMS, to predict the future conditions of groundwater. The inverse modelling using PEST improved the calibration. The implemented groundwater flow model shows a decline in piezometry levels. The first scenario, targeting to conserve the pumping rates over the next
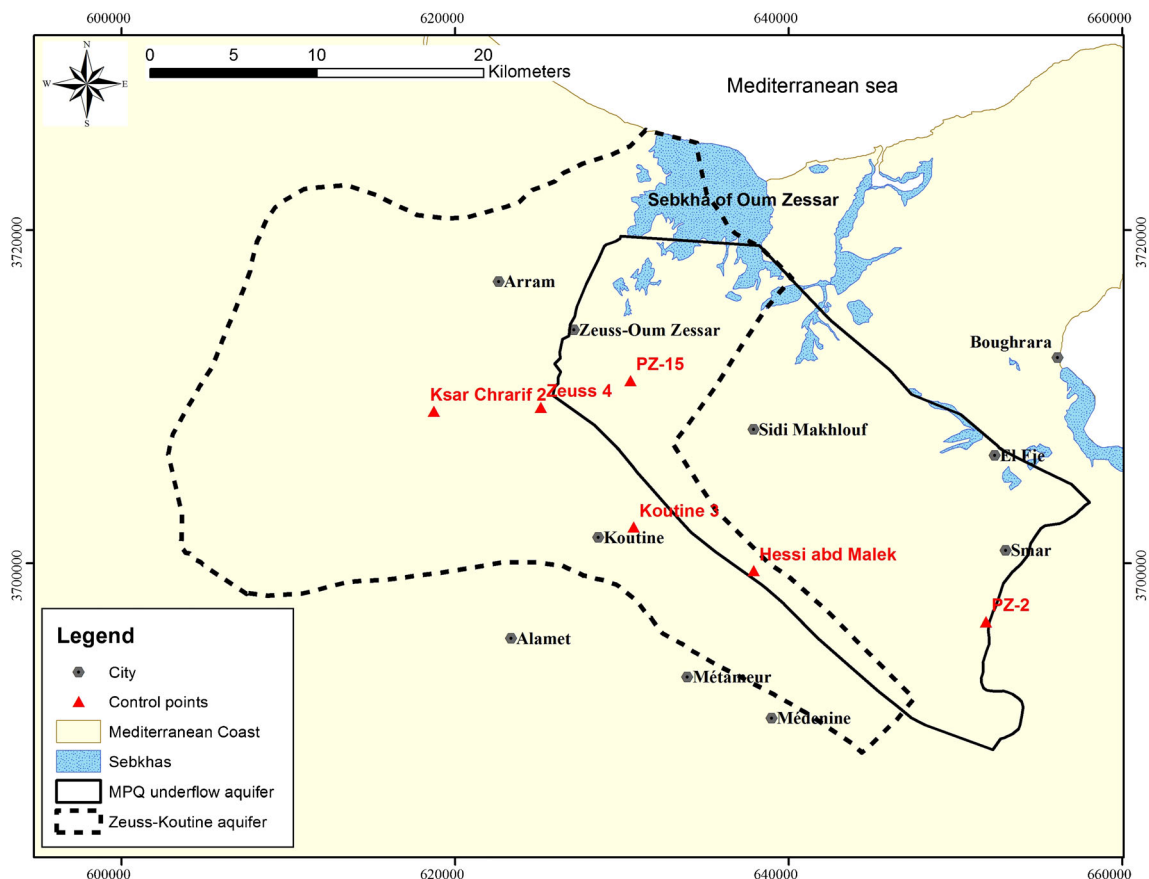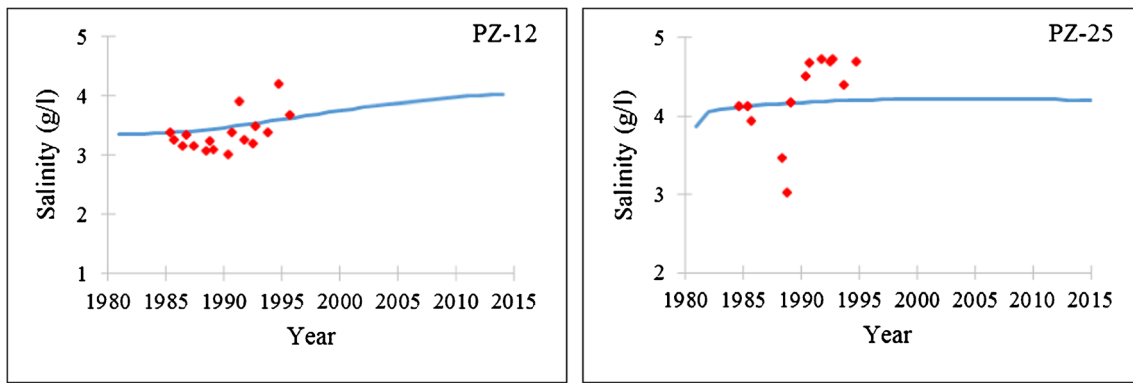

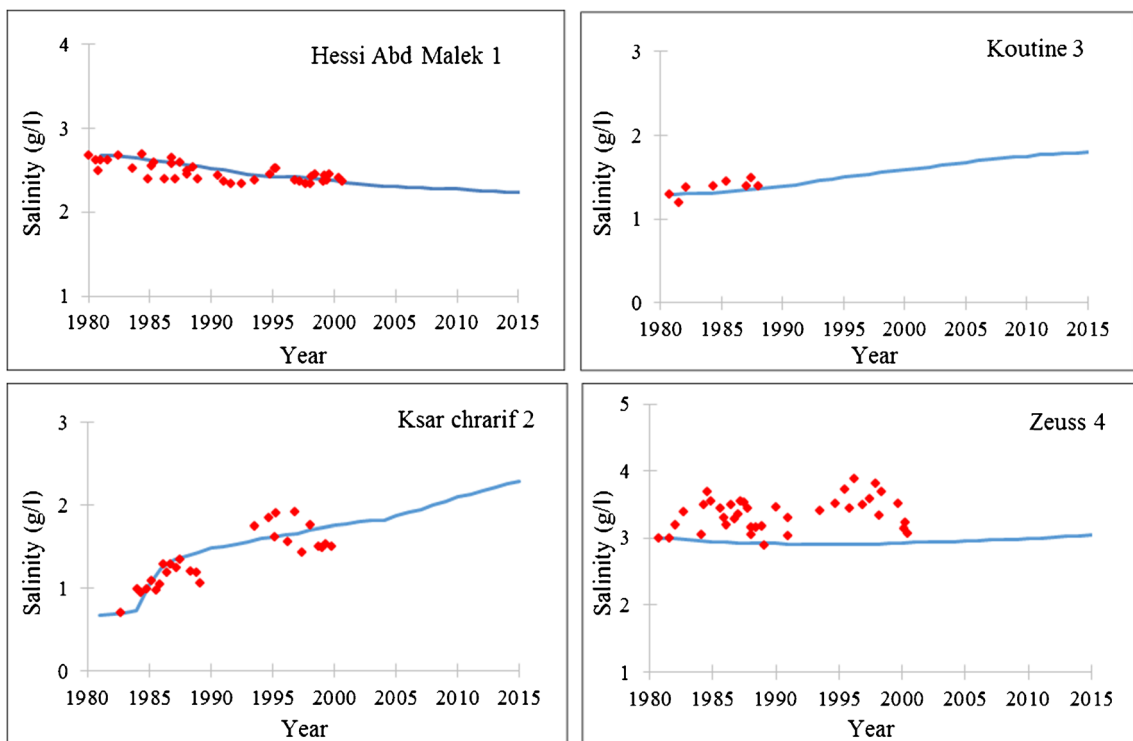**Fig. 14** Map of the control points location

Fig. 15 Temporal reproduction of salinity (g/l) (1981–2015) in two selected observation wells of MPQ underflow aquifer. Straight line corresponds to calculated values, and measured values are marked by filled symbols

35 years, shows that the drawdown reaches 7 m for MPQ underflow aquifer and 24 m for the ZK aquifer. The second scenario, doubling the pumping rates over the next 35 years, shows that the drawdown reaches 9 m for MPQ underflow aquifer and 24 m for the ZK aquifer.

The transport model showed that the salinization process affects the areas closes to the Mediterranean Sea and the Sebkha of Oum Zessar. The recharge areas have the low salinity values ranging from 1 to 2.5 g/l. High salinity reaching 3 g/l in the southeast of the ZK aquifer is due to the inflow from the Triassic aquifer through Tajra fault.

The available data are insufficient to rebuild exactly salinity distribution.

Despite the data lack concerning the geometric characteristics, the hydrodynamic properties of the ZK and MPQ underflow aquifers, and the precise rates of pumping discharges, the hydrodynamic flow model provides an acceptable restitution of the piezometric state. It can serve as a basis for development and management plan of water resources in the studied aquifers. In fact, this study has shown that sensitivity analysis is a suitable tool to deal with uncertainty in flow and transport modelling in case of limited data availability.

Fig. 16 Temporal reproduction of salinity (g/l) (1981–2015) in four selected observation wells of the ZK aquifer. Straight line corresponds to calculated values, and measured values are marked by filled symbols

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