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Numerical Simulation of Groundwater Flow and Solute Transport for the Northern Batinah Area, Oman

Medhat El-Bihery[1, 2], Abdel Aziz Al-Mushikhi[2], Salim Al-khanbashi[2], Ahmed Al Saeedi[2], Ali Mohsin Al-Lawati[2] and Maqboul Al-Rawahi[2]

1. Department of Hydrogeology, Water Resources Research Institute, National Water Research Center, Cairo 13411, Egypt

2. Department of Surface Water and Groundwater Assessment, Ministry of Regional Municipalities and Water Resources, Muscat 113, Sultanate of Oman

Abstract: The northern Batinah occupies approximately 12,150 km^2 in the north of Oman Quaternary deposits and Neogene's upper Fars form the aquifer units. MODFLOW compatible MT3D was used for simulation development of the area. It can be concluded that: (1) The groundwater in the Batinah area generally flows from the south-west to the gulf of Oman in the north-east; (2) Recharge takes place through direct recharge from rainfall and wadi flow by about 902 × 10^3 m^3/day; (3) The hydraulic conductivity attains a relatively wide range between 0.02 m/day and 78 m/day and 0.02 m/day and 60 m/day for the Quaternary and Fars respectively; (4) There is probably less potential for groundwater abstraction in the northern part of the area; (5) The water level decreased by about 6 m over 24 years and (6) The increase of salinity most likely due to a contribution of sea water intrusion from the gulf along the coast. It is recommended that: (1) automatic well control system should be installed to accurate measurements of abstraction; (2) further analysis under different future scenarios should be made and (3) formulate an integrated management plan for the basin.

Key words: Groundwater, numerical modeling, Batinah, Oman.

1. Introduction

Northern Batinah area lies in the north-western part of Oman (Fig. 1). It includes eighteen wadi basins which occupy an area of approximately 12,150 km^2. The area represents one of the most promising areas for sustainable development especially for agricultural activities and animal production.

The groundwater within the north Batinah area has been extensively developed, up to date, provides agricultural, industrial and domestic supplies. Moreover, the area faced drought in the last decade. Such conditions are reflected on the groundwater levels in the area. During the early 1980's, the water levels declined to below sea level in the coastal zone and continue to fall with the result that sea water intrusion has taken place and emerged as major management issue. In this respect, the evaluation of groundwater resources within this area is crucial.

The basic requirement is to apply groundwater modeling techniques to evaluate these resources. Numerical modeling has been initiated to study the flow system and to evaluate key parameters. In order to build the model, geological, hydrological and hydrogeological data were collected and analyzed. The modeling work described herein was undertaken to advance the understanding groundwater flow in the north Batinah area. This paper describes the application of the groundwater by MODFLOW and MT3D with respect to simulating the aquifer system behavior. The results of simulation for calibration and verification are presented. The work is also provided a general insight related to groundwater flow in addition to a clue of salinity variation.

2. Material and Methods

MODFLOW compatible MT3D [1] is a public domain groundwater modeling software package

Corresponding author: Medhat El-Bihery, professor, research field: groundwater modeling. E-mail: melbihery@gmail.com.

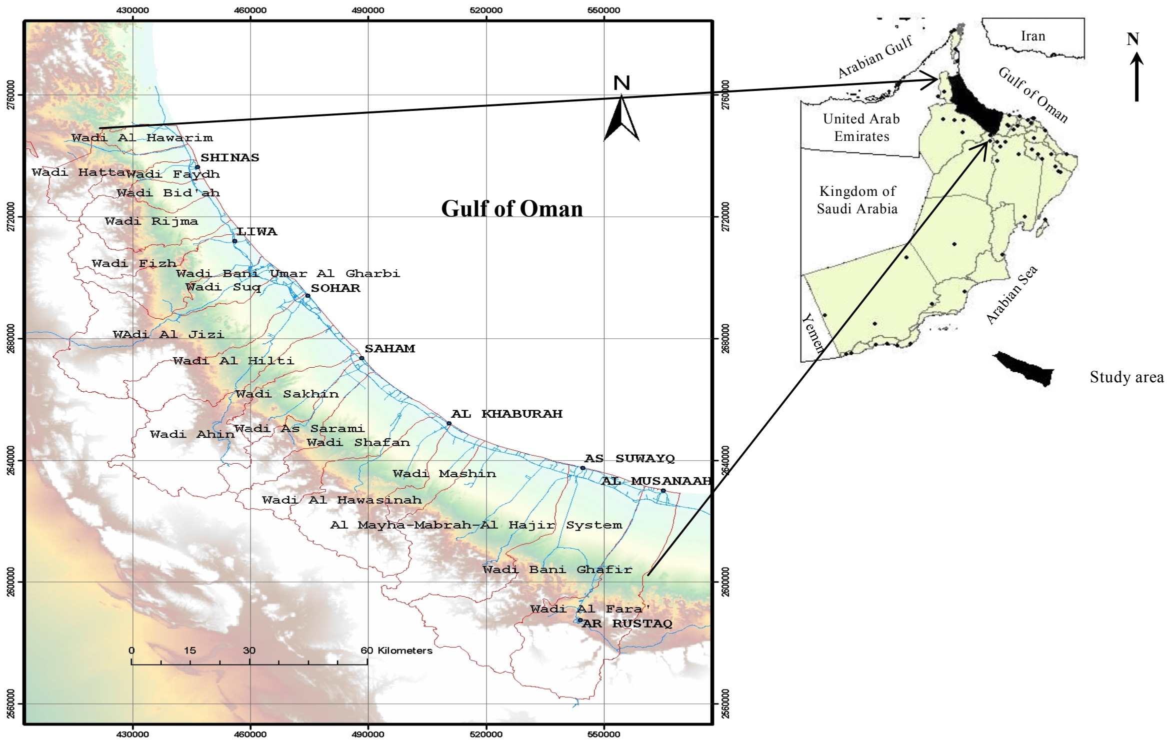

Fig. 1 Location map.

which is used to evaluate the alluvium and the Neogene's upper Fars aquifer system of north Batinah area. In this study, a pre-processor and a post-processor (GMS) are used to interface with MODFLOW. GMS stands for Groundwater Modeling System and is developed by the Environmental Modeling Research Laboratory of Brigham Young University [2].

2.1 Conceptual Model

The main features of the hydrogeological conceptual model (Fig. 2) show that beneath the north Batinah alluvium and upper Fars form the main aquifer system. They extend from the frontal mountains on the southern west edge of the area to the major outflow boundary at the coast. Some parts at the coast form a saline inflow, particularly adjacent to areas of concentrated groundwater pumping. The coastal outflow and inflow will be represented by a specified head boundary in the model. A specified concentration also represents the coastal boundary.

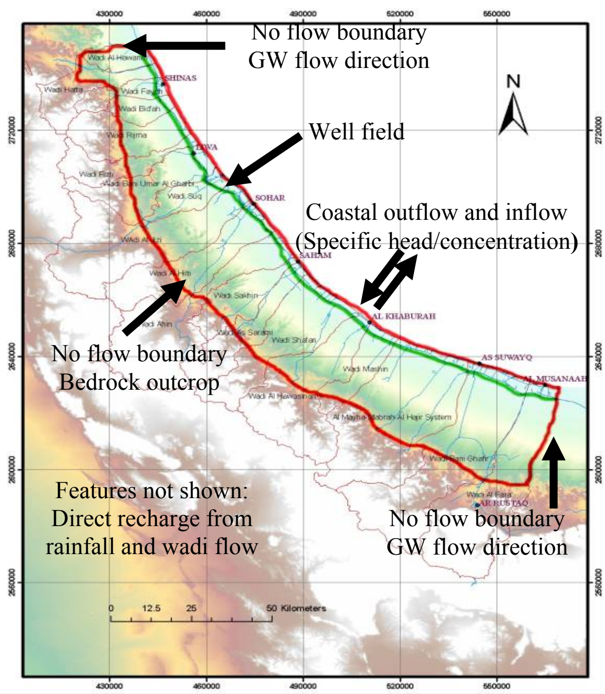

Fig. 2 Conceptual model.

The thickness of alluvium and upper Fars generally range from 10 m to 150 m and from 110 m to 580 m respectively. However, upper Fars pinches out north of the area. The two aquifer units are underlain by the low permeable middle Fars unit (about 50 m thick). The middle Fars and underlying low permeable units are uplifted and bounded the area along the southwest side. So, it is modeled as no flow boundary. At upper most northwest and lower most southeast sides of the model, the boundaries are chosen in such a way that follows the general direction of groundwater flow. On the plain, there is a direct recharge from rainfall and wadi flow leakage. There is also abstraction from wells concentrated mainly at the coast.

2.2 Inverse Model Using Pilot Point Method

In the present work, it is assumed that the hydraulic conductivity and recharge are unknown flow parameters. To parameterize the hydraulic conductivity spatially distributed random variable, the pilot point method is used. Recharge is also assumed spatial variable, but zonation is adopted as a parameterization technique to convert its spatial variability to zones of uniform values. In GMS, several alternatives are available to solve the inverse problem. Here PEST is used [3] to accomplish the calibration of this work.

2.3 Steady State Calibration

The water level measurements done in 1982 have been used to calibrate a steady state model of the area. Calibration target is to calibrate the spatially variable hydraulic conductivity and recharge. Calibrated recharge values would reflect recharge due to rainfall and returned flow from irrigation water in agricultural areas.

2.4 Transient State Calibration

Water level measurements collected in January 1995 and January 2006 has been used to calibrate a transient state model. Two historical groundwater abstractions were estimated at 1,046,114 m^3/day and 1,110,791 m^3/day in 1995 and 2006 respectively. The constant head boundary has been changed to time-variant head in the transient calibration. The model simulates response from 1982 to 2006. Like the steady state calibration discussed earlier, transient calibration of the hydraulic conductivity is obtained using the pilot point approach. Comparing the hydraulic conductivity obtained from this calibration with that of steady state, it can be noted that the main features are the same. This is especially noticeable for high hydraulic conductivity zones at the southeast, northwest and in the middle of the model.

3. Results and Discussion

3.1 Topography and Geomorphology

The topographic surface of the north Batinah area drops rapidly from 3,000 m.a.s.l. south of AR Rustaq at the mountains in the upper catchments of the study area (Fig. 1) to 100 m.a.s.l. towards the north at the base of the piedmont and then to a sea level at the coast. During runoff periods, wadi channels become fully saturated and they act as principal conduit for transmitting an amount of water from the mountains to the alluvial coastal plain.

Two distinct geomorphologic zones can be recognized in the area by its geological setting—hard rock and soft rock [4]. The first zone is mountainous upper basins dominated by volcanic rocks, shale and limestone. The second is alluvial fans and a plain that extends over lower basins to the coast. The area was divided into four geomorphologic zones developed from the mountain to the coast [5]. These zones namely major mountains, frontal mountains, marginal wadi plains and sand/gravel plain. Practically, the area can be divided into only three zones which are major mountains, frontal mountains and coastal plain. The coastal plain is the target area of the present work.

3.2 Geology

3.2.1 Geologic Characteristics

The north Batinah area consists of different geologic units of varying hydrogeological significance.

Due to uplift and erosion processes, most of the geologic units are exposed forming an anticline structure in the south of the area. The units range from Cretaceous to Quaternary (Fig. 3). The oldest rocks have a hydrogeological importance where they are more resistance to erosion, giving the chance of surface runoff occurs. The Hadhramaut Group was first described in Saudi Arabia by Robert Powers [6]. This group was formed of strong grey limestone interbedded with shale which was found under the coastal plain and outcropping at the frontal mountains.

The Fars Group has no distinguishing outcrops in the study area. It contains three principal subdivisions of Neogene's age lower, middle and upper Fars [7-9]. The Neogene's Fars Group lies unconformable on Hadhramaut Group. The lower (marine) and middle Fars Formations are composed of shale and mudstone. The upper Fars Formation (continental facies) is formed of dolomites cemented conglomerate. It forms with the alluvium the aquifer system in the area. Its thickness ranges between 114 m and 582 m.

The Quaternary-aged varicolored sand and gravel commenced deposition in a subsiding continental margin and displays a well developed sequence of alluvial fans and fan remnants [10]. It was described by Bureau Research Geologieet Minerai [11, 12] as a conglomerate with a clay-sand matrix. Its thickness ranges from 8 m to 147 m.

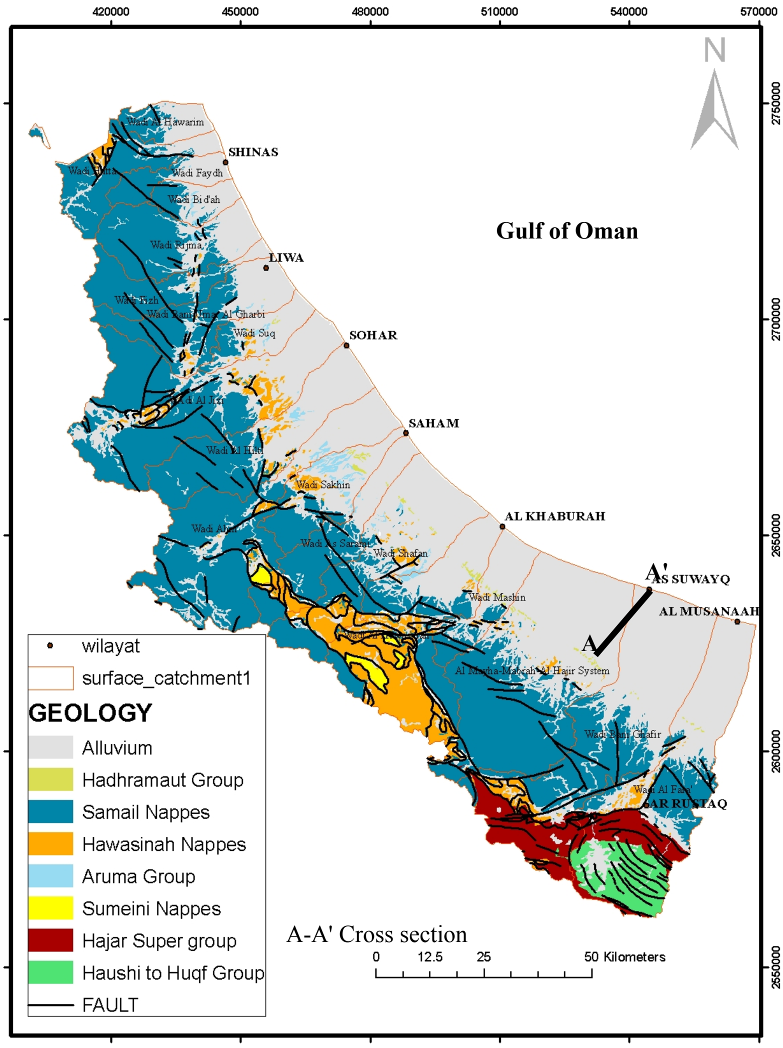

Fig. 3 Geologic map [9].

3.2.2 Structural Framework

The uplifting during late Eocene, after the deposition of Hadhramaut Group, formed the high mountains (anticline) present south-west of the area. The Fars units are subsequently uplifted, became thinning then pinching out near the Jabals towards the south-west (Fig. 4). As a result, the chance of subsurface recharge to the alluvium/upper Fars units is nonexistent. However, the surface recharge moves from the Jabals to the coastal plain via wadi channels. A syncline can be deduced from the outcrops of the Hadhramaut rocks present at the frontal mountains and gravity map [13]. The deformation of Hadhramaut Group formed this syncline passing at the coastal line that was subsequently filled with Fars units and alluvium.

3.3 Hydrogeology

Unlike both Quaternary and upper Fars units, the pre-upper Fars units provided only minor yields and are considered to be of minor importance. The yield from the boreholes tapping the pre-upper Fars units was less than 3.5 m^3/day, indicating that their aquifers poor in the Batinah area [9]. On the other hand, the yield of boreholes completed to the alluvium and the upper Fars units ranges from 480 m^3/day to 7,420 m^3/day and from 320 m^3/day to 3,360 m^3/day respectively. Consequently, it can be concluded that the pre-upper Fars units are generally impermeable and that it can be considered to form the base of aquifer system of north Batinah area. Based on the fore-mentioned data, it can be concluded that the alluvial deposits and upper Fars unit are the most important aquifers in the north Batinah area. Therefore, these two aquifer units are subjected to the simulation of the present work.

The results of pumping tests conducted on some boreholes existed in the area showed that the transmissivity (T) value ranges from 5 m^2/day to 3.2×10^3 m^2/day. The average T value of alluvium and upper Fars is 640 m^2/day and 281 m^2/day respectively. The value of hydraulic conductivity (K) ranges between 0.1 m/day and 83.5 m/day except only one well attains a value of 141 m/day. It was noticed that the K value is highly changed. The very low conductivity is due to the high content of clay or silt in addition to the well developed cementation process. Extensive cementation may locally transfer an alluvial channel into a hydraulic barrier, bringing groundwater to the surface. The storativity (S) value of the upper Fars unit is 1.2×10^{-3} and the specific storage (S_s) is 1.94×10^{-5} m^{-1} where the specific yield (S_y) of alluvium is 3.5%.

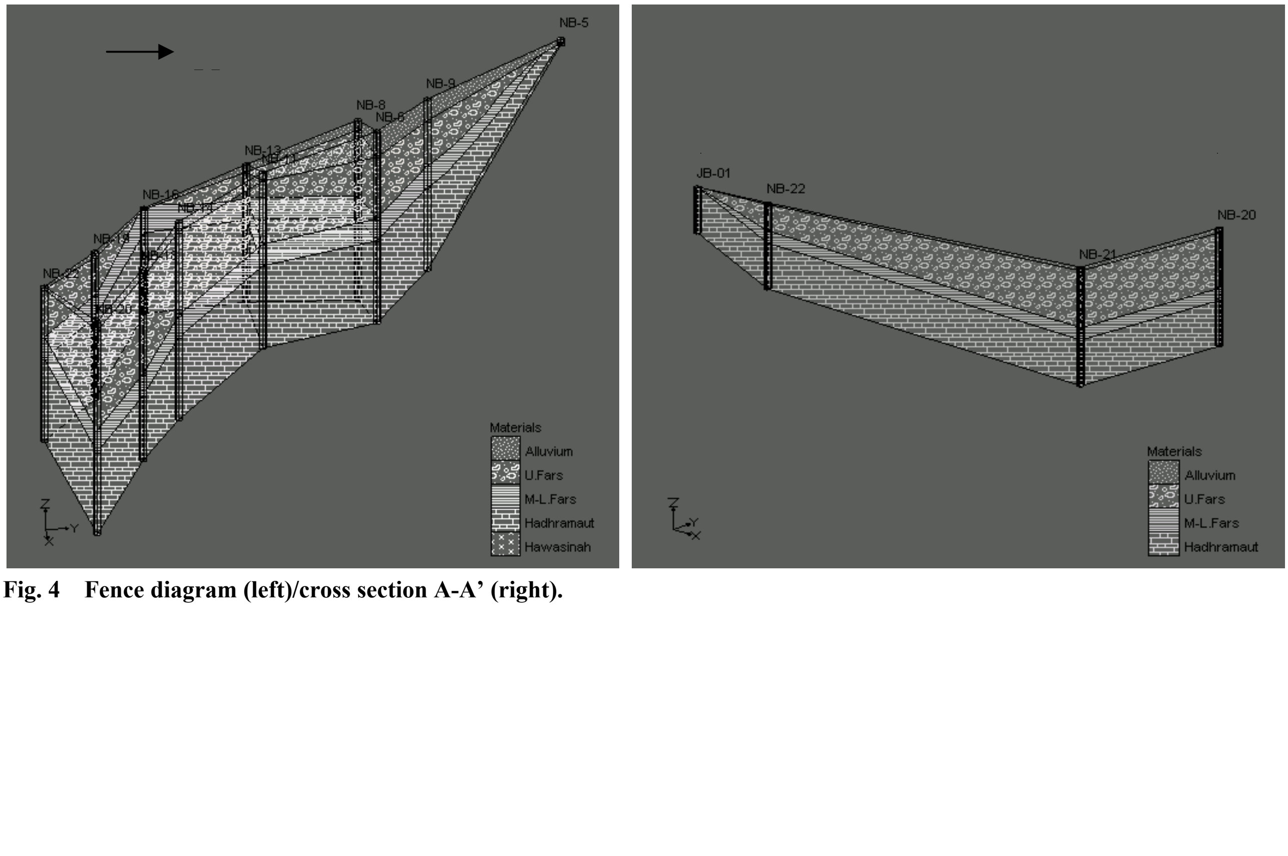

Fig. 4 Fence diagram (left)/cross section A-A' (right).

Major groundwater abstraction is known to have occurred as far as a head 1982. The average abstraction was 261,870 m^3/day which withdrawn only from alluvium in 1982. The total present abstraction is 1.11×10^6 m^3/day and 403.5×10^6 m^3/year. Among them, 387.61×10^6 m^3/year is used for agriculture, 1.181×10^6 m^3/year for livestock, 12.43×10^6 m^3/year for the amount of domestic and 2.277×10^6 m^3/year for municipal, industrial and commercial uses.

Some catchments are not supposed to have further groundwater development, considering the deficit balance of groundwater storage and the increase in EC values near some coastal areas [14]. As indicated, due to the absence of upper Fars unit in addition to the thinning of alluvium in the northwestern part of the area, there is probably less potential groundwater abstraction, when compared to the other discharge locations. Water abstraction is suggested to be decreased by 20% of the present consumption in 2011. This suggestion is proposed for rehabilitation of the aquifer system. Consequently, the total present abstraction should decrease to 322.8×10^6 m^3/year.

The water level is declining at an average rate of 0.27 m/year in the lower catchments and 0.34 m/year in the upper catchments respectively [15]. The water level recorded in 2006 was below sea level in most of the areas located near the coastal settlements. It was reported that the water level is generally parallel to the coast and ranged between -8.3 m.a.s.l. and +56.7 m.a.s.l..

Many of the hand dug wells were only drilled to a depth of 1m to 2 m below the water level. Consequently, relatively small decline in the water level can significantly affect the viability of such wells. Boreholes are generally drilled much deeper and are not so susceptible to small fluctuations in water level. Due to the lack of water level measurements covered the north Batinah area prior 1980s', a steady state model has been developed based on the measurements done in 1982. The model represents condition which supposed to be prior to the start of the major abstraction in the area.

3.4 Hydrochemistry

The isotopic composition of summer and winter rainfall is compared with the groundwater field on the southern part of the area [16]. Stable isotope determination of groundwater samples along the coast of the north Batinah area showed that the aquifer system at depth less than 90 m is recharged mainly by the infiltration of runoff along the wadi channels [17]. Much of this groundwater is less than about five to ten years old and replenished on a frequent basis. Tritium levels at the frontal mountains are generally close to or above 10 TU, signifying that these waters are young and the flow along the wadi channels from the mountain area is rapid, most probably occurring as surface water flow. Tritium levels between 2 TU and 10 TU found in many samples evident that modern rainfall does recharge the coastal aquifer, either directly or indirectly.

The EC of water obtained from the boreholes, completed to either Quaternary or upper Fars units in 2006, ranged between 490 µS/cm and 1,320 µS/cm. However, the EC which is obtained from the borehole drilled south Al Khabourah town was 11,100 µS/cm completed to the pre-upper Fars. This would suggest that the recharge takes place through the Quaternary deposits via direct infiltration and/or wadi flow. Generally, the EC values of groundwater (Fig. 5) gradually increased to northeast from slightly less than 500 µS/cm in the upper catchments to 1,600 µS/cm near the coast. The EC increasing was primarily due to a contribution of sea water intrusion from the Gulf near the coast. Another probable contribution of increasing EC might be through the infiltration of more saline irrigation returns. This is due to the high evaporation which increases the salt content continuously in the soil.

3.5 Recharge

From the previous studies and the observations

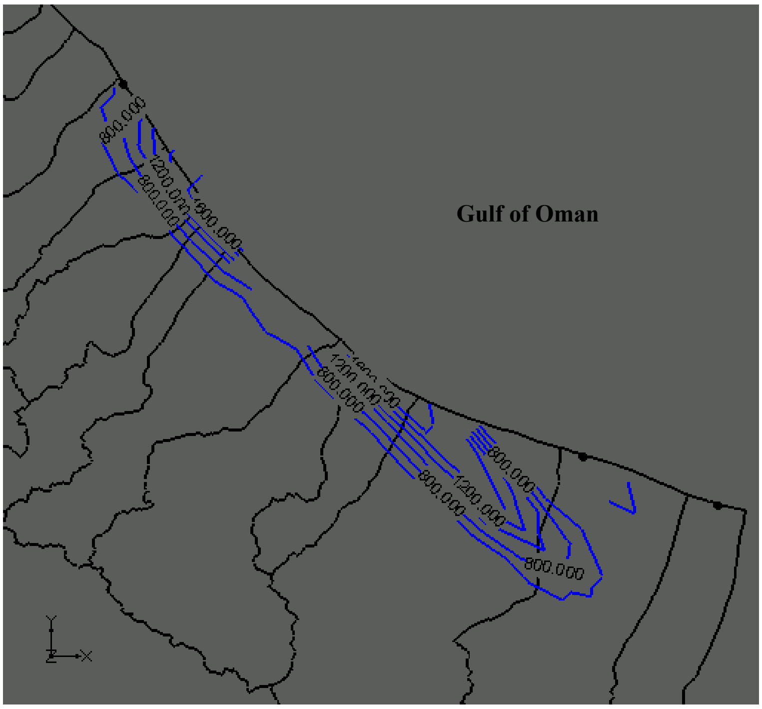

Fig. 5 Electrical conductivity (μS/cm) (2006).

done by Japan International Cooperation Agency [5], it was reported that flood discharge to the sea is rare for the following reasons: (1) Wadi beds in the coastal area which are composed of sand and silt have a large infiltration capacity. Consequently, most of the runoff infiltrated along the wadi bed; (2) Frontal mountain plain area (2,700 km^2) spread out from about 10 km upstream of the seaside for about 35 km to the interior. The surface of this plain area is cemented hard which will easily cause surface runoff. However, the wadi beds have a high infiltration capacity, which will accelerate the depletion of the discharge into the ground and (3) Major mountains are mainly covered with bare rocks and sparse vegetation. Surface runoff occurs easily, but the wadi-beds are covered with gravels where the surface flow can easily infiltrate.

The year of 1976 had heavy rainfall according to the rainfall data of Muscat. Rainfall records in the areas of wadis Suq, Jizzi and Hilti showed that the rainfall that caused significant recharge occurred in 1982 and 1988 [18]. The recharge to the northern Batinah area has been taken place through two main components. Direct recharge is a more significant source to the groundwater system from the rainfall. Indirect recharge is the primary source of recharge to the aquifer system by wadi flow infiltration. The total recharge has been estimated by Hydroconsult [19] for three catchments in the area namely wadi Ahin, wadi Sakhin and wadi Sarami as shown in Table 1. The recharge was also estimated of the eastern Batinah at 2 mm/yr for the lower catchments and 54 mm/yr for the upper catchments [20]. The later amounts have been used for the present work and introduced as initial values to the model.

Table 1 Estimated recharge of three catchments.

Catchment	Hydroconsult 1985 (m^3 × 10^6/year)	Cardew 1980 (m^3 × 10^6/year)	Horn 1978 (m^3 × 10^6/year)
Ahin	21.1	21.1	22.5
Sakhin	3.7	3.7	---
Sarami	7.9	7.9	8.2

3.6 Calibration Results

Calibration process produced a very good comparison between observed and calibrated heads (Fig. 6).

Fig. 7 shows the spatially distributed calibrated hydraulic conductivity. It also shows that the hydraulic conductivity of the two units is identical. The value of K has ranged between 0.02 m/day and 78 m/day and between 0.02 m/day and 60 m/day for the alluvium and upper Fars respectively. The Fig. 7 also shows that high hydraulic conductivity zones exist in southeast, northwest and the middle distance. However, it should be noted that this calibration is rather local because most of the data points exist basically in the coastal area. The correlation between the K values introduced to the model and those driven from the model produced close matching where the calibrated values found within the range 0.1 m/day and 83.5 m/day.

Fig. 8 shows calibrated recharge: the upper catchments have a high recharge value of 3.87×10^{-4} m/day. This is consistent with the fact that high infiltration rate occurs in this part of the study area. The coastal area has a less recharge value of 9.42×10^{-5} m/day.

Fig. 9 shows calibrated head of alluvium and upper Fars units. The head ranged from 72 m.a.s.l. in the upper catchments to zero level along the coast. The head was below sea level (-1.0 m) at wadi Mashin southeast of the Al Khabourah town and wadi Jizi northwest of the Sohar town (Fig. 9). Thus, groundwater flow from southwest to northeast. It was noticed that the hydraulic gradient was steeper in the upper catchments, possibly reflecting the uplifting and thinning of the aquifer units in this area. Drying model cells occur because of its relatively shallow depth and its proximity to the southwestern boundary margins of the model (Fig. 9).

Finally, the inferred flow balance from the steady state model is shown in Table 2. It shows a localized salt water intrusion of 16×10^3 m^3/day and 5×10^3 m^3/day to the alluvium and upper Fars respectively.

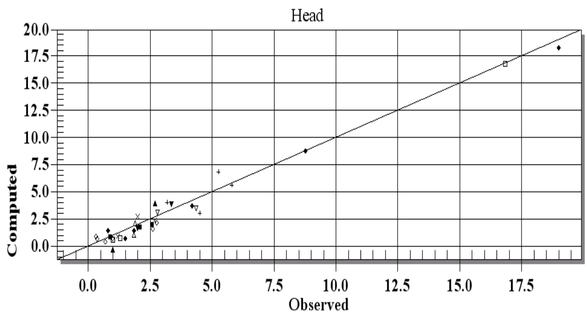

Fig. 6 Computed and observed.

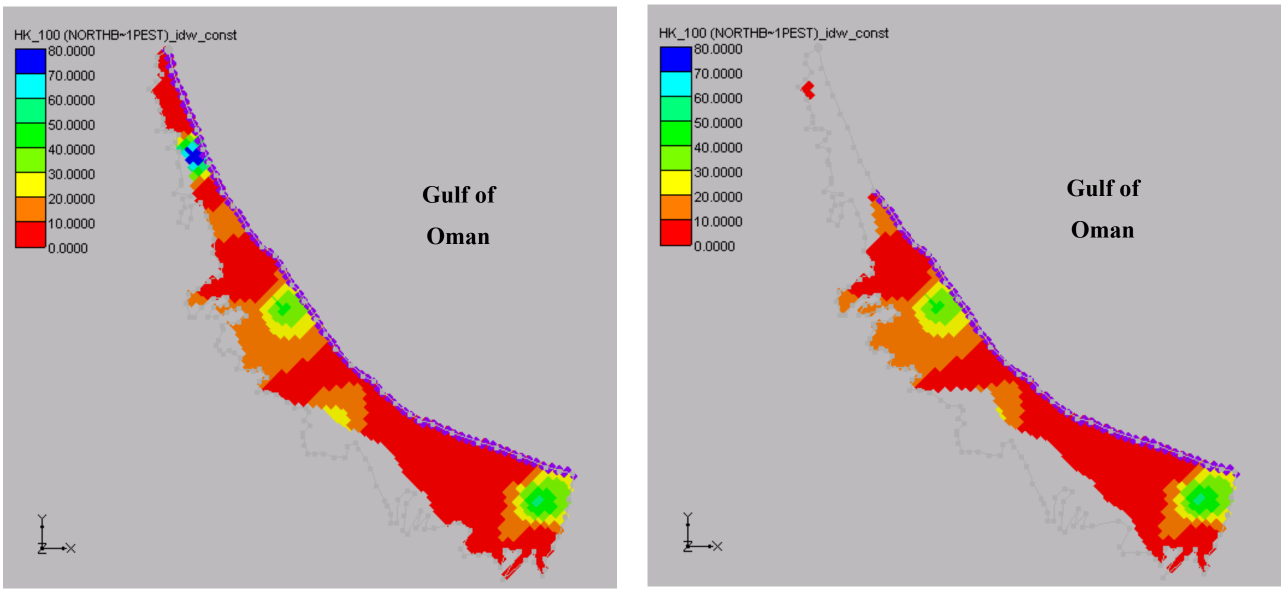

Fig. 7 Calibrated hydraulic conductivity (m/day) of alluvium (left) and upper Fars (right).

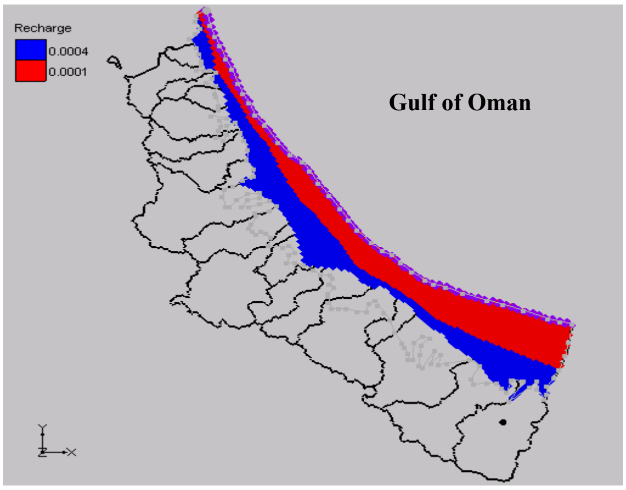

Fig. 8 Recharge zones and calibrated values (m/day).

Such water intrusion occurs at the two areas listed earlier where groundwater level declined below sea level. The Table 2 also shows an estimated recharge of 785×10^3 m^3/day and 117×10^3 m^3/day to the alluvium and upper Fars respectively. This recharge accounts for infiltrated water from rainfall plus returned irrigation water. The last item is an internal flow from alluvium to upper Fars and vice versa. The model estimates it as 345×10^3 m^3/day and 140×10^3 m^3/day respectively.

Comparing observed versus calibrated heads (Fig. 10), it shows acceptable results for data set both in 1995 and in 2006. Although calibration objective function (weighted least square) summed to a value greater than the one obtained for steady state calibration (27 for steady state and 102 for transient), the transient calibration generally produces satisfactory results.

Fig. 11 shows simulated heads for 1995 and 2006 where it reflects reasonable trends to the occurred abstractions. The head ranged from -7.3 m.a.s.l. to

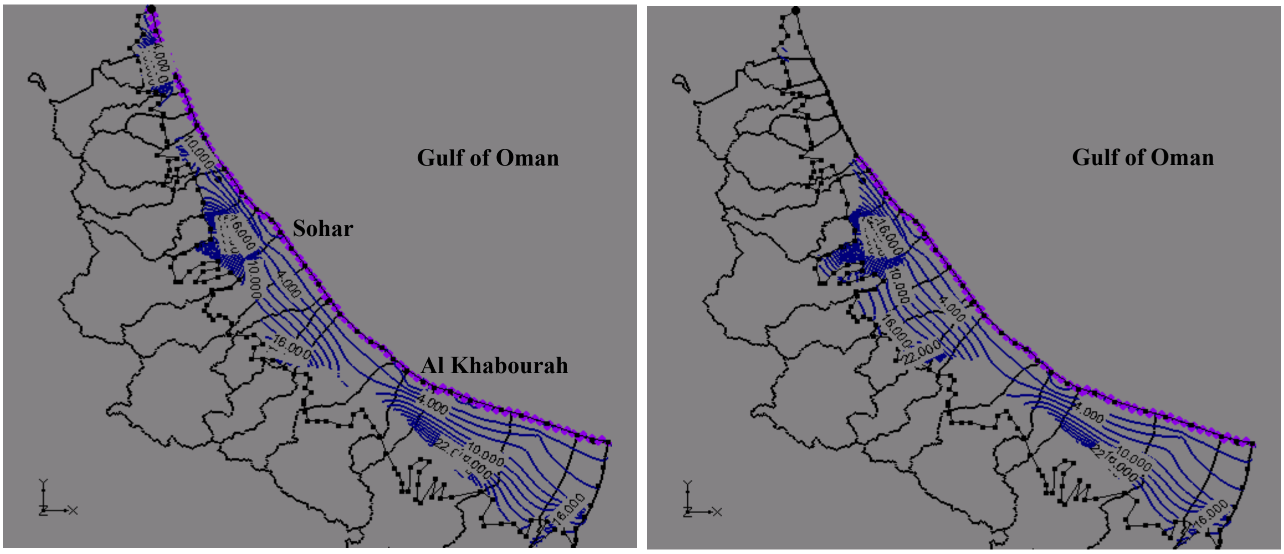

Fig. 9 Calibrated head (m) 1982 alluvium (left) and upper Fars (right).

Table 2 Flow balance for the steady state model (m^3/day).

Item	Inflow	Internal flow	Outflow
Inflow from the gulf (alluvium)	15,960		
Inflow from the gulf (u. Fars)	5,124		
Recharge (alluvium)	785,387		
Recharge (u. Fars)	116,962		
Flow from alluvium to u. Fars		344,832	
Flow from u. Fars to alluvium		139,583	
Abstraction (alluvium)			261,870
Abstraction (u. Fars)			0.0
Outflow to the gulf (alluvium)			334,229
Outflow to the gulf (u. Fars)			327,335

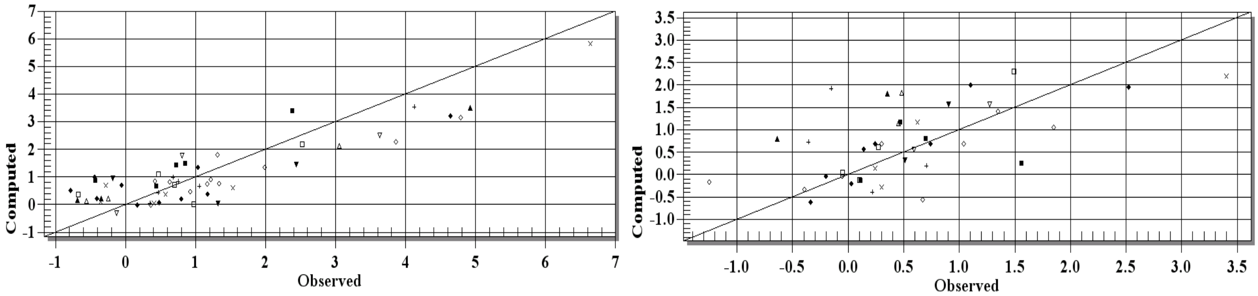

Fig. 10 Calibrated vs observed heads in 1995 (left) and 2006 (right).

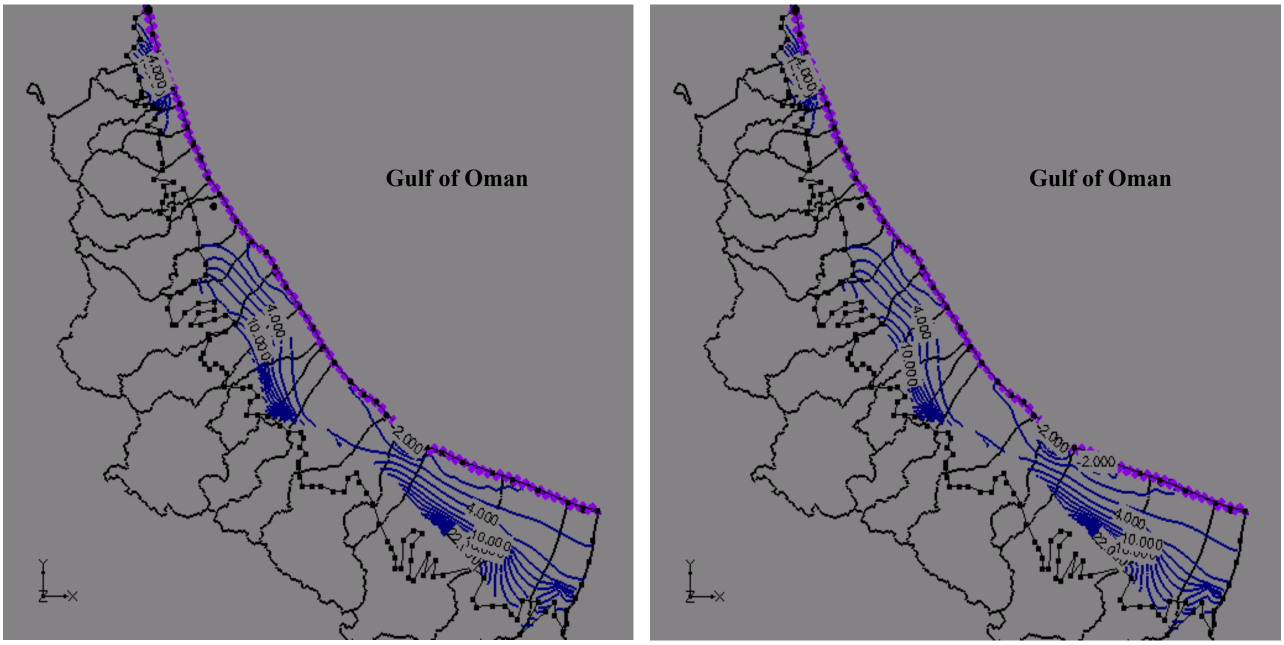

Fig. 11 Simulated head (m) 1995 (left) and 2006 (right).

69.6 m.a.s.l.. Generally, the simulated head overestimate the historical record in 2006 although the overall trends are reproduced. This is an indication that the abstraction used for the calibration understates the actual groundwater abstraction. The impact of transient abstraction on the model is evaluated through the changes of various components within the water balance (Table 3). Table 3 also shows that the abstraction occurred only from alluvium. It also shows that the increase of abstractions was balanced by inflows to the aquifer units from storage as well as from the Gulf of Oman.

3.7 Prediction Scenarios

As suggested earlier that the current abstractions reduced by 20% of the present consumptions (1,110,791 m^3/day). This plan may commence by the beginning of 2011. No information is available relating to any distribution of the abstractions program. Therefore, it has been assumed that the new abstractions will be constant and continuous all over the area.

Two prediction scenarios will be made until the year 2020. The first scenario is made to simulate heads with no change of abstractions. Abstractions are taken to be the same as that at the end of transient simulation (1,110,791 m^3/day). The second scenario is made with abstractions 849,815 m^3/day and maintained throughout the period (2011-2020). The predicted groundwater heads (Fig. 12) show that there

Table 3 Flow balance for the transient state model (m^3/day) in 1995/2006.

Item	Inflow	Internal flow	Outflow
Storage (alluvium)	105,181/10,571		0.0/0.0
Storage (u. Fars)	22,569/2,119		0.0/0.0
Inflow from the gulf (alluvium)	213,965/269,504		
Inflow from the gulf (u. Fars)	167,707/239,474		
Recharge (alluvium)	785,387		
Recharge (u. Fars)	116,962		
Flow from alluvium to u. Fars		484,080/536,743	
Flow from u. Fars to alluvium		343,480/319,631	
Abstraction (alluvium)			1,040,114/1,110,791
Abstraction (u. Fars)			0.0
Outflow to the gulf (alluvium)			199,019/171,783
Outflow to the gulf (u. Fars)			166,637/141,443

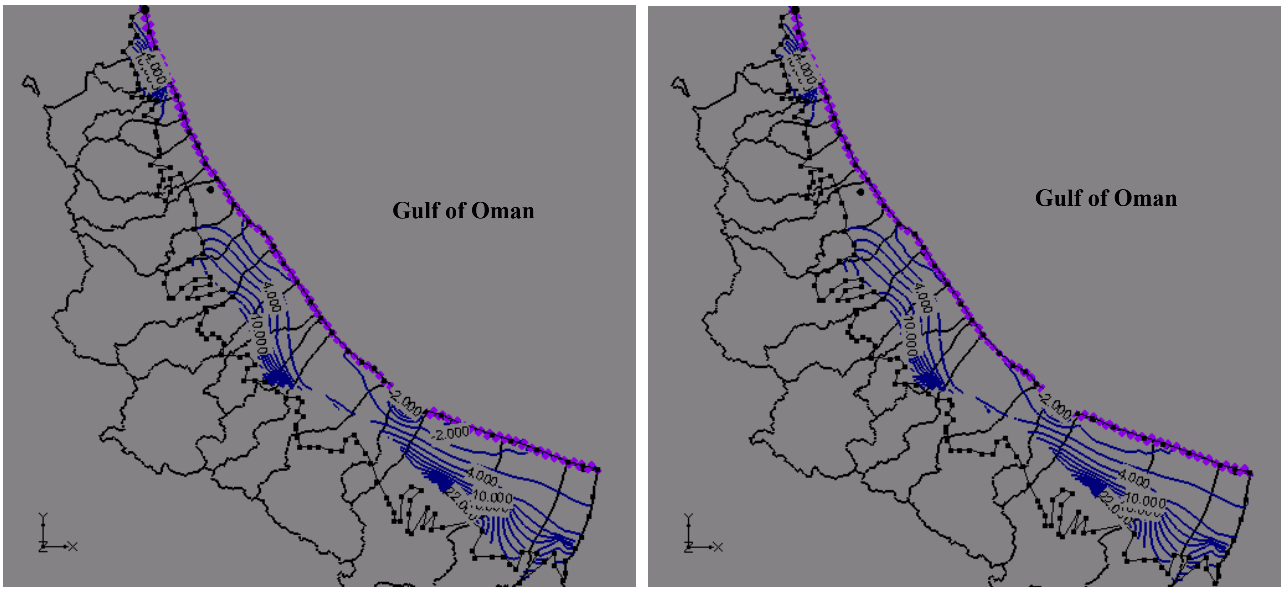

Fig. 12 Simulated head (m) 2020 1st scenario (left) and 2nd scenario (right).

is shrinkage of water level contours in the 2nd scenario especially noticeable along the coast due to the concentration of well fields. The transient water balance from the two simulations is shown in Table 4. It shows small release from the aquifer storage in addition to the increase of inflow from the Gulf of Oman which attains about 518 × 10^3 m^3/day. Fig. 13 shows the evolution of water level at some monitoring wells. It shows that the water level (2nd scenario) will be recovered by about 0.1 m to 1.0 m. This is due to the decrease of abstractions by 20% of the present consumptions in 2011. This leads also to less salt water intrusion from the Gulf to be about 328 × 10^3 m^3/day.

3.8 Solute Transport

Using the calibrated transient groundwater flow model as a basis, a transient solute transport model was developed using the MODFLOW compatible MT3DMS. The solute transport model solves the advection-dispersion transport equations in three dimensions based on calculated hydraulic heads and flow terms derived from the groundwater flow model.

The availability of groundwater salinity data is important for developing the solute transport model. The salinity data are available in 1995 and 2006 and most of the records are electrical conductivity (EC) measurements rather than laboratory determined TDS.

Table 4 Flow balance for the transient state in 2020 (m^3/day) 1st scenario/2nd scenario.

Item	inflow	internal flow	outflow
Storage (alluvium)	246/0.0		0.0/1,055
Storage (u. Fars)	33/0.0		0.0/153
Inflow from the gulf (alluvium)	272,839/177,409		
Inflow from the gulf (u. Fars)	244,845/150,557		
Recharge (alluvium)	785,387		
Recharge (u. Fars)	116,962		
Flow from alluvium to u. Fars		550,533/422,626	
Flow from u. Fars to alluvium		333,760/333,846	
Abstraction (alluvium)			1,110,791/849,815
Abstraction (u. Fars)			0.0
Outflow to the gulf (alluvium)			169,928/207,188
Outflow to the gulf (u. Fars)			139,511/172,105

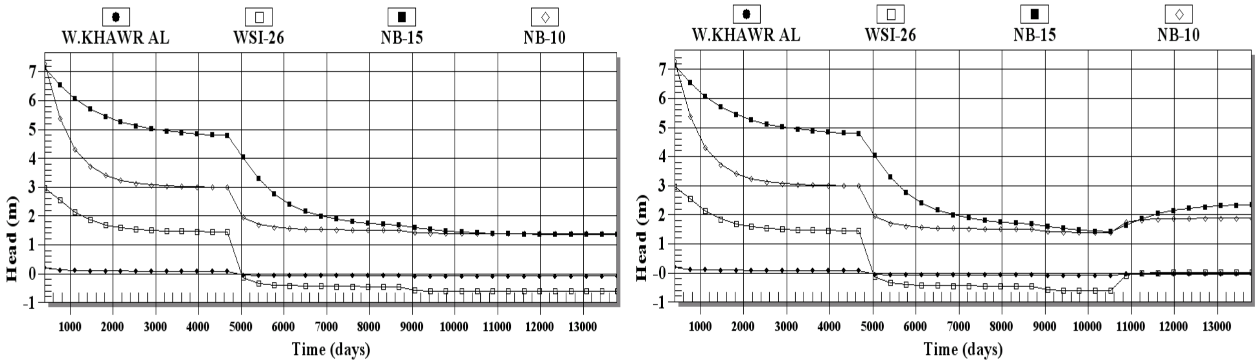

Fig. 13 Evolution of water level 1st scenario (left) and 2nd scenario (right).

The EC measurements are converted to TDS. Therefore, the TDS used includes some experimental error. The model includes boundary conditions for salinity seawater concentration (TDS of 35,000 ppm) for the coastal boundary. It also includes an areally distributed rainfall recharge concentration over the area (TDS of 100 ppm).

Sensitivity trials were used to estimate the longitudinal dispersivity. Values of 2,500 m and 2,000 m for aquifer units 1 and 2 were found to be consistent with the salinity measurements. The transverse dispersivity was set to one-tenth of the longitudinal value, consistent with best practice approaches [21]. Vertical transverse dispersivity was set to 0.25 m.

3.8.1 Solute Transport Results

The model simulation of groundwater salinities (Fig. 14) are compared with the field data. The model results and the field data show a satisfactory match. The groundwater salinities of the year 2006 show a noticeable increase of salinities as a result of increasing abstraction. Cross-sectional salinity distribution is also illustrated (Fig. 15). The salinity hydrographs for two selected observation points are provided (Fig. 16). The salinity hydrographs exemplify two ranges of salinities: low range < 3,000 ppm TDS covers all the area southwest of the coast and moderately high range (3,000-13,000 ppm TDS) is found close to the coast.

4. Conclusion

The north Batinah is the most promising area in the Sultanate of Oman for different development activities especially agricultural purposes. Groundwater within this area has been extensively used to meet the water demand. Numerical model has been developed for the north Batinah area to investigate the flow system and to evaluate the hydrologic parameters. A layered aquifer system has been defined consisting of two units' namely alluvium and Neogene's upper Fars.

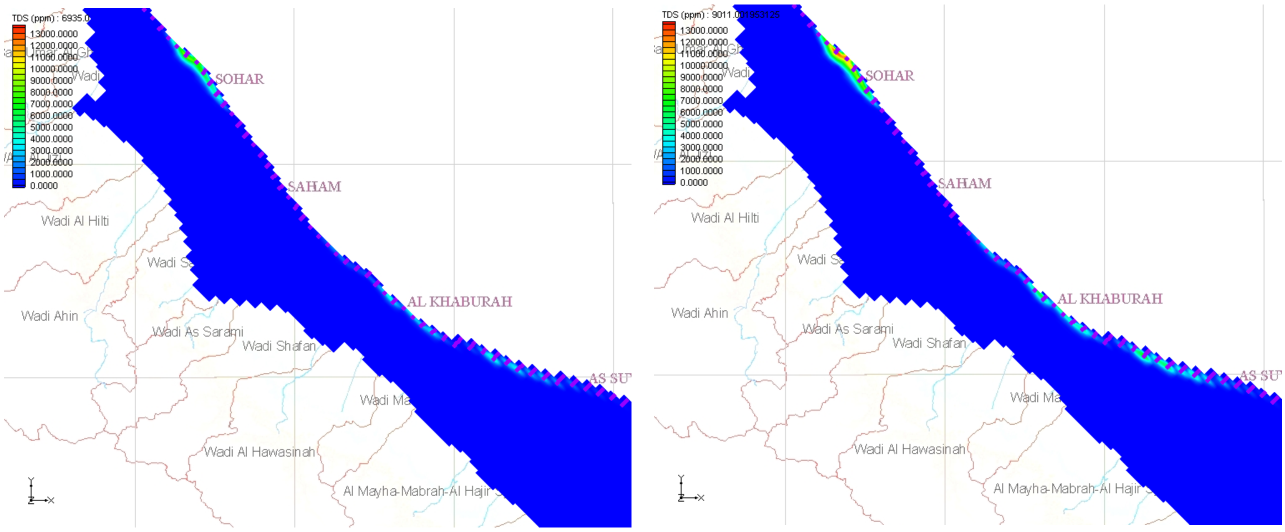

Fig. 14 Simulated salinities 2001 (left) and 2006 (right).

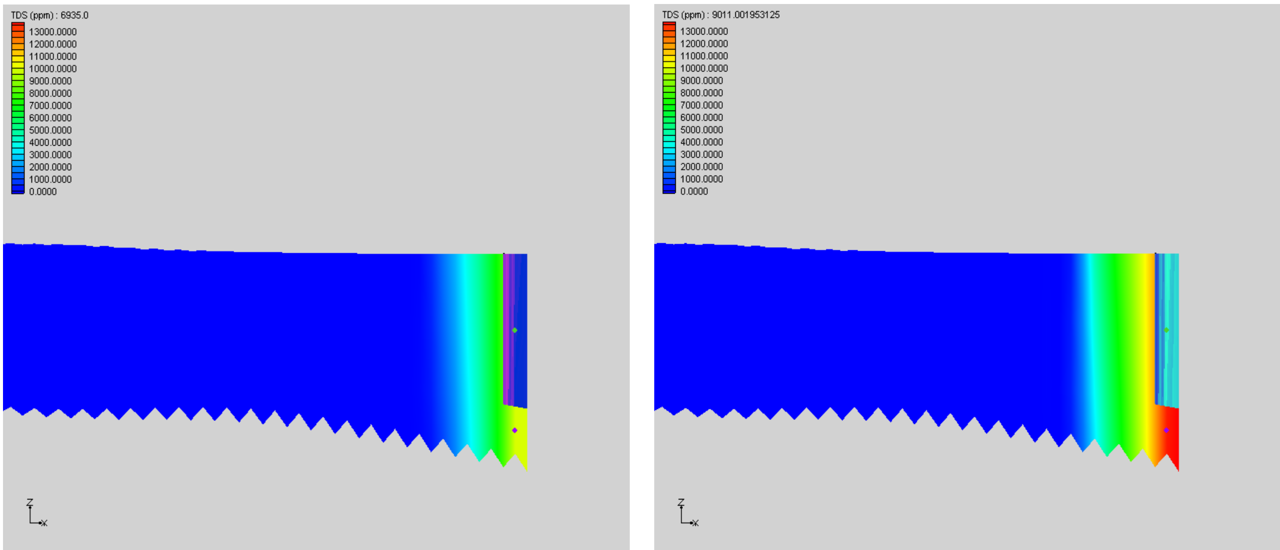

Fig. 15 Salinity cross sections 2001 (left) and 2006 (right).

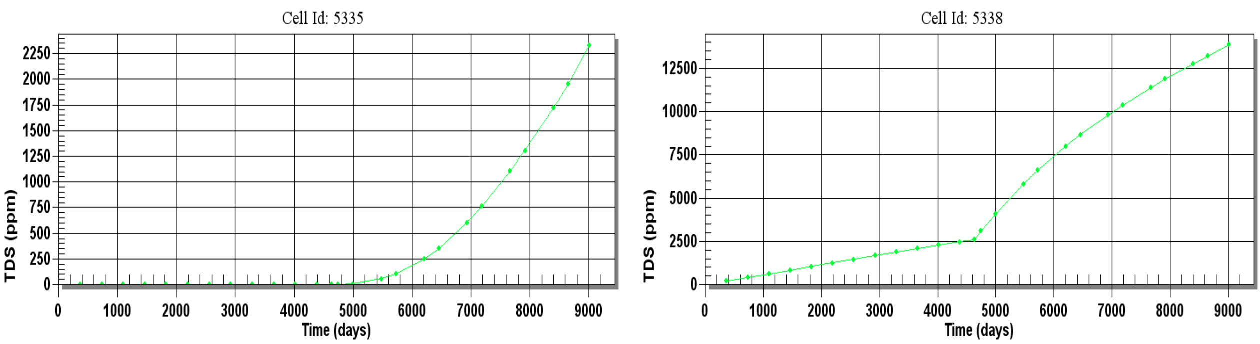

Fig. 16 Salinity hydrographs southwest the coast (left) and close to the coast (right).

Groundwater levels declined to below sea level in the coastal zone since the year 1982. As a result, salt water intrusion has been occurred. It is remarkable that the continuation of the current progress rate of water use will cause the development of salinity problems in the coastal area. The spatial distribution and temporal patterns of the simulated salinities clearly show a low salinity water zone which covers most of the model area except the moderate higher salinity zone (3,000-13,000 ppm TDS) at some locations close to the coast. The cross-section salinity plots shows that there is more saline intrusion at the coast.

The most important conclusions can be stated as follows:

- The main source of recharge to the north Batinah area is through direct recharge from rainfall as well as wadi flow, it is estimated by about 902×10^3 m^3/day from both rainfall plus return flow of irrigation water;
- The total amount of current abstraction is about 1.11×10^6 m^3/day;
- The hydraulic conductivity of the aquifer system attains a moderately wide range from 0.02 m/day to 78 m/day and from 0.02 m/day to 60 m/day for the alluvium and upper Fars respectively;
- A local salt water intrusion from the Gulf attained about 21×10^3 m^3/day and 499×10^3 m^3/day in 1982 and 2006 respectively which will increase to about 518×10^3 m^3/day in 2020;
- The EC increasing was primarily due to sea water intrusion from the Gulf. Also increasing EC might be through the infiltration of more saline irrigation returns;
- The water level declined from (-1-72) m.a.s.l in 1982 to (-7.3-69.6) m.a.s.l. in 2006;
- The water level will be recovered by about 0.1 m to 1.0 m during the period 2011-2020 as a result of decreasing abstractions by 20% of the present consumptions planed in 2011. The salt water intrusion will be also decreased to about 328×10^3 m^3/day in 2020.

It can be stated some recommendations as follows:

- For increasing the groundwater resources in the Batinah area, it has to make effective use of flood water which flow into the sea, using dam-type structures which will recharge the flood water into the aquifer system and increase the groundwater resources;
- Reliable measurements of groundwater level and periodical chemical analysis for water samples;
- Any plan for increasing groundwater abstraction is unaffordable;
- Automatic well control system;
- Further analysis under different future scenarios;
- Formulate an integrated management plan for the basin;
- Increasing public awareness for proper use of groundwater resources.

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