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ORIGINAL ARTICLE

The potential of using beach wells for reverse osmosis desalination in Qatar

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Abstract Qatar is an arid country, with limited water resources. The country relies on desalination of seawater to meet the increasing water demand for municipal and industrial needs, while the agricultural sector uses the precious fresh groundwater. Groundwater underneath Qatar is mostly saline or brackish with small lenses of fresh water in the northern part of the country. Brackish groundwater in Qatar has a Total Dissolved Solids of less than 10,000 mg/l, compared to seawater, which is 35,000 mg/l. Using brackish and saline groundwater for desalination via beach wells is less costly and more environmental friendly than direct sea water intake, which is being used in Qatar. The main challenge facing beach wells usage is their questionable capacity to provide enough quantities for desalination plants. This study investigates the optimal location and the maximum yield of beach wells in Qatar, using Sea Water Intrusion model (SWI2), coupled with MODFLOW. Model results show the maximum yield of wells at a depth of 100 m is 16,000 m^3 per km^2. This quantity is good enough for a medium size reverse osmosis plant. Based on hydrogeological settings, the proposed location for the beach wells is near Al-Khor town and to the north of it.

Keywords Desalination · Beach wells · Seawater intrusion · Qatar · MODFLOW · SWI2

Introduction

Qatar is a small country located in the eastern part of the Arabian Peninsula and extending into the Arabian Gulf. Its width varies between 55 and 90 km and its length is approximately 160 km. The total area of the country is around 11,500 km^2.

Qatar, as most arid countries, has limited natural water resources, which requires looking into other sources. Aquifer is the only source of natural water in the country, which is heavily over-exploited. Because of limited rainfall (less than 80 mm per year on average), groundwater recharge is very little (Kimrey 1985; Alsharhan et al. 1990). The average annual groundwater recharge from rainfall is approximately 60 million m^3 (Eccleston et al. 1981; Schlumberger Water Services 2009; Baalousha 2015, 2016a). This is less than one quarter of the current agriculture water demand, which is around 250 million m^3 per year, in addition to other sectors demand. The stresses on water resources increased further given the high rate of increase in Qatar population due to the influx of expats. Figure 1 shows the trend in population increase, which is expected to continue at the same rate until 2022.

Prior 1950, the population was less than 40,000 (Al-Mohannadi et al. 2003), and the residential communities relied on hand-dug wells in the shallow aquifer, where the groundwater was fresh (Macumber 2011). However, the population has increased sharply and the groundwater is obviously not sustainable. As a result, Qatar has focused on desalination as a more reliable source of water supply, especially with the discovery of large reserves of oil and gas, which provides the needed energy to operate desalination plants. The first desalination plant in Qatar came online in 1962 (Al-Mohannadi et al. 2003).

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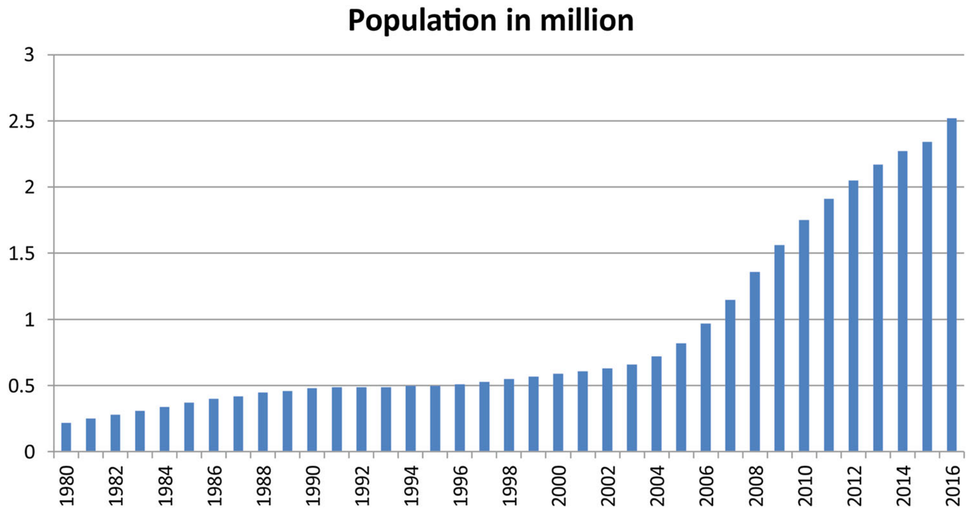

Fig. 1 Population trend in Qatar (based on data from trading economics: http://www.tradingeconomics.com/)

Table 1 Desalination plants and their capacity (Alrashid 2014)

Plant	Technology	Capacity (million m^3/day)
Ras Abu Fontas A	Multi-stage flash distillation (MSFE)	0.25
Ras Abu Fontas A1	Multi-stage flash distillation (MSFE)	0.20
Ras Abu Fontas B	Multi-stage flash distillation (MSFE)	0.15
Ras Abu Fontas B2	Multi-stage flash distillation (MSFE)	0.13
RLPC	Multi-stage flash distillation (MSFE)	0.18
Q power	Multi-stage flash distillation (MSFE)	0.27
RG	Multiple-effect distillation (MED)	0.29
Dukhan	Multiple-effect distillation (MED)	0.01
Total	1.48	

The produced water from desalination plants in Qatar meets 99 % of domestic demand. Nine main desalination plants provide a total of 1.48 million m^3 per day (or 540 million m^3 per year), as shown in Table 1. Around 30–35 % of this amount is lost as leakage, which contributes to the problem of high water table in Doha City (Qatar General Secretariat for Development Planning 2011). In addition to leakage, many construction projects in Doha, including mega projects such as underground train, are altering the water table. In many cases, increased groundwater level creates problems for these projects, so the brackish or saline groundwater is being pumped out and discharged away in open field or back to the sea, with no use of it.

The treated wastewater covers 14 % of the needs, and is being used mainly for landscaping. Despite the shortage in natural water resources, water consumption in Qatar is the highest in the world, with an average of 500 l per capita per day (Qatar General Secretariat for Development Planning 2011). This is due to many socio-economic factors and the development of the country over the last few decades. Locals in Qatar receive water and energy for free, whereas non-Qataris pay a subsidized price (Qatar General Secretariat for Development Planning 2011).

As shown in Table 1, all desalination plants in Qatar use thermal desalination technology, which consumes high energy compared to reverse osmosis, but require less pre-treatment. Direct intake from seawater is used to feed these plants. Given the high salinity of groundwater in all coastal areas of the country resulting from seawater intrusion, pumping this saline groundwater at the shoreline might help counter the seawater intrusion and protect the fresh groundwater resources. The decision whether or not to use groundwater wells as a source for a desalination plant depends on hydrogeological characterisation, aquifer yield and the plant size (David et al. 2009; WateReuse Association Desalination Committee 2011). One of the main challenges for saline/brackish groundwater desalination is the capacity of wells to provide the needed volumes of water as a feed for the plants. Another concern is the effect of brackish/saline groundwater abstraction on the quality of the fresh groundwater. In addition, deep beach wells might be costly, compared to surface water takes, if drilling is needed to large depths (Gille 2003). Other problems of beach wells could be those related to well installations and maintenance such as screen corrosion or boreholes collapse. These could be mitigated through regular monitoring and maintenance.

This paper looks into the hydrogeological settings of Qatar to assess the suitability and reliability of using beach wells for desalination. A three dimensional groundwater flow and seawater intrusion model was developed using the U.S. Geological Survey finite difference-based MODFLOW, with the Sea Water Intrusion (SWI2) package (Bakker et al. 2013). Calibrated hydraulic properties resulting from previous work on groundwater flow modelling were used to develop a variable density groundwater flow model. Various pumping rates are examined using MODFLOW-SWI2 model, and the effect on saline-groundwater interface is explored. This variable density model helps determine aquifer yield and the effect of saline groundwater pumping on the fresh-saline interface. It also helps identify the proper location for beach wells along the coast of Qatar.

Qatar hydrogeology and groundwater resources

Qatar topography is flat; with land elevation varies between 0 near the coast up to 107 m in some areas in the southwest. The geology of Qatar comprises limestone formations mainly from Tertiary period, whereas Quaternary deposits occur only in a form of beach deposits and Sabkha (Al-Hajari 1990), as shown in the surface geology map depicted in Fig. 2.

The main water-bearing geological formations in the country are three: (1) The Dam and Dammam Formation, (2) Rus Formation and, (3) Um Er Radhuma Formation. All these formations are composed of limestone layers with different degrees of dolomite, chalk, and conglomerate (Kimrey 1985; Schlumberger Water Services 2009; Al-Hajari 1990; Vecchioli 1976; Baalousha 2016b). The

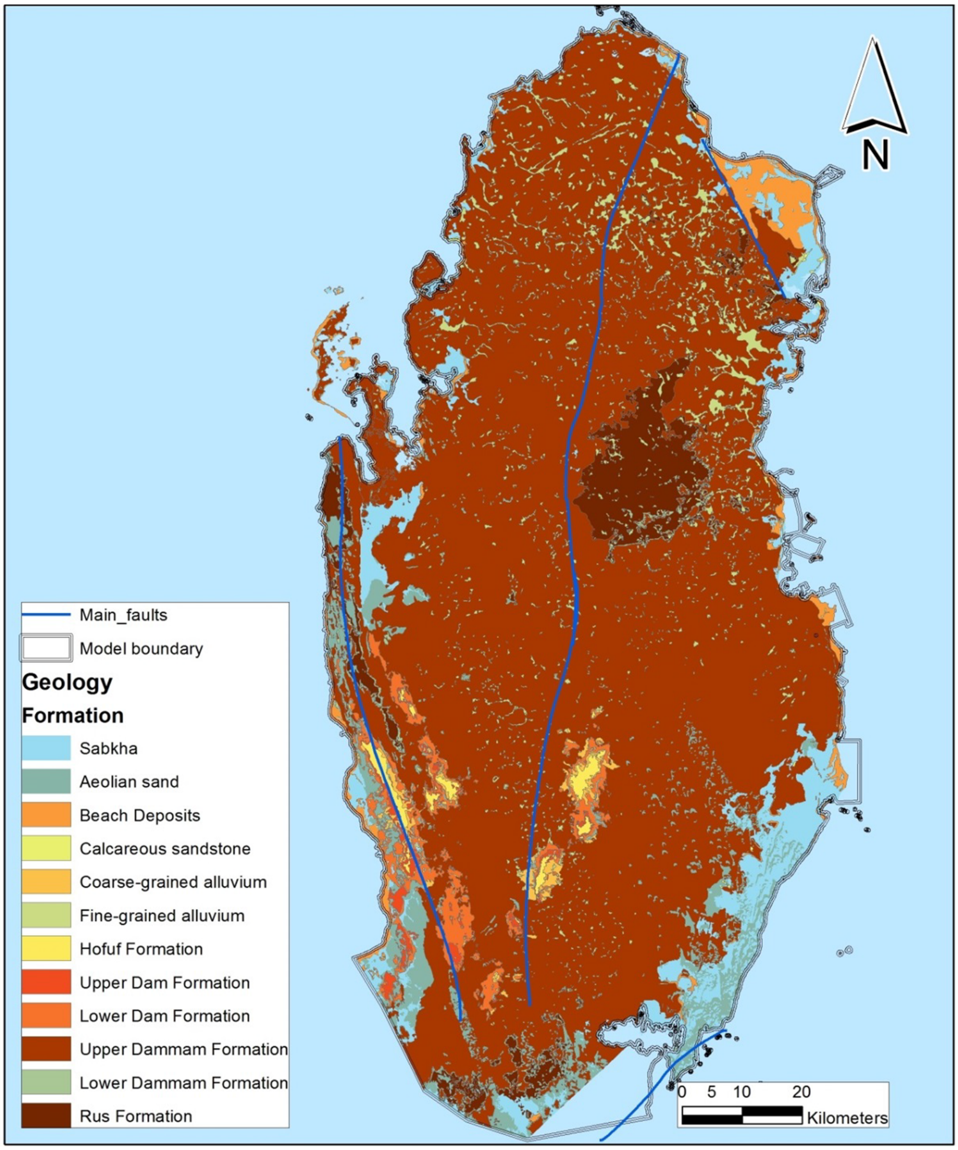

Fig. 2 Surface geology and model boundary (Baalousha 2016b)

uppermost formation, Dam and Dammam, has a thickness of less than 50 m and generally contains no water, except in low lands and in the coastal areas (Eccleston et al. 1981; Baalousha 2016b). Rus Formation (the middle layer) is thicker than the top one, with a thickness of up to 80 m. This formation contains gypsum deposits, in particular in the southern part of the country, making water quality poor due to dissolution of gypsum. The lower water bearing layer is Umm er Radhuma, which has a thickness of up to more than 300 m, and its water is generally brackish or saline.

Most wells penetrate the top two layers, as the quality deteriorates at greater depths. Wells are clustered in the northern part of the country, which contains fresh groundwater in a form of lenses overlaying brackish and saline groundwater. Most of groundwater abstraction is used to irrigate farms that scattered across the country, but mainly in the northern part. Due to overexploitation of groundwater resources, seawater intrusion took place and advanced inland to more than 15 km from the shoreline. In addition, upconing phenomena took place (Schmork and Mercado 1968), where brackish and saline groundwater flows upward into a pumping well. As a result, many wells were abandoned as their salinity becomes high.

The volume of the abstracted groundwater has increased from less than 50 million m^3, in the early seventies to more than 250 million m^3 at present (Eccleston et al. 1981; Schlumberger Water Services 2009). This is around five times the estimated groundwater recharge (Eccleston et al. 1981; Baalousha 2015). Due to heavy pumping and in absence of regulations (Al-Mohannadi et al. 2003; Qatar General Secretariat for Development Planning 2011), the groundwater level has dropped more than 10 m in some places (Schlumberger Water Services 2009).

Figure 3 shows the Total Dissolved Solids (TDS) in 1971 and in 2009 (Schlumberger Water Services 2009). The TDS varies between 1000 mg/l in the north and 10,000 mg/l near the coast. Comparing the two maps, it is obvious the fresh groundwater area has retracted in 2009 into a much smaller area in the northern part of the country, compared to 1971 (dark blue color in Fig. 3). This highlights the need to take urgent measures to counter the effect of continuous saline water encroachment and groundwater quality deterioration.

Sub-surface versus seawater intake

Brackish and saline groundwater wells have widely been used to feed reverse osmosis desalination plants all over the world. Beach wells are very common for this purpose, as they can provide large volumes of water and alleviate the problem of saline water intrusion. They also require less pre-treatment compared with seawater take (Baalousha 2006; David et al. 2009). Beach well are normally arranged in a form of galleries, which can provide reliable quantities and better quality saline water for desalination plants.

For example, desalination plant feed using beach wells has been used in Oman (David et al. 2009) with a capacity of 80,200 m^3/day. One of the largest desalination plant in the world (San Pedro Del Pinatar-Cartagena) in Spain, with a capacity of 34 MGD uses only groundwater intakes (WateReuse Association Desalination Committee 2011). Many other examples of usage of beach wells can be found in the US, the Netherlands (Stuyfzand and Raat 2010), Palestine, and Mexico. Reverse Osmosis plants require less energy than the Multi-stage flash distillation (Muñoz and Fernández-Alba 2008), which is currently being used in Qatar, but the shift will be made over time to RO technology (Darwish et al. 2013).

In addition to their function as a source of water, beach wells can be useful to counter saline water intrusion, as illustrated in Fig. 4. Before pumping, fresh and saline groundwater are static in equilibrium. According to Ghyben–Herzberg equation (Verrjuit 1968), the distance between the sea level line and the interface (z) is:

$$Z = \frac{\rho_f}{\rho_s - \rho_f} h \tag{1}$$

where ρ_f is the fresh water density, ρ_s is saline water density, and h is the distance from water table to sea level line. Knowing that the fresh water has a density of 1 kg/l, saline water density is around 1.025 kg/l, Eq. (1) yields to:

$$Z = 40h \tag{2}$$

Equation (2) means that a one unit drop in the water table (h in Fig. 4) results in 40 units upward movement of the fresh-saline water interface (distance z in Fig. 4).

When the saline groundwater is pumped from the zone below the interface, downward cone of fresh water develops, which is the opposite effect of upconing. This might counter the saline water intrusion effect. The distance z after pumping is larger than it before pumping, as the interface moves a distance dz downward (Fig. 4b).

It is well known that brackish water desalination has less adverse environmental impact than saline water desalination, and it should be given priority for desalination over seawater (Muñoz and Fernández-Alba 2008). Saline and brackish groundwater requires no pre-treatment as it is naturally filtered, so the desalination cost is reduced. Brackish groundwater may reduce the energy consumption by half due to its lower salinity (Muñoz and Fernández-Alba 2008), which reduces the adverse impact of burning fossil foil. Saline water intake may disrupt maritime activities and may kill organisms that collide with intake

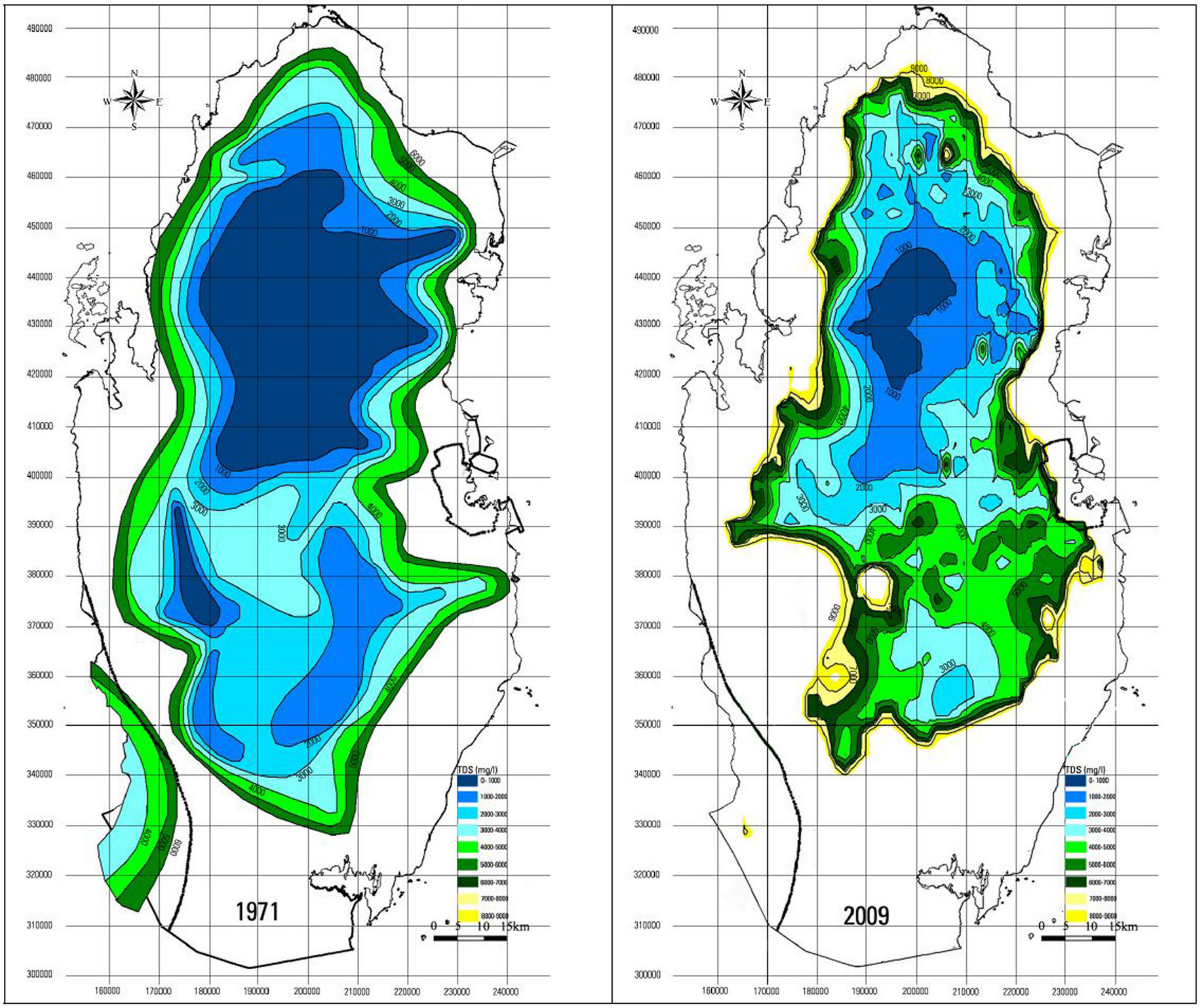

Fig. 3 Total dissolved solids (TDS) in groundwater in 1971 (*left*) and in 2009 (*right*) (Schlumberger Water Services 2009)

screen (DHV Water BV, BRL Ingénierie 2004). The resulting brine of brackish groundwater desalination has less impact on the environment than that of saline water. In addition, beach wells intake eliminates one of the main challenges for desalination using sea water intake, which is the algal bloom in the Arabian Gulf (Parka et al. 2013).

Model development

MODFLOW is a finite difference-based three dimensional flow model (Harbaugh et al. 2000), and it has widely been used for various flow problems (Harbaugh et al. 2000; Chiang 2005; Baalousha 2012a; Anderson et al. 2015; Baalousha 2012b). MODFLOW supports various packages representing hydrogeological features such as rivers, streams, well, etc. In this study, the saline water intrusion was simulated using the Sea Water Intrusion package (SWI2) with MODFLOW-2005 (Bakker et al. 2013). The SWI2 package simulates the saline-groundwater interface movement in a 3D environment using the different density flow considering the density difference between saline and fresh water. The reader can refer to (Bakker et al. 2013) for more details about the mathematical implementation of SWI2 package.

Groundwater flow model

The 3D conceptual flow model for saline water intrusion was developed based on the earlier work (Baalousha 2016b) of a groundwater flow model. The model comprises the three geological formations representing the three geological formations presented earlier in this study. The model domain was discretised into a uniform grid of 500

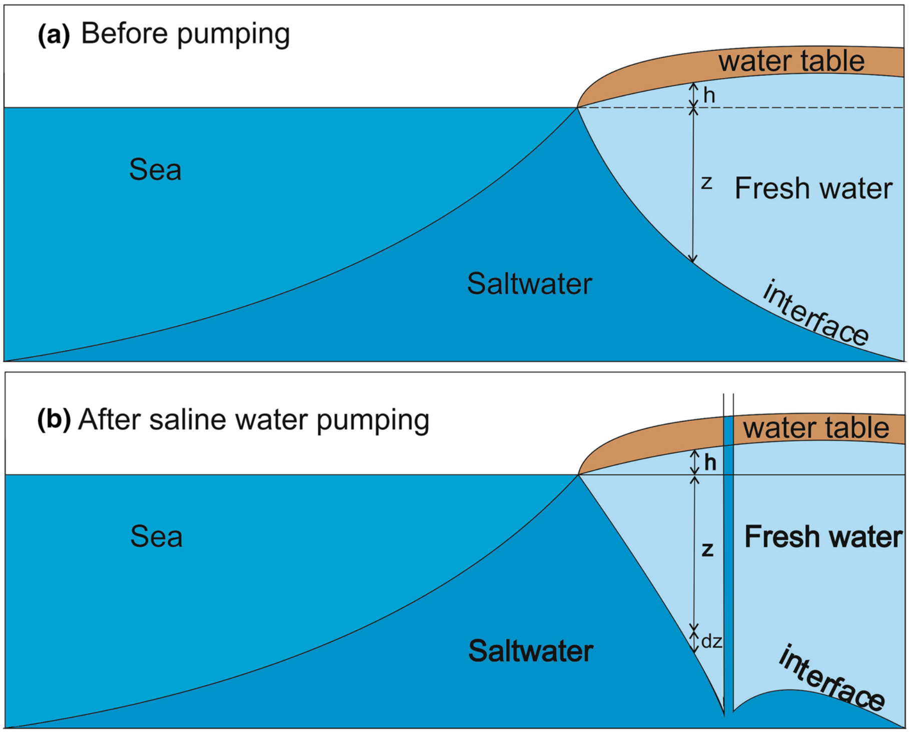

Fig. 4 Saline-fresh groundwater interface **a** before pumping and **b** after saline groundwater pumping

by 500 m, forming 208 columns and 390 rows. Hydraulic conductivity is the most important factor for beach wells and groundwater abstraction as they determine the capacity of a pumping well. Parameter Estimation and Uncertainty Analysis program (PEST) (Doherty 2005) was used to calibrate hydraulic conductivities and rainfall recharge.

Groundwater flow calibration results show the north and the north eastern parts of the aquifer have the highest hydraulic conductivity values. Figures 5, 6, 7 show the calibrated hydraulic conductivity of the three model layers from top to bottom; respectively. The calibrated hydraulic conductivity values reach more than 200 m per day in areas north of Doha and in the central part of the northern half of the peninsula. In the lower layers, maximum values of hydraulic conductivities reach more than 60 m per day (Baalousha 2016b). In general, coastal areas with high hydraulic conductivities are those to the north of Doha City.

These coastal areas of high hydraulic conductivities will be targeted for beach wells, as is explained in the following section.

Sea water intrusion (SWI2) model

The Sea Water Intrusion package (SWI2) is a modelling tool compatible with finite difference-based MODFLOW code (Bakker et al. 2013). It simulates the movement of fresh-saline groundwater interface, stratified flow and variable density flow. The advantage of SWI2 over other saline water intrusion models is its time efficiency, especially for regional scale models (Dausman et al. 2010).

SWI2 Package requires initial saline-fresh groundwater interface, which was identified based on the TDS survey (shown in Fig. 3). Other parameters are the same as in the flow model (Baalousha 2016b), which include the calibrated hydraulic conductivities and the calibrated rainfall recharge. Beach wells were introduced into Modflow-SWI2 model, which supports different types of wells including, including horizontal, radial, vertical and slant wells (Bartak et al. 2012; Cartier and Corsin 2007). The most economic ones are the vertical wells, so they were used. A group of vertical wells were placed in the north-eastern coast of Qatar, as shown in Fig. 7. Wells' maximum depths are 100 m below mean sea level, with screens in the last 20 m. The model was run for 20 years, with daily time steps.

Results and discussion

The variable density model was run first without pumping to see the saline-fresh groundwater interface and levels prior pumping. Figure 8 shows the regional groundwater levels in the plan view, which vary between 0 near the coast up to more than 14 m (above mean sea level) in the centre of the northern part of the country. The locations of the proposed beach wells are also shown on the map, with two cross sections through the two selected locations.

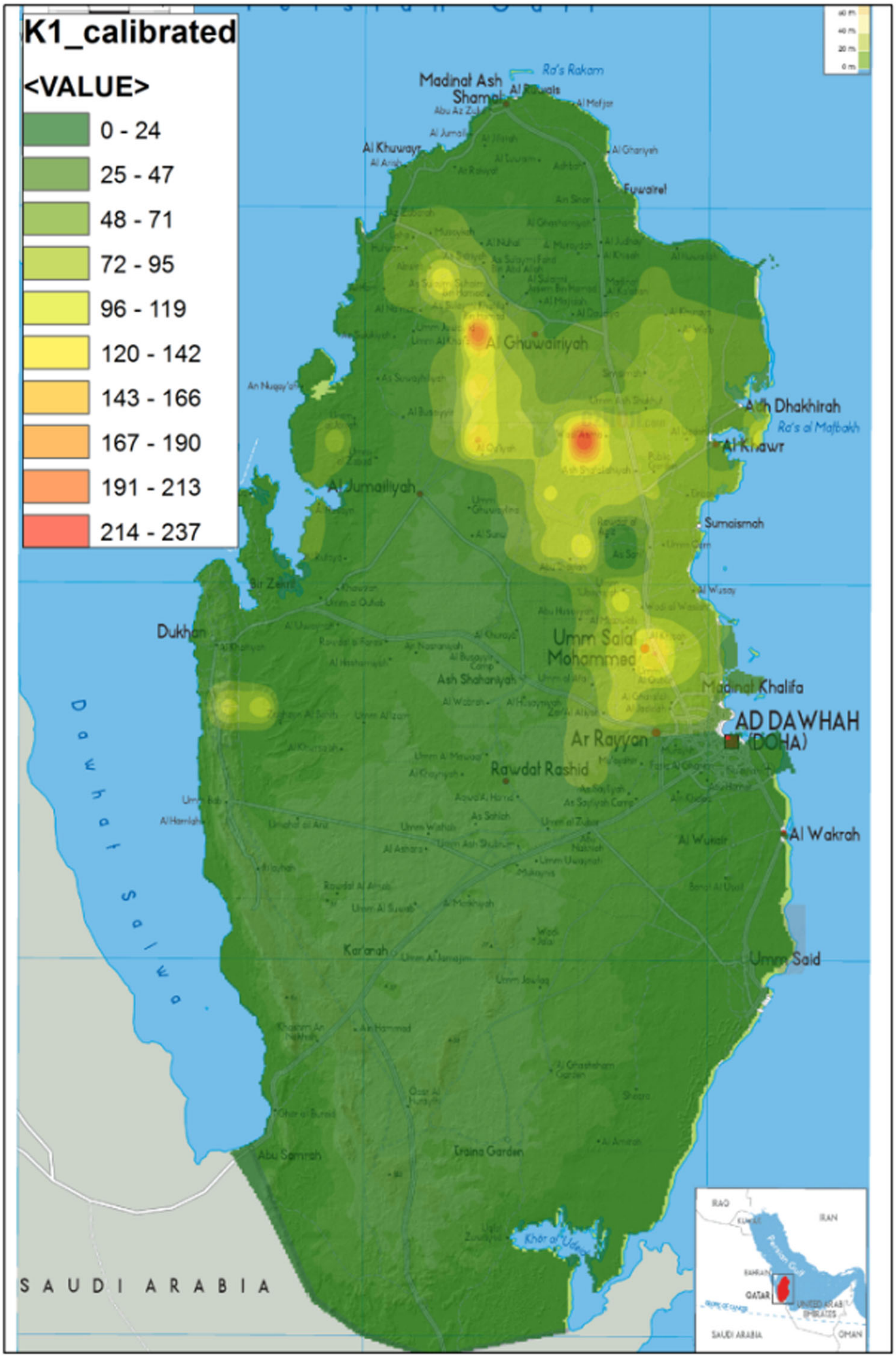

Fig. 5 Calibrated hydraulic conductivity values (m/day) for the top layer of the model (Baalousha 2016b)

Before pumping, the interface between fresh and saline groundwater is advanced inland and not affected by wells. Figure 9 shows a cross section A–A, which cuts through wells near Al-Khor town. The blue areas show the fresh groundwater zone and the area underneath shows the saline groundwater. Pumping wells appear in the right of the section, with screens located in the saline groundwater zone. The legend shows the fresh and saline groundwater head, relative to mean sea level, which corresponds to those in the plan view shown in Fig. 8.

After several iterations, and given the hydrogeological settings of Qatar, it was found that the maximum pumping rate possible is 4000 m^3 per model cell per day, which is equivalent to 1600 m^3 per day per km^2. The changes in

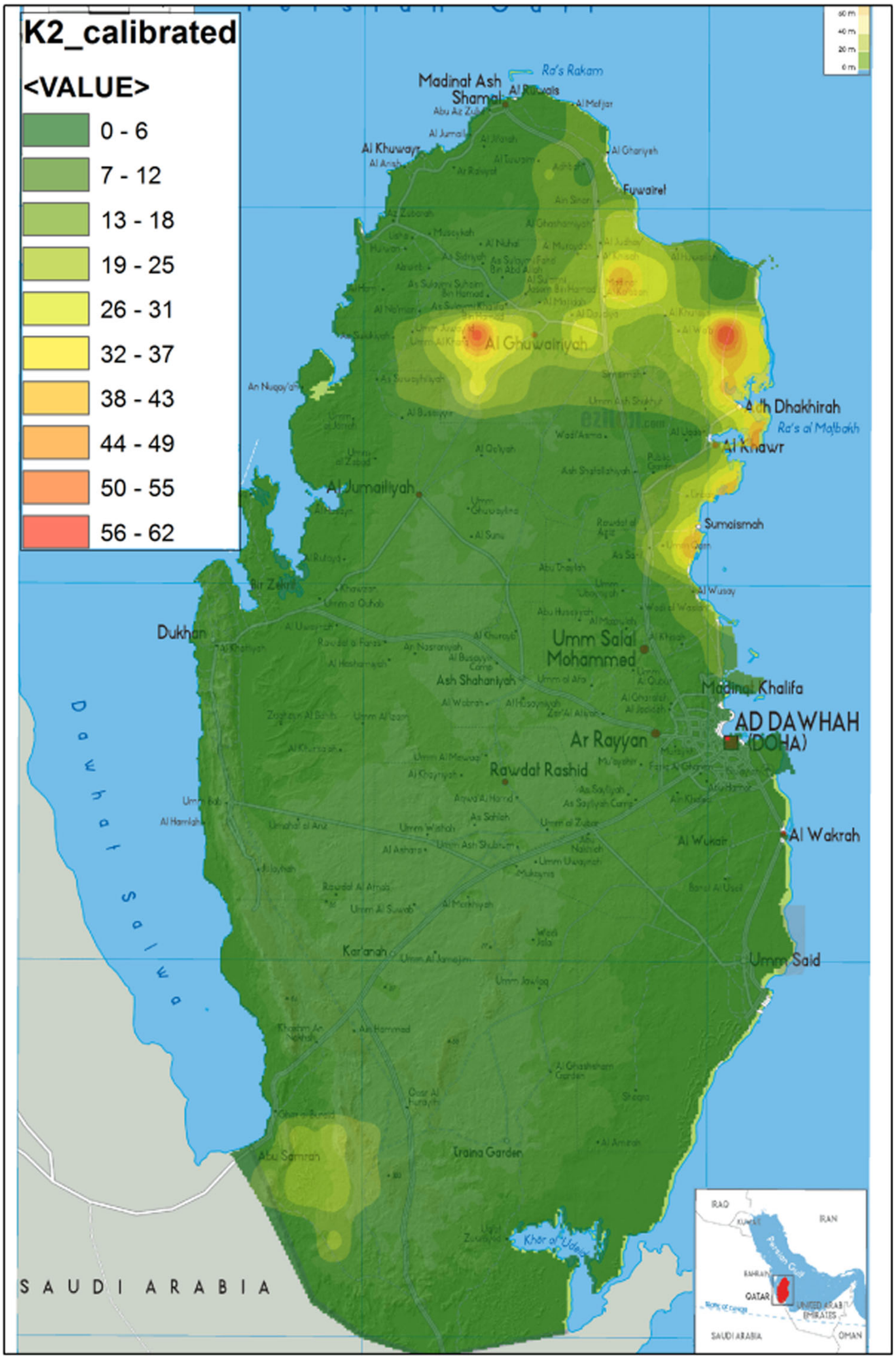

Fig. 6 Calibrated hydraulic conductivity values (m/day) for the middle layer of the model (Baalousha 2016b)

saline-groundwater interface are obvious after 20 years of continuous pumping at a rate of 4000 m^3/day for each well, as shown in the lower picture of Fig. 9. The cone-shaped interface is clear around the wells, which indicate the fresh groundwater pushes the saline water downward as a result of saline groundwater pumping (opposite effect of upconing phenomena).

Similar behavior has been found at cross section B–B, as shown in Fig. 10. The interface has moved downward as a result of saline water pumping, pushing more fresh water down. In both cases, the maximum drawdown at well-head was found to be 40 m after 20 years of pumping.

It should be noted that the number of wells and their configuration can be changed as long as the maximum

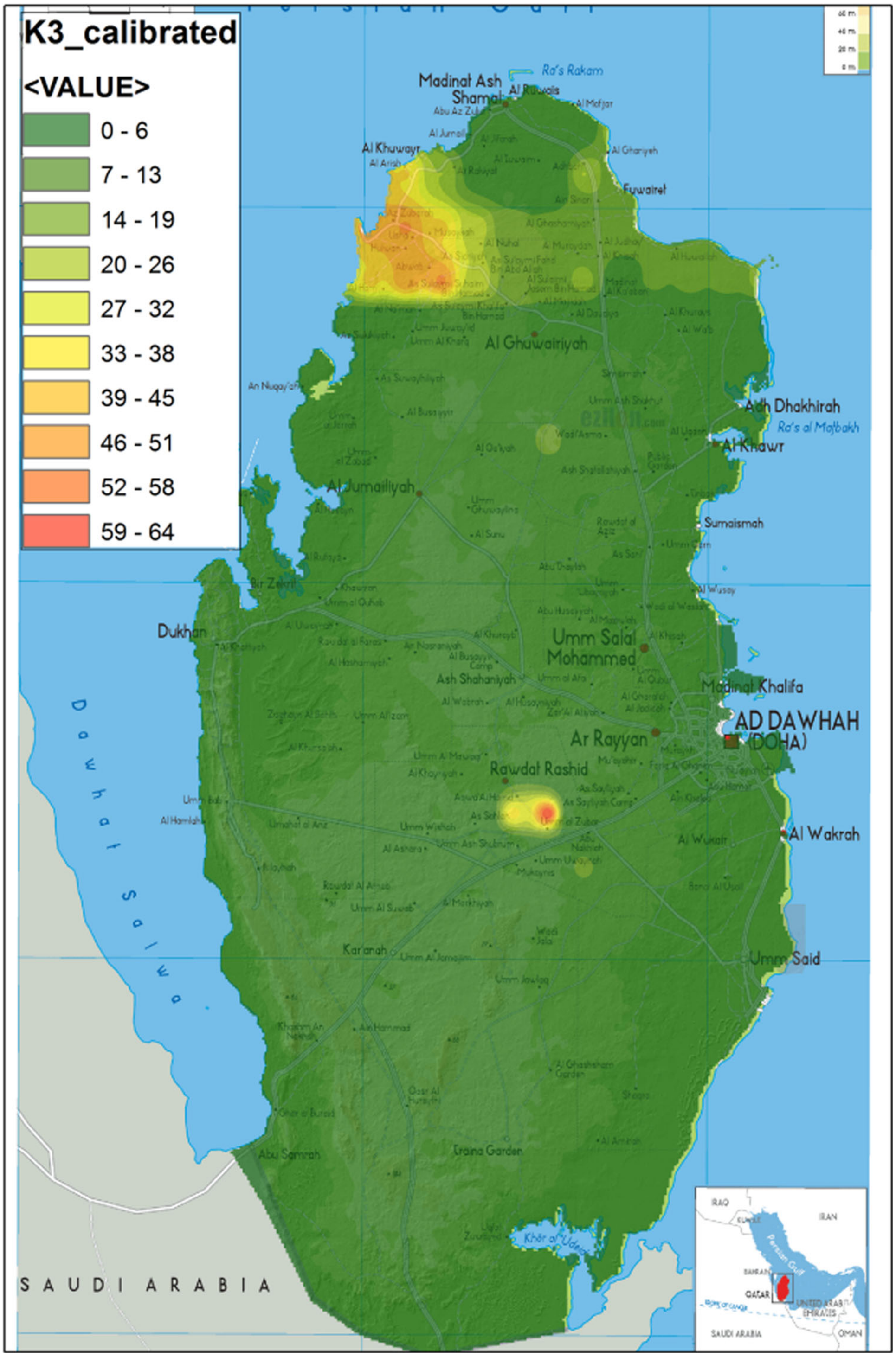

Fig. 7 Calibrated hydraulic conductivity values (m/day) for the bottom layer of the model (Baalousha 2016b)

abstracted volume of 16,000 m^3 per km^2 is maintained. The quantity of abstracted water can be significantly increased if the depths of wells increased. A feasibility study might be needed in this case to decide whether to increase the depths or not, and to compare the cost of drilling deeper than 100 m with the cost of direct sea water intake.

Conclusions

This study explores the possibility and the yield of beach wells for reverse osmosis desalination plants. The use of sub-surface water as intake for desalination plants has a great benefit as it reduces the environmental impact and

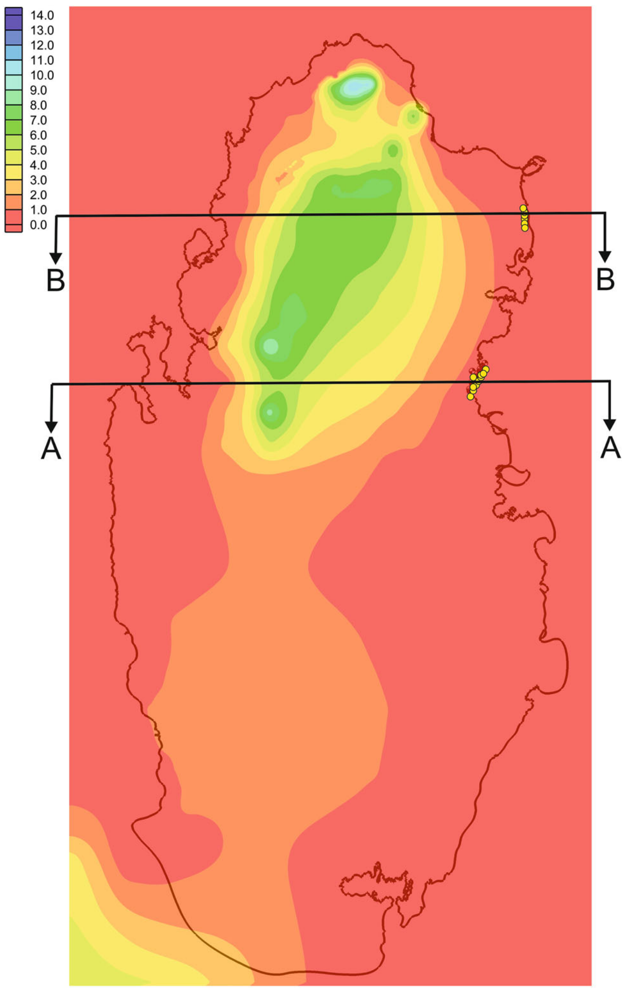

Fig. 8 Simulated groundwater head (meters above mean sea level), location of beach wells and cross-sections

provides better water quality. Examples of beach wells in many countries around the world show that no pre-treatment is required for reverse osmosis plants. One factor that may hinder the decision of using beach wells is their capacity to provide enough quantities of water to feed the plants.

A numerical variable density flow model has been developed to test the effect of pumping saline groundwater on both fresh and saline groundwater. The proposed locations of beach wells were selected based on hydrogeological settings and thickness of the aquifer, and the possible effect on fresh water quality. To maximize wells yield, the proposed wells penetrate the thick lower aquifer, namely Um er Radhuma Formation. As drilling cost increases with depth, the proposed maximum depth is 100 m, with screens in the last 20 m of the well.

Numerical modelling results show the wells at the proposed location can supply 16,000 m^3 per day per km^2. Well spacing in this study was 500 m, which corresponds to model grid size. The spacing and configuration can be changed but maintaining the same volume per km^2. Model results show the use of beach wells can counter the saline water intrusion, which deteriorates the fresh groundwater reserve in Qatar.

The best location for beach wells, given the hydrogeology of Qatar, is near Al-Khor town and to the north of it along the coastline. The well yields can significantly increase if the depth is increased and/or if horizontal wells are used, but this might increase the cost. The series of beach well should be drilled within 100 m of the coastline and it is recommended to use 10 in. well screens or larger.

This capacity of 16,000 m^3 per km^2 might be useful for a medium-size reverse osmosis plant, like the MED plant currently operating in Dukhan Township, and they can be used to artificially recharging the aquifer. In addition to being more environmental friendly than the direct sea water intake, beach wells can counter the

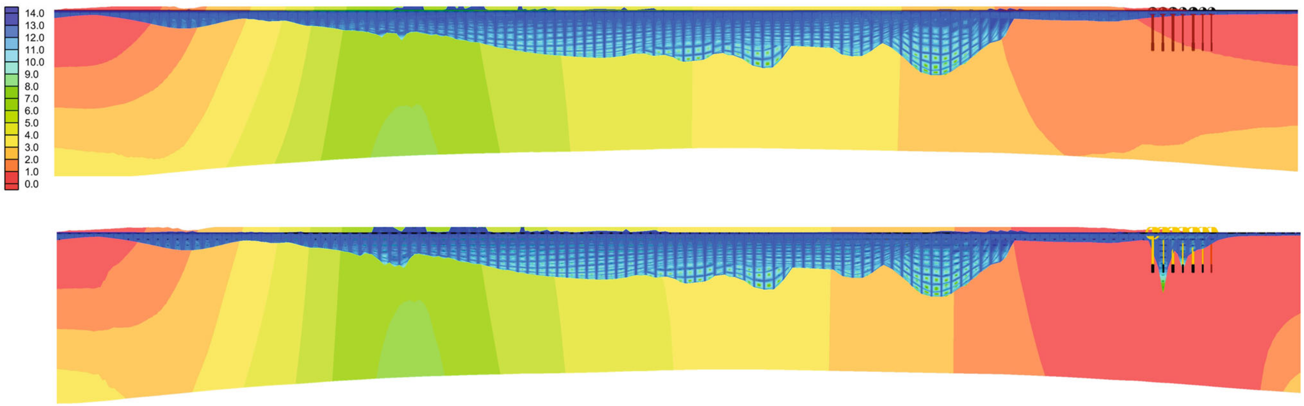

Fig. 9 Cross section A–A showing the saline-fresh groundwater interface, with groundwater levels in the background. The *top* section is before pumping and the *bottom* one after 20 years of pumping

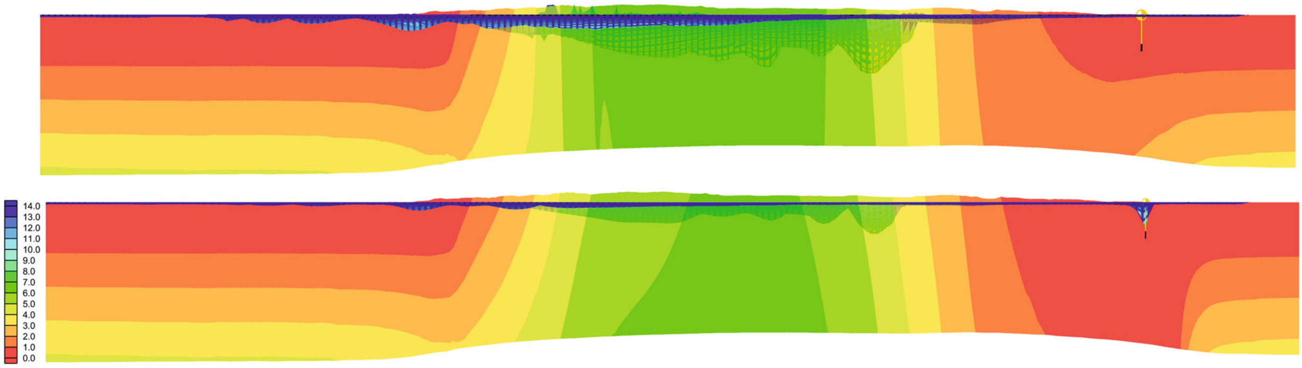

Fig. 10 Cross section B–B showing the saline-fresh groundwater interface, with groundwater levels in the background. The *top* section is before pumping and the *bottom* one after 20 years of pumping

saline water intrusion, solve the problem of high water table in coastal areas and enhance groundwater quality.

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