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A NUMERICAL GROUNDWATER FLOW MODEL OF WADI SAMAIL CATCHMENT USING MODFLOW SOFTWARE

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ABSTRACT: The climate in most of Gulf Cooperation Council (GCC) countries is considered arid with limited water resources. Proper management of scarce water resources is therefore necessary for sustainable water supply while meeting the growing water demands. A three-dimensional finite-difference groundwater flow model of Wadi Samail Catchment was developed to simulate groundwater flow and to evaluate the sensitivity of the model to the varying of input parameters. Model inputs include lithology of the aquifer derived from borehole data, observed groundwater levels, rainfall, and initial hydraulic conductivity values from pumping tests. The aquifer was divided into four layers. The steady-state calibration was carried out using data in 14 monitoring wells in July 2016. The hydraulic conductivity (k) and recharge values were calibrated using observed groundwater levels with the estimated root mean squared error (RMSE) of 0.8m. The estimated parameters were verified with groundwater levels in October 2016. The RMSE between observed and simulated water levels was 0.81m. The calibrated model was then used to assess the sensitivity of the model to the changes in pumping rate, hydraulic conductivity (k), and recharge. Results showed that the water levels were most sensitive to the changes in hydraulic conductivity of the first layer. While pumping rates and recharge were less sensitive compared to the hydraulic conductivity. In conclusion, the sensitivity analysis results can be used as a management tool for sustainable water resources.

Keywords: Numerical groundwater model; Calibration; Sensitivity analysis; Wadi Samail catchment

1. INTRODUCTION

Groundwater is a precious, very limited resource and shared without having any fixed boundaries. It is exposed to many risks and great pressure as a result of the rapid increase in population, along with social, agricultural, and industrial developments. All these factors have resulted in a substantial increase in water demands, placing high pressures on limited water resources. The main threats to water resources are population growth, urbanization, and climate change [1].

Climate in most of Gulf Cooperation Council (GCC) countries is arid with limited water resources. Consequently, they depend on groundwater and desalination to meet water demand. The annual rainfall in this region is less than 100 mm/yr, and the evaporation rate is more than 3000 mm/yr [2]. The limitation in water resources, especially in arid regions like Oman, has led to improve the level of water management and conservation practices for continuous water supply for growing population and development demands [3]. Recharge dams and artificial recharge schemes have been implemented to augment the richness of groundwater aquifers[4].

For management purposes, the aquifer properties should be examined adequately to understand the groundwater condition and contaminant transport [5]. Numerical groundwater modelling has been used as a tool [6] for understanding spatial variation of aquifer properties, which ultimately used for the management and protection of water resources under present and future conditions.

This study aims to simulate the groundwater flow in Wadi Samail Catchment in Sultanate of Oman using a steady-state groundwater model. The developed model then will be used to assess the sensitivity of the groundwater level to the changes in pumping rates, hydraulic conductivity (k), and recharge.

2. STUDY AREA

The Sultanate of Oman is picturesquely located in the south-east of the Arabian Peninsula [3]**.** It has a total area of 309,500 km² and a coastline of almost 3,165 km. It is located in an arid region of the world and characterized by limited water resources. Mean annual rainfall throughout most of Oman is relatively low, less than 100 mm and sporadic, but in mountain areas, precipitation is higher up to 350 mm [7]. Wadi Samail catchment has a total area of 1720 km^2, and it is triangular in shape, as shown in Fig.1. The catchment can be divided into two-part; upper and lower, which are connected by narrow gorge at Al-Khoudh town [8].

3. GEOLOGY

The Samail Catchment consists of three main tributaries: Wadi Al-Rusail, Wadi Al-Khoudh, and

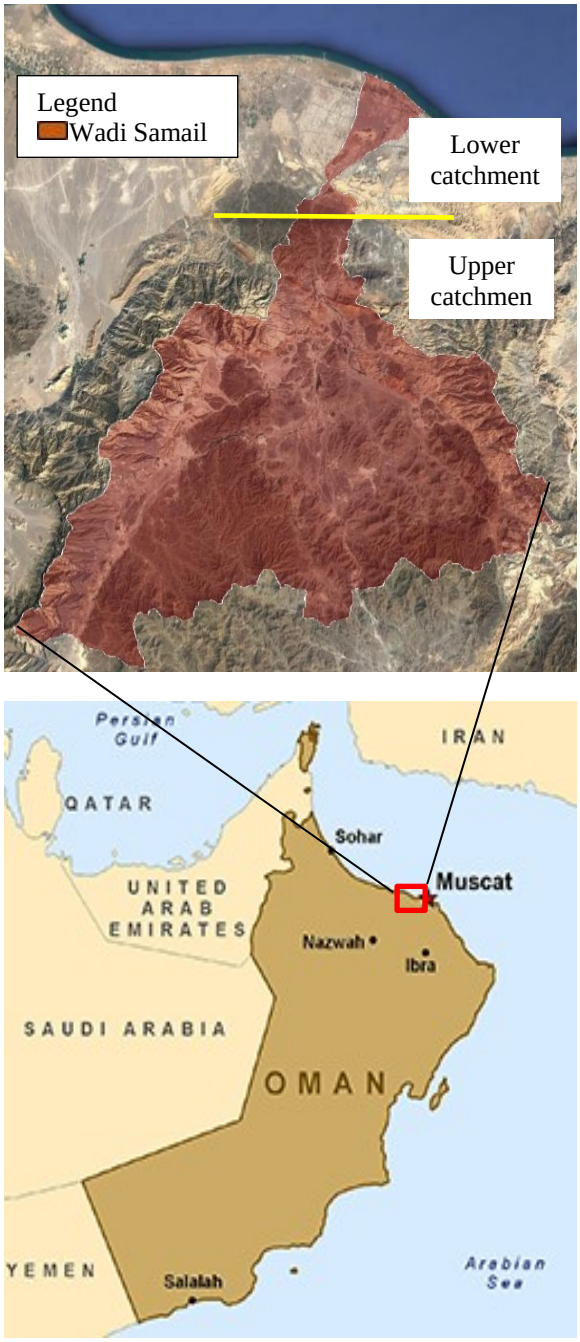


Fig. 1 Study area

Wadi Samail. It narrows and forms a gorge at Al-Khoudh town, after which the drainage system spreads to form a delta fan closer to the coast [8]. Al-Khoudh alluvium aquifer represents the lower reaches of the Samail Catchment.

The geological setting of the Al-Khoudh fan consists of crystalline bedrock formation, mainly ophiolites mantled by unconsolidated alluvium deposits [8]. The alluvium is over 300 m extends upto 600 m thick, and it is represented in three significant units of lithology succession as illustrated in Fig.2:

- Upper gravel: composed of large size gravel including boulders
- Clayey gravel
- Cemented gravel more compacted and conglomeratic due to CaCO3 rich solution and pressure

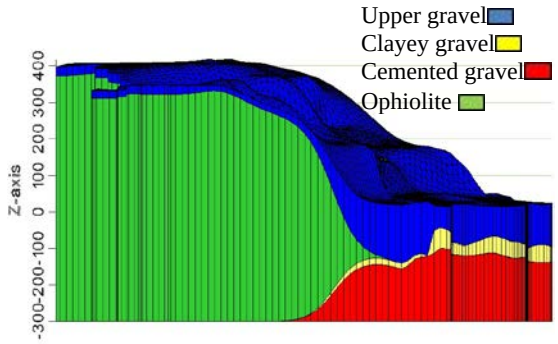


Fig. 2 Geologic cross-section of study area

4. DATA

4.1 Borehole data: the Ministry of Regional Municipalities and Water Resources (MRMWR) provided data of 47 boreholes covering the whole catchment area. Figure 3 represent lithology of two boreholes, which were used to develop the 3-D cross-section of the study area (Fig. 2).

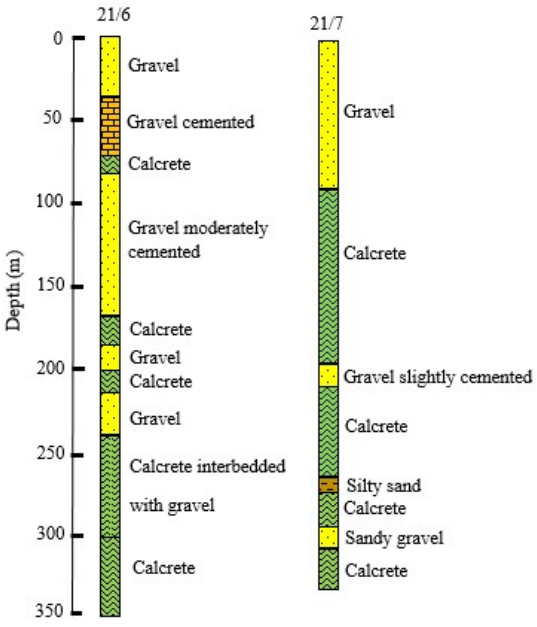


Fig. 3 Lithology of wells 21-6 and 21-7 bores [9]

4.2 Groundwater levels: groundwater level observations were obtained from the MRMWR.

Temporal variation of groundwater levels in some observation wells which were used for model calibration are illustrated in Fig.4, Fig.5 and Fig. 6 for the wells PZ-7, SNA-3B, and 21-6S, respectively.

Groundwater levels in these wells experienced a significant seasonal and annual fluctuations attributed to recharge from erratic rainfall and groundwater pumping [10].

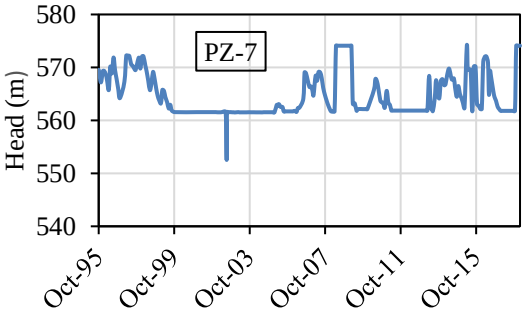


Fig.4 Hydrograph of observation well PZ-7

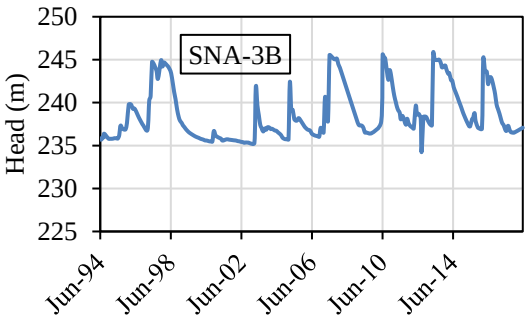


Fig. 5 Hydrograph of observation well SNA-3B

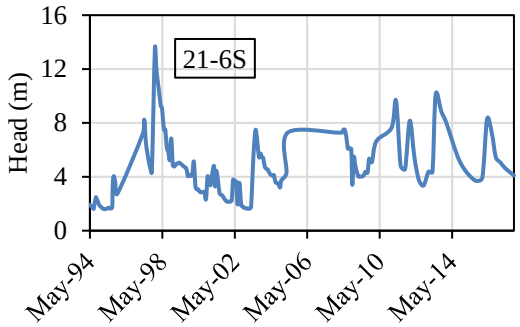


Fig. 6 Hydrograph of observation well 21-6S

4.3 Pumping wells: There are about 60 pumping wells located in the lower catchment area and used by the Public Authority of Water (PAW). Montly pumping rates from these wells were obtained. In addition, domestic irrigation well data was obtained from the National Well Inventory (NWI) from the MRMWR.

The pumping wells used in the model were categorized as water supply wells and private wells. Figure.7 displays the monthly pumping rates of three selected water supply wells. Pumping rates are subjected to a great level of temporal variation due to changes in demand.

4.4 Recharge: groundwater recharge was entered in the model as a percentage of observed rainfall from 6 stations. This percentage value was estimated in model calibration stage.

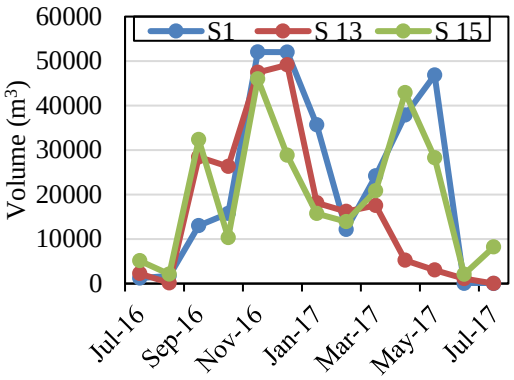


Fig. 7 Pumping rates from wells in Al- Khoudh wellfield (PAW, unpublished data, 2018)

4.5 Hydraulic conductivity: Initial hydraulic conductivity values (Table 1) were estimated based on borehole data. In addition, hydraulic conductivities estimated by pumping tests in past studies were also used.

5. GROUNDWATER FLOW MODEL

MODFLOW, which is a three-dimensional, finite-difference groundwater flow model [11], was used to simulate the groundwater flow. The governing equation for steady state groundwater flow in an inhomogeneous aquifer is [11]:

$$\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{zz}\frac{\partial h}{\partial z}\right)=W \quad (1)$$

where k is the hydraulic conductivity, h is the potentiometric head and W is the volumetric flux per unit volume. When q is discharge per unit width (Fig.8), Equation (1) can be simplified for unidirectional flow with Dupuit assumption [12] as:

$$h_1^2 = h_o^2 - \frac{2qx}{k_1} \quad (2)$$

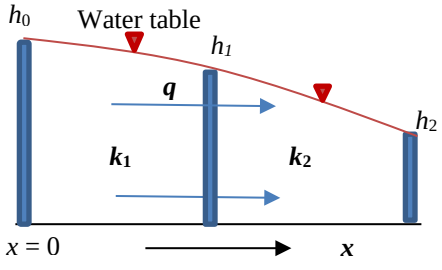


Fig.8 Unidirectional groundwater flow in a two-zone aquifer

The conceptual model was developed using data obtained from observation wells, pumping wells, and boreholes. The boundaries of the study area were formulated as shown in Fig.9. The aquifer was divided into four layers: upper gravel, clayey gravel, cemented gravel, and ophiolites. The first layer was divided further into five zones based on available borehole data. Finer adjucements to these boundaries were made during model calibration following the trial and error method. Also, the recharge coverage was divided into 3 zones using spatial variation of rainfall data. Based on borehole data, a 3-D cross-section was built to identify the properties and thickness of layers for 3-D grid formation (Fig. 2). The conceptual model and 3-D cross-section were mapped to MODFLOW to simulate the groundwater flow movement.

6. RESULTS AND DISCUSSION

The steady-state groundwater flow model was run using data in July, 2016. The calibration of model was conducted by using water levels of 14 observation wells that covers the whole catchment, as shown in Fig.9. These observed water levels varied from 569.2 m above mean sea level in upstream to 0.47 m in downstream.

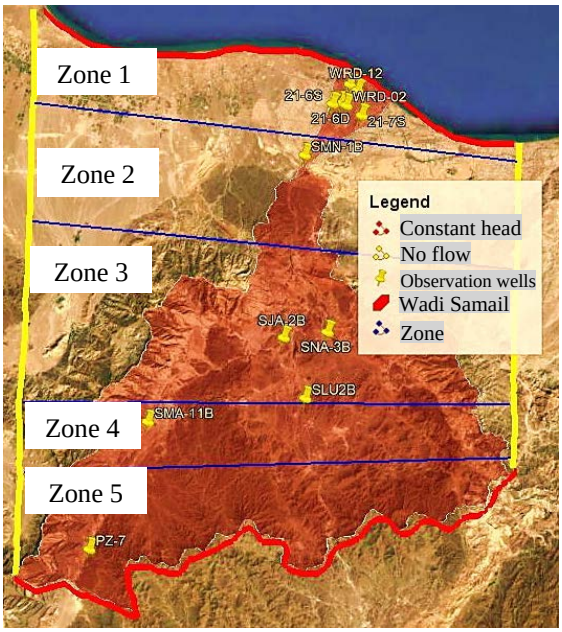


Fig. 9 Boundaries of the study area, location of observation wells and zones of Layer 1

The automated parameter estimation (PEST) method as well as the manual trial and error method were used for calibrating the model parameters. The manual trial and error method showed consistent results than the other method if we compared with the initial values of hydraulic conductivity. Since the geology of the aquifer is very complex, PEST was unable to determined the parameters accurately. Table 1 shows the comparison between the initial hydraulic conductivity values used in the conceptual model and the calibrated values by two different calibration methods: PEST and manual. It can be noticed that the hydraulic conductivity of Zone 1 in Layer 1 (upper gravel) is higher in the PEST method compare to the manual method. This can be due to the complexity of aquifer geology and the absence of adequate observation wells to represent the water level variations in different layers. Instead, manual trial and error method was proved to be performing better in this study area. Results show that the calibrated hydraulic conductivity values of Layer 1 decrease towards upstream where the ophiolite formation become dominant.

Table 1 Comparison between the initial hydraulic conductivity values and calibrated values obtained by PEST and manual methods.

Hydraulic conductivity (m/d)		Initial value	Calibrated value by PEST	Manually calibrated value
Upper gravel	Zone1	35	50	40.9
	Zone2	6	5.78	5.8
	Zone3	4.78	5.02	4.9
	Zone4	0.35	0.46	0.4
	Zone5	0.38	0.51	0.48
Clayey gravel		10	0.13	0.153
Cemented gravel		1	0.14	0.1
Ophiolites		0.436	0.12	0.163

The results of manual calibration are shown in Table 2. Calibrated parameters were able to simulate a significantly large groundwater level variation (approximately equals to 568.8 m from upstream to the downstream) with a residual head less than 2m. The root mean squared error (RMSE) for the steady-state simulation was calculated and found to be 0.8m.

Figures 10 and 11 show the plots of computed head versus observed head for the lower and upper catchments, respectively.Also,they show the match between the simulated head and observed head for the manual calibration. The data which is above the 45˚-line represent an overestimation of the groundwater head by the model while the data which lie under the line are underestimated by the model. In addition to the effect of hydrogeological complexities, these differences between observed and simulated values can also be attributed to the unaccounted pumping in domestic level.

Table 2 Calibration result

Observation well ID	Observed head	Computed head	Residual head
PZ-7	569.26	569.95	-0.69
SMA-11B	404.54	404.33	0.21
SLU2B	307.31	307.26	0.05
SJA-2B	253.99	253.33	0.66
SNA-3B	242.63	241.66	0.97
SMN-1B	69.91	70.52	-0.61
WRD-10	3.32	2.7	0.62
WRD-02	3.14	4.77	-1.63
WRD-12	1.84	2.57	-0.73
21-6D	7.19	6.7	0.49
21-6S	7.7	7.2	0.5
RGS-5HS	0.47	1.4	-0.93
RGS-5F	1.47	2.05	-0.58
21-7S	9.62	8.47	1.15

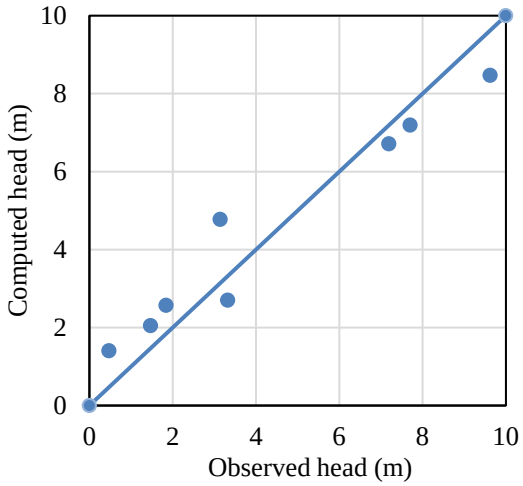


Fig. 10 Computed vs. observed head values for lower catchment

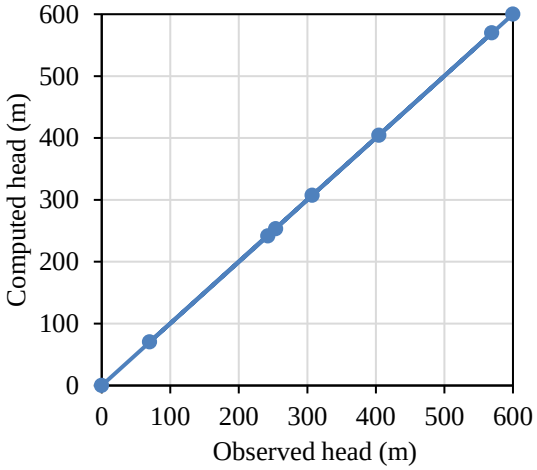


Fig. 11 Computed vs. observed head values for upper catchment

Once the aquifer parameters were estimated, another simulation was run using groundwater levels observed in October 2016 to verify the accuracy of the calibrated parameters. Figure 12 displays the computed heads from the simulation and the residual heads. The mean residual head was 0.35 m, and the RMSE is 0.81 m.

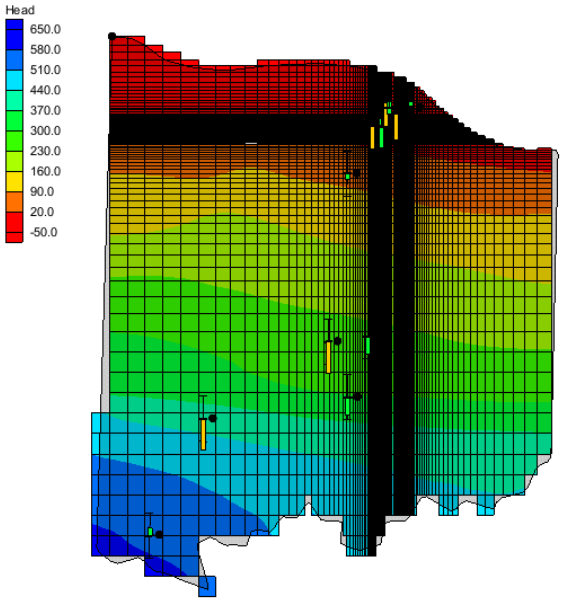


Fig.12 Validation of the model using data in Oct 2016

7. SENSITIVITY ANALYSIS

A sensitivity analysis was conducted using the calibrated groundwater flow model by varying the pumping rates, hydraulic conductivity, and recharge based on the calibrated values. RMSE and the mean error (ME) between the observed and simulated values were used to indicate the sensitivity of the parameters that changes from calibrated values. Each of the calibrated parameters were increased consistently by 10% upto 100% above the calibrated values and decreased on the same manner. Figures 13, 14, 15 and 16 show the sensitivity of pumping, hydraulic conductivity, and recharge parameters.

According to Fig.12, as the pumping rate increases, the mean error increased positively. For example, for a 70% increase from the calibrated value, the ME was found to be 2.81 m. This means that the observed water level is higher than the computed water level due to increased drawdown in simulations. While for a 70% decrease from the calibrated value, the ME increased negatively to -2.7 m, which indicates that the computed water level rises above the observed water level. While the RMSE showed that as the pumping increased, the residual error increased, and the same pattern occurred for the reduction in pumping rates.

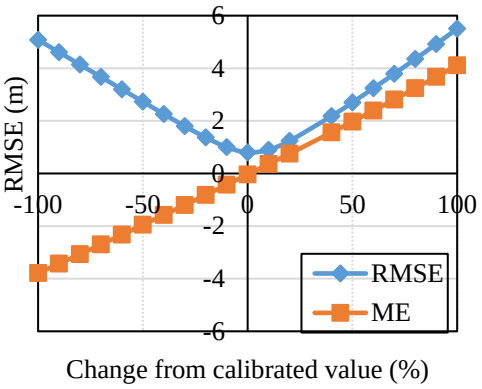


Fig.13 Sensitivity of pumping

It was noticed that the hydraulic conductivity of Layer 1 was more sensitive to the changes compared to the hydraulic conductivities of other layers (Figures 14 and 15). When the hydraulic conductivity of the Zone 2 in Layer 1 is decreased by 80% from its calibrated value, RMSE reached to 83 m. According to Equation 2, decreased hydraulic conductivity in Zone 2 decreases hydraulic head at the interface between Layer 1 and Layer 2, where most of the observation wells used to calculate the RMSE are located. Increased hydraulic conductivity shows less significance compared to the effect of the decreased hydraulic conductivity. This is because of the smaller hydraulic gradient exist between Zones 1 and 2 (Fig. 12). Increased hydraulic conductivity may reduce the hydraulic gradient there but change in hydraulic head at the interface will be comparatively smaller. The remaining layers were less sensitive to the changes from the calibrated hydraulic conductivity values as seen in Fig.15 with RMSE values less than 2 m.

Similarly, sensitivity of the recharge in Zone 2 was the greatest compared to the significance of other zones as shown in Fig.16. Because groundwater flows towards the sea, water level change in the zone immediately upstream to the most of the observation wells (Zone 2) proved to have a dominant effect to variate the RMSE.

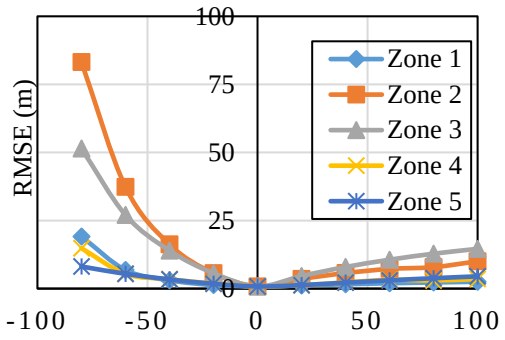


Fig.14 Sensitivity of hydraulic conductivity in different zones

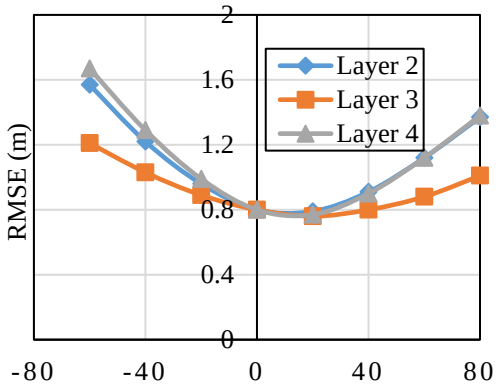


Fig. 15 Sensitivity of hydraulic conductivity

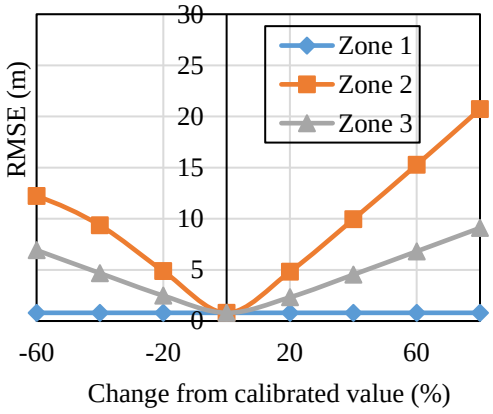


Fig. 16 Sensitivity of recharge

8. CONCLUSIONS

A well-known numerical groundwater model; namely MODFLOW has been implemented to simulate the groundwater level in an arid watershed of Oman. The model consists of four computational layers which were classified based on the borehole data. Calibrated parameters proved to be reliable due to smaller RMSE estimated in both calibration and verification stages. The manual calibration with the help of PEST is more suitable for aquifers with complex geology. Model simulations further indicated that the hydraulic conductivity is more sensitive than the pumping rate and recharge. Increased pumping rates may have negative impact especially near to the coast. Therefore, for water resource management purposes, the groundwater levels should be regularly monitored, and the effect of pumping should be evaluated.

9. ACKNOWLEDGMENTS

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10. REFERENCES

1. Akbarpour, S. and Niksokhan, M., Investigating effects of climate change, urbanization, and sea level changes on groundwater resources in a coastal aquifer:an integrated assessment. Environmental Monitoring Assessment, 2018. 190: 579: p. 1-16.
2. AL-Zubari, W., Alternative Water Policies for the Gulf Cooperation Council Countries Elsevier Science 2003(Water Resources Perspectives: Evaluation, Management and Policy.): p. p. 155-167.
3. MRMWR, Water Resources in Oman. 2008: p.1-140
4. Dragoni, W. and Sukhija, B., Climate change and groundwater: a short review. Geological Society, London, Special Publications, 2008. 288(1): p. 1-12.
5. Di Maio, R, Fabbrocino,S., Forte,G., & Pigegari,E.,Athree-dimensional hydrogeological–geophysical model of a multi-layered aquifer in the coastal alluvial plain of Sarno River (southern Italy). Hydrogeology Journal (2014) 22: 691–703, 2014(DOI 10.1007/s10040-013-1087-8).
6. Rabbani, M. and Warner, J., A finite-element linked model for analysis of solute transport in 3-D space of multilayer subsurface systems. Journal of Hydrology, 1997. 199: p. 163-182.
7. MRMWR, Water Resources in Oman. 2012. 3rd: p. 1-140.
8. Abdalla, O. and Al-Rawahi,S., Groundwater recharge dams in arid areas as tools for aquifer replenishment and mitigating seawater intrusion: example of AlKhod, Oman. Environmental Earth Sciences, 2013. 69(6): p. 1951-1962.
9. Macumber, P., Al Khawd Fan Groundwater Investigation Sultanate of Oman, 1997: p. 1-96.
10. Zekri,S.,AlMaktoumi,A.,Abdalla,O.,Akil,J.,& Charabi,Y.,Hydrogeological and economical simulations: emergency water supply for Muscat. Water Policy, 2014. 16(2): p. 340.
11. McDonald, M. and Harbaugh, A., A modular three-dimensional finite-difference ground-water flow model. U.S.Geological Survey report, 1988. 83-875: p. 1-539.
12. Todd, D. and Mays, L., Groundwater Hydrology. John Wiely & Sons,Inc., 2005.3rd: p.1-652.

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