Arab J Geosci (2012) 5:1151–1161
DOI 10.1007/s12517-011-0304-9

The use of injection wells and a subsurface barrier in the prevention of seawater intrusion: a modelling approach

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Received: 23 November 2010 / Accepted: 14 February 2011 / Published online: 1 March 2011

Abstract Damsarkho (Latakia, Syria) coastal aquifer is under severe hydrological stress due to the overexploitation of a shallow groundwater table for irrigation and tourism. Excessive pumping during the past few decades has caused a significant lowering of groundwater levels, which has in turn lead to seawater intrusion into the aquifer. Meteoric infiltration and flow from the adjoining carbonate aquifer recharges the Damsarkho aquifer. Natural outflow occurs through a diffuse flow into the sea, while artificial outflow occurs through intensive extraction of groundwater via wells. Water exchange in the aquifer takes place both naturally (leakage) and artificially (multi-screened wells). For the purpose of planning and management, SEAWAT, a variable density solute transport computer code, was used to study groundwater volume and quality. Seawater intrusion was represented by a three-dimensional finite difference model using the SEAWAT numerical code of Visual-Modflow software; the conceptual model is based on field and laboratory data collected between 1960 and 2003. Results obtained from the model establish that seawater intrusion is essentially due to withdrawal near the coast during the irrigation season, which occurs almost entirely in the Damsarkho plain. This simulation also demonstrates that the use of injection wells or a subsurface barrier would both represent a good method with which to improve water quality and prevent seawater intrusion.

Keywords Seawater intrusion · Coastal aquifer · SEAWAT · Injection well · Subsurface barrier

Introduction

In many coastal areas, the growth of human settlements, together with the development of agricultural, industrial and tourist activities, has led to the overexploitation of aquifers. Such overexploitation commonly results in a rise in the freshwater–saltwater interface (seawater intrusion) and thus degradation of the chemical quality of groundwater. Under natural conditions, the geometry of the saltwater wedge depends on the hydraulic properties of the aquifer, the physical properties of the two fluids (Henry 1964a, b) and on aquifer geometry (Abarca et al. 2007). The Mediterranean provides many clear examples of the presence of seawater intrusion (Abou Zakhem and Hafez 2003; Arfib and de Marsily 2004; Bonacci and Roje-Bonacci 1997; Chiocchini et al. 1997; El-Bihery and Lachmar 1994; Paniconi et al. 2001; Petalas and Diamantis 1999), with the Spanish coast not an exception (Calvache and Pulido-Bosch 1994; Giménez and Morell 1997; Iribar and Custodio 1992; Padilla et al. 1997a, b). This phenomenon has also been observed on the Syrian coast north of Latakia (the Damsarkho plain). The Damsarkho coastal plain is currently experiencing seawater intrusion thanks to irrational exploitation of the aquifer via hundreds of wells of different types, depths and pumping rates. The first in-depth investigation of the problem was undertaken in 2000 by Abed Rabo, who specified the location and extent of the intrusion by chemical analysis and measurement of groundwater levels. The next study was carried out in 2003 by Abou Zakhem and Hafez, who used analysis of electrical conductivity and isotopic elements to investigate the phenomenon. The results

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obtained in these two studies have confirmed the existence of intrusion.

The deterioration of groundwater quality is currently a limiting factor for local economic growth; agriculture has either been completely abandoned or has been directed towards crops which can tolerate brackish water.

The intrusion of seawater in coastal aquifers was first conceptualised independently by Badon-Ghijben (1889) and Herzberg (1901), who assumed hydrostatic equilibrium, immiscible fluids and the existence of a sharp interface between fresh- and saltwater in a homogeneous unconfined aquifer. Both authors found that the depth of the freshwater–saltwater interface below sea level (z_s) is forty times the water level above sea level (1):

$$Z_s = \frac{\rho_f}{\rho_s - \rho_f} h_f \tag{1}$$

Where ρ_f is the density of freshwater, ρ_s is the density of saltwater and h_f is the elevation of the water table above sea level.

Due to molecular diffusion and hydrodynamic dispersion, fresh- and saltwater are actually miscible liquids: the contact between the two fluids is therefore a transition zone rather than a sharp interface. The situation is further complicated by the fact that saltwater intrusion itself changes the fluid density, so that this parameter varies in space and time as a function of changes in concentration, temperature and pressure in the fluid. Furthermore, the porous medium itself is usually stochastically heterogeneous. In order to properly reproduce the mechanism of saltwater encroachment, a variable density flow and transport modelling approach is therefore generally adopted. This study presents a conceptual and numerical model devised for the simulation of the hydrodynamics of the multi-aquifer system of the Damsarkho plain. The model will be used for hydrodynamic simulation and appropriate management of local water resources, with the aquifer system representing a good example of the recent saltwater intrusion of coastal plains.

Potential solutions to saltwater intrusion

A variety of different measures are commonly used to control seawater intrusion and protect groundwater resources, although the overriding principle of most is to increase the flow of fresh groundwater and/or reduce the flow of saltwater. As such, there are a number of methods with which to prevent saltwater contamination of groundwater, including subsurface barriers and artificial recharge.

Subsurface barriers

Defined as underground semi-impervious or impervious structures constructed in coastal aquifers, subsurface barriers are used to simultaneously impede the inland infiltration of seawater and increase the groundwater storage capacity of an aquifer.

Subsurface barriers are generally located between the area of seawater and the production wells, and are constructed parallel to the coast. Since they work on the same basis as a dam across a river, to engineers they are also known as 'underground dams'.

Not only may barriers completely stop the encroachment of seawater, their function as dams means water also collects behind them, although complete depth of cut-off is required for a barrier to be effective with respect to the latter. These two benefits of subsurface barriers can be achieved simultaneously, with the cost highly dependent on the depth of cut-off, length of wall and specific material availability.

Artificial recharge

Todd (1980) defines artificial recharge as the augmentation of the natural movement of surface water into underground formations. A variety of artificial recharge techniques are currently available, including water spreading and recharge wells (Todd 1980). The chosen construction method depends on several factors, such as topography, geology, soil conditions and the availability of water surrounding the area.

Application of the surface-spreading technique is dependent upon several factors, with the foremost often being the cost and availability of land. The cost of land is an important issue, particularly in urban areas, since availability of land for flooding is a necessary condition of the method. Another factor to be considered is the type of soil (Todd 1980), with gravel or gravel and sand strongly recommended, as the effectiveness of the surface spreading technique is questionable where clogging problems are encountered (Bear 1972).

The rate of infiltration is high only at the beginning of the operation and decreases considerably after reaching peak levels. This decrease is caused mainly by the filling of soil pores by water. Saturated soil conditions reduce the pore space available for, and thus the rate of, water infiltration.

Another method of artificial recharge is the use of recharge wells; a technique involving the transfer of water from the surface into an aquifer. The type of well employed may be an ordinary pumping well or one specially designed for the purpose. Particularly attractive are dual-purpose wells which have two functions: to discharge and recharge water from/to the aquifer. Use of a dual-purpose well is economically preferable to the construction of a specialised recharge well. The general purpose of recharge wells is to overcome the high cost of the water spreading technique in areas where suitable land is scarce and/or expensive.

In addition to clogging problems, several other difficulties are associated with the recharge well technique. For instance, a large amount of dissolved air is carried together with recharge water, whilst water quality research has indicated that a variety of bacteria are also found in recharge water. Under certain circumstances, bacteria can grow quickly and eventually reduce the filtering area of the well screen (Civan 2007; van Beek et al. 2009)

Problems associated with injection wells include the fact that a relatively large number of wells are required, high maintenance costs are necessary to prevent plugging of wells, and most importantly, a source of freshwater is required.

Overview of the SEAWAT package in VISUALMODFLOW

The SEAWAT-2000 software package enables modelling of groundwater, coupling flow and transport (Langevin and Guo 2002), using the flow and transport equations of two widely accepted codes; MODFLOW (Harbaugh et al. 2000; Mcdonald and Harbaugh 1988) and MT3DS (Zhang and Wang 1998). Some modifications are also employed to include density effects based on the extended Boussinesq assumptions. The governing flow and transport equations in SEAWAT-2000 are shown in (2) and (3). Since the programme has been used previously to simulate variable density flow through complex geological conditions, it was applied in the present study to predict the behaviour of groundwater flow, in the search for the best solution to seawater intrusion into the Damsarkho aquifer. The governing flow equation can be written as

$$\frac{\partial}{\partial Xi}\left[\rho K_f\left(\frac{\partial h_f}{\partial Xi}+\frac{\rho\text{-}\rho_f}{\rho_f}\frac{\partial z}{\partial Xi}\right)\right]=\rho_{Sf}\frac{\partial h_f}{\partial t}+\theta\frac{\partial h_f}{\partial t}+\partial\frac{\partial\rho}{\partial t}-\rho sq_s \tag{2}$$

where Xi is the i th orthogonal coordinate, K_f is the equivalent freshwater hydraulic conductivity (L/T), S_f is the equivalent freshwater specific storage (1/L), h_f is the equivalent freshwater head, T is the time (T), θ is the effective porosity (dimensionless), ρsf is the density of source and sink (M/L3), qs is the volumetric flow rate of sources and sinks per unit volume of aquifer (1/T) and qs is the volumetric flow rate of sources and sinks per unit volume of aquifer (1/T).

The governing transport equation can be written as

$$\frac{\partial(\theta C_k)}{\theta t}=\frac{\partial}{\partial X}\left(\theta Dij\frac{\partial C_k}{\partial Xj}\right)-\frac{\partial}{\partial Xi}(\theta viC_k)+qsC_{sk}+\sum Rn \tag{3}$$

Where Ck is the dissolved concentration of species k (M/L3), Dij is the hydrodynamics dispersion tensor ($L$2/T), Cks is the concentration of the source or sink flux for species k (M/L3) and ΣRn is the chemical reaction term ($ML$3/T).

The study area

The Damsarkho coastal plain is located north of the town of Latakia, Syria and is composed of marine and alluvial sediments which cover an area of about 40 km^2. The study area is characterised by a Mediterranean climate, with wet winters and dry summers, while the average annual rainfall varies from 800 to 1,000 mm/year (Selkhozpromexport 1979). The Damsarkho plain is characterised by the presence of good aquifers, which consist of loose sands, gravelly sands, sandstone, limestone and sandy gravelly clay. With an average thickness of around 25 m, these aquifers are in direct contact with seawater. A geological map of the study area is provided in Fig. 1.

The main geometric–structural and hydrogeological characteristics of the Damsarkho multi-aquifer system were reconstructed on the basis of a general geological reconstruction and the 17 geological wells located across the plain (Fig. 2). The system is composed of five layers (sandy clay, limestone, sandy clay with gravels, marl and dolomite), although these layers occasionally combine to form a single-layer aquifer. The study area and geological sections are illustrated in Figs. 2 and 3. As shown in Fig. 3, the most interesting aquifer with respect to this study is the limestone aquifer, which has large hydraulic conductivity levels due to the presence of karst phenomena (Abed Rabo 2000).

Before salinisation of groundwater took place, the area was affected by the natural hydraulic gradient, in which groundwater movement was seaward. Minor inland seawater intrusion did occur due to the hydrodynamic balance between fresh and saline waters, but this scenario changed with the intensive exploitation of groundwater. Although major intrusion of seawater was initiated with the development of agriculture at the beginning of the 1970s, interest in this problem at the time consisted only of reports and general recommendations.

Over time the demand for water greatly increased, and with the number of unlicensed wells randomly extracting groundwater also increasing, the problem has only been exacerbated.

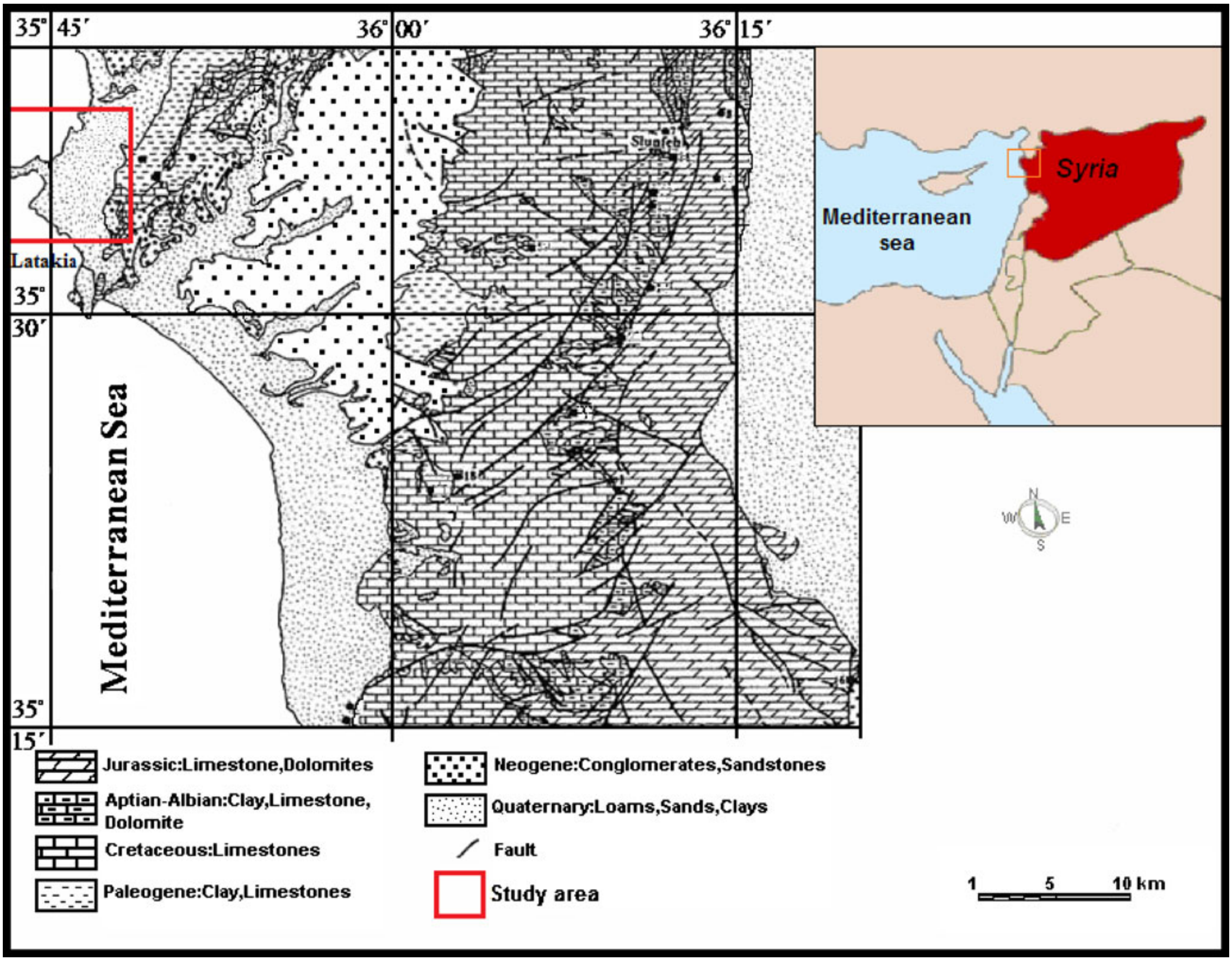


Fig. 1 Location and geological map of the study area (after Ponikarov 1966)

All of this has lead to a decrease in the levels of groundwater, as well as in the abundance of freshwater flowing seaward. With measurements of groundwater indicating that levels in some wells are lower than the sea surface, seawater has moved into the land through the permeable aquifer formations.

The gradual increase in salinity is noticeable at both the centre and boundaries of the plain, especially in summer months thanks to increased pumping (Abed Rabo 2000).

The phenomenon of salinisation has generally been neglected, despite resulting in the deterioration of 35 % of citrus trees and the destruction of large areas cultivated with fruit trees and crops, as well as the impairment of the physical and chemical properties of soil due to the high concentration of sodium ions in well water (Abed Rabo 2000).

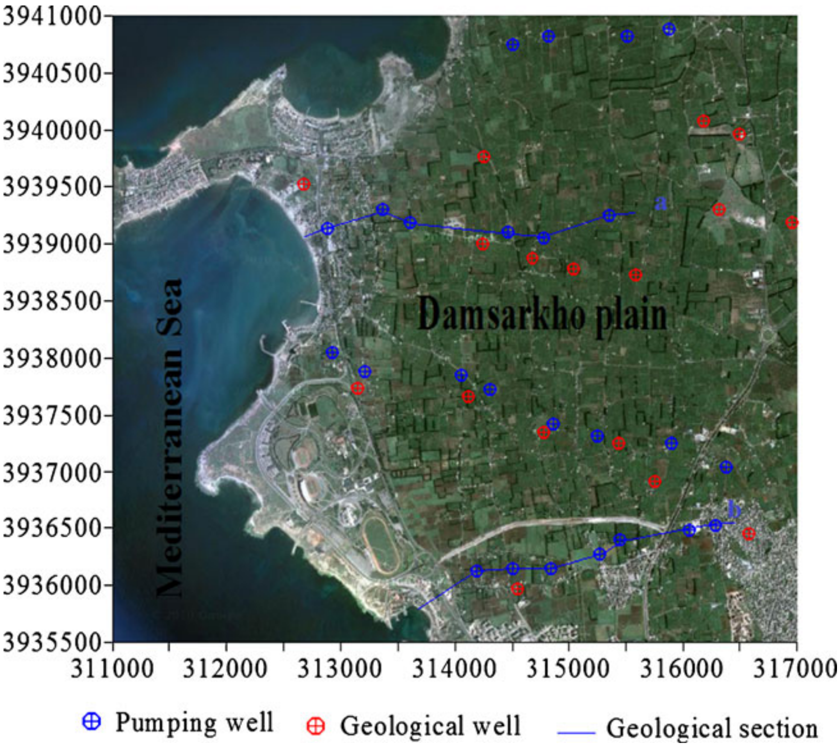
The main source of irrigation water in the region varies seasonally, with more rain water used in winter and extracted groundwater in the summer months. There are more than 700 wells in the Damsarkho plain, with depths ranging from 2 to 40 m and a mean pumping rate of around 15 L/s.

Recharge of the Damsarkho aquifer derives primarily from direct infiltration of rainfall and deep percolation of excess irrigation and surface water, but also partially from underground recharge in the eastern part of the aquifer. The aquifers of the Damsarkho plain are shallow groundwater reservoirs, in which the general movement of water is slightly seaward.

Mesh discretisation

Based on the SEAWAT code (Langevin and Guo 2002), the model developed simulates transient variable density groundwater flow and solute transport for the period from 1966 to 2010, using a database developed by Abed Rabo (2000). Regularly spaced finite difference 50 × 50 m cells on the horizontal plane are used, with the final grid consisting of 120 rows and 120 columns in the horizontal, and five regularly spaced layers in the vertical direction (Fig. 4).

Fig. 2 Aerial photograph of the Damsarkho plain showing the locations of geological wells and sections, with the co-ordinates given in metres (adapted from Google Earth)



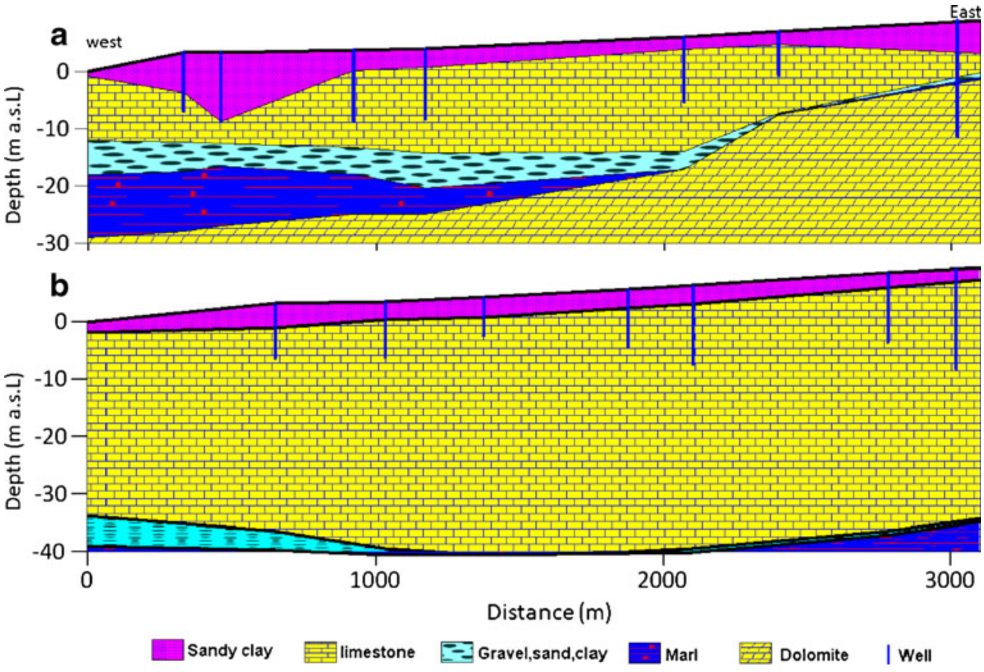
Model boundaries and aquifer parameters

A constant head value was attributed to cells along the coastline in which groundwater was in contact with the sea surface. The flux, assigned to the eastern boundary of the aquifer (Abed Rabo 2000; Kovács and Szanyi 2004), was determined via use of the general head boundary.

Initial head levels were taken from those measured in groundwater obtained from pumping wells (Abed Rabo 2000). The resulting piezometric map is shown in Fig. 5.

Flow conditions were used to determine inflows and outflows, which varied in time and space. These were thus also employed to simulate meteoric infiltration in the model (areal recharge). Effective precipitation was initially estimated

Fig. 3 Geological sections through selected pumping wells. The locations of the sections are shown in Fig. 2. Note that all wells discharge from the second limestone layer



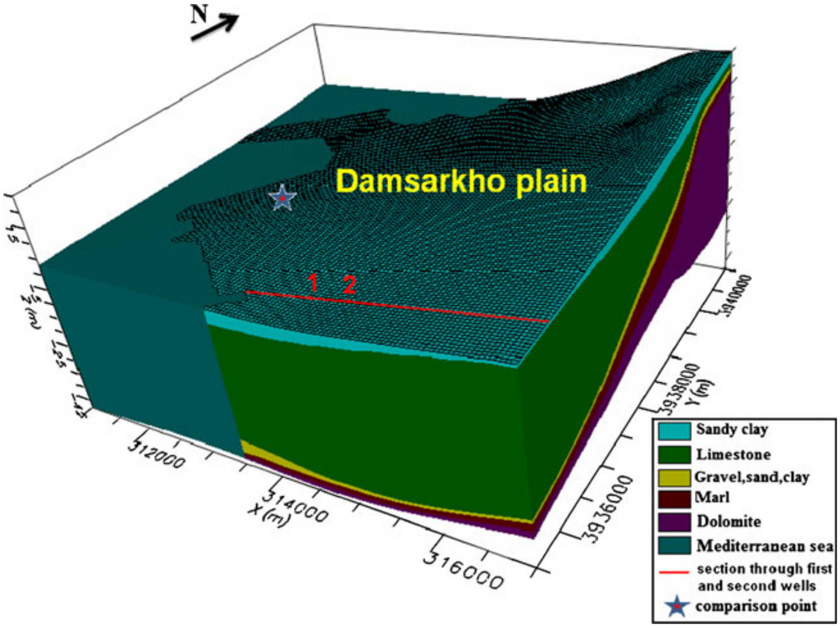


Fig. 4 Three-dimensional grid of the study area, showing the location of the comparison section and point. Position of first and second wells shown in Fig. 2

according to Abed Rabo (2000) on a daily basis, depending on (transient) simulation conditions. A discharge condition was assigned to those wells exploiting the aquifer, and was estimated using statistical data and distributed according to the density of the respective wells. The ability of VISUAL-MODFLOW to simulate hydraulic connections between aquifer layers through multi-screened wells was exploited to specify discharge rates. Due to the lack of reliable data regarding surface water and groundwater withdrawal for agricultural purposes, these quantities were estimated on the basis of information provided from an earlier survey of the area (Abed Rabo 2000).

Hydraulic properties (hydraulic conductivity, porosity and specific yield of the five layers included in the model) were estimated using the EnviroBrowser programme (groundwater data management programme; GEOREF Systems Ltd); these parameters are shown in Table 1.

Well discharge ranged between 3 and 20 l/s, with most exploitation occurring in the dry months. Concentrations of solids were assigned as 0 g/l on the eastern boundary and

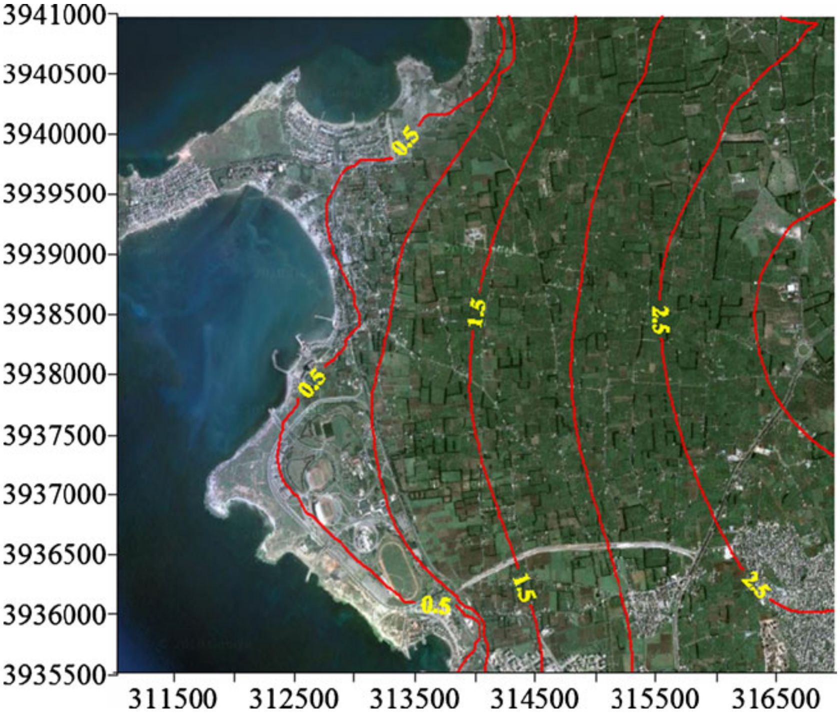


Fig. 5 Piezometric map of the Damsarkho plain after Abed Rabo (2000)

Table 1 The hydraulic properties of the five model layers

Layer	Porosity (1)	Hydraulic conductivity (m/s)	Specific yield (1)
Sandy clay	0.25	5.00e-7	0.07
Limestone	0.18	1.50e-4	0.05
Sand, clay, gravel	0.30	9.00e-5	0.25
Marl	0.25	4.05e-6	0.25
Dolomite	0.18	7.80e-4	0.05

40 g/l on the coast. The most important boundaries are shown in Fig. 6.

The concentration and density of freshwater were taken as 0 and 1,000 kg/l, respectively, while the concentration and density of seawater were 35 and 1,027 kg/l, respectively.

Results and discussion

This study simulated the period from 1960 to 2010, using available data (Abed Rabo 2000; Abou Zakhem and Hafez 2003; Syrian Irrigation Ministry, unpublished) to follow both past and current seawater intrusion. The results of the model were then compared with measured field data in order to check its validity.

Possible solutions

As mentioned previously, although many methods of preventing seawater intrusion are available, two such procedures will be tested separately here. To determine the effectiveness of each method, their expected effects were simulated up to the year 2020, with the results from each simulation then compared with each other. The suggested places of injection wells and subsurface barrier are shown in Fig. 7.

The results calculated by the model approximate well with published data (Abou Zakhem and Hafez 2003), so it can be concluded that the model will produce sufficiently accurate simulations of both intrusion amelioration techniques and their effects on seawater intrusion (until 2020). Analysis of these results will then enable identification of the most effective control method.

Subsurface barrier

After installation of the subsurface barrier in the model (thickness 1 m, hydraulic conductivity 1.5 10^{-9} m/s), it can be observed that the inland movement of seawater intrusion is stopped, and in some places also pushed back seaward.

The projected change between 2010 and 2020 is shown in a section drawn through the first and second wells (Fig. 8).

From analysis of Fig. 8, the following points can be drawn:

1. The salinity of groundwater is significantly reduced between the first well and the subsurface barrier.
2. A decrease in salinity can be observed in all layers, although the decline in the fourth and fifth layers is less than that occurring in the other layers.
3. The salt concentration at the top of the wall is much smaller than at the bottom.

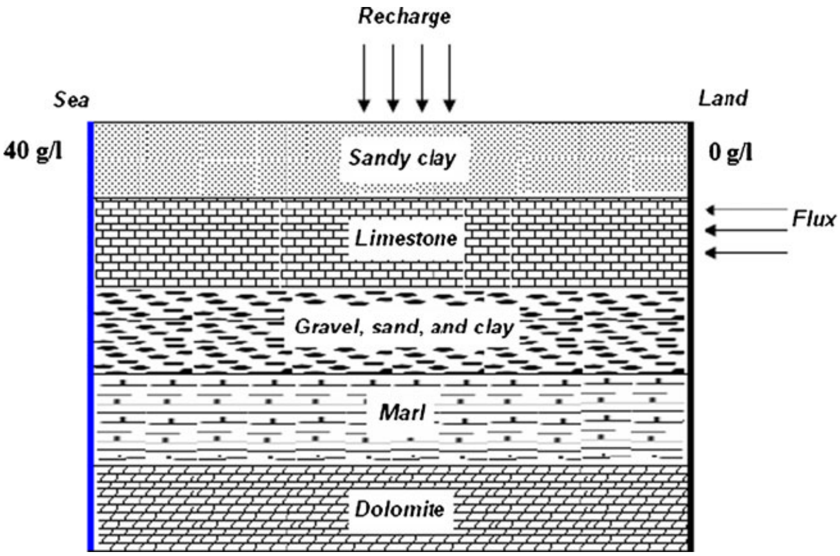
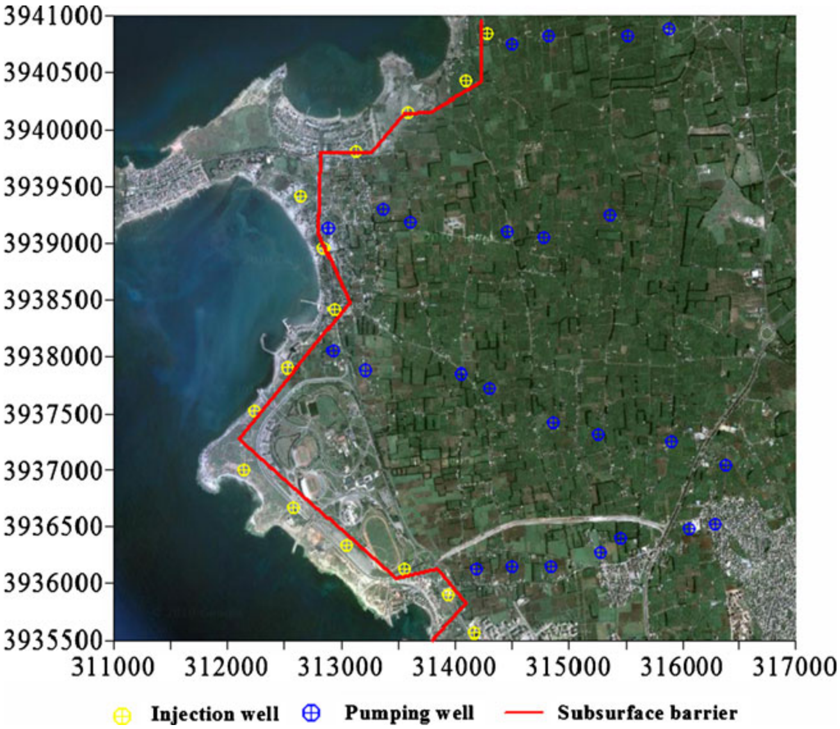


Fig. 6 Schematic cross-section of the modelled area, showing the most important boundaries used in the model

Fig. 7 Aerial photograph of the Damsarkho plain showing the locations of pumping and injection wells and subsurface barrier, with the co-ordinates given in metres (adapted from Google Earth)



4. The hydraulic balance values at the sea boundary illustrate the effectiveness of this technique, with the flow entering inland through this boundary decreasing by more than four times (Table 2).

According to these results, it can be concluded that use of a subsurface barrier represents a good solution preventing seawater intrusion into the Damsarkho plain region. However there is one disadvantage of the method, since with the water

Fig. 8 Simulated change in TDS concentration (mg/l) in the section drawn through the first and second wells after installation of a subsurface barrier (**a** 2010, **b** 2020)

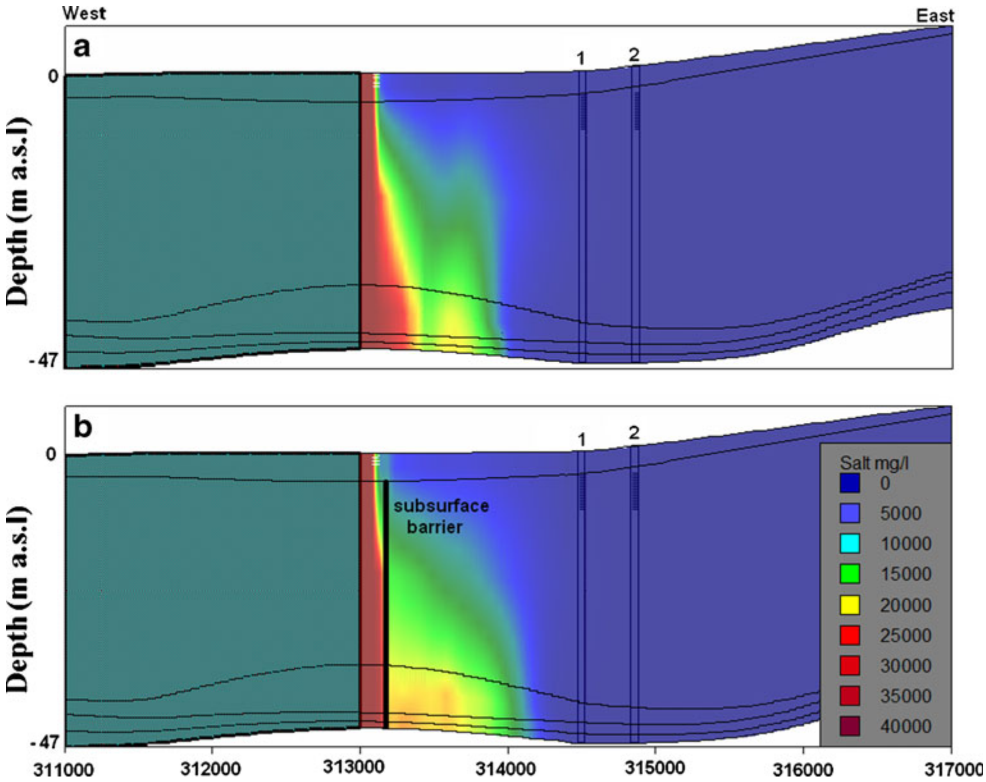


Table 2 Simulated hydraulic balance of the Damsarkho area

	Time	Layer	Sea		Recharge (m^3)	well		Storage	
			In (m^3)	Out (m^3)		In (m^3)	Out (m^3)	In (m^3)	Out (m^3)
a	January 2010	1	1	253	34,416	0	0	3,684	5,175
		2	2,178	171,777	30,972	0	0	9,459	4,161
		3	36,993	6,202	1,260	0	0	605	1,701
		4	420	50	540	0	0	88	146
		5	76,095	1,670	3,121	0	0	4,770	843
	August 2010	1	0.3	191	0	0	0	27,930	0.3
		2	2,187	12,761	0	0	73,146	74,607	0
		3	26,801	4,325	0	0	1,686	4,761	0.2
		4	311	37	0	0	0	357	0
		5	62,118	751	0	0	2,223	7,155	0
b	January 2020	1	0	64	8,820	0	0	3	14,931
		2	600	28,067	10,668	0	0	0	33,558
		3	5,385	1,428	465	0	0	0	2,072
		4	40	11	173	0	0	0	152
		5	5,955	648	969	0	0	0	2,775
	August 2020	1	0	59	0	0	0	26,412	0.3
		2	774	22,818	0	0	73,146	59,493	247
		3	6,247	581	0	0	1,685	4,002	0
		4	31	5	0	0	0	329	0
		5	7,980	243	0	0	2,223	5,016	0
c	January 2020	1	0.3	100	8,871	0	0	0	10,998
		2	1,524	54,210	10,611	0	0	0	42,795
		3	13,650	2,190	450	0	0	0	3,111
		4	105	21	175	0	0	0	203
		5	16,053	1,161	960	0	0	0	3,930
	August 2020	1	0	125	0	0	0	11,166	0
		2	633	97,248	0	62,370	80,910	49,008	0
		3	8,451	8,439	0	20,940	1,686	3,237	0
		4	59	87.9	0	4	0.3	204	0
		5	8,079	8,820	0	2,916	2,223	4,194	0

a Before using solutions, *b* after using subsurface barrier, *c* after using injection wells

table in the zone behind the wall rising due to the accumulation of water, this area may become swamp as a result.

Injection wells

Applied throughout the world in the prevention of saltwater intrusion, injection systems operate on the principle that water injected through a well increases pressure in the surrounding area, thus raising the level of the water table relative to the sea (Badon-Ghijben 1889; Herzberg 1901). Shallow injection wells were introduced in the model between the sea and production wells, with a screen in the range of −20 to −40 m, a distance of 500 m between them and an injection yield of about 11 l/s. The effectiveness of injection wells depends on several factors; the most important of which being the location and length of screen, the volume of injected water, as well as the hydraulic conductivity of the targeted layer.

The projected change from 2010 to 2020 after the introduction of an injection well is shown in a section drawn through the first and second production wells (Fig. 9).

From analysis of Fig. 9, the following points can be drawn:

1. The salinity of groundwater is significantly reduced, with the decline more marked than that achieved using the subsurface barrier.
2. As was the case with the subsurface barrier method, salinity decreased in all layers. This decline was steeper

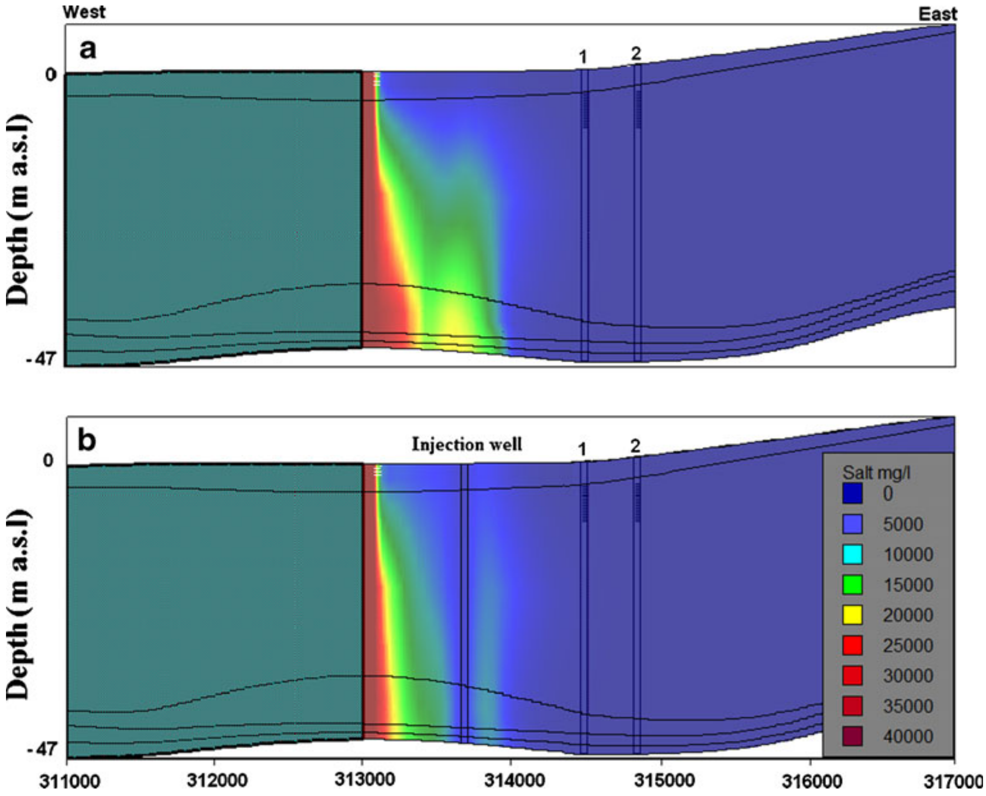


Fig. 9 Simulated change in TDS concentration (mg/l) in the section drawn through the first and second production wells after the introduction of injection wells (**a** 2010, **b** 2020). See Fig. 2 for the relative position of pumping and injection wells on the Damsarkho plain

in the second layer due to its greater thickness and hydraulic conductivity.

3. Changes in the hydraulic balance at the sea boundary clearly demonstrate the effectiveness of the injection well method, with flow entering landward through this boundary decreasing. This decline is greater in deeper layers (Table 2).

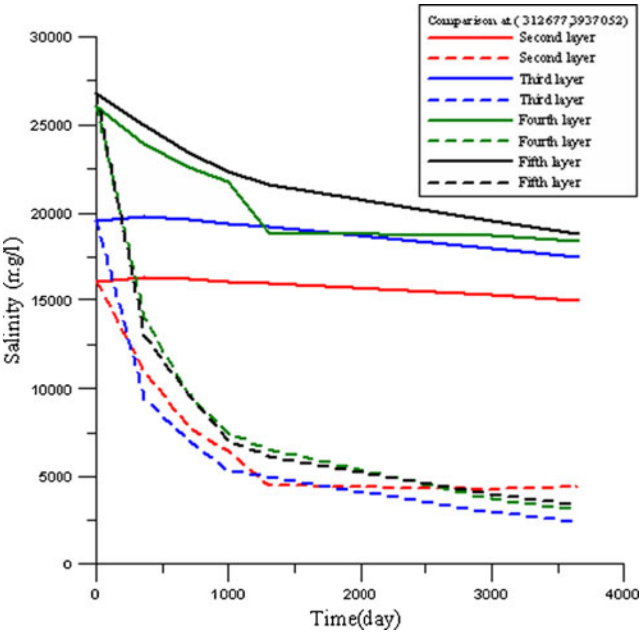


Fig. 10 Relative decrease in salinity with depth over ten years at the comparison point, after introduction of each seawater intrusion alleviation method. *Solid line* subsurface barrier, *dotted line* injection system

Comparison of seawater intrusion prevention techniques

In order to compare the effectiveness of the two solutions to seawater intrusion, salinity changes in all layers were tracked over a period of 10 years at a point 100 m from the subsurface dam and from the injection well (see Fig. 4 for location of comparison point). The results of this comparison are presented in Fig. 10.

Analysis of this comparison reveals that in both cases, the salt content is significantly reduced in all layers. However, this decrease is greater after introduction of the injection wells than the subsurface barrier.

Conclusion

The deterioration of groundwater quality in the Damsarkho coastal aquifer is mainly the result of saltwater intrusion. This intrusion, which has been caused by excessive groundwater abstraction and lowering of freshwater levels, has been amplified by the hydrogeological characteristics of the formation, with highly permeable areas of the aquifer in contact with the sea.

SEAWAT has proved to be a useful tool with which to simulate the transition zone of the Damsarkho coastal aquifer. The results obtained from the model have been used to identify locations for a potential subsurface barrier and a number of reinjection wells, as well as to predict the pattern of future intrusion, if the current excessive rate of abstraction continues.

From our results, it can be confirmed that both the subsurface barrier and injection systems represent good solutions to the seawater intrusion problem. Installation of a subsurface barrier is suggested as being the most economic, despite its initial high cost, since it would not have to be repaired over time. Although the injection well method is projected as being the most effective practical solution, problems remain regarding the source of the injected water and the potentially high future repair costs.

References

Abarca E, Carrera J, Sanchez-vila X, Voss CI (2007) Quasi horizontal circulation cells in 3D seawater intrusion. J Hydrol 339:118–129

Abed Rabo R (2000) Study of seawater intrusion into fresh groundwater in the coastal area. Masters Thesis, Damascus University

Abou Zakhem B, Hafez R (2003) Environmental isotopes study of the aquifer system in the coastal area (Syria). AECS-G/FRSR report no. 285, Syria

Arfib B, de Marsily G (2004) Modeling the salinity of an inland coastal brackish karstic spring with a conduit-matrix model. Water Resour Res 40:W11506. doi:10.1029/2004WR003147

Badon-Ghijben W (1889) Nota in Verband met de Voorgenomen Put boring Nabij Amsterdam [Notes on the probable results of well drilling near Amsterdam]. Tijdschrift van het Koninklijk Instituut van Ingenieurs, Den Haag, pp 8–22

Bear J (1972) Dynamics of fluids in porous media. Elsevier, New York

Bonacci O, Roje-Bonacci T (1997) Sea water intrusion in coastal karst springs: example of the Blaž Spring (Croatia). Hydrol Sci J 42 (1):89–100

Calvache ML, Pulido-Bosch A (1994) Modeling the effects of salt-water intrusion dynamics for a coastal karstified block connected to a detrital aquifer. Ground Water 32:767–777

Chiocchini U, Gisotti G, Macioce A, Manna F, Bolasco A, Lucarini C, Patrizi GM (1997) Environmental geology problems in the Tyrrhenian coastal area of Santa Marinella, Province of Rome, central Italy. Environ Geol 32(1):1–8

Civan F (2007) Reservoir formation damage, 2nd edn. Gulf Professional Publishing, Elsevier

El-Bihery MA, Lachmar TE (1994) Groundwater quality degradation as a result of overpumping in the Delta Wadi El-Arish Area, Sinai Peninsula, Egypt. Environ Geol 24(4):293–305

Giménez E, Morell I (1997) Hydrogeochemical analysis of salinization processes in the coastal aquifer of Oropesa (Castellón, Spain). Environ Geol 29:118–131

Harbaugh AW, Banta ER, Hill MC (2000) MODFLOW-2000, the US Geological Survey modular ground water model—user guide to modularization concepts and the Ground-Water Flow Process. US Geology Survey Open-File Report 00–92

Henry HR (1964a) Effects of dispersion on salt encroachment in coastal aquifers. Water-Supply Paper 1613-C, Sea Water in Coastal Aquifers: C71-84, U.S. Geological Survey

Henry HR (1964b) Interfaces between salt water and fresh water in coastal aquifers. Water-Supply Paper 1613-C, Sea Water in Coastal Aquifers: C35-70, U.S. Geological Survey

Herzberg A (1901) Die Wasserversorgung einiger Nordseebaeder {The water supply of selected North Sea towns}. ZF Gasbeleucht Wasserversorg 44:815–819

Iribar V, Custodio E (1992) Advancement of seawater intrusion in the Llobregat delta aquifer. In: Custodio E, Galofre A (eds) SWIM study and modelling of saltwater intrusion into aquifers. CIMNE–UPC, Barcelona, pp 35–50

Kovacs B, Szanyi J (2004) Hidrodinamikai és transzport modellezés I. és II. Miskolci egyetem, Miskoc. Hungary

Langevin CD, Guo W (2002) User's guide to SEAWAT, A computer program for simulation of threedimensional variable density groundwater flow. US Geological Survey, Open-File Report 01–434, Tallahassee, Florida

McDonald MG, Harbaugh AW (1988) A modular three-dimensional finite-difference ground-water flow model. US Geology Survey Technical Water-Resources Investigation 6- A1

Padilla F, Secretan Y, Leclerc M (1997a) On open boundaries in the finite element approximation of two-dimensional advection–diffusion flows. Int J Numer Methods Eng 40:2493–2516

Padilla F, Benavente J, Cruz-Sanjuliân J (1997b) Numerical simulation of the influence of management alternatives of a projected reservoir on a small alluvial aquifer affected by seawater intrusion (Almunecar, Spain). Environ Geol 33(1):72–80

Paniconi C, Klhaifi I, Giacomelli A, Tarhouni J (2001) A modelling study of seawater intrusion in the Korba coastal plain, Tunisia. Phys Chem Earth Part B Hydrol, Oceans Atmos 26(4):345–351

Petalas CP, Diamantis JV (1999) Origin and distribution of saline groundwaters in the upper Miocene aquifer system, coastal Rhodope area, northeastern Greece. Hydrogeol J 7 (3):305–316

Ponikarov VP (ed) (1966) Explanatory notes of the geological map of Syria, scale 1200000, sheets 1–37 XIX,1-36 XXIVSelkhozpromexport (1979) Hydrogeological and hydrological surveys and investigation in four areas of Syrian Arab Republic, vol. 1 and 2, Hydrology

Selkhozpromexport (1979) Hydrogeological and hydrological surveys and investigation in four areas of Syrian Arab Republic, vol. 1 and 2, Hydrology

Todd DK (1980) Groundwater hydrology, 2nd edn. Wiley, New York

van Beek CGEM, Breedveld RJM, Juhasz-Holterman M, Oosterhof A, Stuyfzand PJ (2009) Cause and prevention of well bore clogging by particles. Hydrogeology 17:1877–1886

Zhang C, Wang PP (1998) MT3DMS, A modular three-dimensional multispecies transport model for simulation of advection, dispersion and chemical reactions of contaminants in groundwater systems. Documentation and user's guide. Departments of Geology and Mathematics, University of Alabama