

3D simulation of a multi-stressed coastal aquifer, northeast of Tunisia: salt transport processes and remediation scenarios

Anis Chekirbane · Maki Tsujimura ·
Atsushi Kawachi · Hiroko Isoda · Jamila Tarhouni ·
Abdallah Benalaya

Received: 6 January 2014 / Accepted: 27 June 2014 / Published online: 24 July 2014
© Springer-Verlag Berlin Heidelberg 2014

Abstract A salinization of groundwater by oilfield brine and seawater intrusion was detected in the plain of Wadi Al Ayn and Darouda in CapBon, northeast of Tunisia. The objective of this work is to simulate the historical trends of saltwater distribution in the study area and to predict its future dynamics under some proposed countermeasures for remediation. Based on the developed model with SEAWAT, the oilfield brine plume needs at least 5 years to be naturally reduced to less than the half of its actual size, while the seawater–freshwater interface can reach an inland extent of 1.3 km with a TDS of 10 g/L if no countermeasures will be taken until the next three decades. The tested remediation plan by model demonstrated that the artificial recharge with treated wastewater is the best solution to stop seawater intrusion just after 2 years of percolating 1 m/day with TDS of 1.5 g/L of recharge

water. The natural remediation of the oilfield brine plume can be enhanced by imposing optimized pumping rates and installation of a restricted pumping perimeter.

Keywords Salinization · Numerical simulation · SEAWAT · Remediation · Coastal aquifer

Introduction

Groundwater salinization is a major concern in arid and semi-arid regions. In fact, freshwater stored in coastal aquifers is particularly susceptible to degradation due to its proximity to seawater in addition to its vulnerability to numerous salt waste derived from industrial activities and higher population densities. It was shown that density contrast has a significant effect on the spatial distribution of contamination in coastal aquifers (Simmons et al. 2001). Understanding the dynamics of interaction between saltwater bodies and fresh groundwater could allow better strategies to control and well manage the stressed aquifers. The best management of salinized aquifers suggests a deep knowledge of this process. Traditional hydrodynamic and hydrochemical investigations are not sufficient to understand the saltwater dynamics. Thus, more efficient techniques are needed to identify and clearly delineate the freshwater–saltwater interactions, such as modeling procedure (Saidi et al. 2013).

Density-driven groundwater flow models are being increasingly used to solve scientific, engineering and water resources management issues such as saltwater intrusion, contaminated site remediation and fresh groundwater discharge into oceanic water bodies (Guo and Langevin 2002). Several simulations models of density-dependent groundwater flow were developed like SUTRA (Voss

A. Chekirbane (✉)
Water Researches and Technologies Center (CERTE), Borj Cedria Technopark, BP 273, 8020 Soliman, Nabeul, Tunisia
e-mail: anischkirbene@gmail.com

M. Tsujimura
Faculty of Life and Environmental Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8577, Japan

A. Kawachi · H. Isoda
Alliance of Research of North Africa (ARENA), University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8577, Japan

J. Tarhouni
National Agronomical Institute of Tunisia (INAT), University of Carthage, 43, Avenue Charles Nicolle, 1082 Mahrajène city, Tunis, Tunisia

A. Benalaya
Higher School of Agriculture of Mograne (ESAM), University of Carthage, 1121 Mograne, Zaghouan, Tunisia

1984), MOCDENS-3D (Sanford and Konikow 1985), FEMWATER (Lin et al. 1997), CODESA-3D (Lecca 2000) and SEAWAT (Guo and Langevin 2002). SEAWAT code has shown efficiency in simulating several related variable density groundwater flow problems like seawater intrusion into coastal aquifers (e.g. Qahman and Larabi 2006; Jin et al. 2009; Cobaner et al. 2012), saltwater intrusion from ephemeral rivers (Bauer et al. 2006), submarine groundwater discharge (Langevin 2003), brine transport (Mastrocicco et al. 2012) and groundwater flow near salt domes (Bakker et al. 2004).

In Wadi Al Ayn and Daroufa plain, which is located in CapBon peninsula in northeast of Tunisia (Fig. 1), a sudden increase in groundwater salinity was registered since

2002. Nevertheless, the origin and processes of groundwater salinization are still poorly understood. Salinization of groundwater in this zone is a spatially and temporally variable phenomenon which is depending from different salt sources, especially the infiltrated oilfield brine near Wadi Al Ayn and the intruded seawater in the coastal part near Wadi Daroufa. It constitutes one of the rare cases of multi-salt contamination sources and it opens perspective to observe the system reaction to such complex pollution (Chekirbane et al. 2013). The study area was subject of a multi-disciplinary study including hydrodynamic, hydrochemical and geophysical investigations which constitute important inputs for the numerical simulation. The objective of the present study is to simulate the historical trends

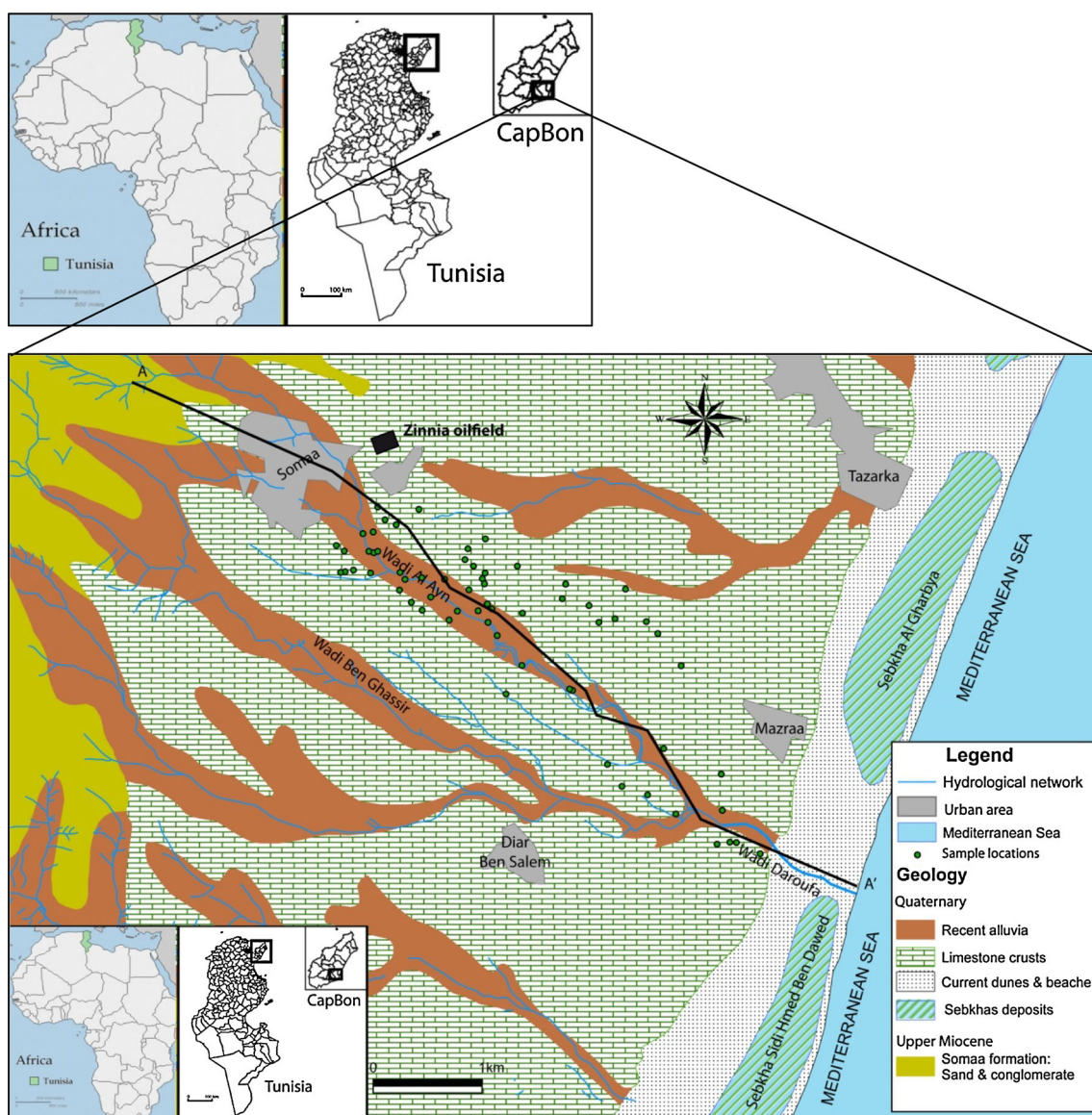


Fig. 1 The location map of the study area showing the sample locations and the regional geology (extracted and modified from the geological map of Nabeul Prefecture)

of saltwater distribution in the groundwater flow system of Wadi Al Ayn and Daroufa plain and to predict its future dynamics under some proposed countermeasures for remediation.

Study area

The study area is the plain of Wadi Al Ayn and Daroufa, a coastal floodplain located in the southeastern part of Cap-Bon peninsula, northeastern of Tunisia (Fig. 1) which is known as one of the most touristic, industrial and agricultural productive zones in Tunisia with a contribution of 15 % (CCI CapBon 2011). Since 2000s, farmers were claiming a decreasing in their production because an increased groundwater salinity. In fact, some water wells were abandoned and consequently farming activities of their owners were stopped leading to an additional jobless and financial problem in the region. The study area is situated in the vicinity of the Zinnia oilfield concession which has been exploited since 1994. Oil production is accompanied by water with high salinity called oilfield brine. In fact, petroleum-bearing formations usually contain brine (altered seawater trapped in sediment pores). Large volumes of brine usually accompany oil and gas production. High chloride concentrations commonly characterize oil-field pollution of groundwater. Brine can be toxic to crops, corrosive to metal, and unsafe to drink (Hudak and Wachal 2001). Since the beginning of exploitation of Zinnia oilfield in 1994 until its end in late 2009, the separated brine from oil are directly rejected via a pipeline in the sandy bed of Wadi Al Ayn without any treatment (Chkirbene 2008). Therefore, the groundwater flow system of Wadi Al Ayn and Daroufa plain might be under a stress caused by overexploitation as well as contamination from multiple salinization sources.

Hydrogeologic characterization of the groundwater flow system of Wadi Al Ayn and Daroufa

Geological settings

The outcropping formations in the oriental coastal plain of CapBon are mainly Mio-Plio-Quaternary sediments (Ben Salem 1992). The simplified lithostratigraphic column of Wadi Al Ayn plain is mainly composed by Quaternary, Upper Miocene and Middle Miocene.

Figure 1 shows the geological map of the study area. The upstream region of Al Ayn plain, western Somâa City, is composed by the Upper Miocene which corresponds to Tortonien geological age known in Tunisia as Somâa formation, a detrital continental sediments mainly composed

by an alternation of sand and conglomerates with frequent clay lenses resulting from the erosion of the top of the anticline of Abderrahmen Mountain (Colleuil 1976).

The lower part of Middle Miocene is composed of lenticular sandstones and marls with lignite levels belonging to the geological age of Serravalian–Tortonian, called in Tunisia as Saouaf formation (Kouzana et al. 2010). In contrast to the neighboring northern area, Pliocene outcrops do not exist in the study area and that was believed because of the widespread of erosion during the Miocene orogeny (Ennabli 1980). Sedimentary discontinuity is characterizing the deposit of Quaternary sediments above Upper Miocene formation (Ben Salem 1992). The coastal consolidated sandy dunes from Tyrrhenian are outcropping in northern Tazarka city with a width of 1–2 km, an altitude which can reach 30 m and a thickness varying between 10 and 50 m (Zghibi et al. 2011). However, these dunes are disappearing near Daroufa region where they are buried beneath the outcropping Wadi alluvia and found in a depth around 100 m as it is shown in an established longitudinal cross section A–A' along Wadi Al Ayn and Daroufa (Fig. 2) based on a performed geophysical survey in April 2011 (Chekirbane 2013) and some available boring data.

Quaternary outcrops consist mainly in encrusted limestone largely extended and rich in calcite, silica, sometimes in gypsum and alumina and frequently colored by iron salts (Kouzana et al. 2010). They are also represented by the Holocene deposits which are formed by recent alluvia observed near Wadi Al Ayn, Wadi Daroufa, Sebkha Al Gharbya and current dunes and beaches.

Hydrogeological settings

The regional hydrogeology of the coastal oriental aquifer of CapBon was studied by numerous previous works. Several studies focused mainly in understanding the flow and hydrological budget of the regional groundwater flow system (Rouatbi 1968; Ennabli 1980; Rekaya 1989; Jemai 1996; Khlaifi 1998; Paniconi et al. 2001; Kerrou 2008; Zghibi et al. 2011; Trabelsi et al. 2013). Some others have dealt with characterizing the qualitative degradation of the aquifer caused by seawater intrusion (Kouzana et al. 2009; Slama 2010; Ben Hammouda et al. 2011). All the mentioned authors focused exclusively on regional groundwater flow; there was no previous works which studied small scale groundwater flow and contamination. The hydrogeological basin of Wadi Al Ayn covers an area of 20 km² located in the southwest of the large coastal plain of CapBon which has a total area around 400 km².

In Al Ayn plain, the Quaternary sediments and the top layers of the Upper Miocene are hosting a significant shallow aquifer used principally for irrigation and drinking

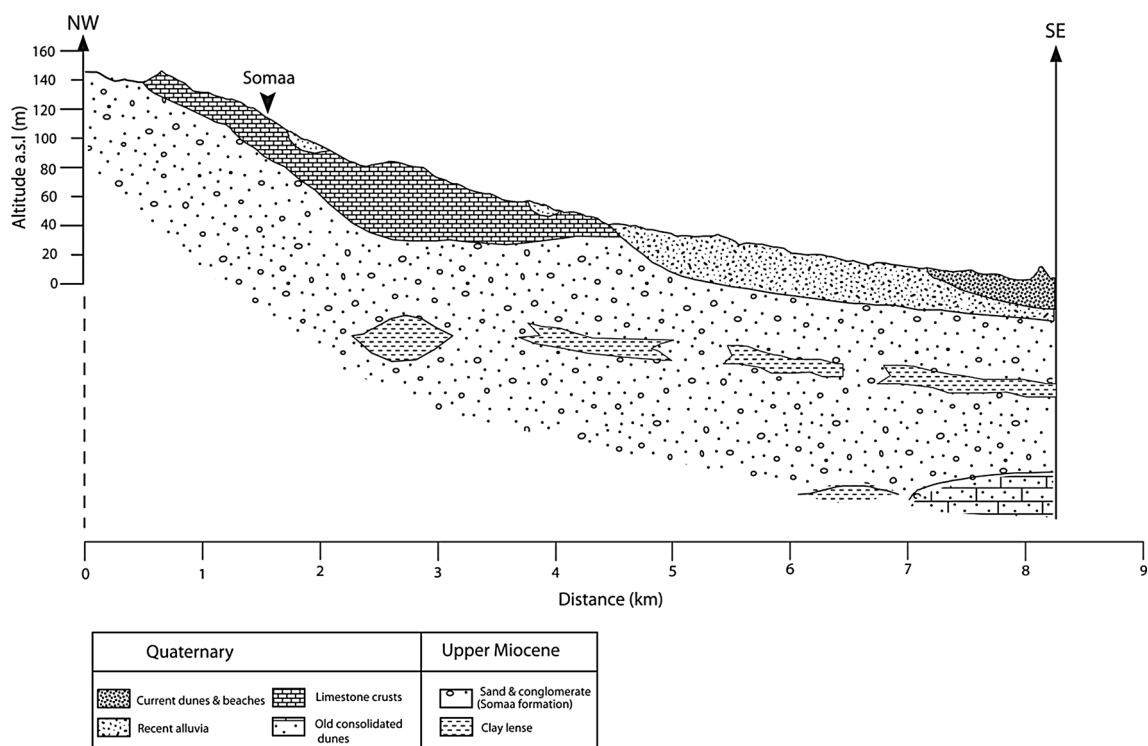


Fig. 2 Geological cross section A–A'

purposes. The first deposits are mainly composed of Wadi alluvia and the latter consist of Somâa formation with sand and conglomerate. The frequent presence of clay lenses interbedded in the sandy layers of Somâa formation (Upper Miocene) turns the aquifer in some locations into a multi-layered system.

Piezometric behavior

The groundwater level map of Wadi Al Ayn plain was established based on 34 observation wells in April 2011 (Fig. 3).

Groundwater in the study area is characterized by a shallow flowing type mostly controlled by topographical changes as it is shown for instance in contour 15 and 40 m following, respectively, changes in topographical contours 30 and 60 m.

In the upstream region near Somâa City, the groundwater table depth does not exceed 10 m of depth in the alluvial deposits of Wadi Al Ayn where it constitutes an underflow aquifer.

The main flow direction is south-east following the shape of the Wadi. In the middle part of the plain, near the location of AYR2 and AYR3, the major flow directions are respectively south-east and north-east with a hydraulic gradient of nearly 5 %. In these locations, the aquifer is hydraulically connected to the hydrological network; the

Wadi water, mainly composed of non treated wastewater and oilfield brine may be infiltrated and spread according to the main flow direction which can explain the high salinity measured in some wells in the Wadi vicinity (Fig. 3). The downstream region, near Wadi Daroufa, is characterized by lower hydraulic gradient because of the flat topography. However, an inversion of the groundwater flow gradient is registered and the contour zero is appearing at 2 km inland. Closer to the shore line, groundwater contour becomes negative; a probable seawater intrusion is occurring in this area which can explain the high salinity of some neighboring wells. This phenomenon is frequent in the eastern coastal aquifer of CapBon since the 1990s and was reported by several authors. In fact, in Korba area (located 10 km in the northeastern of Wadi Al Ayn watershed), seawater intrusion is occurring (Paniconi et al. 2004; Kouzana et al. 2010; Zghibi et al. 2011).

Methodology

Numerical modeling of density-dependent groundwater flow: governing equations

Variable density groundwater flow and transport have recently been one of the important topics in hydrological sciences. Consequently, a large number of numerical models

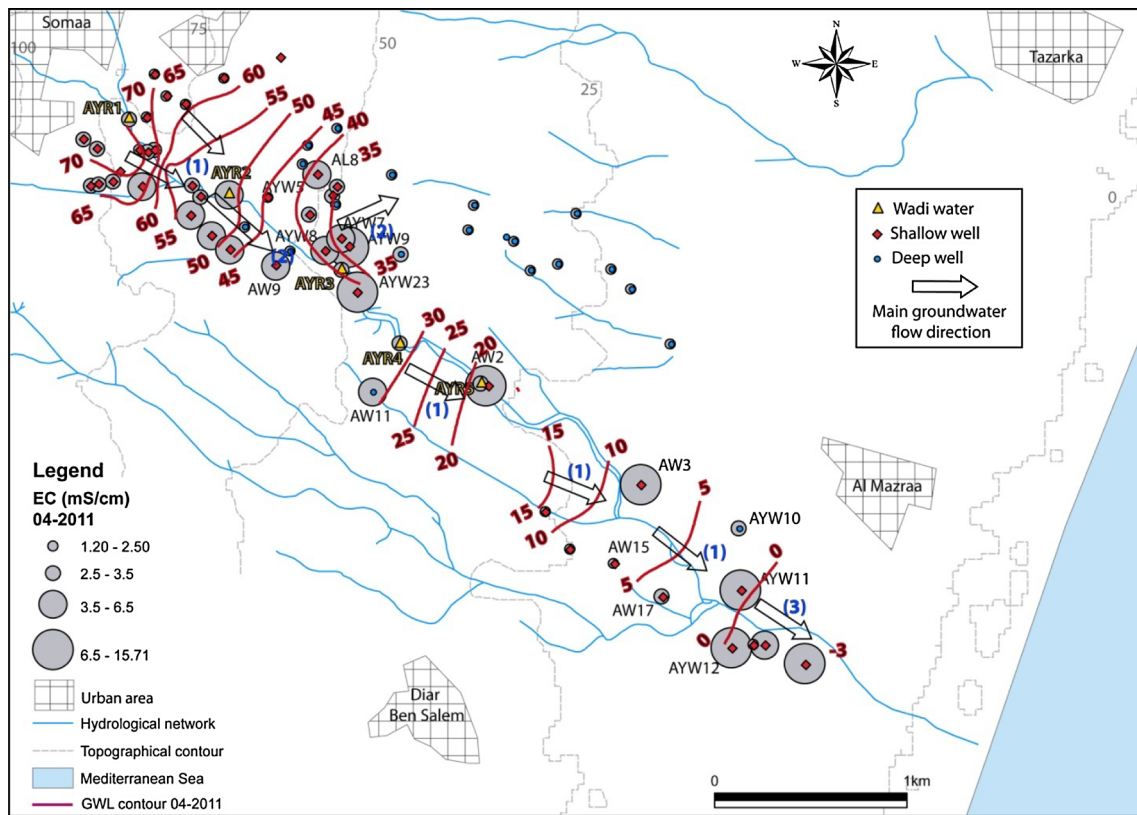


Fig. 3 Groundwater contour map and the spatial distribution of the electrical conductivity in the study area (April 2011). (1) Underflow type following under the Wadi bed, (2) recharged area from the Wadi water, (3) negative groundwater head = seawater intrusion

of salt transport have been developed in order to cope with the diversified environmental problems such as seawater intrusion in exploited coastal aquifers, leakage from landfills and disposal of industrial wastes in alluvial aquifers.

SEAWAT in conjunction with VISUAL MODFLOW graphical user interface was chosen as the basis for numerical simulation because of its ability to solve density-driven groundwater flow in porous media. It is a coupled version of MODFLOW (Harbaugh et al. 2000) and MT3DMS (Zheng and Wang 1999; Zheng 2006) designed to simulate three-dimensional, variable-density groundwater flow and multi-species transport (Langevin et al. 2008). Variable density flow (VDF) process uses MODFLOW methodology to solve the variable density groundwater flow equation and the MT3DMS for solving the transport equation.

The VDF process solves the following form of the variable-density groundwater flow equation Eq. (1):

$$\nabla \cdot \left[\rho K_o \left(\nabla h_o + \frac{\rho - \rho_o}{\rho_o} \nabla z \right) \right] = \rho S_{s,o} \frac{\partial h_o}{\partial t} + \vartheta \frac{\partial \rho}{\partial C} \frac{\partial C}{\partial t} - \rho_s q'_s \tag{1}$$

where ρ , ρ_o , fluid densities [$M L^{-3}$] in flow field and at the reference (freshwater); h_o hydraulic head [L] vs. reference;

K_o freshwater hydraulic conductivity [$L T^{-1}$]; $S_{s,o}$ specific storage [L^{-1}] vs. equivalent freshwater head; C salt concentration [$M L^{-3}$]; ϑ porosity [unitless]; t time [T]; x_i is the orthogonal coordinate [L]; q'_s : source or sink [T^{-1}] of fluid of density ρ_s [$M L^{-3}$].

In the case of VDF, head (h) is not only varying according to pressure and elevation changes but it depends also from the density (ρ). Thus, the concept of equivalent fresh water head (h_f) is introduced to take in account the difference in density while calculating the heads (2):

$$h_f = \frac{P}{\rho_r g} + Z \tag{2}$$

where ρ_r is the reference density, usually taken as the reference of fresh groundwater at reference chloride concentration [$M L^{-3}$], and P is the pressure [$M L^{-1} T^{-2}$].

The flow equation is solved jointly with solute transport Eq. (3):

$$\frac{\partial(\vartheta C)}{\partial t} = \nabla \cdot (\vartheta D \cdot \nabla C) - \nabla \cdot (qC) - q'_s C_s \tag{3}$$

where C_s salt concentration [$M L^{-3}$] of source/sink flux; D hydrodynamic dispersion coefficient tensor [$L^2 T^{-1}$]; q specific discharge [$L T^{-1}$]. For VDF, fluid density is assumed to depend only from solute concentration since

the pressure and temperatures effects are ignored (Langevin et al. 2003). Thus, an equation of state is used by SEAWAT to convert solute concentration to fluid density:

$$\rho = \rho_o + \frac{\partial \rho}{\partial C} C \quad (4)$$

where $\partial \rho / \partial C$ is the linear slope of density over concentration.

Model discretization, boundary conditions and model parameters

Domain discretization

A finite-difference mesh in SEAWAT was used to discretize the groundwater flow system of Wadi Al Ayn and Daroufa plain (Fig. 4). The model domain is composed of 102 rows, 143 columns, and 5 layers. The grid spacing is 60 by 30 m while the layer thicknesses are variable with maximum depth reaching 86 m below mean seal level according to the geophysical survey that we performed in the area.

Boundary conditions

Constant head and a concentration of 35 g/L were specified to the model cells along the coast. The effect

of tidal fluctuation was not taken into consideration because it is assumed to be limited to a short distance from the shore line (Narayan et al. 2007; Jin et al. 2009; Cobaner et al. 2012). A constant concentration linearly ranging from 67 to 4.5 g/L was also imposed for the cells of Wadi Al Ayn during the period 1994–2009 (oilfield brine infiltration). The lateral boundaries are assumed to be no-flow boundaries because the flow lines are parallel to them as it is previously shown in the groundwater contour map (Fig. 3).

The use of general head boundary (GHB) in some location is dictated by the influence of recharge from some adjacent and neighboring formations and they are consequently interpolated from measured heads along the boundaries.

Model parameters

Zoned hydraulic conductivity maps are created using geological information from field description, geophysical surveys and previous studies (Chekirbane 2013) (Fig. 5). Values are averaged for each zone and the mean horizontal hydraulic conductivity ($K_x = K_y$) is assigned to every zone. The vertical hydraulic conductivity (K_z) is assumed to be the tenth of the horizontal one. The calibrated

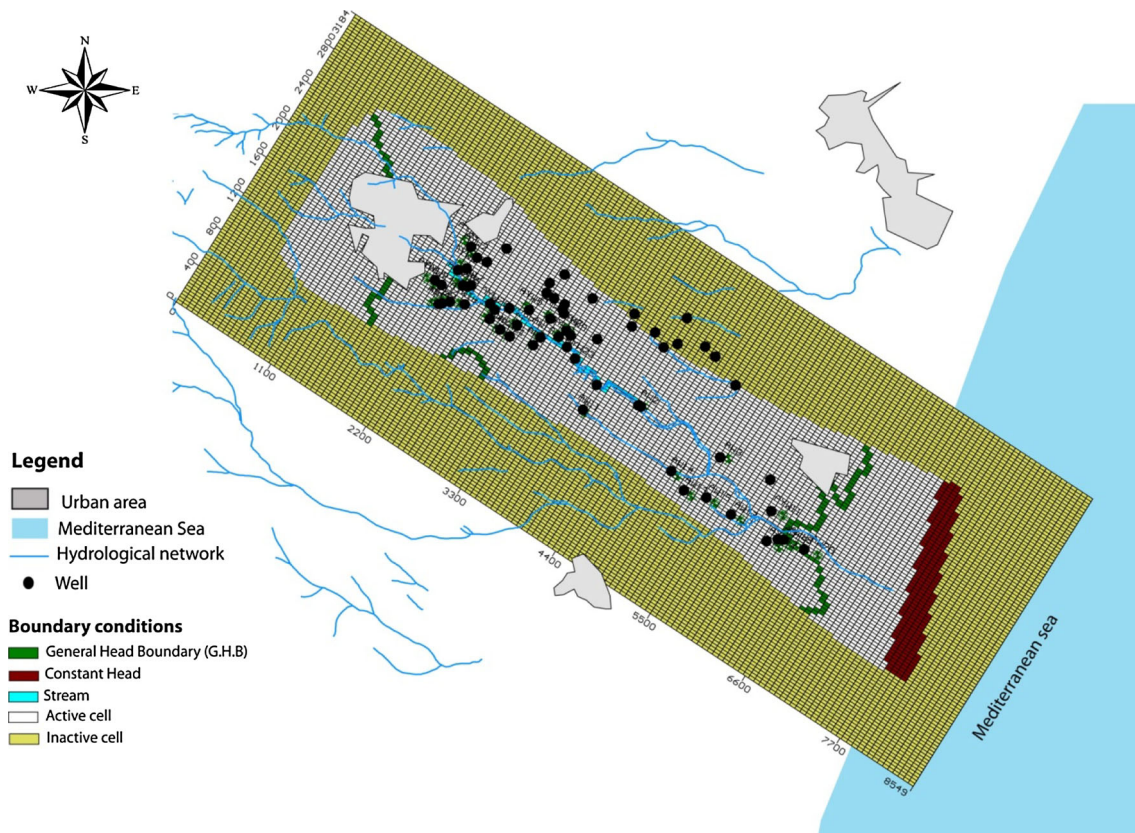


Fig. 4 Finite-difference grid and boundary conditions

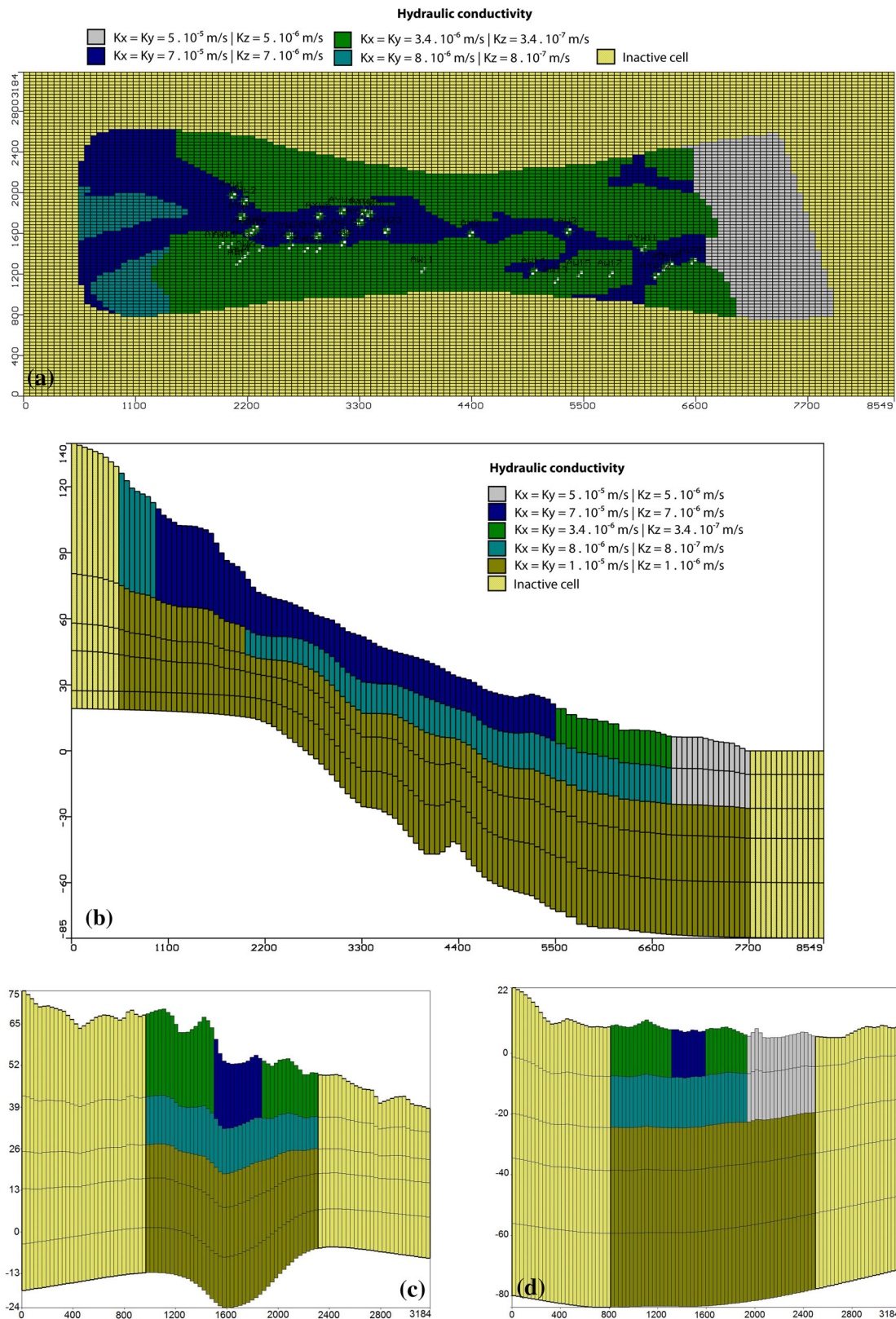


Fig. 5 Hydraulic conductivity cross sections: **a** top layer, **b** longitudinal cross section, **c** upstream cross section (Wadi Al Ayn) and **d** downstream cross section (Wadi Daroufa)

Table 1 Aquifer parameter values after calibration

Stratigraphic unit	$K_x = K_y$ (m/s)	K_z (m/s)	S_s (m^{-1})	Porosity	D_{Long} (m)	D_{Trans} (m)
Current dunes and beaches	5×10^{-5}	5×10^{-6}	10^{-5}	0.3	10	2
Wadi alluvia	7×10^{-5}	7×10^{-6}	10^{-5}	0.3	7	1.4
Limestone crusts	3.4×10^{-6}	3.4×10^{-7}	10^{-5}	0.3	1	0.2
Marine Quaternary	8×10^{-6}	8×10^{-7}	10^{-5}	0.3	2	0.4
Somâa formation	10^{-5}	10^{-6}	10^{-5}	0.3	2	0.4

$K_x = K_y$ horizontal hydraulic conductivity, K_z vertical hydraulic conductivity, S_s specific storage, D_{Long} longitudinal dispersivity, D_{Trans} transversal dispersivity

horizontal hydraulic conductivity is estimated to 5×10^{-5} m/s for current dunes and beaches formations located near the coastal part, 7×10^{-5} m/s for the recent Wadi alluvia, 3.4×10^{-6} m/s for limestone crusts, 8×10^{-6} m/s for Marine Quaternary formation and 10^{-5} m/s for Somâa formation. The other model parameters including specific storage, porosity and dispersivity are presented in Table 1.

The considered recharge in the model consists of the infiltrated rainfall and the percolated water from Wadi Al Ayn. Ennabli (1980), Paniconi et al. (2001) and Kerrou (2008) considered the recharge of the eastern coastal aquifer of CapBon by infiltration of precipitation to be less than 10 % of the average annual rainfall. The percolated water from Wadi was estimated based on the measured inflow and outflow in 2011. In fact, the total calculated inflow is 29.788 L/s and the infiltrated quantity calculated by water budget method is 9.01 L/s, which mean that the Wadi contribution in aquifer recharge is 30.24 %. Nazoumou (2002) estimated the infiltration from Wadi in semi-arid area in central Tunisia to 30 % of the annual runoff. According to the mentioned study and the results of the present study, the total percolated water from Wadi Al Ayn for 2011 is 0.308 Mm³.

The existing groundwater abstraction data is globally covering the entire eastern aquifer of CapBon. Specific data for the alluvial aquifer of Wadi Al Ayn and Daroufa does not exist. Thus, for the extended period from 1980 to 2003, the pumping rate of 52 wells was proportionally extracted from the total amount of groundwater abstraction. Nevertheless, the pumping rate for 2010 was calculated based on field interviews performed in the study area (Table 2) and the monitored groundwater level in five monitoring exploited wells. The estimated 2010 value is more precise than the other year values since the data of every single

Table 2 Estimated groundwater abstraction from the groundwater flow system of Wadi Al Ayn and Daroufa

Year	Pumping rate (m ³ /year)
1980	246,753.2
1985	268,842.7
1990	258,535
1995	259,436
2000	292,672.4
2003	280,800
2010	229,142.2

well is treated separately than the total amount is obtained by simple algebraic sum. Owing to the high density of dug wells in the study area, it was difficult to collect a complete pumping rate data from all the exploited wells. In the coastal part of the aquifer domain (Daroufa area), 11 pumping wells are identified and added to the model, where we assumed their pumping rate to be the same as the monitored well AW18 which is located in the same area.

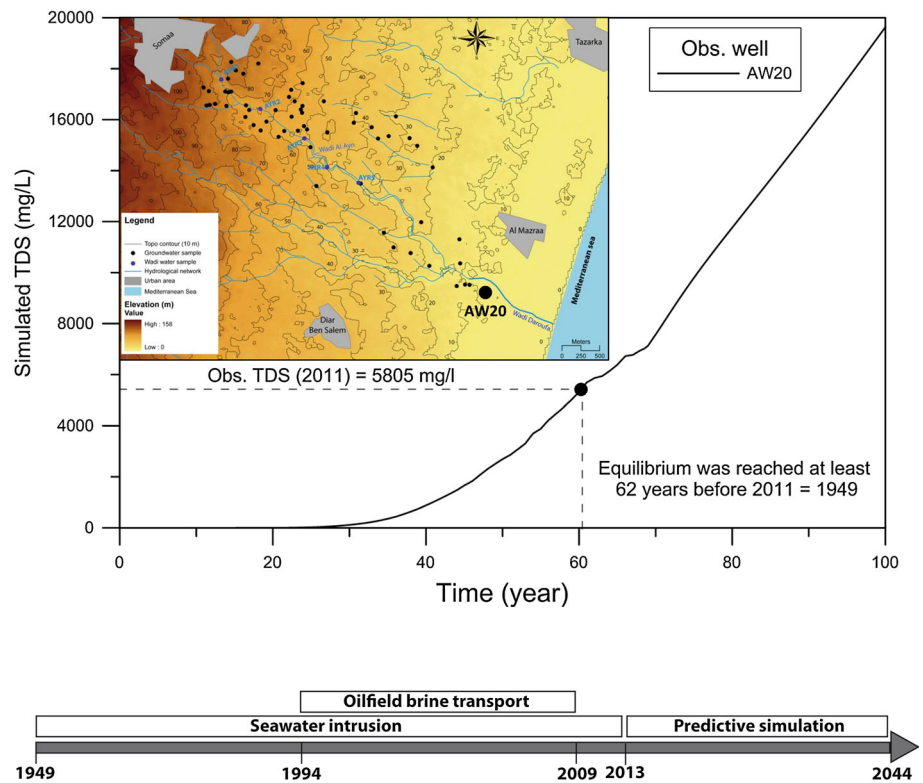
Initial conditions and time discretization

A steady state simulation was performed based on the earliest stable hydrological state of the eastern coastal aquifer of CapBon. The results of groundwater level as well as salt distribution from the steady state simulation were considered as initial conditions for transient simulation.

The equilibrium period was determined after running the performed SEAWAT model for 100 years and the idea is to determine the required time for the seawater fringe to reach the nearest TDS monitoring well to the coast line (AW20). The predicted TDS in the monitoring well AW20 reached 5,805 mg/L (observed TDS in November 2011) after 62 years (Fig. 6). It means that the equilibrium between seawater and fresh groundwater was reached 62 years before 2011, which is the year 1949. Therefore, when concerning the time discretization in the developed VDF model of the groundwater flow system of Wadi Al Ayn and Daroufa, the starting date was chosen as 1949. The chosen date seems to be reasonable since the early study of the entire aquifer of the eastern coastal aquifer of CapBon does not detect any seawater intrusion based on the piezometric map of 1962 (Ennabli 1980).

Accurate solution of the variable-density flow problem requires a specific time stepping. The temporal discretization scheme in SEAWAT model is a combination of MODFLOW and MT3DMS time discretizations. Time steps are derived from stress periods and they are further divided into transport steps. SEAWAT solves flow and transport equations (1) and (3) for each time step using explicit or implicit approaches described in Langevin et al. (2003). When concerning the present study, the flow and transport equations are solved implicitly using generalized conjugate gradient (GCG) solver. The length of

Fig. 6 Time discretization of the numerical model



time step is depending from Courant number (Cr) which should be less than or equal to one. It denotes the ratio of the advective distance during one time step to the spatial discretization (Eq. 5):

$$Cr = \frac{v\Delta t}{\Delta l} \tag{5}$$

where v [$L T^{-1}$] is the velocity, Δt [T] is the time step and Δl [L] is the grid size in the direction of v . The higher the Cr , the longer is the time step and hence a large number of iteration is needed for the solution convergence (Al-Maktoumi et al. 2007).

For the present model, the Courant number was specified as 0.75 in approximation with the heterogeneous and anisotropic aquifer materials, allowing three quarters of the flow and transport over a distance equal to one grid spacing.

Model calibration

Model calibration was performed using trial-and-error approach. The gap between observed and simulated heads and TDS was minimized by adjusting the hydraulic conductivities as well as dispersivities of the lithostratigraphic units. During the calibration, a total of 36 observed hydraulic head values measured in 2011 are used (Fig. 7) in addition to head time series of five wells continuously monitored during the period 2011–2012. An overall correlation coefficient of 0.98

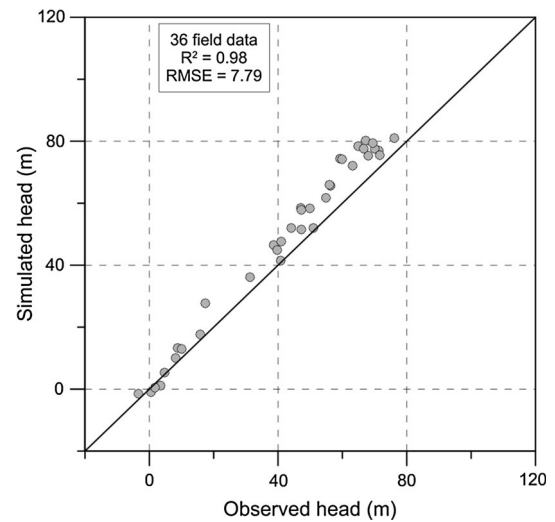


Fig. 7 Observed versus simulated heads

and a root mean square error of 7.79 values are obtained after finishing the model calibration, indicating a reasonably good match between the observed and simulated heads.

When concerning the TDS calibration, only the salt concentration measured in wells located in the vicinity of Wadi Al Ayn or near Daroufa plain were mainly considered (13 wells) (Fig. 8). The correlation coefficient and root mean square error are respectively 0.47 and 3,703.

Furthermore, salt concentration and the spatial extension of the saltwater distribution were also compared with the iso-2D resistivity pseudosections and they show a satisfying

agreement; the lower the resistivity of the aquifer horizon, the higher is the salt concentration of its water (Fig. 9a).

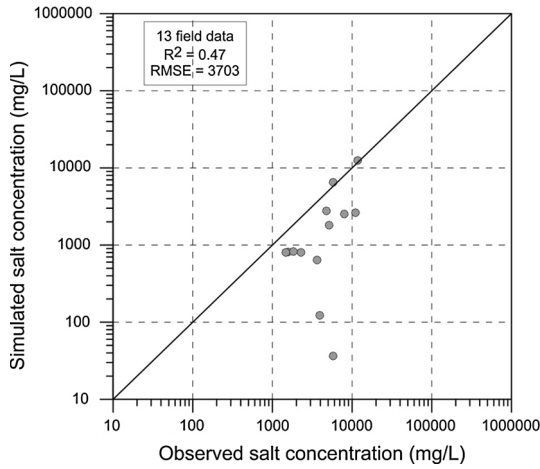


Fig. 8 Observed versus simulated TDS

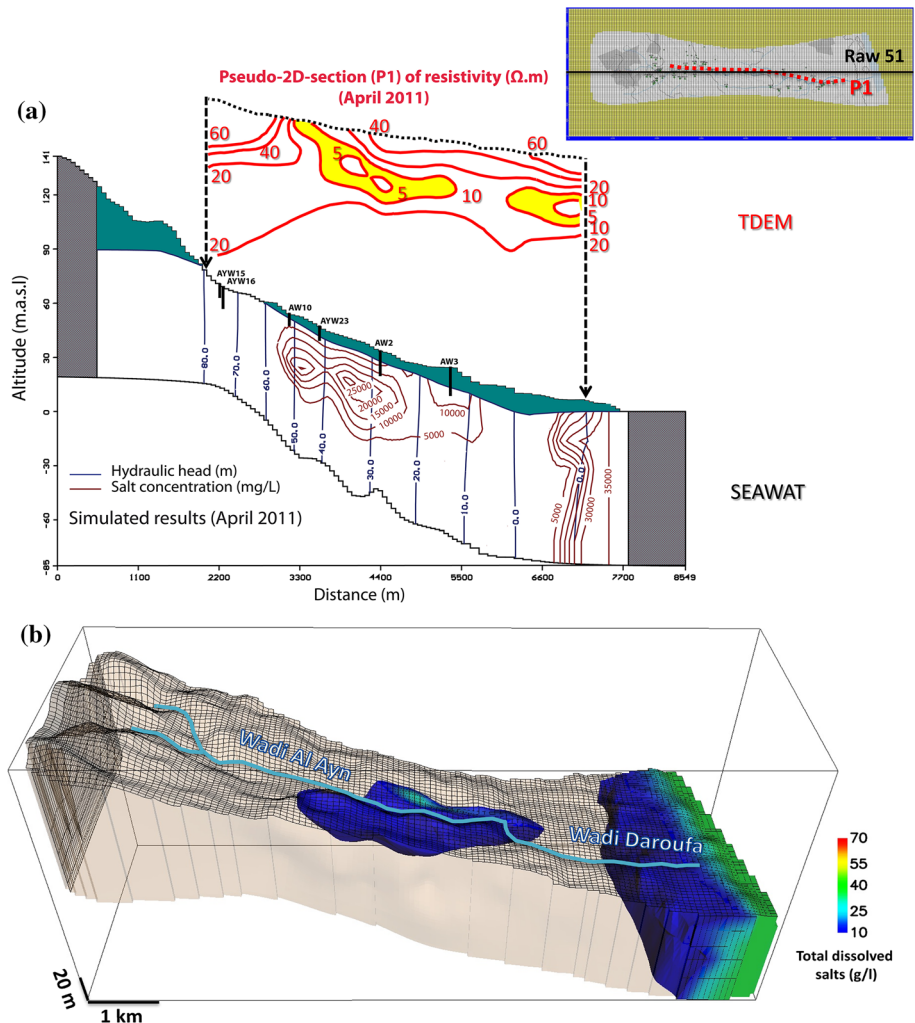
Simulation results

Retracement of the extent of saltwater plumes

The developed variable density groundwater flow and salt transport model was temporally discretized into two periods: the first one started from 1949 until 1994 where the system is only subject of a unique stress; the seawater intrusion in Daroufa area, near the coast and a second period extended from early 1994 until late 2009 when a second stress, in addition to seawater intrusion, was added: the infiltrated oilfield brine into the alluvial aquifer beneath Wadi Al Ayn (Fig. 6).

The obtained results are satisfyingly reproducing the salt distribution situation observed in April 2011 (Fig. 9a). The model shows that the longitudinal extent of the oilfield brine plume (TDS >10 g/L) is around

Fig. 9 a Comparison between the simulated hydraulic head and salt concentration of April 2011 and the observed salt concentration converted from TDEM data of April 2011. **b** 3D distribution of the simulated salt concentration of April 2011



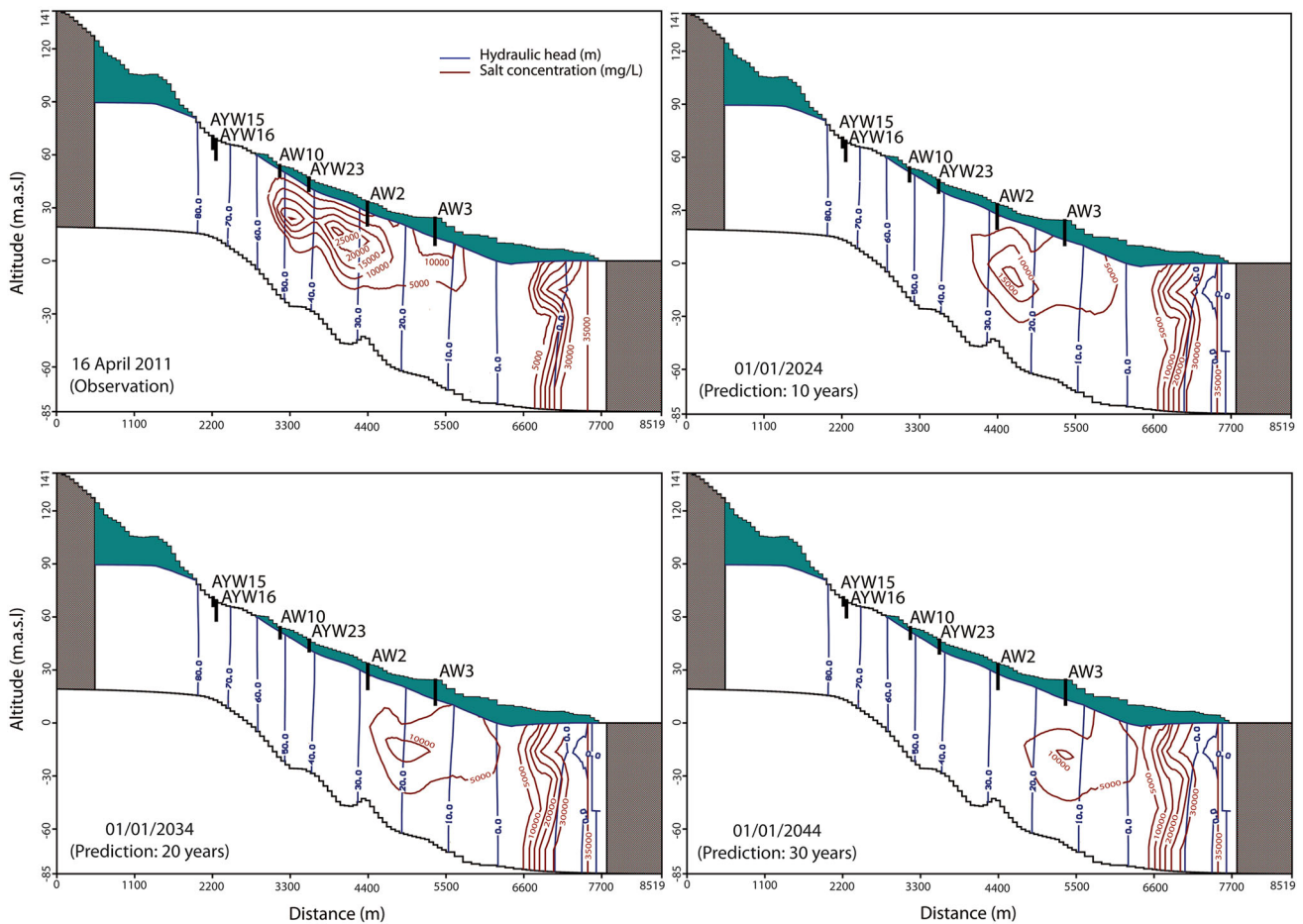


Fig. 10 Prediction of saltwater without any remediation countermeasure (scenario 1)

2 km and the seawater intruded the aquifer for an inland distance near 1 km. The 3D distribution of salt in the aquifer gives an idea about the transversal extent of the saline water plume (Fig. 9b) which shows that the oil-field brine plume has its largest transversal extent in the middle part of Wadi Al Ayn plain and the maximum of seawater intrusion is registered beneath the middle and downstream part of Wadi Daroufa. That could be explained by the sufficiently porous media constituting the wadis beds and their neighboring alluvial sediments.

An acceptable agreement was found between salt concentration simulated by SEAWAT model and a pseudo-2D-section of resistivity determined based on TDEM data performed in April 2011 (Chekirbane et al. 2012; Chekirbane 2013). Therefore, the numerical model can be used for predictive simulations.

Future exploitation scenarios of the groundwater flow system of Wadi Al Ayn and Daroufa

Once calibrated, the developed numerical model can serve to predict the future behavior of the groundwater flow and salt concentration under different scenarios and constraints.

Scenario 1

Under this scenario, we suppose that no countermeasures are taken to control the depression cone of groundwater and the saltwater plumes. The recharge and groundwater abstraction are considered the same as the values of the year 2010.

The results of scenario 1 (Fig. 10) show that the oilfield brine plume found in upstream of the aquifer needs at least 5–10 years to be naturally reduced to less than the half of its actual size, while in the coastal part of the aquifer the seawater–freshwater interface can reach an inland extent of 1.3 km with a TDS more than 10 g/L. Therefore, the aquifer situation will be aggravated and unsustainable. Thus, another scenario including some countermeasures is needed to remediate the actual situation of the groundwater flow system of Wadi Al Ayn and Daroufa.

Scenario 2

This scenario is based in some remediation countermeasures which are the application of artificial recharge of the aquifer with treated wastewater and optimized pumping

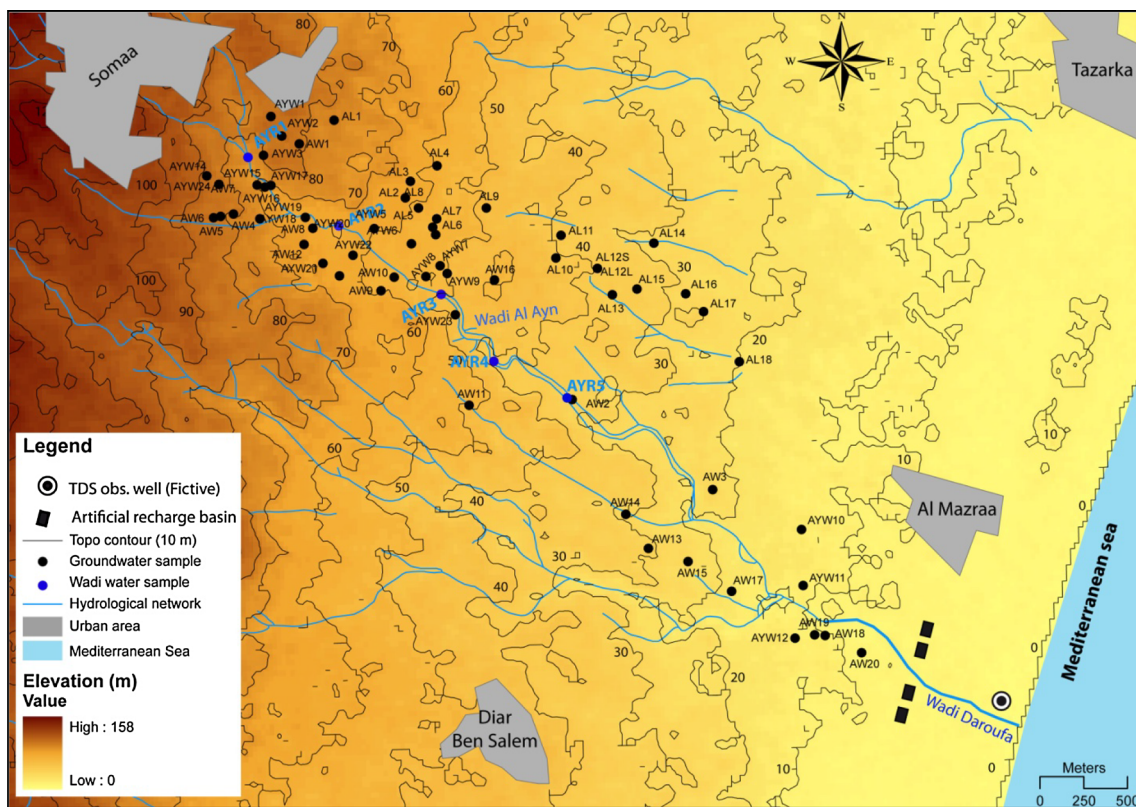


Fig. 11 Proposed location of the artificial recharge basins and TDS observation well

rates of the wells exploiting the shallow aquifer according to crop water needs.

The artificial recharge will be specially applied to remediate the coastal part of the aquifer near Daroufa area (Fig. 11).

Four percolation basins of 30 m × 50 m dimension are proposed to infiltrate a daily amount of 0.25 m of treated wastewater per basin during the period extended from 2014 to 2044. The percolated water can be provided from a neighboring wastewater treatment plant (Maamoura plant) which is programmed to be installed near Wadi Daroufa with an expected treatment capacity of 8,435 m³/day

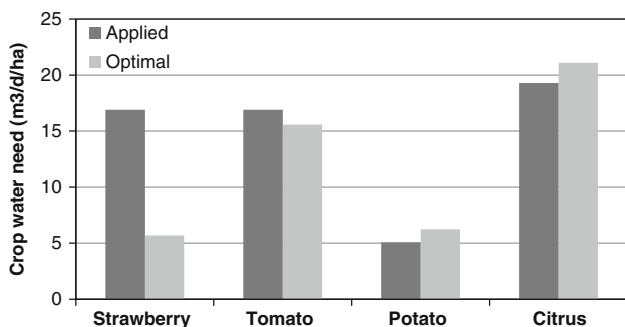


Fig. 12 Comparison between the applied and optimized pumping rates

(CRDA of Nabeul 2004). The measured TDS of the existing wastewater in Wadi Al Ayn is around 1.5 g/L. Thus, the predictive simulation of the seawater intrusion remediation was performed based on the above-mentioned parameters.

In parallel to the proposed project of artificial recharge, the pumping rates from the exploitation wells was optimized according the natural water needs of the available crops in the study area using FAO method (Allen et al. 1998) (6, 7):

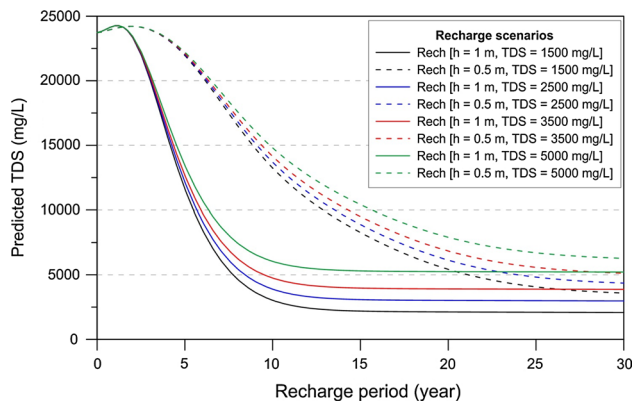


Fig. 13 Sensitivity analysis of the model for recharge quantity and quality

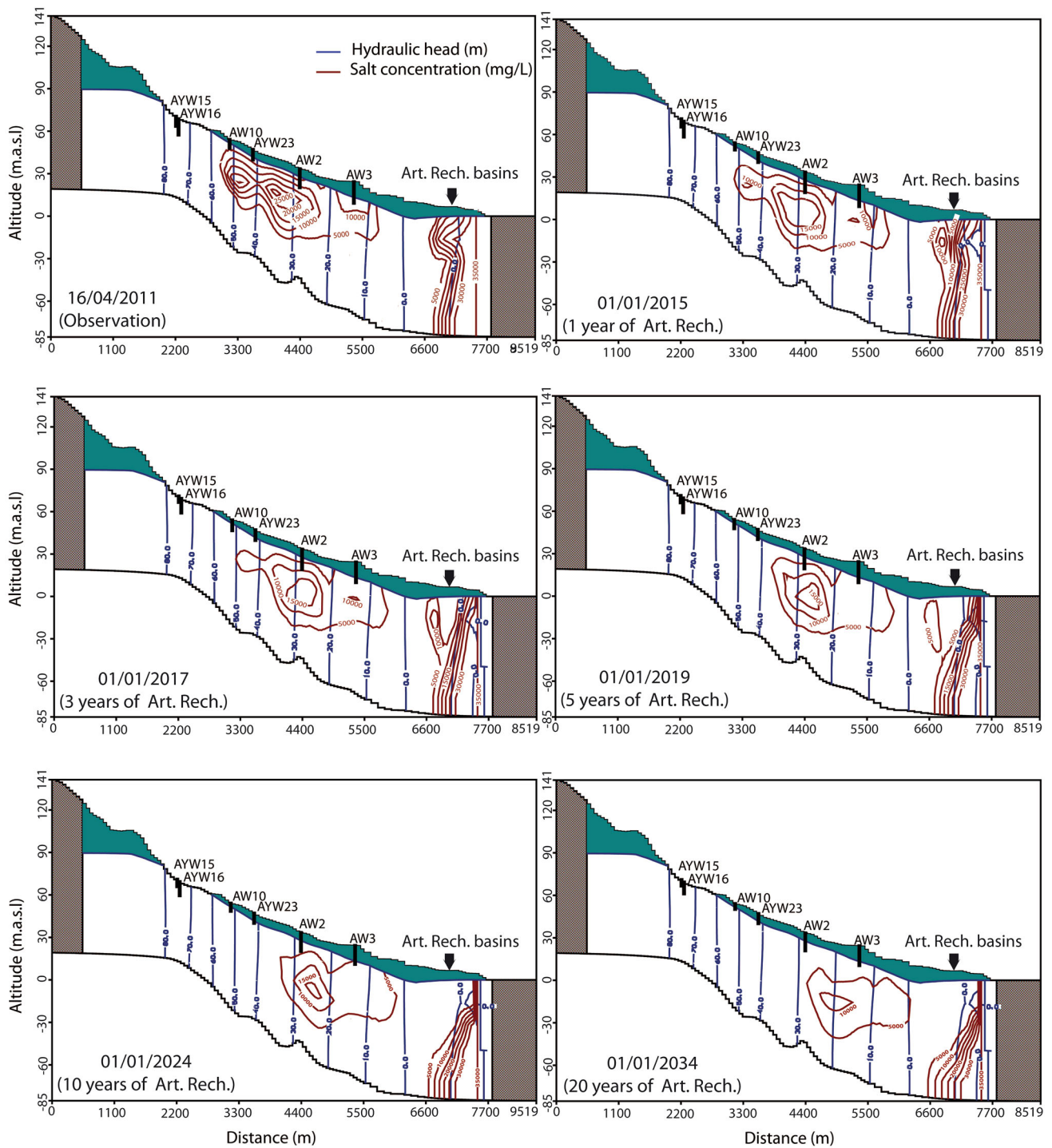


Fig. 14 Prediction of saltwater evolution under the artificial recharge scenario (scenario 2)

$$ET_{crop} = ET_0 \times K_c \tag{6}$$

$$ET_0 = K_{pan} \times E_{pan} \tag{7}$$

where ET_{crop} is the crop evaporation or crop water needs (mm/day), K_c the crop factor, ET_0 the reference evapotranspiration (mm/day), K_{pan} the pan coefficient = 0.45–1.1 for Sunken Colorado pan, E_{pan} the pan evaporation (mm/day).

When concerning tomato, potato and citrus plantation, the optimized and applied pumping rates are close, contrary to the strawberry case where the farmers are irrigating it with more than three times of its optimal water requirement (Fig. 12). That could be explained by the fact that strawberry is a relatively new crop in the study area and the farmers are lacking experience on its practice comparing with the ordinary and traditional plantations (tomato, potato, and citrus).

Optimal artificial recharge conditions

The efficiency of the artificial recharge is usually function of the quantity and quality of the water used for recharge. A sensitivity analysis of the 3D VDF model for the amount of percolated water and its TDS was performed (Fig. 13). From the viewpoint of quantity, the model was tested for two recharge amounts: 1 m per day for four basins and 0.5 m per day for two basins which is respectively equivalent to a capacity of 6,000 and 3,000 m³/day. The mentioned amount is limited because of the capacity of the recharge water source which may be the wastewater treatment plant of Maamoura with a capacity of 8,435 m³/day.

When concerning the recharge water quality, TDS of 1,500, 2,500, 3,500, and 5,000 mg/L was tested for the two proposed amounts. A fictive well located 100 m far from the coast line near Wadi Daroufa (Fig. 11) is used to observe the variation of predicted TDS versus time.

The model shows sensitivity for both amount and quality of recharge water. However, the sensitivity for the amount is much more important than quality. Necessary time to remediate the aquifer from salinization, especially the seawater intrusion, is shorter for high recharge water amount with the lowest TDS. Therefore, the most efficient scenario of artificial recharge can be based on percolating 0.25 m/day/basin of water having a TDS of 1,500 mg/L.

Proposal of an adaptive management plan

The artificial recharge with treated wastewater seems to be an efficient countermeasure solution to stop the seawater intrusion (Fig. 14). Its immediate effect starts to be observed just after 3 years of application. A period between 5 and 10 years is recommended to remediate the seawater intrusion in the coastal part of the aquifer and to have an acceptable recovery of the seawater–fresh groundwater equilibrium.

When concerning the plume of oilfield brine, a period of 10 years is sufficient to reduce its longitudinal extent to less than 50 % of its actual dimension. The simulation results are predicting that a plume core of 10 g/L with an extent around 250 m will remain in a depth ranging from 30 to 40 m under AW3 well after 30 years of exploitation. Enhance of the natural remediation of saltwater plume derived from the oilfield brine might be possible by installing a prohibited pumping perimeter near AW3 well and by controlling the discharges into the wadis.

Conclusion

The hydrodynamic, hydrochemical, and geophysical data served to build a conceptual model and they constituted the

input of a numerical model constructed with VISUAL MODFLOW and SEAWAT code to retrace the salt dynamics and predict its behavior under remediation scenario. The effect of oilfield brine and seawater intrusion in groundwater salinization were successfully reproduced and confirmed by the 3D numerical model. The oilfield brine plume needs at least 5 years to be naturally reduced to less than the half of its actual size, while the seawater–fresh groundwater interface can reach an inland extent of 1.3 km with a TDS more than 10 g/L if no countermeasures will be taken until the next three decades.

The artificial recharge with treated wastewater seems to be an efficient countermeasure solution to reduce the effect of seawater intrusion especially in the coastal part of the aquifer. Its immediate effect starts to be observed just after 3 years of application. A period between 5 and 10 years of artificial recharge is recommended in order to remediate the seawater intrusion in the coastal part of the aquifer and to have an acceptable recovery of the seawater–fresh groundwater equilibrium. When concerning the plume of oilfield brine, a period of 10 years is sufficient to reduce its longitudinal extent to less than 50 % of its actual dimension. Enhancing its natural remediation might be possible by installing a prohibited pumping perimeter near AW3 well and by protecting the Wadi's water from any kind of contaminant which may reach the saturated zone of the alluvial aquifer.

Acknowledgments This work was supported by the Science and Technology Research Partnership for Sustainable Development (SATREPS) program, funded by the Japan Science and Technology Agency (JST) and the Japan International Cooperation Agency (JICA), Japan. The authors would also like to thank the anonymous reviewers for their constructive comments.

References

- Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation Drainage Paper No. 56, FAO, Rome, Italy
- Al-Maktoumi A, Lockington DA, Volker RE (2007) SEAWAT 2000: modeling unstable flow and sensitivity to discretization levels and numerical schemes. *Hydrogeol J* 15:1119–1129
- Bakker M, Oude Essink GHP, Langevin CD (2004) The rotating movement of three immiscible fluids—a benchmark problem. *J Hydrol* 287:270–278
- Bauer P, Held RJ, Zimmermann S, Linn F, Kinzelbach W (2006) Coupled flow and salinity transport modelling in semi-arid environments: the Shashe River Valley, Botswana. *J Hydrol* 316:163–183
- Ben Hammouda MF, Tarhouni J, Leduc C, Zouari K (2011) Understanding the origin of salinization of the Plio-Quaternary eastern coastal aquifer of CapBon (Tunisia) using geochemical and isotopic investigations. *Environ Earth Sci* 63(5):889–901
- Ben Salem H (1992) Contribution a la connaissance de la geologie du CapBon: stratigraphie, tectonique et sedimentologie. Thesis (Ph.D.), Faculty of Sciences of Tunis

- CCI CapBon (2011) Chambre de Commerce et d'Industrie du CapBon, Tunisia [online]. Available from: <http://www.cciacapbon.org.tn>. Accessed 4 December 2011
- Chekirbane A (2013) Interaction between groundwater and saline surface water in alluvial aquifers of ephemeral coastal streams, north-east of Tunisia. Thesis (Ph.D.), University of Tsukuba, Japan
- Chekirbane A, Tsujimura M, Kawachi A, Isoda H, Tarhouni J, Yamada W, Takahashi M, Amri F (2012) Mapping of groundwater salinization using time domain electromagnetic induction in a small coastal semi-arid aquifer in CapBon, North-eastern of Tunisia. In: Proceeding of 22nd salt water intrusion meeting, 17–22 June 2012, Armaçao dos Buzios, Brazil
- Chekirbane A, Tsujimura M, Kawachi A, Isoda H, Tarhouni J, Benalaya A (2013) Hydrogeochemistry and groundwater salinization in an ephemeral coastal flood plain: Cap Bon, Tunisia. *Hydrol Sci J* 58(5):1097–1110
- Chkirbene A (2008) Hydrogéochimie et indices de pollution des eaux du système aquifère phréatique de la plaine d'oued Al Ayn au Cap-Bon. Thesis (Master), Higher School of Agriculture of Mograne, Zaghuan, Tunisia
- Cobaner M, Yurtal R, Dogan A, Motz LH (2012) Three dimensional simulation of seawater intrusion in coastal aquifers: a case study in the Goksu Deltaic Plain. *J Hydrol* 465:262–280
- Colleuil B (1976) Étude stratigraphique et néotectonique des formations néogènes et quaternaires de la région Nabeul – Hammamet (CapBon, Tunisie). Thesis (Ph.D.), Nice University, France
- CRDA of Nabeul (2004) Projet de recharge des nappes du CapBon à partir des eaux usées traitées. Project report, CRDA of Nabeul
- Ennabli M (1980) Étude hydrogéologique des aquifères du Nord-Est de la Tunisie pour une gestion intégrée des ressources en eau. Thesis (Ph.D.), Nice University, France
- Guo W, Langevin CD (2002) User's guide to SEAWAT: a computer program for simulation of threedimensional variable-density ground-water flow. U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, Chapter A7, p 77
- Harbaugh AW, Banta ER, Hill MC, McDonald MG (2000) MODFLOW-2000, the U.S. Geological survey modular ground-water model—user guide to modularization concepts and the ground-water flow process: U.S. Geological Survey
- Hudak FH, Wachal DJ (2001) Effects of brine injection wells, dry holes, and plugged oil/gas wells on chloride, bromide, and barium concentrations in the Gulf Coast Aquifer, southeast Texas, USA. *Environ Int* 26(7–8):497–503
- Jemai S (1996) Evolution de l'état de la nappe de Korba: Étude hydrogéochimique et modélisation numérique. Thesis (Master), Agronomical National Institute of Tunisia (INAT), Tunisia
- Jin L, Blake S, Zheng C, Wu J (2009) A modeling study of seawater intrusion in Alabama Gulf Coast, USA. *Environ Geol* 57:119–130
- Kerrou J (2008) Deterministic and probabilistic numerical modelling towards sustainable groundwater management: application to seawater intrusion in the Korba aquifer (Tunisia). Thesis (Ph.D.), Neuchâtel University, Switzerland
- Khlaifi I (1998) Contribution à l'étude de l'intrusion marine par un modèle de transport tridimensionnel: interfaçage avec des systèmes d'information géographique. Thesis (Master), University of Tunis El Manar
- Kouzana L, Ben Mammou A, Sfar Felfoul M (2009) Seawater intrusion and associated processes: case of the Korba aquifer (CapBon, Tunisia). *CR Geosci* 341(1):21–35
- Kouzana L, Benassi R, Ben Mammou A, Sfar Felfoul M (2010) Geophysical and geochemical study of the seawater intrusion in Mediterranean semi arid zones. Case of the Korba coastal aquifer (CapBon, Tunisia). *J Afr Earth Sci* 58(2):242–254
- Langevin CD (2003) Simulation of submarine ground water discharge to a marine estuary: Biscayne Bay, Florida. *Ground Water* 41(6):758–771
- Langevin CD, Shoemaker WB, Guo W (2003) MODFLOW-2000, the U.S. Geological survey modular ground-water model—documentation of the SEAWAT-2000 version with the variable-density flow process (VDF) and the integrated MT3DMS transport process (IMT). US Geological Survey, Open-File Report 03-426, p 43
- Langevin CD, Thorne DT Jr, Dausman AM, Sukop MC, Guo W (2008) SEAWAT version 4: a computer program for simulation of multi-species solute and heat transport. U.S. Geological Survey Techniques and Methods Book 6, Chapter A22, p 39
- Lecca G (2000) Implementation and testing of the CODESA-3D model for density-dependent flow and transport problems in porous media. Environment Area, CRS4, Pula, Italy (Internal report)
- Lin HJ, Rechards DR, Talbot CA, Yeh GT, Cheng JR, Cheng HP, Jones NL (1997) A three-dimensional finite-element computer model for simulating density-dependent flow and transport in variable saturated media: version 3.1. US Army Engineering Research and Development Center, Vicksburg, MS
- Mastrocicco M, Colombani N, Sbarbati C, Petitta M (2012) Assessing the effect of saltwater intrusion on petroleum hydrocarbon plumes via numerical modeling. *Water Air Soil Pollut* 223:4417–4427
- Narayan KA, Schleeberger C, Bristow KL (2007) Modelling seawater intrusion in the Burdekin delta irrigation area, North Queensland, Australia. *Agric Water Manag* 89:217–228
- Nazoumou Y (2002) Impact des barrages sur la recharge des nappes en zone aride : Etude par modélisation numérique sur le cas de Kairouan (Tunisie centrale). Thesis (Ph.D.). Ecole Nationale d'Ingénieurs de Tunis
- Paniconi C, Khlaifi I, Lecca G, Giacomelli A, Tarhouni J (2001) A modeling study of sea water intrusion in the Korba coastal plain, Tunisia. *Phys Chem Earth (B)* 26(4):345–351
- Paniconi C, Khlaifi I, Lecca G, Giacomelli A, Tarhouni J (2004) Modeling and analysis of seawater intrusion in the coastal aquifer of eastern CapBon, Tunisia. *Transp Porous Media* 43(1):3–28
- Qahman K, Larabi A (2006) Evaluation and numerical modeling of seawater intrusion in the Gaza aquifer (Palestine). *Hydrogeol J* 14:713–728
- Rekaya M (1989) Le contexte hydrogéologique de la nappe aquifère de la côte orientale du CapBon (Tunisie) et les problèmes causés par la surexploitation. General Direction of Water Resources, Tunis
- Rouatbi R (1968) Étude hydrogéologique primaire de la région Tafelloune, CapBon oriental. Bureau of Hydraulic Resources Inventory (BIRH), Tunis
- Saidi S, Bouri S, Ben Dhia H (2013) Groundwater management based on GIS techniques, chemical indicators and vulnerability to seawater intrusion modelling: application to the Mahdia–Ksour Essaf aquifer, Tunisia. *Environ Earth Sci* 70(4):1551–1568
- Sanford WE, Konikow LF (1985) A two-constituent solute transport model for ground water having variable density. US Geological Survey Water-Resources Investigations Report 85-4279, p 89
- Simmons CT, Fenstemaker TR, Sharp JM Jr (2001) Variable-density groundwater flow and contaminant transport in heterogeneous porous media: approaches, resolutions and future challenges. *J Contam Hydrol* 52(1–4):245–275
- Slama F (2010) Field experimentation and modeling of salt transfer in Korba coastal plain: impact of seawater intrusion and irrigation practices. Thesis (Ph.D.), Neuchâtel University, Switzerland
- Trabelsi F, Tarhouni J, Ben Mammou A, Ranieri G (2013) GIS-based subsurface databases and 3-D geological modeling as a tool for the set up of hydrogeological framework: Nabeul–Hammamet coastal aquifer case study (Northeast Tunisia). *Environ Earth Sci* 70(5):2087–2105

- Voss CI (1984) SUTRA: a finite-element simulation model for saturated–unsaturated, fluid-density-dependent ground-water flow with energy transport or chemically reactive single-species solute transport. US Geological Survey, Water-Resources Investigation Report 84-4369, p 409
- Zghibi A, Zouhri L, Tarhouni J (2011) Groundwater modelling and marine intrusion in the semi-arid systems (CapBon, Tunisia). *Hydrol Process* 25(11):1822–1836
- Zheng C (2006) MT3DMS v5.2 supplemental user's guide: Technical report to the U.S. Army Engineer Research and Development Center, Department of Geological Sciences, University of Alabama, p 24
- Zheng C, Wang PP (1999) MT3DMS—a modular three-dimensional multispecies transport model for simulation of advection, dispersion and chemical reactions of contaminants in ground-water systems: documentation and user's guide: U.S. Army Corps of Engineers Contract Report SERDP-99-1