

3D Groundwater Modelling for Sustainable Resource Management – A Case Study

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ABSTRACT: Groundwater is a major natural source of water for domestic, industrial and agricultural uses. Nowadays, exploitation of groundwater resource has increased, leading to over consumption, which results in ecological problems such as decreased groundwater levels, water exhaustion etc. Hence assessment of groundwater availability is essential for the sustainable management of groundwater resources. In the present work, a numerical model for groundwater flow was developed in transient state using MODFLOW2000. The study area extends from Karikkakom to Kadinamkulam region located in the coastal belt of Trivandrum district, Kerala, India. Parameters of groundwater flow model for each layer were estimated through calibration. Groundwater head in the observation wells were simulated and predicted for future years. Simulated ground water head shows a decreasing trend. Two different scenarios were analysed for groundwater flow.

KEYWORDS: Groundwater, Numerical model, Modflow

I. INTRODUCTION

Groundwater constitutes the most important natural water resources all over the world. The use of groundwater models is prevalent in the field of environmental hydrogeology. A simulation of groundwater flow that takes into consideration the parameters and properties variability of aquifer is only possible through mathematical modeling. Groundwater flow and fate and transport models have been applied to investigate a wide variety of hydrogeologic conditions.

Groundwater flow models are used to calculate the rate and direction of movement of groundwater through aquifers and confining units in the subsurface. Numerous studies have been conducted in the last decades using professional groundwater software, such as Visual MODFLOW, GMS, FEFLOW, SEAWAT and the integration of some ones. The best tool available to help groundwater hydrologist to meet challenges of prediction is usually by a groundwater flow model. The most widely used numerical groundwater flow model is Visual MODFLOW which is a modular three-dimensional finite-difference groundwater flow model. Due to its capability, MODFLOW is widely used to simulate different types of groundwater problems in different geographical regions, such as the arid, semi-arid and tropical areas.

Prof. F De Smedt (2008) studied groundwater – surface water interaction modelling using Visual MODFLOW and GIS. The model was developed under steady state condition. Izrar Ahmed and Rashid Umar (2009) conducted a study on groundwater flow modelling of Yamuna–Krishni interstream whereas Rajamanikam and S Nagan(2010) conducted a study on groundwater quality modelling of Amaravathi river basin. In both the studies model simulates the groundwater flow for steady and transient conditions.

The objectives of the present study is to develop a numerical model for ground water flow for an unconfined aquifer using MODFLOW 2000, to predict the ground water heads in the study area for a period of ten years (2014 – '24) and to study the effect of increase in pumping and recharge on groundwater head.

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II. METHODOLOGY

Software, MODFLOW 2000 is used for modelling of groundwater flow. It is a three dimensional block centered finite difference model. It is able to predict groundwater head under different scenarios.

A. GOVERNING EQUATION FOR GROUND WATER FLOW

MODFLOW performs the mathematical computations and simulation. It utilizes a numeric solution for the equation governing groundwater flow through porous media:

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

Where K_{xx}, K_{yy}, K_{zz} are values of hydraulic conductivity along the x, y, z axes. 'h' is the hydraulic head; W is the volumetric flux per unit volume and represents source or sink of water; S_s is the specific storage of porous material and t is the time.

a. Effect of Grid Size On Modelling

The density of cells in a computational grid needs to be fine enough to capture the flow details, but not so fine that the overall number of cells in the domain is excessively large, because problems described by large numbers of cells require more time to solve. Using a mesh of adequate geometrical mesh quality is an important part of controlling discretization error. The grid pecelet number is the ratio of spatial discretization and the dispersion length. It should match the following constraints.

$$P_x = \frac{\Delta x}{\alpha_L} \leq 2 \quad P_y = \frac{\Delta y}{\alpha_T} \leq 2 \quad P_z = \frac{\Delta z}{\alpha_T} \leq 2 \quad (2)$$

Where P_x, P_y and P_z are Peclet number, $\frac{\Delta x}{\alpha_L}$, $\frac{\Delta y}{\alpha_T}$, $\frac{\Delta z}{\alpha_T}$ are the grid spacing, α_L and α_T are the longitudinal and transverse dispersivities.

III. STUDY AREA

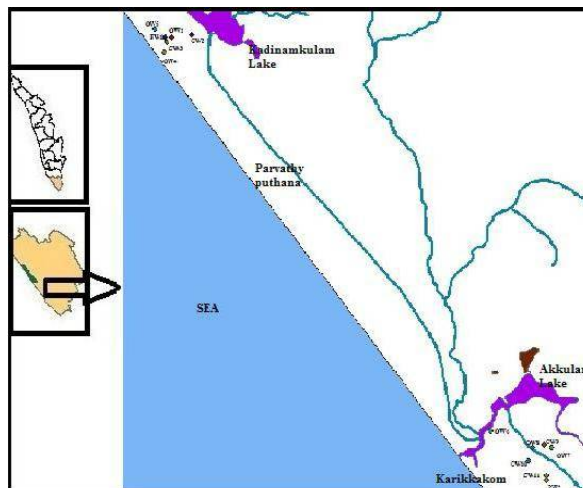


Fig.1. Study Area

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The study area lies between the latitude of 8^o 30' 7.2"N and 8^o 37' 14.4"N and between the longitude of 76^o 56' 9.6"E and 76^o 47'45.6"E in the coastal region of

Karikkakom to Kadinamkulam of Thiruvananthapuram district, having a total area of about 57 km² as shown in Fig. 1. Pumping rates were collected from Kerala Water Authority and lithological data from Central Groundwater Board (CGWB) are given in Table 1 and 2.

TABLE I. PUMPING RATE
(SOURCE: KERALA WATER AUTHORITY)

Location of Pumping well	Pumping rate (m ³ /day)
Karikkakom	300
Kadinamkulam	265

TABLE II. LITHOLOGICAL DATA OF THE STUDY AREA
(SOURCE: CENTRAL GROUNDWATER BOARD)

Layers	Thickness (m)
Unconfined Aquifer	28
Aquiclude	2
Aquifuge	10
Aquitard	14

IV. RESULTS AND DISCUSSION

1) Model Discretization

The model domain should be divided in to finite difference grid for simulation such that in the plan view, the model grid consists of 50 columns and 50 rows.

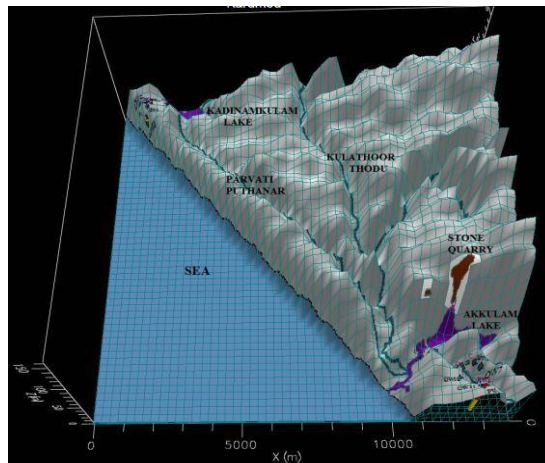


Fig. 2. Finite difference grid of the study area

Fig. 2 shows spatial discretization of the study area. For numerical modelling two pumping wells and eleven observation wells were selected.

2) Boundary conditions

The boundary conditions of the model domain depend on many considerations, such as domain extend, water bodies and physical features within the study area. In this study river boundary, no flow boundaries, constant head boundary, concentration boundary, recharge and evapotranspiration are defined for the flow and contaminant transport model. Constant head cells are used to describe model boundaries with known heads such as aquifer contacts with major surface water features. For the flow model a constant head of 0 m is specified for sea. Parvathy Puthanar, Kadinamkulam Lake and Akkulam Lake are considered as three river boundaries of the study area, shown in Fig. 3.

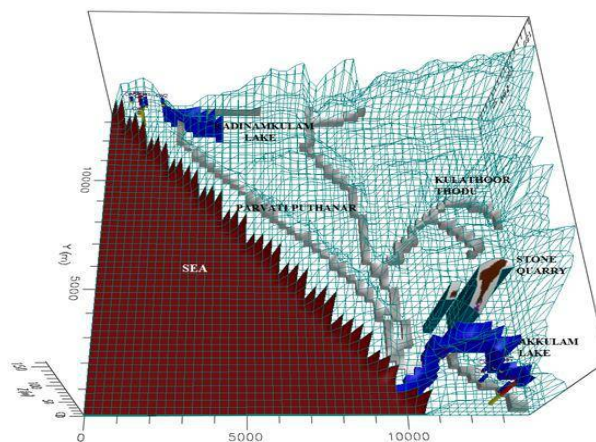


Fig. 3 Boundary conditions of the numerical model

3) Groundwater Flow Modelling

The software, MODFLOW (finite difference model) was be used to deal the hydrodynamics of the flow through porous media.

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a) Model Calibration

Calibration of numerical model is achieved through a trial and error approach by adjusting the values of two key parameters, hydraulic conductivities and specific storage, until the hydraulic head values calculated by the model matches with the observed values. Scatter plot showing the goodness of fit between the observed and calculated heads is shown in Fig. 4. The hydrogeologic parameters of different layers of the study area obtained after calibration is given in Table 2. To study the effect of grid size on modelling; the model grid size is changed on the basis of pecelet number. Then again the model is calibrated by changing the hydrogeological characteristics and its scatter plot is shown in Fig. 5.

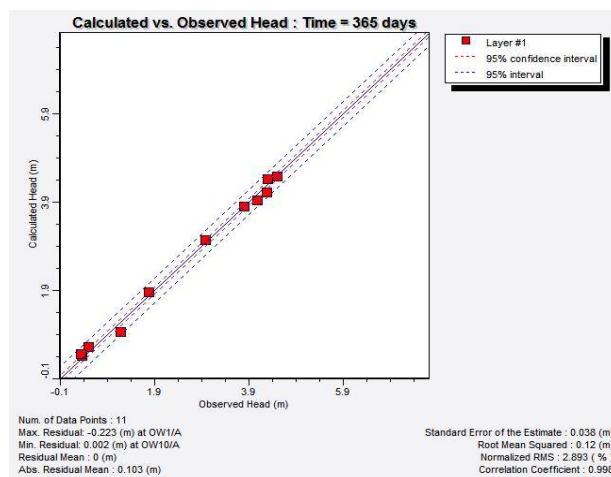


Fig. 4 Calibration graph for groundwater flow model under normal grid size

After the calibration of model an overall correlation coefficient of 0.998 and normalized RMS value of 2.893% is obtained under normal grid size (50 x 50) and a correlation coefficient of 0.998 and normalized RMS value of 2.842% is obtained under a grid size 70 X 70, which satisfy the Peclet number, $Pe = 2$. A reasonable good match between the observed and calculated groundwater heads is obtained for grid size 70x70 and this grid size was adopted for simulation and sensitivity analysis.

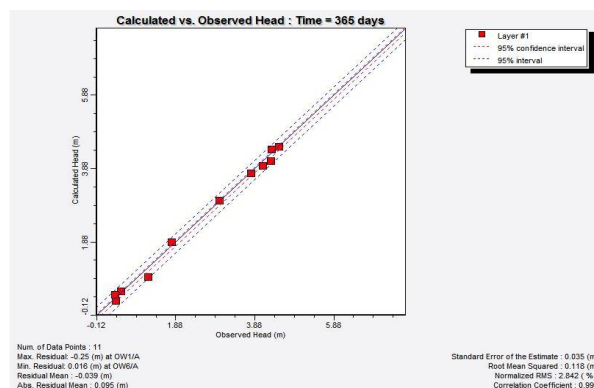


Fig. 5 Calibration graph for groundwater flow model ($Pe = 2$)

TABLE 2. CALIBRATED PARAMETERS OF GROUNDWATER

FLOW MODEL

Layers	Hydraulic conductivity (m/day)	Specific storage (m^{-1})	Effective porosity	Total porosity
Unconfined Aquifer	30	1×10^{-5}	0.15	0.3
Aquiclude	0.5	5×10^{-7}		
Aquifuge	0.05	0.0006		
Aquitard	6	0.0006		

b) Preparation of water table contour map

To prepare the water table contour map, water level data of each well is converted into the elevation of water table with respect to mean sea level (msl). Water table contour map indicates the groundwater level variation in the study area and is shown in Fig.6. It shows that the elevation of groundwater table varies from 10 to 100m. The directions of flow are illustrated in the Fig.7. The groundwater velocity vectors indicate that the groundwater flow is towards the sea.

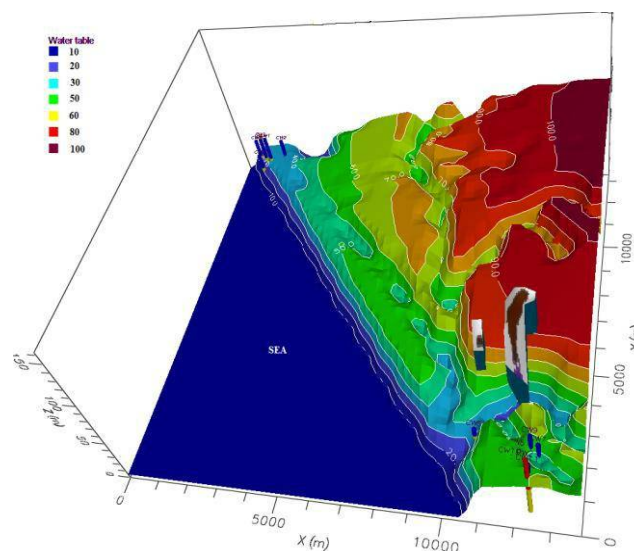


Fig. 6 Water table contour map

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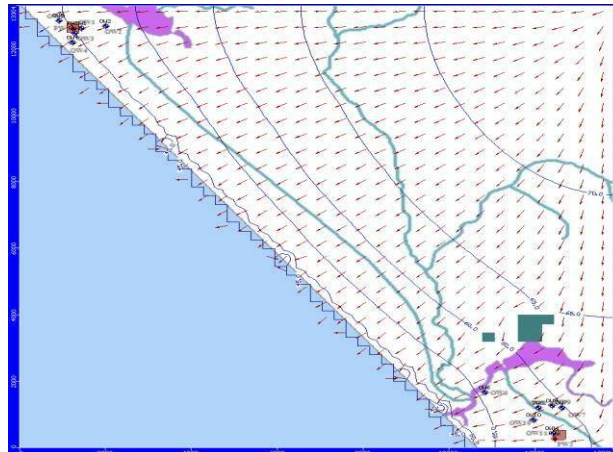


Fig. 7 Direction of groundwater flow

c) Simulation of groundwater head

Monthly water level data of observation wells from 2013 - 2014 was used as observation heads in the model. The model was run in transient state to yield calculated heads for observation wells in the study area for the same period. The simulated head in observation wells at Kadinamkulam and Karikkakom are shown in figures 8 and 9.

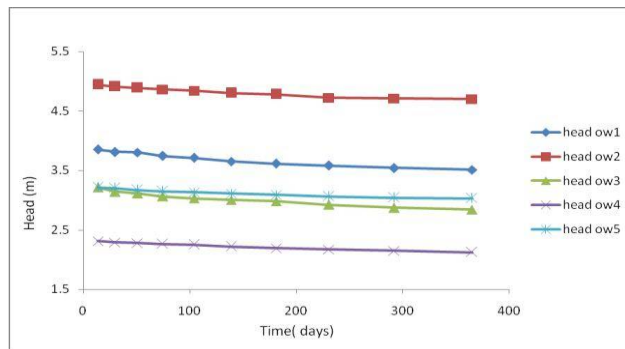


Fig.8 Simulated head in observation wells at Kadinamkulam (OW1 to OW5)

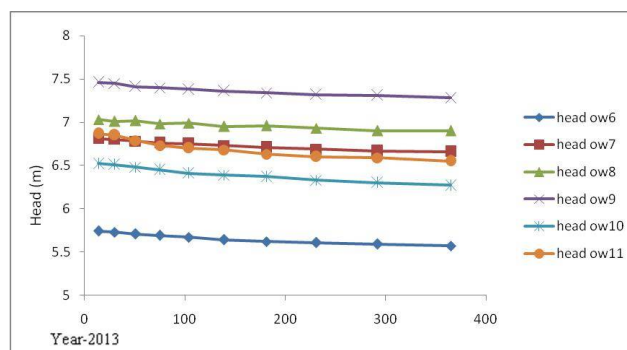


Fig. 9 Simulated head in observation wells at Karikkakom (OW6 to OW11)

d) Prediction of groundwater head

Groundwater head was predicted for 10 years (2014-2024) using the simulated model. Fig.10 shows the predicted head in observation wells at Kadinamkulam. After prediction, it is seen that the head in observation wells at Kadinamkulam shows a decreasing trend in future years under normal pumping rate. The groundwater head in all observation wells at Kadinamkulam shows a decreasing trend up to 2000 days from the year 2013. This may be due to the effect of pumping. After 2000 days onwards all the above wells maintain a constant groundwater head, which may be due to the effect of recharge boundaries, near the pumping well.

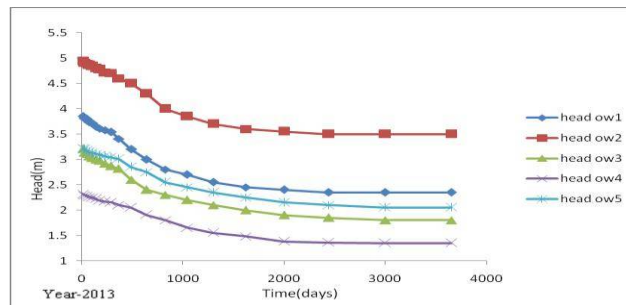


Fig.10. Predicted head in observation wells at Kadinamkulam

Fig.11 shows the predicted head in observation wells at Karikkakom. The groundwater head in all observation wells except OW8 at Karikkakom shows a decreasing trend up to 3000 days from the year 2013. This may be due to the effect of pumping. After 3000 days onwards all the above wells maintain a constant groundwater head, which may be due to the effect of recharge boundaries. Head in observation well OW8 shows a decreasing trend up to 1500 days from the year 2013 and later it maintain a constant head due to the effect of contribution of water from Parvathy Puthanar during 24 hours of continuous pumping in every day (Cinaya and Sindhu, 2013).

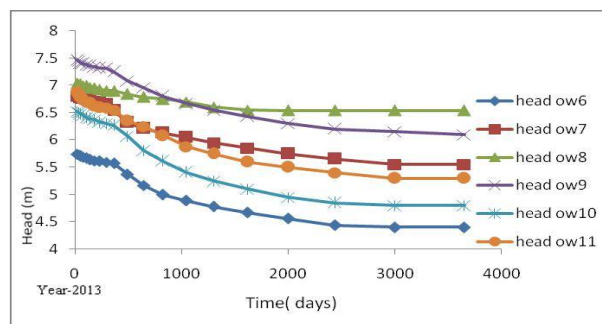


Fig.11 Predicted head in observation wells at Karikkakom

e) Scenario Analysis

Using the simulated model groundwater head was predicted for future years through scenario analysis. In this study two scenarios were considered.

i. Scenario I - Increase in pumping rate for every year by 1.5%

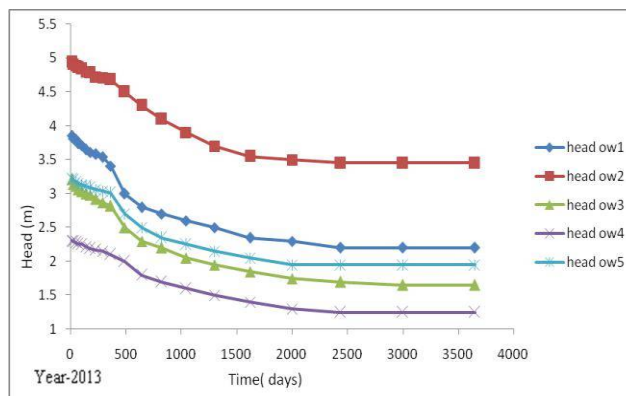


Fig.12 Predicted groundwater head in observation wells at Kadinamkulam under increase in pumping rate for every year by 1.5%

In Scenario I, the groundwater head is predicted by assuming an increase in pumping rate for every year by 1.5% (Sindhu et al., 2013) and keeping the entire boundary and field conditions same for future ten years as those in the simulation period. Due to increase in pumping the groundwater head in all the observation wells decreases compared to normal pumping. The decrease in groundwater head in observation wells at Kadinamkulam and Karikkakom during the year 2014-2024 under increase in pumping rate for every year by 1.5 % is shown in figures 12 and 13.

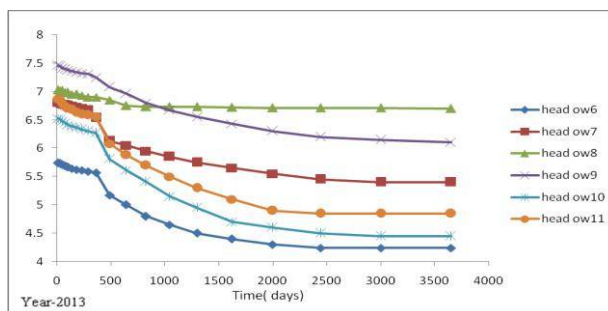


Fig. 13 Predicted groundwater head in observation wells at Karikkakom under increase in pumping rate for every year by 1.5%

It also shows that the groundwater head in all the observation wells except OW8 at Karikkakom have a decreasing trend upto 2500 days from the year 2013 and later onwards a constant groundwater head is maintained due to the effect of recharge boundary but groundwater head in the observation well OW8 shows a decreasing trend up to 600 days from the year 2013 and later onwards

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maintain a constant head due to the effect of Parvathy Puthanar.

ii. Scenario II—Increase in recharge for every year by 2%

In scenario II, the effect of increase in recharge of 2% on groundwater head is studied. Predicted groundwater head in observation wells at Kadinamkulam and Karikkakom for future 10 years is shown in figures 14 and 15. All other boundary and field conditions are assumed to be the same as those in simulation period. Figures 16 and 17 revealed that the groundwater head in all the observation wells at Kadinamkulam and Karikkakom shows an increasing trend up to 2500 days from the year 2014 and later onwards a constant groundwater head is maintained due to the effect of recharge boundary near pumping wells .

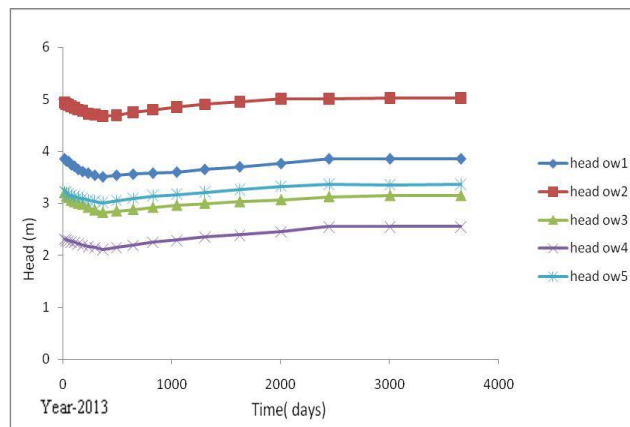
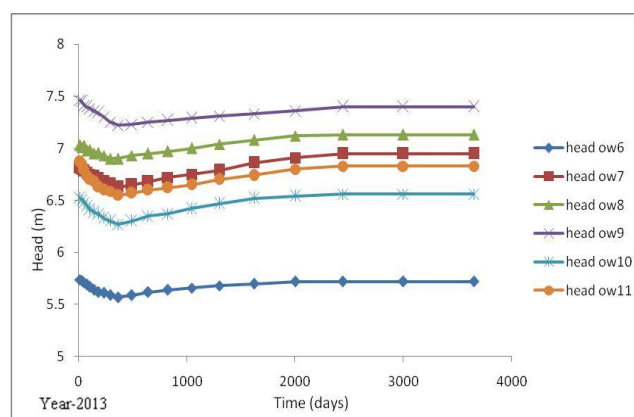


Fig. 14 Predicted groundwater head in observation wells at Kadinamkulam under increase in recharge for every year by 2%



groundwater head can be increased by providing recharge facilities.

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V. CONCLUSIONS

Groundwater is a major natural source of water for domestic, industrial and agricultural uses. A numerical model for groundwater flow was developed in transient state using MODFLOW2000. Parameters of the model for each layer were estimated. Groundwater head was predicted for a period of 2014-'24 using the simulated model. Predicted groundwater head shows a decreasing trend under normal pumping rate. Groundwater head in all the observation wells except OW8 at Karikkakom have a decreasing trend upto 2500 days from the year 2013 and later onwards a constant groundwater head is maintained.

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