International Journal of Water Resources and Arid Environments 2(2): 56-63, 2013
ISSN 2079-7079

Feasibility Study of Using Treated Wastewater to Mitigate Seawater Intrusion along Northern Coast of Oman

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Abstract: The coastal plain aquifers in Sultanate of Oman are suffering from seawater intrusion due to huge water deficit in the coastal communities thereby seriously deteriorating the groundwater quality. Among other options in arid countries like The Sultanate, one of the viable one is the use of treated wastewater to recharge the coastal aquifers. This option is viable because of the availability of tertiary treated wastewater from the treatment plants managed by Haya Wastewater Company, Oman. In the present study MODFLOW for groundwater flow is implemented and calibrated in one of the most important coastal plain aquifers in Al-Batinah region, Sultanate of Oman. The calibrated model is then used to study the effect of treated wastewater injection into the aquifer on groundwater levels. It was ascertained that the available treated wastewater could be used as an effective option to defy seawater intrusion into this region by raising groundwater table.

Key words: Wastewater Reuse · Seawater Intrusion · MODFLOW · Coastal Aquifers

INTRODUCTION

Sultanate of Oman is located on the south-eastern corner of the Arabian Peninsula. Approximately one third of the country's population lives in the north-eastern part of The Sultanate called Al-Batinah, which represents about 4% of the country's total area. This area comprises of fertile agricultural land and thus vitally important for the country's agricultural produce. According to an estimate more than 50% of the country's cultivated land is located in Al-Batinah. The Sultanate is classified as an arid country due to an average annual rainfall of approximately 100 mm. The major source of fresh water is rainfall in the upper catchments resulting in the replenishment of the aquifers underneath. As a result of persistent water deficit due to excessive pumping in the area, the quality of water is continuously deteriorating due to seawater intrusion. Consequently, a number of agricultural farms have been abandoned and many others are facing salinity hazard at present.

The need thus arises to mitigate seawater intrusion into Al-Batinah coastal aquifer using economically viable solutions. After the establishment of Haya Wastewater Company, Oman, the treatment of wastewater is better organized and as a result huge quantities of treated wastewater are available. Presently, only a part of the treated wastewater is being utilized for irrigation of non-edible crops like flowers and other ornamental plants in urban areas. Most of this valuable water resource is disposed off.

The present study aims at the implementation and calibration of MODFLOW for groundwater flow in one of the most important aquifers in Al-Batinah region. After that the effect of treated wastewater injection into the aquifer on seawater intrusion is studied using this numerical model. Once implemented, this model can be used as an effective management tool in mitigating seawater intrusion in Al-Batinah region.

Study Area: The study area includes parts of three wadi basins west of the Capital Area, namely Wadis At-Taww, Al-Ma'awiI and Bani Kharus. The island of Jaza'ir Suwadi and the sabkha which forms Ras-Suwadi are the most notable coastal features. Irrigation is the major water use. It has increased substantially over the past four decades and is concentrated along the coastal strip.

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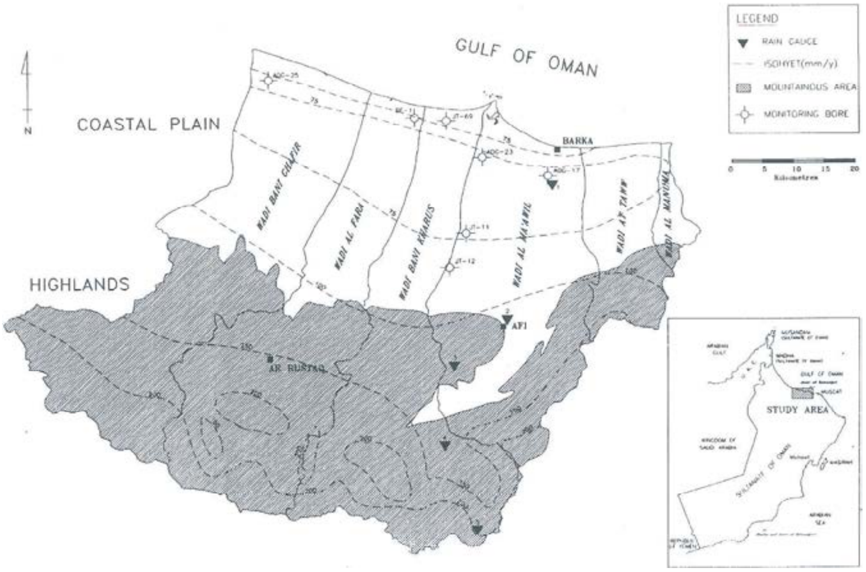

Fig. 1: Map of the study area (courtesy: [2])

Important irrigation areas, usually fed by aflaj are also found within the highland valleys and at the foot of the mountains. Recharge dams have been built in the coastal plain in Wadis Al-Ma'awil, At-Taww and Rubkah (an At Taww tributary) and Wadi Al-Fara, to increase recharge and minimize flood flow discharge to the sea. The location map of Batinah region with the coastal plain aquifers is shown in Figure 1.

The coastal alluvial aquifer of the Batinah has allowed the development of the most extensive agricultural region of the country. Here, water is extracted from both shallow dug wells and boreholes. The traditional agriculture of the Batinah is concentrated close to the coast where the water table is closest to the surface and most accessible.

The rainfall in Batinah region mainly happens during winter season as evident from the data shown in Table 1.

Water balances for Eastern Batinah aquifers were reported by [2]. All the aquifers showed great water deficit during that year. Obviously the water deficit was increased after 1995 which is depicted by increasing salt-water intrusion into Batinah aquifers. The latest data on water deficit in Barka-As-Suwaiq and As-Seeb areas was given by [4] as shown in Table 2.

The projected flows of wastewater from Muscat Governate are shown in Table 3 [5].

Considering a deficit of 90.8 MCM in Barka and As-Suwaiq area it is clear that the total quantity of treated wastewater from all the Haya Wastewater Company's treatment plants can be used to compensate for the water deficit in Barka-As-Suwaiq area until year 2025.

Well hydrographs of some of the monitoring wells shown in Figure 2 clearly show the severity of decline in water table during recent years.

The well hydrographs for the monitoring wells located closer to the shoreline are shown in Figure 3. The well in the immediate vicinity of the shoreline (JT-72) shows a mild decline in water table because it is close to the sea and therefore the deficit of freshwater would be balanced by the intrusion of seawater. Other monitoring wells (DW-4, JT-57 and NC-5) clearly show a steeper decline in water table after year 1999 as compared to the previous years. In DW-4 the water table lies approximately 9 m below mean sea level in year 2010.

The monitoring wells located a bit farther from the shoreline show a rather mild decline in the water table until year 1994 and then a recovery until year 1998 (Figure 4). But after that a steep decline in water table is depicted by the three wells including a slight recovery from year 2007 to 2009. In JT-10 the water table reaches approximately 5m below mean sea level in year 2010.

The most serious condition is depicted in the monitoring wells located close to the highland areas (Figure 5). Even the wells located upstream of recharge dams (BKD-3, JT-68 and JT-11) show a steep decline in water table after year 1999. Before year 1999, there has been a cyclic variation is the water table in these wells and the average water table has been the same over the years. However, after year 1999, this balance seems to be disturbed and major deficit is clearly depicted.

Table 1: Mean Annual Rainfall at Seeb Station

Year	1975	1976	1977	1978	1979	1980	1981	1982
Mean Annual Rainfall (mm)	77	152	183	42	20	4	110	133
Year	1983	1984	1985	1986	1987	1988	1989	1990
Mean Annual Rainfall (mm)	80	2	1	94	194	63	70	79

Table 2: Water balances for coastal plain aquifer in Eastern Batinah, all the volumes are in million cubic meter (MCM) per year [4]

			Water Consumption (MCM)			
Area	Recharge (MCM)	Water available (MCM)	Agriculture	Domestic/Industrial/Municipal	Total	Deficit (MCM)
As-Seeb	52.9	53.2	45.82	9.39	55.2	2.0
Barka- As-Suwaiq	71.7	83.3	173.68	0.38	174.1	90.8
Total	124.6	136.5	219.50	9.77	229.3	92.8

Table 3: Wastewater flow projections [5]

Year	2010	2015	2020	2025
Flow (m^3/d)	64,919	151,089	187,766	201,335
Average Annual Quantity (MCM)	23.70	55.15	68.53	73.50

Fig. 2: Locations of selected monitoring wells in Batinah catchments using Google Earth

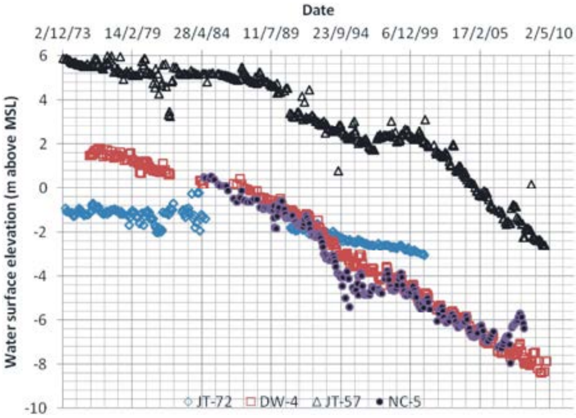

Fig. 3: Well hydrographs for monitoring wells closer to shoreline

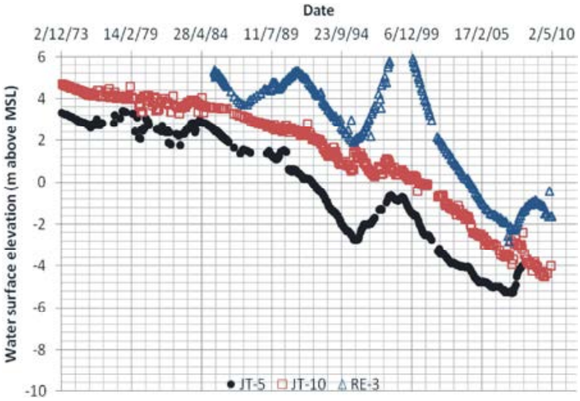

Fig. 4: Well hydrographs for monitoring wells located farther from shoreline

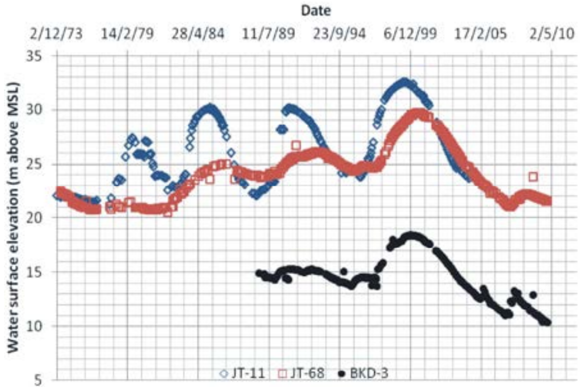

Fig. 5: Well hydrographs for monitoring wells closer to highland areas

In the coastal zone, the aquifer is unconfined, with a relatively shallow water table within 20 meters of the ground surface. Water table typically fluctuates over a relatively small amplitude range of a meter or less.

The response is remarkably consistent throughout the zone, indicating that hydrogeological conditions near the coast are relatively uniform. The response of coastal monitoring wells showed that direct rainfall recharge is much more significant than previously thought. It occurs more frequently and is volumetrically, more important than indirect recharge from wadi flood flows. Response to rainfall is observed in all monitoring wells within the coastal zone. Direct recharge of precipitation occurs more often than wadi flow recharge and affects the whole area more evenly, producing more widespread and longer lasting water level rises [2].

The alluvial sequence in Batinah coastal plain has been divided into two hydro stratigraphic units, Layer 1 (Sub-Recent and Recent alluvium) and Layer 2 (Ancient alluvium), which is shown in Figure 6. Groundwater is extracted from Layer 1, which has relatively low clay content and is not extensively cemented. Hydraulic conductivity is high, typically 20 m/d and water quality is good. However, due to the proximity to the seawater interface and the presence of underlying marl near the coast containing highly saline waters, the risk of contamination and seawater intrusion is high.

The older Layer 2 closer to the highland front has much lower hydraulic conductivity (average 1 m/d) and porosity (Figure 7), but in general appears to contain good quality water and forms an important intermediate unit between the highlands and Layer 1. Its thickness suggests that it is also important in terms of storage [2].

These descriptions of layers will be useful in developing the conceptual model of the groundwater model of the coastal plain aquifers in Batinah.

Numerical Model: The groundwater flow model design of the selected Batinah aquifers consisted of the following stages:

- Definition of the model geometry (lateral and vertical extent of the area to be modeled defined by model boundaries, grid layout and position and number of layers).
- Definition of boundary array, i.e. cell types (active, inactive, constant-head cells).
- Input of hydrogeologic parameters for each cell such as hydraulic conductivity (horizontal and vertical, including possible anisotropy), transmissivity, storage properties and porosity.
- Definition of boundary conditions (boundaries with known head, known flux, or head-dependent flux).
- Definition of initial conditions (distribution of hydraulic head).

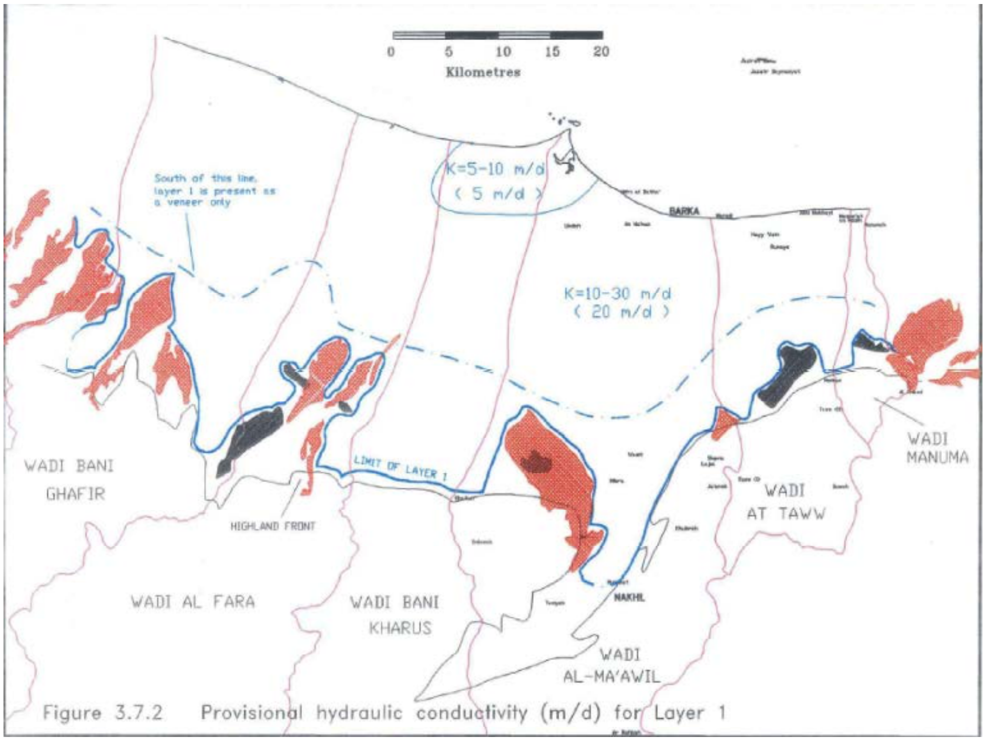

Fig. 6: Hydraulic conductivity of Layer 1 in Eastern Batinah aquifers [2]

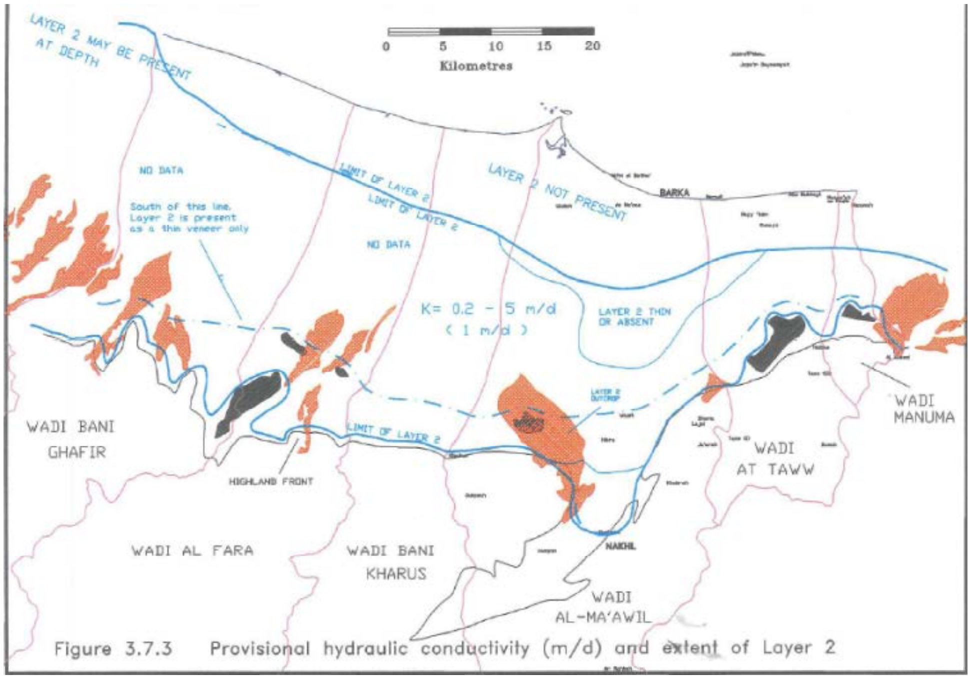

Fig. 7: Hydraulic conductivity of Layer 2 in Eastern Batinah aquifers [2]

- Definition of stresses acting upon the system such as aerial recharge, evapotranspiration, well pumpage, outflow through springs, drains, inflow of water from other sources (recharge wells, adjacent aquifer).
- Model run, which included choosing a mathematical method for solving the system of algebraic equations, iteration criterion and acceptable error criterion for terminating the iteration process.
- Calibration and sensitivity analysis. This was the lengthiest and most demanding part of any modeling process.
- Prediction of groundwater levels for various recharge scenarios using treated wastewater.

Governing Equations: In the present study the Groundwater Modeling System (GMS) is used that includes MODFLOW in addition to other models for groundwater transport processes.

MODFLOW is a computer program that numerically solves the three-dimensional ground-water flow equation for a porous medium by using a finite-difference method. Although MODFLOW was designed to be easily enhanced, the design was oriented toward additions to the ground-water flow equation. Frequently there is a need to solve additional equations; for example, transport equations and equations for estimating parameter values that produce the closest match between model-calculated heads and flows and measured values.

The partial-differential equation of ground-water flow used in MODFLOW is [1] [3]:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \tag{1}$$

where K_{xx} , K_{yy} and K_{zz} are values of hydraulic conductivity along the x, y and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T); h is the potentiometric head (L); W is a volumetric flux per unit volume representing sources and/or sinks of water, with $W<0.0$ for flow out of the ground-water system and $W>0.0$ for flow into it (T^{-1}); S_s is the specific storage of the porous material (L^{-1}); and t is time (T).

Equation (1), when combined with boundary and initial conditions, describes transient three-dimensional ground-water flow in a heterogeneous and anisotropic medium, provided that the principal axes of hydraulic conductivity are aligned with the coordinate directions.

Conceptual Model: First of all a conceptual model for eastern Batinah plain is developed. The conceptual model is a three-dimensional representation of the groundwater flow and transport systems based on all available geologic and hydrogeologic data for the study area. A complete conceptual model includes geologic and

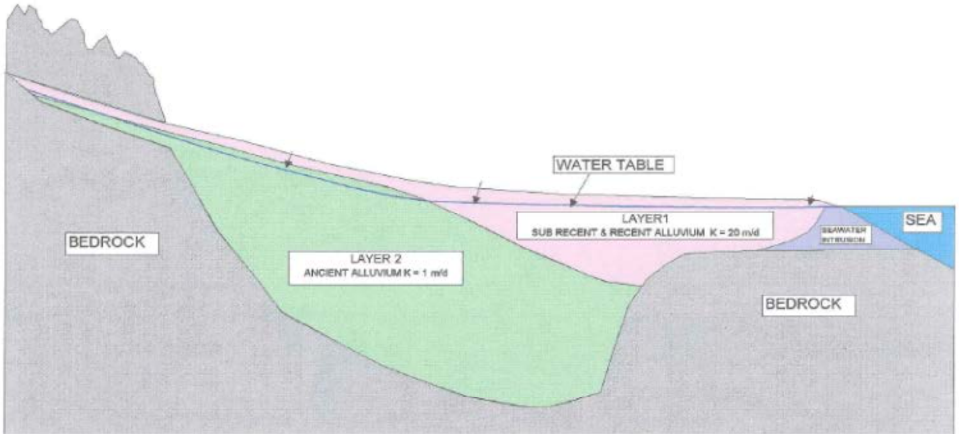

Fig. 8: Conceptual model of the Eastern Batinah plain

topographic maps of the area, bore-logs depicting the physical and chemical parameters associated with the aquifers and the salinity data. The conceptual model of the study area is shown in Figure 8.

The next step was model construction that is primarily the conversion of the conceptual model into the input files for the numerical model then running the model under steady state to demonstrate that the model can predict the aquifer flow properties. Next step is the calibration in order to demonstrate that the model is capable of producing field measured heads and flows, which are used as calibration values or targets. After the calibration the model is used to predict water table fluctuation and seawater intrusion accordingly in Eastern Batinah coastal aquifers.

Model Parameters: The preliminary results were computed using an average rainfall of 85mm/year in the coastal plain as suggested by [2]. It was assumed that 25% of the rainfall is used as groundwater recharge whereas the rest becomes surface runoff which ultimately is evaporated or discharged to the sea. Both the layers were implemented in the model using the conceptual model. The top and bottom layers are shown in Figure 9 and Figure 10. The northern boundary of the model represents the sea where groundwater level is zero as expected. The top layer extends over the whole model domain whereas the bottom layer (Layer 2) is not present in approximately 40% of the model domain. This is in accordance with the observed data from the study area by [2].

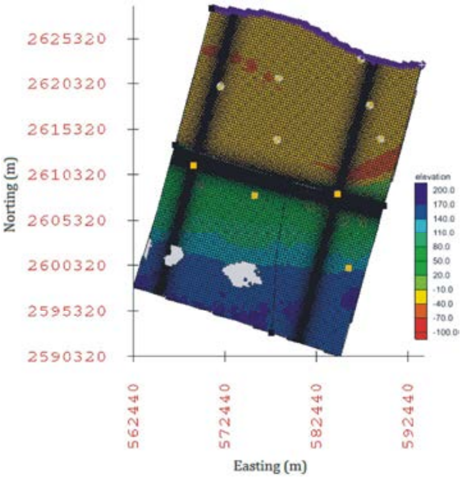

Fig. 9: Bottom Elevations of the top layer (Layer 1) of Batinah coastal aquifer

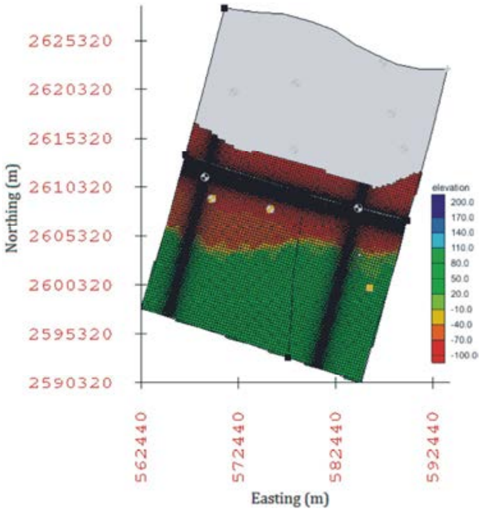

Fig. 10: Bottom Elevations of the bottom layer (Layer 2) of Batinah coastal aquifer

Model Calibration: The model calibration was carried out using the available data of groundwater levels, recharge and pumping data. One of the major challenges is the

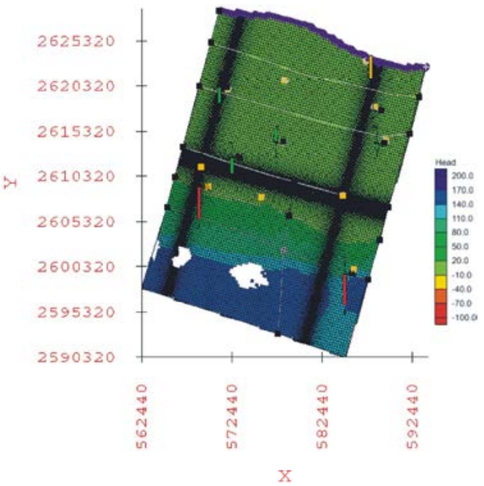

Fig. 11: Groundwater elevations after the calibration of MODFLOW

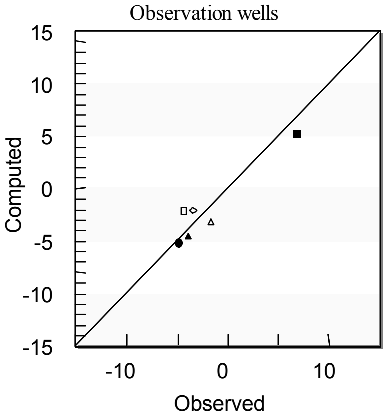

Fig. 12: Calibration of the model using observed water surface elevations

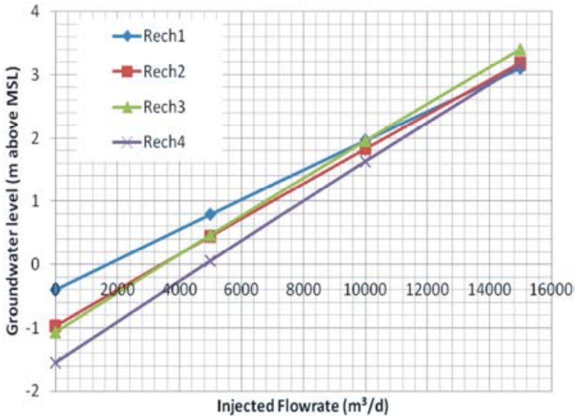

Fig. 13: Effect of artificial recharge on groundwater levels along the shoreline

pumping data which is not reliable. Because of that the pumping rates have to be assumed based on whatever data is available. The initial values of hydraulic conductivity were used as per suggestions by [2] and then these values along-with pumping rates were refined using the comparison between the observed and computed groundwater levels.

The groundwater elevations after calibration are shown in Figure 11. The observation wells were selected such that the calibration could be achieved for the whole aquifer area. The error bars are shown beside the locations of the observation wells. A green color bar shows that the computed groundwater elevation differs up to 1.5m from the observed values. Smaller the error bar, better the agreement between computed and observed values. Further comparison between observed and computed values is shown in Figure 12. The data points above the 45° line show that the model overestimated the groundwater elevations and the ones below the line underestimated results. For a perfect agreement between the computed and observed values, the points should lie on the line. Here the points lie very close to the line showing a good agreement between the computed and observed values.

It was found that in the southern part of the aquifer, the calibration was not up to the mark, however, in the present study it is more important to have better calibration in the coastal region, since the proposed injection of treated wastewater will be done in that area. Here it is obvious that the coastal region is very well calibrated.

Recharge Using Treated Wastewater: After the calibration the model was run to study the effect of the treated wastewater recharge using four injection wells along the shoreline. The coordinates of these wells and the injected flow rate scenarios are shown in Table 4.

In case of no artificial recharge the groundwater levels at these locations is below mean sea level (Figure 13), which means seawater intrusion is happening at these locations. With the increase in the recharge by injection, the groundwater level increases. It should be noted that in order to maintain zero seawater intrusion, the freshwater level at the coast should be at least 0.65m above mean sea level. Using the artificial recharge, this condition will reach in the four recharge wells when the injected flow rate will be approximately 4400, 5700, 5600 and 6900 m^3/d, respectively (Figure 13). At this stage approximately 35% of the treated wastewater produced in Year 2010 can be utilize to defy seawater intrusion in Barka region. However, this quantity will be just sufficient to keep seawater from intruding into freshwater aquifer.

Table 4: Locations of Recharge Wells and Groundwater Elevations

				Groundwater levels MSL (m)			
Recharge Well	Easting (m)	Northing (m)	Flow (m^3/d)=	0	5000	10000	15000
Rech1	575000	2626000		-0.401	0.79	1.96	3.104
Rech2	580000	2625160		-0.967	0.445	1.827	3.183
Rech3	585000	2623000		-1.068	0.462	1.952	3.398
Rech4	591000	2620000		-1.549	0.058	1.631	3.15

CONCLUSIONS

MODFLOW has been implemented in the coastal plain aquifer in Barka region where seawater intrusion is evident because of over-pumping of groundwater. After calibration of the model, it is applied to study the technical feasibility of the treated wastewater recharge and its effects on the groundwater elevations. It has been found that approximately 35% of the treated wastewater from year 2010 can be utilized to barely defy seawater intrusion. However, based on the projections of agricultural water demand greater quantities can be utilized for recharge in the area.

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