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Ground water flow modelling using visual modflow

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Abstract
Groundwater model has become an essential tool for hydro geologists to perform various tasks including the assessment and prediction of groundwater, the detection of groundwater pollution etc. The large-scale regional groundwater systems are simulated using various user-friendly modelling tools working on the recent powerful computers. The main components of modelling include the conceptual model, the mathematical model and the graphical representation of hydrogeological system. In this study, a three-dimensional finite difference modelling program namely Visual MODFLOW was used for the study and prediction of aquifer system in a drought prone study area. The base map of the study area, various layers of the geological strata and their geological properties, boundary conditions, well data and recharge conditions were fed in to the model as inputs. The model was then calibrated and validated, after which future groundwater conditions were predicted.

Keywords: Groundwater models, visual modflow, calibration, validation, prediction

Introduction
Groundwater is the most treasured and widely distributed natural water resource, which constitutes the largest available source of water for water supply and irrigation in semi-arid regions. The total water resource available in the world is estimated as $1.37x10^8$ million ha-m. Only 2.8% of this water is available as fresh water at any time on the earth. This 2.8 % includes 2.2% of surface water and 0.6% of ground water, which is available beneath the earth's surface. Out of the 0.6 %, only the water available within 800 m depth be economically extracted using the present drilling technology. This accounts to 0.3% ($41.1x10^4$million ha-m) of the total ground water. So, groundwater can be referred as the largest fresh water source on earth other than the polar ice caps and glaciers. It was accounted that amount of ground water within 800 m from the ground surface is over 30 times the amount in all fresh water lakes and reservoirs, and about 3000 times the amount in the stream channels.

More than 90% of our rural population is primarily dependent on groundwater (Chandrasekhar *et al.*, 1999) [2]. Nowadays, the depletion of groundwater is undergoing a rapid increment for meeting the water needs of increasing population. So, it is important to analyze and predict the future trends in groundwater flow. Moreover, the contaminations in groundwater should also be assessed for the groundwater flow models are used to calculate the rate and direction of movement of groundwater through aquifers (Khadri and Chaitanya, 2016) [3]. In present study, Visual MODFLOW 2.8.1. Package is used for the assessment and prediction of groundwater in the study area.

Materials and Methods
Groundwater Modelling
Significant advances in regional groundwater flow modeling have been driven by the demand to predict regional impacts of human inferences on groundwater systems and associated environment (Zhou and Li, 2011) [4]. Moreover, the groundwater modelling gained a wide attention due to the availability of innovative software packages and powerful computers. The regional groundwater flow systems are analyzed by transient groundwater models by simulating regional conditions. A mathematical equation-based computer-generated model provides a scenario based on specific assumptions and input values, rather than providing a unique solution to an environmental problem. The required input parameters and boundary conditions fed in to the model, whose variations shows some dramatic changes in the model output. The sensitivity of each input parameter can be found by conducting a sensitivity analysis. Then, the calibration of the model for the provided site condition is done followed by the prediction to generate results for a range of sensitive parameters.

Visual Modflow
MODFLOW is the U.S. Geological Survey modular finite-difference flow model, which is a set of computer programs that solves the ground water flow equations (Harbaugh, 2005) [1]. It is a 3-D finite-difference groundwater flow model developed by Michael G. McDonald and Arlen W. Harbaugh, which is popular nowadays. MODFLOW uses block-centered finite difference approach for simulating the groundwater flow in aquifers. This software package widely used by hydro geologists, allows both steady-state and transient simulations. The code of this software is written primarily in the computer language, FORTRAN and compiled on Windows or Unix operating systems. In this work Visual MODFLOW 2.8.1 ground water modeling package is utilized to quantify ground water-surface water interaction.

Mathematical Model for Groundwater Flow
Groundwater modelling provides a conceptual understanding of the physical problem. And translating the physical flow system in to mathematical terms. The mathematical conversion helps to generate a simplified version of the hydrogeological system and thereby reasonable alternatives can be predicted, tested and compared.

Most of the groundwater models uses a three-dimensional combination of water balance equation and Darcy's law, given by:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)\pm W=S_s\frac{\partial h}{\partial t} \quad \text{.....1}$$

where, *Kx*, *Ky* and *Kz* are the hydraulic conductivity values along the *x*, *y* and *z* coordinate axes, *h* is the potentiometric aquifer head, *W* is the volumetric flux per unit volume representing sources and/or sinks of water (W<0.0 for flow out of the groundwater system, and W>0.0 for flow in of the groundwater system), S_s is the specific storage of the aquifer and *t* is the time taken for the change in head.

McDonald and Harbaugh (1988) [5] used a finite difference version of this equation in MODFLOW, where the groundwater flow system is divided into a grid of cells. For each cell there is a single point called node at which the head is calculated.

Study area
The present study is carried out in a representative river basin namely Nileshwar of Kasargod district, which is a drought prone district of northern Kerala.

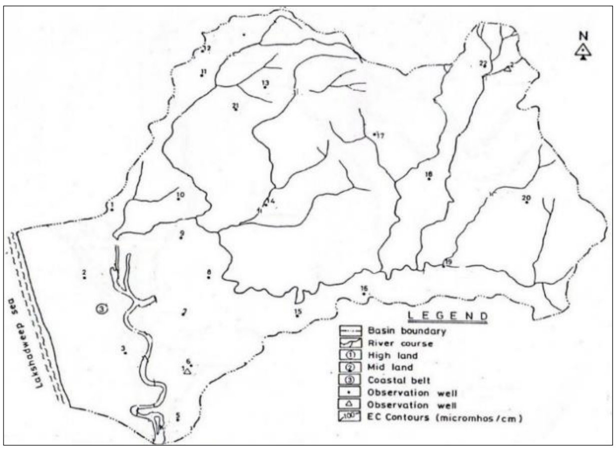

Fig 1: Map of the study area

The drainage area of about 190 sq. kms includes all the three physiographic regions, such as highland, midland and lowland. The area lies between north latitudes 12˚ 13' and 12˚ 23' and east longitudes 75˚ 05' and 75˚ 17'. A 46 m long river originates at an elevation of 140 m above MSL and the river bed falls rapidly to 15 m above MSL within a short distance of 8 kms. The river finally joins the Lakshadweep sea. The basin having an undulating topography has been divided into three units namely the coastal belt or lowland in the west, the midland region in the central portion and the highland in the east, comprising the foot hill and hill ranges of Western Ghats.

The average annual rainfall of the region is 3,600 mm. Since a major portion of it is confined to only 3-4 months in a year, the rest of the year was particularly dry. The project area is rectangular with 22.04 km long and 18.53 km wide. The study area is bounded by Lakshadweep sea in the west and all other sides by no distinct land feature topography or geological structure. The model area is extending from 0 m to 22040 m on the Lambert co-ordinate system (west to east or x-direction) and from 0 m to 18530 m in the y direction in the Belgian Lambert co-ordinate system.

Hydrogeology of the Study Area
The principal geologic formation of the basin includes red soil, lateritic soil, clay, weathered rock, hard rock and sandy soil. The details of geology of the soil and its hydraulic conductivity are given in table 1.

Table 1: Geological cross section of study area

S. No	Layer No	Soil type	Hydraulic Conductivity (m/day)
1	Layer 1	Red soil	51.84
2	Layer 2	Lateritic soil	3.25
3	Layer 3	Clay	0.0000864
4	Layer 4	Weathered rock	2.39
5	Layer 5	Hard rock	0.0000001
6	Layer 6	Sandy soil	4.32

Recharge
The study area is covered by phreatic, semi-confined and confined aquifers. Spatially distributed recharge over the entire first layer of the study area (in mm/y) was taken as one in tenth of the average precipitation for the purpose of the study.

Data Collection
The following data were available for the study area: -

- Digital elevation model with 30m by 30m grid size covering the whole study area was created by digitising the topographic map of the area.
- The basic meteorological data required for running the model, recharge was collected from the precipitation data.
- Hydrogeologic and geologic characteristics and parameters of the study area including the hydraulic conductivity and bottom elevations of layers were collected from previous work.
- Well data collected from the area, their location and recent measurements.

Detailed Methodology
The model was developed using VISUAL MODFLOW 2.8.1. Microsoft Excel was used for input data preparation and the data were exported to visual MODFLOW using the import elevation command.

a. Model Creation

Visual MODFLOW supports the use of base maps in all modules of the program. The base map of the study area was imported into the model. The x and y coordinates of the south- west corner of the study area is fixed as (0,0). The x and y coordinates of the North-east corner obtained as (22040 m, 18530 m). The model is based on a rectangular block-centred grid network covering the entire model domain. For, this a proper cell size was chosen in order to avoid any type of interpolation while importing the topographic map. Visual MODFLOW requires model data to be entered in consistent units; selected units were meters and day, and for recharge mm y^{-1} was used.

Table 2: Model domain and units of measurement

S. No.	Specification	Value
1	Maximum model elevation	250 m
2	Minimum model elevation	-20 m
3	Layers	6
4	Grid cell size	25
5	Rows	30
6	Columns	30

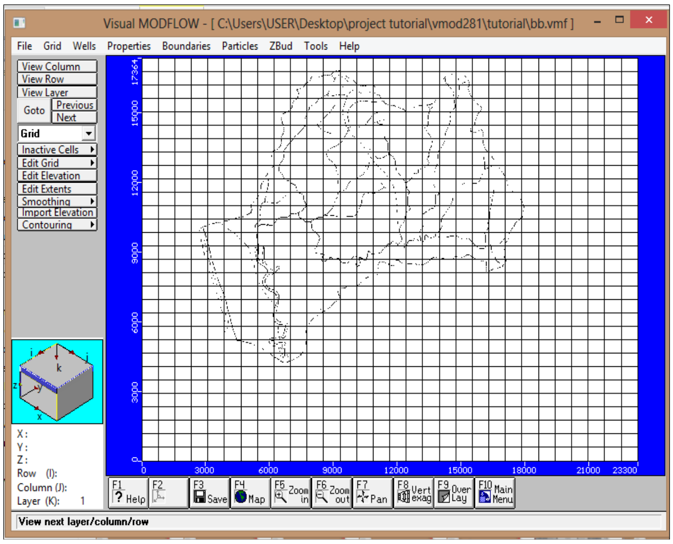

Fig 2: Grid formations to the study area

b. Importing elevation

Surface elevation and bottom elevation data of the six layers were from Microsoft Excel

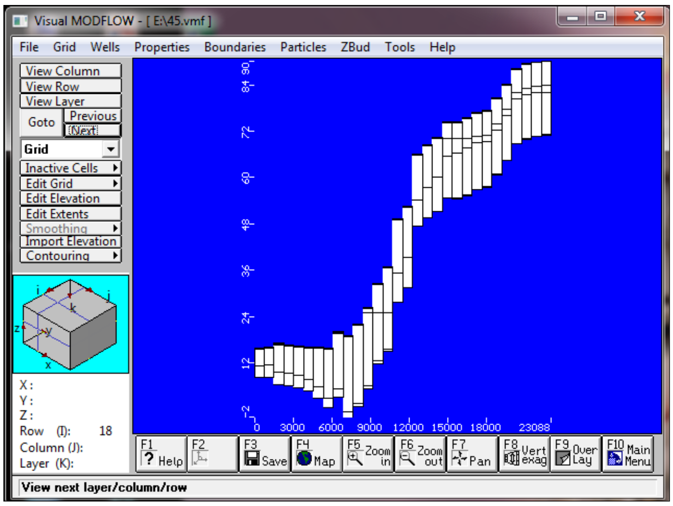

Fig 3: Cross section of importing elevation

c. Adding Wells

The necessary observation points for the model were taken from the inventory and their coordinates as well as the calculated groundwater potential were imported into the software.

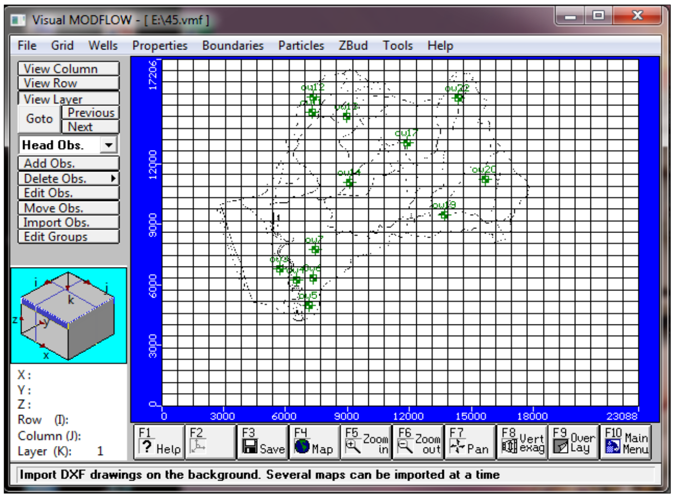

Fig 4: Adding wells to the study area

d. Adding Properties

The hydraulic conductivity values for different layers were added.

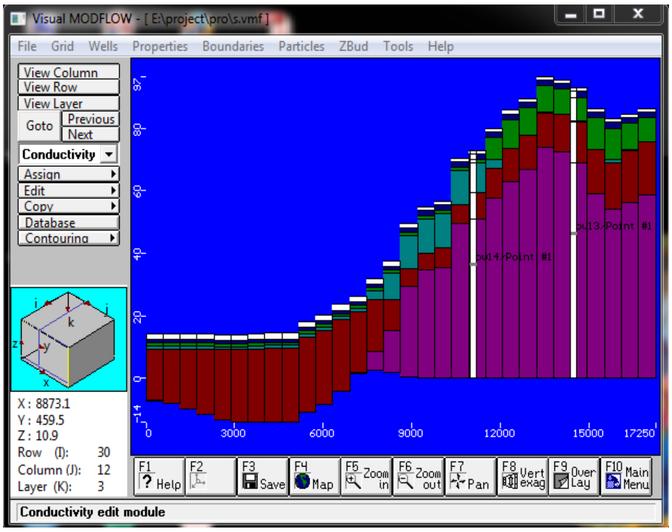

Fig 5: Adding Properties to the study area

e. Adding Boundaries

The boundary conditions represent the systems' relationship with the surrounding areas. Model results depend on the quality of these input parameter. For the study area two types of boundaries supported by MODFLOW were chosen: river and constant head.

River boundary: The river stage elevations, bottom elevation and conductivity values for the different locations of the study area were entered.

Constant head boundary: The East boundary is considered as constant head boundary.

f. Recharge

The recharge package is designed to simulate aerial distributed recharge to the groundwater system of the study area. Mostly, the aerial recharge occurs by the precipitation that percolates into the groundwater system.

g. Modflow Run

After entering all the input parameters, the model run command was carried out for the steady state condition of the study area.

Initial head options, recharge options, WHS Solver parameters, anisotropic factor, layer type and rewetting options were also selected appropriately.

Results and Discussion

The study was mainly intended to identify the characteristics of groundwater in the study area by ground water modelling using MODFLOW 2.8.1. Rainfall is found to contribute a major share of the groundwater. The undulating topography of the study area had a tremendous influence on the groundwater resources. The behaviour of the groundwater was precisely assessed and the following results were obtained.

MODFLOW output provides contours of head equipotential, head difference, drawdown, elevation, net recharge and water table. It also provides graphs of calculated versus observed heads, calibration of residual histogram etc. Model output also provides velocity vectors with direction of flow.

Model Calibration

The model is calibrated for steady state conditions. The calibration curve is obtained by changing the conductivity values. The scatter plot for computed versus observed head for selected observation wells were shown in fig. 7. This figure indicated that there is a good agreement between the calculated and observed water levels in most of the wells. The error obtained during model run was minimized by calibration. The further existing errors are due to the effect of boundary conditions (rivers).

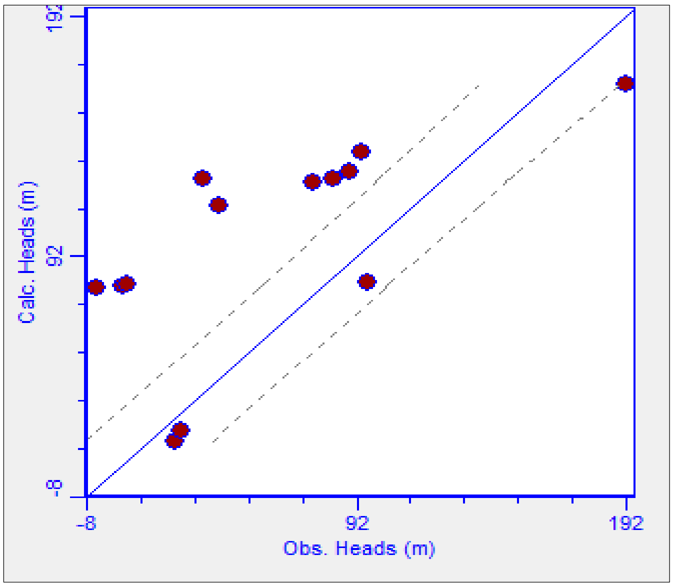

Fig 6: Calculated VS Observed heads (Calibration curve)

Model Validation

Following calibration, the groundwater flow model was validated with data, which were not used for calibration. For this study purpose 13 wells were selected in the study area and water samples and water level data were collected for three seasons of a particular year. From fig. 8. It was observed that the water table values of the validated model were matching with the calculated values.

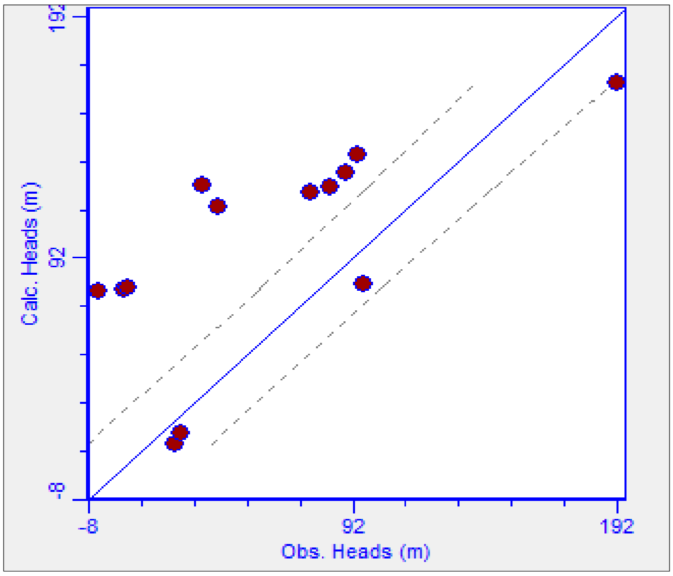

Fig 7: Calculated vs observed head (Validation Plot)

Model Prediction

The reliable prediction of the water table is possible only if a validated model is available. From the available validated model, we had predicted the water table values of the next two years by adding 730 more days in the output and time steps of [Run] command. The water table and net recharge after 2 years were predicted and depicted in fig. 8. and fig. 9.

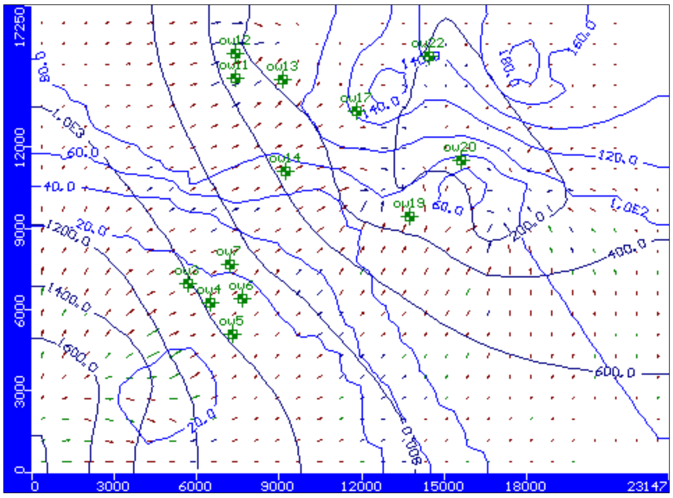

Fig 8: Water table

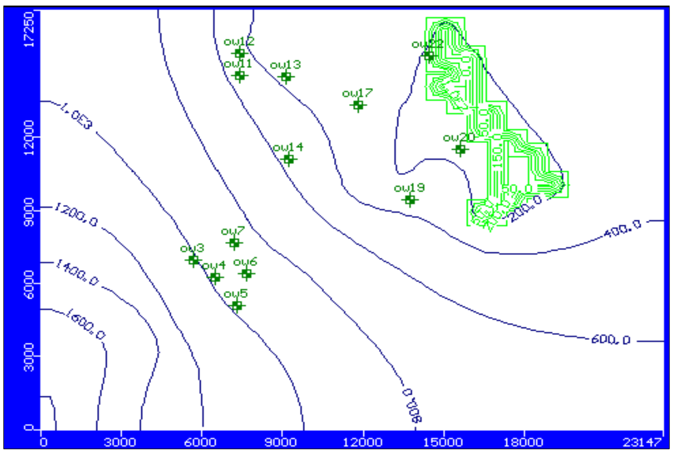

Fig 9: Net recharge

The result clearly depicts that the net recharge after 2 years would be concentrated to the positions were observation well 20 and 22 were installed. From our study, we had observed that there is no appreciable change in the water table of the study area for the next two years.

Conclusions

A steady state groundwater model for the proposed study area has been developed by using Visual MODFLOW 2.8.1. The model water balance was calculated. The distributed recharge wells vertical and horizontal hydraulic conductivity of the six layers, constant head and river boundary conditions were the inputs to the groundwater system. The groundwater level and the flow budget were calculated as outputs of the model.

The most significant limitations were founded as the uncertainty of parameter estimates and boundary conditions. Slight alterations in parameters such as hydraulic conductivity and recharge can lead to dramatic differences in model output. Similarly, boundary conditions strongly control the flow regime, and so a poor representation of the data could result in an inaccurate model. In this study we had done the calibration, validation and prediction of the model and obtained the output. The output model could be used for further groundwater modelling studies.

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