Vol. 50, No. 1, pp 29-37, 2022
Indian Journal of Soil Conservation

Simulation of groundwater flow using visual MODFLOW: A case study for the command area of Chalakudy river diversion scheme

E.B. Gilsha Bai*, K.P. Rema, S. Sajeena and D. Sasikala

Department of Irrigation and Drainage Engineering, Kelappaji College of Agricultural Engineering and Technology, Kerala Argicultural University, Tavanur, Malappuram, Kerala.

*Corresponding author:
E-mail: gilsha.bai@kau.in (E.B. Gilsha Bai)*

ARTICLE INFO

DOI : 10.59797/ijsc.v50.i1.156

Article history:
Received : May, 2021
Revised : February, 2022
Accepted : March, 2022

Key words:
Conceptual model
Groundwater
Modelling
Simulation
Visual MODFLOW

ABSTRACT

Numerical models are proper tools for studying the status of groundwater, the world's largest water resource. Among the various models developed, visual MODFLOW is a simple, reliable, user-friendly and widely used model. The present study was conducted to simulate groundwater levels and flow in the command area of the Chalakudy River Diversion Scheme (CRDS) that lies in the typical midland region of Kerala where the humid tropical climate is existing. The area is characterized by a well-drained lateritic unconfined aquifer above the weathered rocky aquifer. Hard rock is lying below these two layers of the unconfined aquifer. Considering all these, a numerical conceptual model was created in visual MODFLOW software. The model was calibrated against historical observed water level data from 1996 to 2010 and validated using observed water level data from 2011 to 2014. Calibration and validation created a model that was capable to generate measured groundwater levels and flow. Sensitivity analysis of the model showed that groundwater level of the area was more sensitive to groundwater recharge and hydraulic conductivity. Influence of the specific storage of the aquifer on groundwater level was comparatively less. The model was used to predict groundwater levels for10 years from 2015 to 2024 under two scenarios. The scenario I considered the existing rate of groundwater abstraction and recharge. An annual decrease in groundwater recharge at the rate of 5% and an increase in groundwater draft at the rate of 10% was considered in scenario II. Even though the model shows the impact of reduced recharge and increased pumping rate on groundwater levels, the decline of groundwater levels is not drastic. This showed the immense scope for conjunctive use of surface and groundwater in the command area.

1. INTRODUCTION

Recently, the introduction of mathematical models accelerated groundwater research efforts. Several modelling software packages are in use for groundwater studies. Visual MODFLOW is a comprehensive and user-friendly groundwater modelling software that has a wide range of applications in the assessment of groundwater quantity, flow characteristics, and quality (Chen *et al*., 2017; Li Z. *et al*., 2019; Osman and Bruen, 2002; Sobeih *et al*., 2017; Wang *et al*., 2008). The software uses GIS technology to provide a visual interface for the user. Visual MODFLOW, the finite difference flow model with a graphical interface, can accept excel files, surface grids, GIS and AutoCAD data as input data sources (Chitsazan and Movahedian, 2015; Li F. *et al*., 2019). In India, hydrogeologists use the software to solve groundwater flow problems. (Hariharan and Kumar, 2017; Khadri and Pande, 2016; Mohanty *et al*., 2018; Sajeena and Kurien, 2019).

Due to the ever-increasing population, dwindling water resources place additional strain on fresh water sources (Kushwaha *et al*., 2009). Even in humid tropical regions, surface water resources alone cannot meet agricultural water demands. Summer days are very hot in these areas. The people move towards the groundwater sources to fulfil the domestic and agricultural demands. Over extraction may lead to a decrease in the quantity as well as quality of groundwater (Lamsoge *et al.*, 2014). Researchers, academicians, and administrators are giving importance to proper planning of the use of water resources to save mankind from extinction. The combined use of surface water and groundwater to meet the water demand for agriculture is the core of this planning. Conjunctive use of the major water resources is necessary for sustainability. For planning conjunctive water use, the nature and flow characteristics of both water resources should be studied (Raul *et al*., 2011). Groundwater models, especially visual MODFLOW, are a good choice for carrying out groundwater simulation studies for this purpose.

The present study was conducted from 2016 to 2019 to know the groundwater flow characteristics in the command area of a river diversion scheme (the Chalakudy River Diversion Scheme) in order to develop a conjunctive irrigation water management model for the command area. The Chalakudy river is 145 km long and originates from the Anamalai hills, Parambikulam Plateau, and Nelliampathy hills of the Southern Western ghats and flows westwards through three districts, *viz.,* Palakkad, Thrissur, and Ernakulam, of Kerala. Chalakudy River Diversion Scheme (CRDS) is a major irrigation project in the state that diverts the river flow through left and right bank canals without a storage facility at the weir site. The study area is extended to two adjacent districts, Thrissur and Ernakulam, in the central portion of Kerala (Fig. 1). The command area lies between the north latitudes of 10^{0}8'45" and 10^{0}24'28" and the east longitudes of 76^{0}12'37" and 76^{0}22' 17". It covers 400 sq km and is comprises of 15 panchayaths and one municipality. The climate in the area is humid tropical with an average annual rainfall of 3194 mm and an average temperature that varies from 25.77°C to 35.12°C. The specific objective of the study is to assess the dynamic response of the aquifer in the area to groundwater extraction and recharge.

2. MATERIALS AND METHODS

The visual MODFLOW model developed in the study was calibrated using 15 years of data from 1996 to 2010 on groundwater levels and pumping and validated using 4 years of data from 2011 to 2014. After this, the model was used to analyse various scenarios to identify the scope of conjunctive use of surface water and groundwater in the CRDS command area.

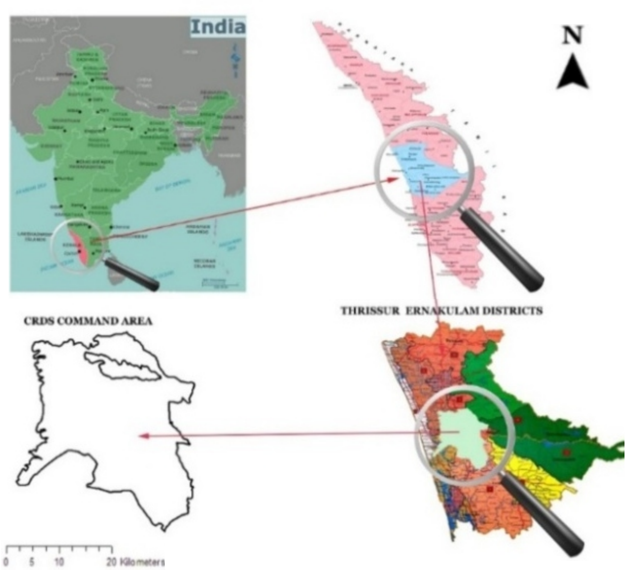


Fig. 1. Location map of the study area

Conceptual Model of the Study Area

The conceptual model of the study area was developed using satellite imagery and well log data from 18 wells within the area maintained by the state groundwater department. Lithological data revealed that laterite is the predominant type of soil in this region, and its thickness ranges from 3 m to 15 m. Below the lateritic patch, weathered rock and hard rock formations exist. Hence, the conceptual model of the CRDS command area was developed with two aquifer layers: the upper lateritic layer and the lower weathered rock layer. The hydrogeological parameters showed that the average elevation of this midland region is 20 m above the mean sea level (CGWB, 2013). Groundwater from the aquifer is abstracted through dug wells and shallow-depth bore wells. The depth of the water table in the study area fluctuates from 0.59 to 14 m below ground level. The transmissivity of the aquifer in the area varies from 22 to 288 sq m day^{-1}. (CGWB, 2013 and Varma, 2017). The Chalakudy river, passing through the centre of the study area, forms the main drainage line in the area.

Discretization of the Study Area

After conceptualization, the area was discretized into 60 rows and 60 columns of a 0.5 × 0.5 km finite difference grid. The area outside the command area boundary was made inactive. The elevation of the surface and the bottom layers were further added in text format. The surface topography was generated from a DEM of the study area. The elevation of the sub-surface aquifer layer was calculated from the lithological data obtained from the State Government Groundwater Department. For each 91-day interval in between two consecutive observations of groundwater level, the hydrological parameters were assumed to be constant.

Wells

Data on pumping rate and groundwater level are the important inputs to the visual MODFLOW model. The user can add, delete, or edit the data graphically with the drop-down menu in the "well" section of the software. Quarterly water level data, *i.e.,* monsoon, post-monsoon, *rabi,* and pre-monsoon, from 17 observation wells of the Central Groundwater Board (CGWB) were used in the study. The pumping data of 14 wells, 11 dug wells and 3 bore wells in the command area, collected from the Kerala Water Authority, was used as input to the model.

Hydrogeological Properties

The hydrogeological properties of the layers, hydraulic conductivity, specific storage, specific yield, and porosity are the other inputs to the model. The values of these properties for laterite and weathered rock were collected from literature. The calibration of the model was initiated with the hydraulic conductivity values of 8.64 m day^{-1} for the laterite layer and 0.864 m day^{-1} for the weathered rock layer (CGWB, 2009). The vlaues of storage properties initaily taken is shown in Table 1 (Todd, 1980).

Initial Head

An initial head value is required to assign water head distribution over the study area for simulation in the visual MODFLOW model. Water level data collected from the CGWB was used for this. The monsoon water level data during 1996 was assigned as the initial heading for the study.

Boundaries

Boundary conditions such as recharge to the area, rivers, drains, constant head, general head, walls, and evapotranspiration (ET) are necessary for the development of a groundwater model in visual MODFLOW. At least one boundary is necessary to run the model.

Recharge

The visual MODFLOW model requires input to recharge the area for running the simulations. The recharge to the study area includes recharge from rainfall, canal seepage, and return flow from irrigated land. Recharge from rainfall was calculated using the formula developed by the Irrigation Research Institute, Roorkee (Kumar and Seethapathi, 2002). Annual rainfall recharge was computed using rainfall data from 1996 to 2014.

$$R = 1.35\,(P - 14)^{0.4} \qquad ...(1)$$

Where, R - Rainfall in inches; P - Precipitation in inches.

Return flow from the irrigated field was calculated according to the guidelines of CGWB, and recharge from canal flow was computed from the measurement of canal seepage loss.

River Head

The Chalakudy river, which flows through the central portion of the command area, formed an important boundary condition in the model. Two other rivers, Periyar and Kurumaly, flowing along the southern and northern boundaries of the command area, respectively, were also considered as boundary conditions while developing the regional groundwater flow model. The input of data on river stage, river bed bottom, and conductance for each grid cell is required to run the model if a river boundary exists in the model. River conductivity was calculated using the formula as follows:

$$C = \frac{K \times L \times W}{M} \qquad ...(2)$$

Where, C - Conductance of the river bed (L^2T^{-1}); K - Hydraulic conductivity of the river bed (LT^{-1}); L - Length of the river (grid size) (L); W - Width of the river in the grid (L); M - Thickness of river bed (L).

Evapotranspiration (ET), which is a loss from groundwater through capillary rise, needs to be entered into the input module. It was calculated as 24% of annual rainfall based on crop water requirement calculations using CROPWAT 8.0 software, and it was assumed to occur uniformly across the entire CRDS command area. Drain is another boundary condition to simulate the effect of agricultural drains on aquifer head. Drains are located some distance along the boundary of the study area.

Model Calibration and Validation

Model calibration is the process of systematically changing the input parameters, mainly hydraulic conductivity, to arrive at a calculated head that is almost equal to the field observed water levels. The model was calibrated using historical water level data from 17 observation wells from 1996 to 2010. Quarterly water level data, *i.e.,* monsoon, post-monsoon (*kharif*), post-monsoon (*rabi*), and pre-monsoon, were used. According to the data availability, 60 stress periods of 91 days each (three months) were used for calibration. The water level in July 1996 was taken as the initial condition. Both steady and transient state model runs were done for the calibration. The transient run includes the calculation of heads for various time steps. In the present study, the criteria used for calibration were root mean square error (RMSE). Calibration was continued until no further reduction in RMSE value was obtained.

Using the calibrated values of various input parameters, the model was validated. Water level data from 2011 to 2014 was used for verifying the calibrated model. After the validation, the model was used to predict the aquifer response for various strategies.

Sensitivity Analysis

Sensitivity Analysis is the process of varying the model input parameters within some acceptable range to get the corresponding variation in model outputs. Variation in output values determines the sensitivity of the model to various input parameters. In the present study, the sensitivity analysis was done by changing input parameters *viz.,* hydraulic conductivity, specific storage and annual recharge.

Prediction Using the Model

To analyse the scope for conjunctive management of two major water resources, *i.e.,* surface water and groundwater, the visual MODFLOW model developed for the CRDS command area was used to predict groundwater conditions under two scenarios.

Scenario I: Recharge to the aquifer and pumping from the command area continues as in the present condition. That is the end of the validation period, 2014.

Scenario II: Recharge to the aquifer decreases annually at the rate of 5% from the end of the validation period, 2014. At the same time, pumping increases annually at a rate of 10% from the end of the validation period. Expected climate change, urbanization, and changes in irrigation demands, etc. are the reasons for this assumption.

3. RESULTS AND DISCUSSION

Visual MODFLOW provides several outputs like contours of head equipotential, drawdown, head difference, elevation, net recharge, and water table. It also gives graphs of calculated and observed heads, head *vs.* time, normalised RMS *vs.* time, drawdown *vs.* time, etc.

Steady-State Calibration

The model was calibrated for steady-state groundwater flow. The aquifer condition of the year 1996 is assumed as the initial condition for calibration. Calculated water levels were compared with the water levels observed from 17 wells, including 3 bore wells, within the command area. Several input parameters (hydraulic conductivity, specific storage, specific yield, river stage, recharge, discharge through the drain, etc.) were changed systematically to get calculated heads in the acceptable range. An acceptable limit was defined as a RMSE value of less than 5, which represents a 95% confidence level. The plot of the calculated *vs.* observed water level of 17 observation wells is shown in Fig. 2. From the figure, it is clear that there is good agreement between calculated and observed water levels in most of the wells. The calibrated model has a hydraulic conductivity of 571.1 m day^{-1} for the laterite layer and 0.432 m day^{-1} for the weathered rock layer. Storage properties of the calibrated model are shown in Table 1. The general soil type in the command area was lateritic, with high porosity and specific yield.

Transient State Calibration

In the transient state calibration, the model was used to compute water levels for each time step. Water levels from 1996 to 2010 in 60-time steps were used for calibration. Hydraulic conductivity, boundary conditions, and the water levels observed from the steady state calibration were taken as the initial conditions for the transient state calibration. Graphs of computed versus observed water levels for two stages (1826th day and 4746th day) are shown in Fig's 3 and 4. The nearness of computed and observed water levels is obvious in the figures.

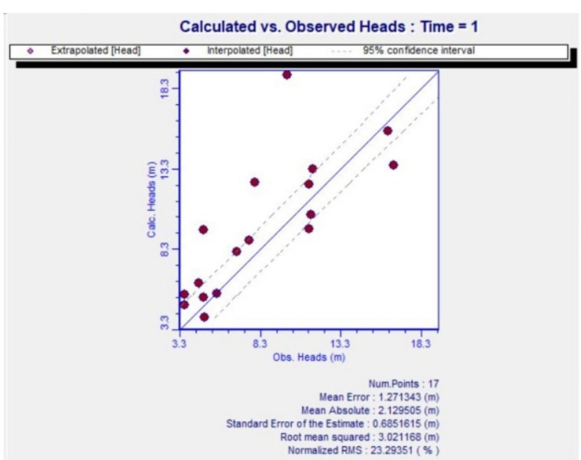


Fig. 2. Observed *vs.* computed water levels after steady-state calibration

Table: 1
Aquifer storage properties at the beginning and end of the calibration

Aquifer property	Initial values	Final values
Specific Storage (Ss) (m^{-1})	0.0003	0.0009
Specific yield (Sy)	0.15	0.38
Effective porosity	0.38	0.40
Total porosity	0.45	0.45

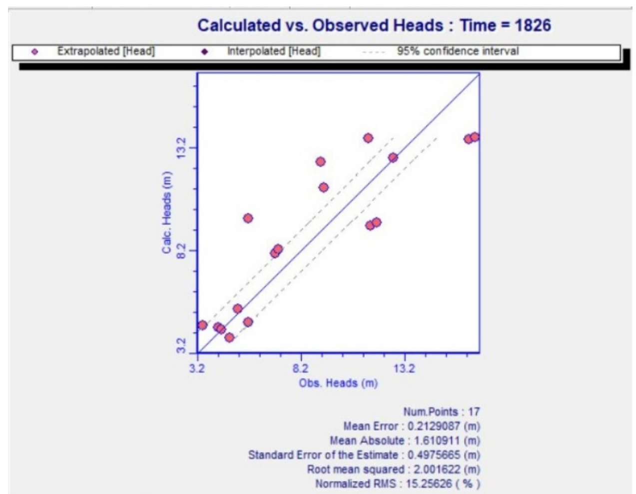


Fig. 3. Observed *vs.* computed water levels on 1826th day of the calibration period

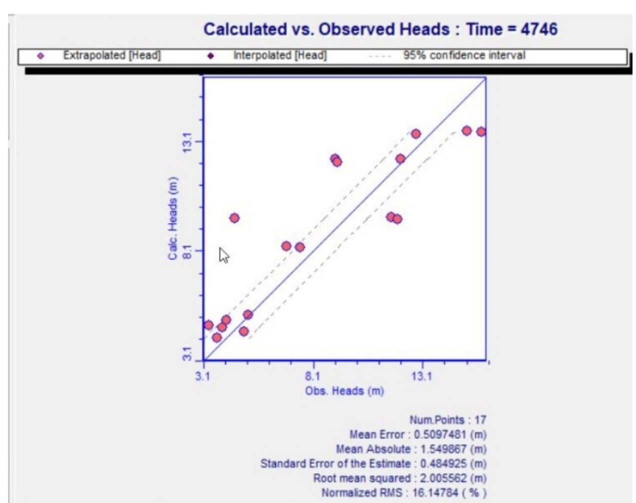
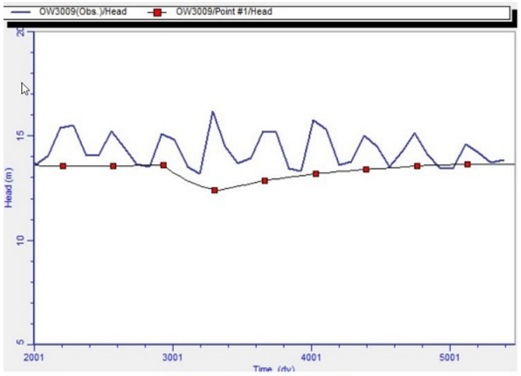
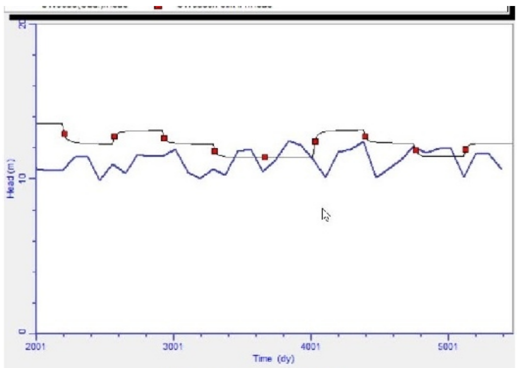


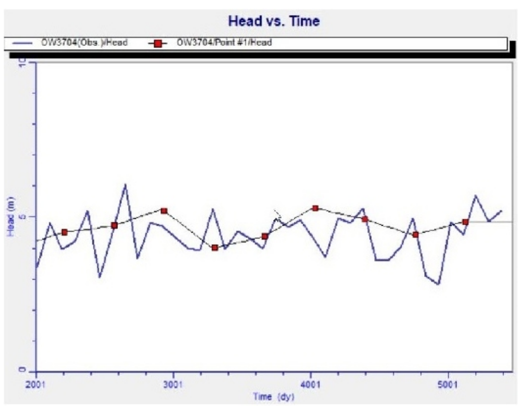
Fig. 4. Observed *vs.* computed water levels on 4746th day of the calibration period



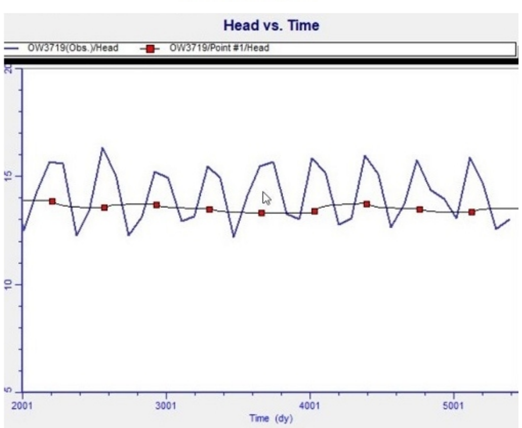
Well at Angamaly 3009



Well at Konnakuzhi 3699



Well at Potta 3704



Well at Mupliyam 3719

Fig. 5. Computed and observed head *vs* time graph of selected wells after calibration

Computed and observed water levels against time (calibration period) of selected wells are shown in Fig. 5. From the figure, it is seen that the computed water levels are comparable with the observed water levels.

The water table contour map of the study area after steady state calibration is shown in Fig. 6. It is clear from the figure that the water table elevation is high, 15 to 20 m, towards the northeast portion of the study area. This is because of the higher surface elevation of the area. Water level elevation decreases towards the southwest direction as the topography of the area slopes towards the southwest. The lowest water table elevation was observed towards the low-lying paddy area. The majority of the command area has a water table elevation in the range of 9 m to 14 m. Through the centre of the command area, the Chalakudy river flows from east to west. Water table contour values also decrease from east to west in this region.

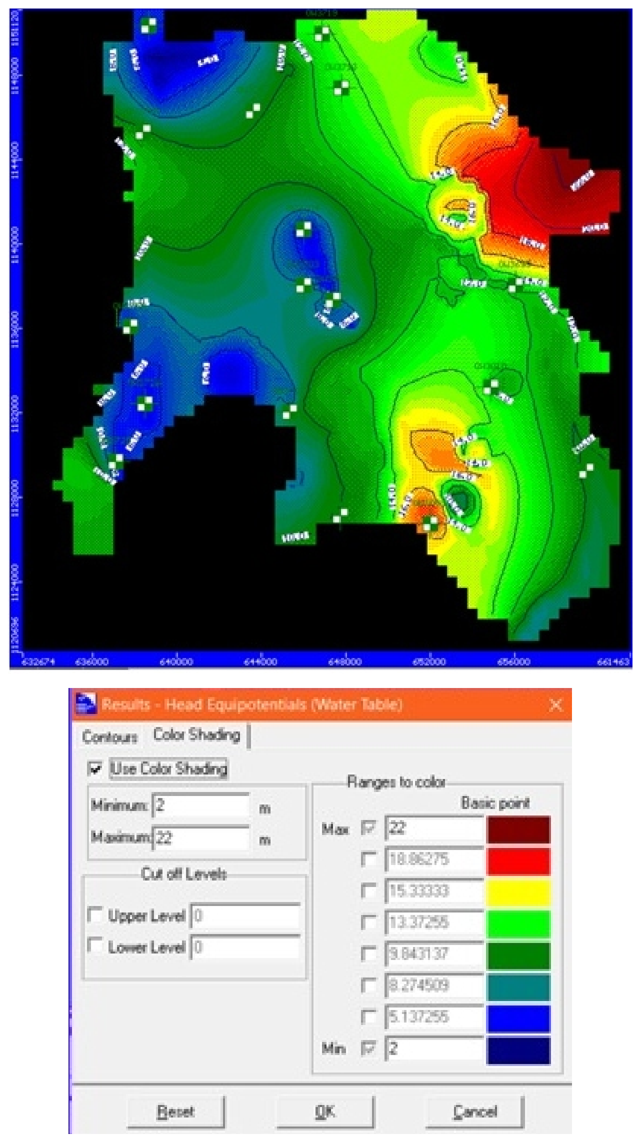


Fig. 6. Water table contour map after calibration

Model Validation

The model was validated using water level data from 2011 to 2014. Fig. 7 shows the scatter diagram of computed and observed water levels of 17 observation wells in the command area. Table 2 shows the computed and observed water levels. From the figure and table, it is obvious that there is a good agreement between computed and observed water levels after validation. In the case of well number 3729, the observed water level is 5.62 m above MSL, and the calculated water level is 5.54 m above MSL. Graphs showing head vs time of selected wells after the validation (Fig. 8) also imply this. The model can now be used to predict future groundwater conditions in the region.

Sensitivity Analysis

Sensitivity analysis revealed that groundwater recharge and hydraulic conductivity were the most sensitive input

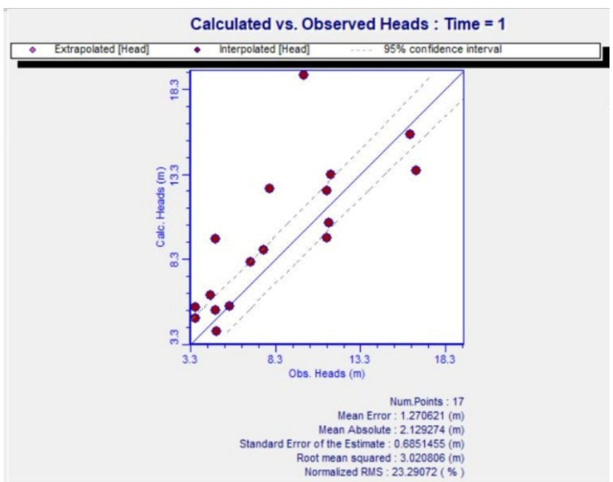


Fig. 7. Computed *vs.* observed water levels after validation

Table: 2
Observed and calculated water levels after validation

Well number	Observed water level (m above MSL)	Calculated water level (m above MSL)	RMSE
3704	4.85	4.07	0.779
3729	5.62	5.54	0.083
3701	4.74	5.28	0.540
3715	3.60	5.49	1.890
3759	4.49	6.16	1.673
3728	3.61	4.81	1.200
3703	6.82	8.14	1.324
3727	7.59	8.86	1.273
3015	11.31	9.54	1.769
3718	11.53	13.25	1.719
3699	11.31	12.31	1.001
3058	9.98	12.51	2.530
3010	7.98	12.43	4.446
3714	11.42	10.43	0.994
3009	16.22	15.62	0.582
3719	16.57	13.48	3.088
3717	4.79	9.5	4.174

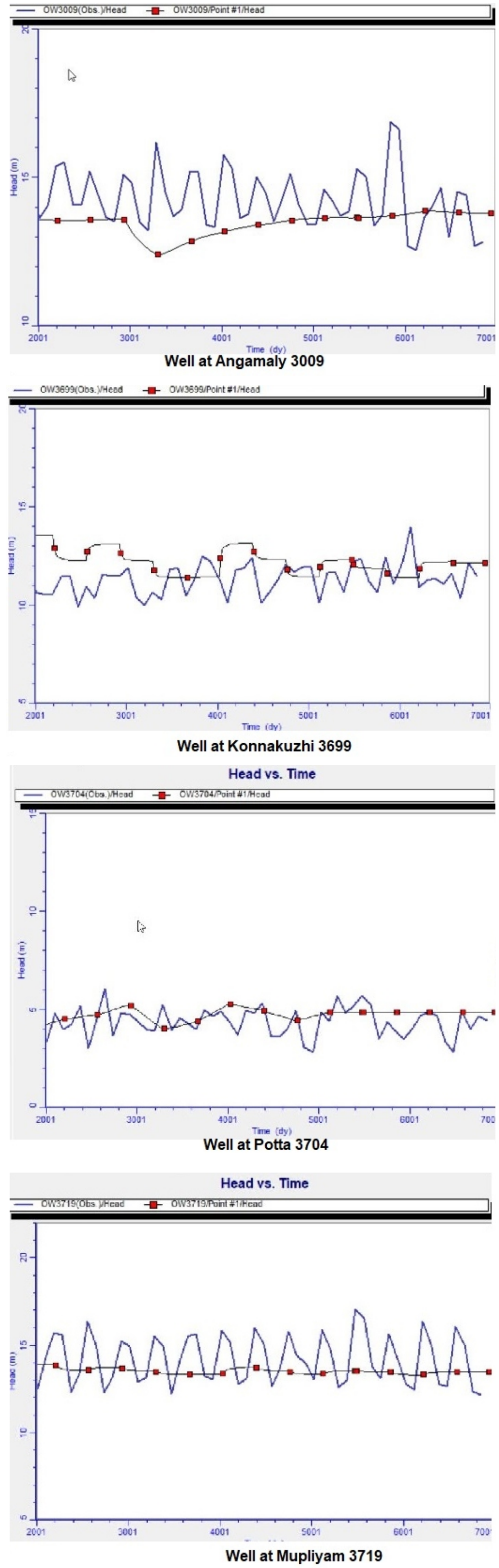


Fig. 8. Computed and observed head *vs.* time graph of selected wells after validation

parameters to the model. The groundwater level of the area responds rapidly to the variation in recharge and hydraulic conductivity of the aquifer. whereas the groundwater level was less sensitive to the specific storage of the aquifer. Fig. 9 shows the sensitivity chart of the observation well at Muriyad.

Prediction of future water levels

Predicted water levels of selected wells using the developed visual MODFLOW model for the CRDS command area are shown in Fig's 10 and 11. Water table contour map for the predicted scenarios are presented in Fig's 12 and 13. Fig. 10 shows the water level according to the scenario I after 10 years from the end of the validation period. That is, the groundwater level in 2024 if the recharge and pumping rate continue as such in the present condition. From the figure, it is clear that the water level continued at almost the same level for 10 years after the validation period.

Fig. 11 shows the predicted results of some selected wells when the model runs according to the second scenario. Expected future changes in recharge and pumping rates are incorporated into this scenario. Water levels show a decreasing tendency as the year progresses from the end of the validation period. Changes in rainfall patterns, reductions in surface water availability due to this change, reductions in rechargeable soil surface due to urbanization, etc. may reduce the aquifer recharge considerably. On the other hand, the withdrawal rate of groundwater may increase due to an increase in population, urbanization, industrialization, and a change in irrigation demands. The developed model showed a response to these expected changes.

Even though the model shows the impact of reduced recharge and increased pumping rates on groundwater levels, the decline in groundwater levels is not drastic. In a span of 10 years, the average decline in water level is nearly 50 cm. This showed that there is immense scope for conjunctive use of surface and groundwater in the command area.

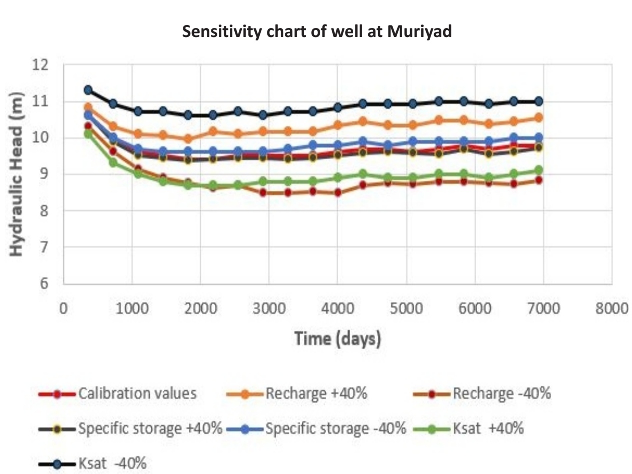
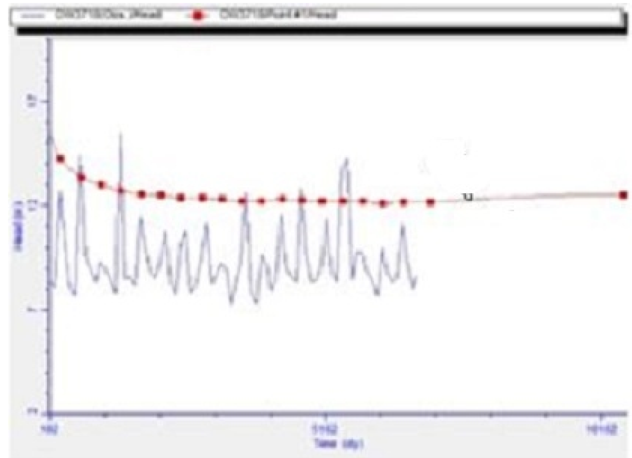
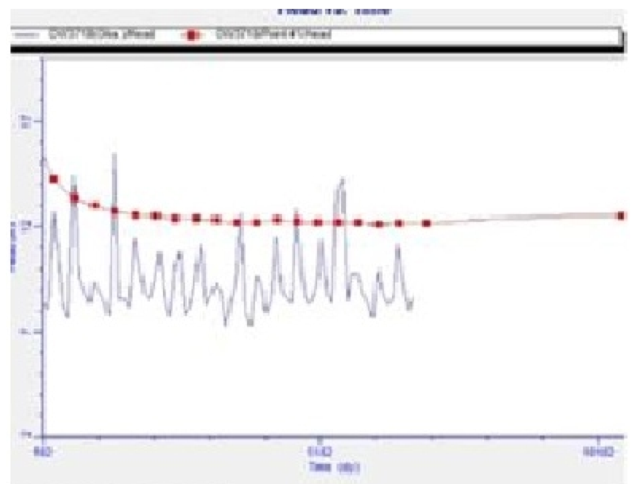


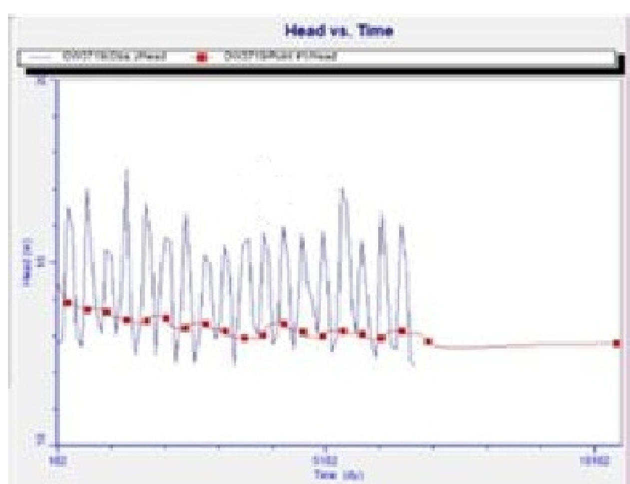
Fig. 9. Sensitivity chart of observation well at Muriyad



Well at Angamaly 3009

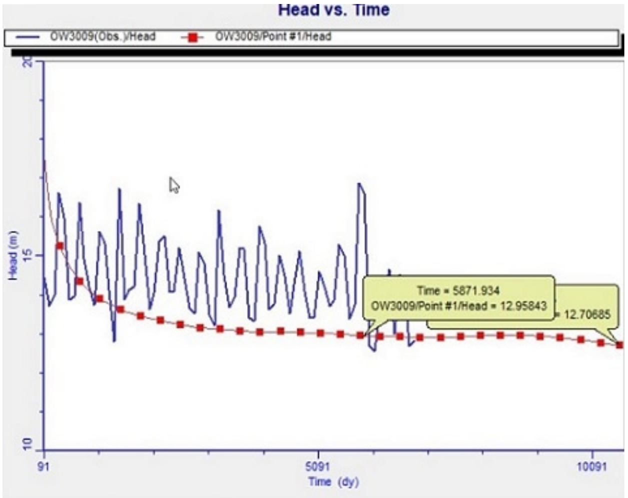


Well at Mattathur 3718

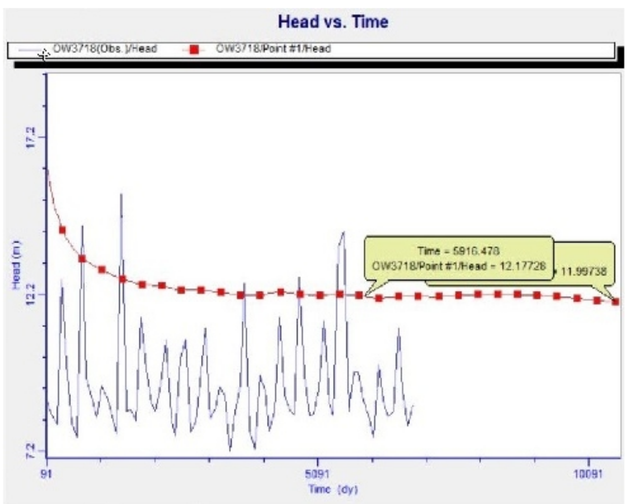


Well at Mupliyam 3719

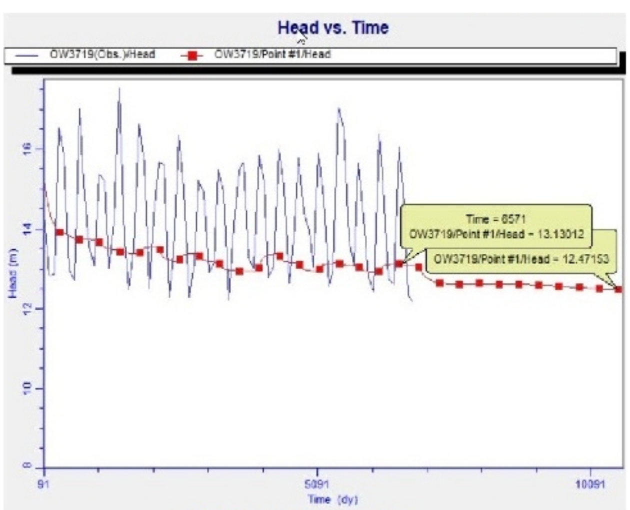
Fig. 10. Scenario I - Predicted water levels of selected wells after 10 years from the end of the validation period



Well at Angamaly 3009



Well at Mattathur 3718



Well at Mupliyam 3719

Fig. 11. Scenario II - Predicted water levels of selected wells after 10 years from the end of the validation period

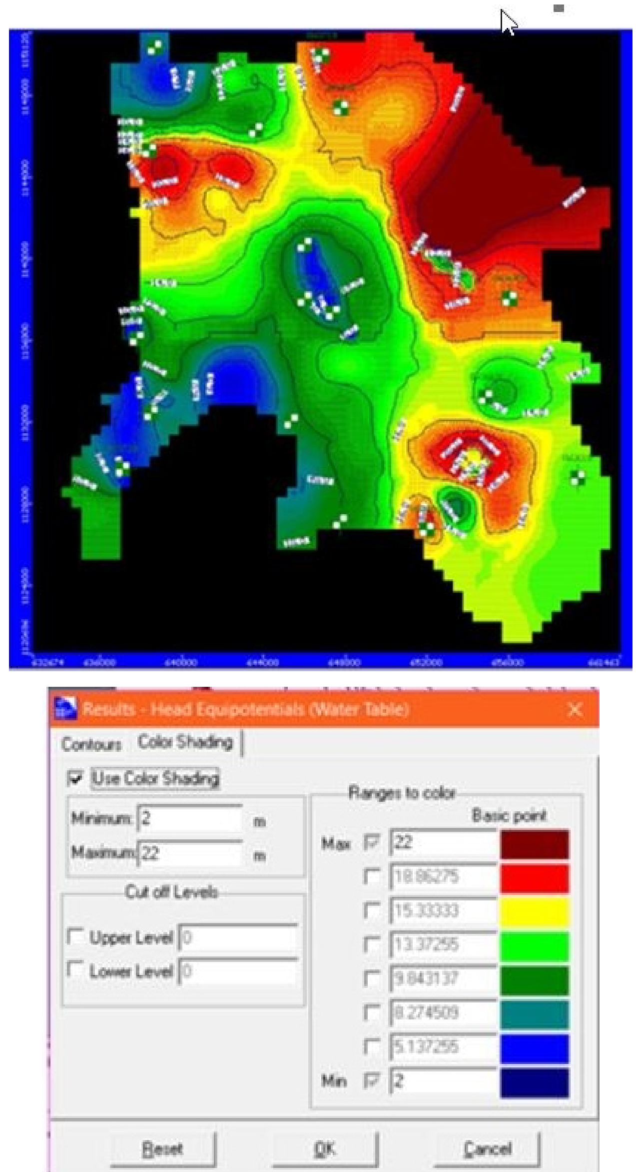


Fig. 12. Scenario I - Predicted water table contour after 10 years from the end of the validation period

4. CONCLUSIONS

Visual MODFLOW is a well-established tool for the simulation of groundwater flow. The groundwater model of the CRDS command area developed in the visual MODFLOW software was used for prediction of two scenarios. The prediction of different scenarios of groundwater recharge and pumping revealed the necessity of increasing recharge when the increase in abstraction is unavoidable. The groundwater source in the area is able to withstand slight variations in pumping without much effect on the groundwater level. Prediction of groundwater levels using the model assuming a 5% annual reduction in recharge and a 10% annual increase in pumping resulted in an average decline of 0.55 m in groundwater levels after 10 years from

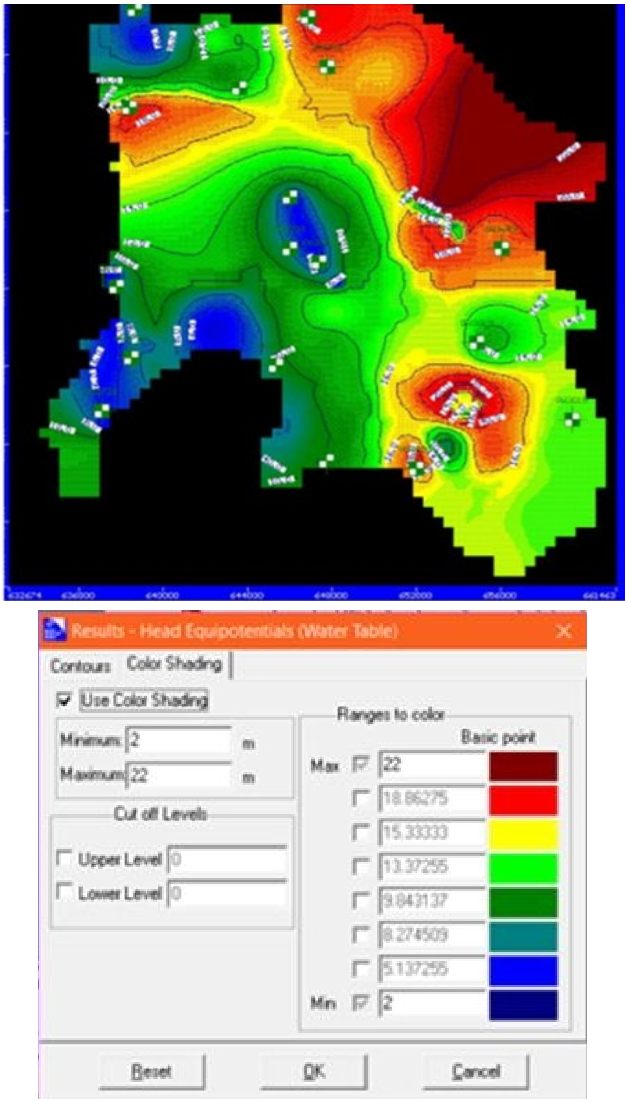


Fig. 13. Scenario II - Predicted water table contour after 10 years from the end of the validation period

the end of the validation period in the study area. This prediction showed the possibility of groundwater withdrawal for irrigation without a drastic declination in water levels. It can be concluded from the study that the integrated management of water resources through the conjunctive use of surface water and groundwater is possible in the command area of CRDS.

ACKNOWLEDGEMENT

The authors are thankful to Kerala Agricultural University for funding the project. Moreover the first author is grateful to the University for granting study leave for three years from September, 2016.

REFERENCES

CGWB (Central Ground Water Board). 2009. *Report of the ground water resource estimation committee*. Ministry of Water Resources. Govt. of India, New Delhi, 107p.

CGWB (Central Ground Water Board). 2013. Groundwater information booklet of Thrissur district, Kerala state. In: Ground Water information booklet of Thrissur District: 1-27.

Chen, M., Izady, A. and Abdalla, O.A. 2017. An efficient surrogate-based simulation-optimization method for calibrating a regional MODFLOW model. *J. Hydrology*, 544: 591-603.

Chitsazan, M. and Movahedian, A. 2015. Evaluation of artificial recharge on groundwater using MODFLOW model (Case Study: Gotvand Plain-Iran). *J. Geosci. Environ. Prot.*, 3: 122-32.

Hariharan, V. and Uma Shankar, M. 2017. A review of visual MODFLOW applications in groundwater modelling. *IOP Conf. Ser. Mater. Sci. Eng*., 263: 032025, doi: 10.1088/1757-899X/263/3/032025.

Khadri, S.F.R. and Pande, C. 2016. Groundwater flow modeling for calibrating steady state using MODFLOW software: a case study of Mahesh River basin, India. *Model. Earth Syst. Environ.,* 2: 39, doi: 10.1007/s40808-015-0049-7.

Kumar, C.P. and Seethapathi, P.V. 2002. Assessment of natural groundwater recharge in upper Ganga canal command area. *J. Applied Hydrol.*, 15(4): 13-20.

Kushwaha, R.K., Pandit, M.K. and Goyal, R. 2009. MODFLOW based groundwater resource evaluation and prediction in Mendha sub-basin, NE Rajasthan. *J. Geol. Soc. India,* 74: 449-58.

Li, F., Liu, Y., Yong Zhao, Y., Deng, X. and Jiang, R. 2019. Regulation of shallow groundwater based on MODFLOW. *Appl. Geogr.*, 110: 102049.

Li, Z., Gao, P. and Lu, H. 2019. Dynamic changes of groundwater storage and flows in a disturbed alpine peatland under variable climatic conditions. *J. Hydrol.*, 575: 557-568.

Mohanty, S. Jha, Madan, K. Gupta, V. Chaudhari, S.K. and Mal, B.C. 2018. Numerical analysis of a deltaic aquifer system for sustainable management of groundwater. *Indian J. Soil Conserv.* 46(2): 151-159.

Osman, Y. and Bruen, M.P. 2002. Modelling stream-aquifer seepage in an alluvial aquifer: an improved loosing-stream package for MODFLOW. *J. Hydrol.*, 264: 69-86.

Raul, S.K., Panda, S.N., Hollander, H. and Billib, M. 2011. Integrated water resource management in a major canal command in eastern India. *Hydrol. Process*. 25: 2551-2562, doi: 10.1002/hyp.8028.

Sajeena, S. and Kurien E.K. 2019. Studies on groundwater resources using visual modflow - A case study of Kadalundi river basin, Malappuram, Kerala. *Indian J. Soil Cons.,* 47(1): 21-29.

Sobeih, M.M., El-Arabi, N.E., Helal, E.E.D.Y. and Awad, B.S. 2017. Management of water resources to control groundwater levels in the southern area of the western Nile delta, Egypt. *Water Sci.,* 31: 137-50, http://dx.doi.org/10.1016/j.wsj.2017.09.001.

Todd, D.K. 1980. *Groundwater hydrology*, John Willey Sons. Inc, New York, 535p.

Varma, A. 2017. *Groundwater resource and governance in Kerala: Status, Issues and Prospects*. Forum for Policy Dialogue on Water Conflicts in India, Pune, 105p.

Wang, S., Shao, J., Song, X., Zhang, Y., Huo, Z. and Zhou, X. 2008. Application of MODFLOW and geographic information system to groundwater flow simulation in North China plain, China. *Environ. Geol.,* 55:1449-62, doi: 10.1007/s00254-007-1095-x.