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# Assessment of Groundwater in Ghataprabha Sub-Basin Using Visual MODFLOW Flex

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**Abstract:** In the present study, an attempt is made to simulate the current groundwater level in the Ghataprabha sub-basin (Krishna basin) in southern India. For this purpose, a single layered aquifer was conceptualized using Visual MODFLOW Flex ver.14.2. Model calibration was carried out using Parameter Estimation (PEST), with $R^2$, RMSE and NRMSE as model evaluation criteria. Model behaved well with the value of 0.99, 6 m and 2.13% for $R^2$, RMSE and NRMSE respectively. Groundwater modelling results showed that there is an increase of 1.46 m of groundwater level in 5 years. Incorporating the increasing trend of groundwater level in planning water resource projects would be fruitful.

***Keywords:*** *Groundwater, Ghataprabha, PEST, Visual MODFLOW FLEX*

## 1. Introduction

Groundwater is finite yet most valuable natural resources for human survival, economic development and ecological diversity. Due to its several inherent qualities such as consistent temperature, widespread and continuous availability, excellent natural quality, limited vulnerability, low development cost and drought reliability, it has become an important and dependable source of water supplies in all climatic regions including both urban and rural areas of developed and developing countries [1] [2]. However, with the ever growing population, industrialization, urbanization, and technological advancement in agriculture, most of the hard rock aquifers in India may have already been stressed [3].

Ghataprabha, a sub basin of mighty Krishna River basin in peninsular India, has been facing a severe water shortage problem for both irrigation and domestic purposes over the past few years [4]. Every year in summer most surface water sources dry up, causing serious water shortages for both domestic and irrigation purposes. In addition, because of the capricious nature of the south-west monsoon in India, the availability of surface water cannot be ensured in the right quantity at the required time. Hence, the majority of the irrigated area in the Ghataprabha basin is being cultivated with the help of groundwater acquired from dug wells and tube wells. However, the unrestricted excessive pumping of groundwater has resulted in groundwater lowering in some parts of the study area [2].

As we cannot see into the subsurface formation, we need a tool that could provide insight into the complex system behavior; this is where groundwater models come into play. The findings of modeling would be very helpful to develop safe exploitation and management policies. However, modeling in hard rock aquifer is difficult as it is constrained to its prevailing heterogeneity [5] and data availability.

In this study, Visual MODFLOW Flex 14.2 developed by Schlumberger Water Services, was as an interface to MODFLOW, a three dimensional numerical engine. MODFLOW uses finite difference method to describe the movement of groundwater.

## 2. Study Area

### 2.1 Introduction

Ghataprabha sub-basin lies approximately between latitude 15° 45' and 16° 25' N and longitude 74° 00' and 75° 55' E. Total catchment area of the sub-basin is 8829 $km^2$, out of which 6815.988 $km^2$ (77.2%) lies in Karnataka and rest 2013.012 $km^2$ (22.8%) falls under Maharashtra. Most of the sub-basin area is flat to gently undulating except for isolated hillocks and valleys [6].Geographical location and talukas associated with the study area has been displayed in figure 1.

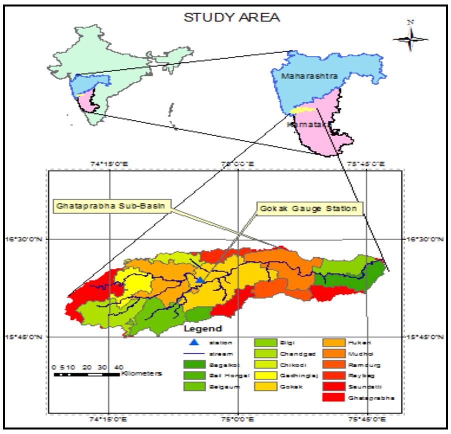


***Figure 1:*** *Ghataprabha Sub-basin*

## 2.2 Climate

The climate of sub basin is marked by a hot summer and a mild winter. Summer usually commences in mid of February and ends on May, April being the hottest month with an average daily maximum temperature of $37.5^0$ C and minimum of $19.5^0$ C. Winter records the mean daily maximum and minimum temperature of $29.3^0$C and $19.3^0$C respectively. Average annual rainfall in the study is 650 mm. Southwest monsoon contributes about 65% of total precipitation, remaining 35% being contributed from northeast monsoon. Rainfall shows spatio-temporal variation. The humidity is high during the monsoon period accounting for 85% and low during non-monsoon accounting for about 30%.

## 2.3 Land Use, Soil and Agriculture

According to National Water Development Agency (NWDA) report, 1991 [7], in Ghataprabha sub-basin, agriculture which covers 63.7% of area is the largest consumer of water in Ghataprabha basin. The dominating soil types are black soil, blend of black, red soil and lateritic soil. Black soil occurs in shallow depth (25-30 cm) with moderately well drain and high permeability properties. Coarse black soil occurs very deep (100-150 cm) and covers low lying areas, with poor drainage and low permeability. Major crops grown in the basin under rain fed condition are jowar, wheat, cotton, groundnuts, tobacco, chilies, wheat, pulses, etc. and under irrigation schemes are sugarcane, paddy, wheat, maize, tobacco, turmeric, vegetables etc.

## 2.4 Hydrogeology

Geologically, the area is underlain by rocks of Archaean crystallines to recent alluvium. Groundwater in the study area occurs in weathered to semi weathered and fractured hard rock, under unconfined to semi-confined state. Groundwater, in this region, is usually found to be tapped by dug wells, dug cum bore wells and bore wells.

A hard rock aquifer usually extends the first tens of meters from ground level [8]. In this case, a shallow unconfined aquifer extends 30 m from the top. The fractured aquifer below the shallow zone and extend down to 80 m and beyond [9]. In the canal command area, the depth to water level varied between 2 to 8 mbgl during post -monsoon period. The entire area indicates a rise in water level during the period of canal operation [10].

## 3. MODFLOW

Any device that represents an approximation of a field condition is a model [11] [12]. Groundwater flow model solves the distribution of head under certain assumptions and provided boundary conditions. MODFLOW can simulate confined, leaky confined and unconfined aquifers and only simulates saturated flow in a porous medium with uniform temperature and density [13]. Visual MODFLOW Flex is a graphical user interface (GUI) with MODFLOW as a 3-D numerical model, for which the governing equation is

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

$K_{XX}$, $K_{yy}$ and $K_{zz}$ are the hydraulic conductivity along the x, y, and z coordinate axes, ($Lt^{-l}$); h is the potentiometric head (L); W is a volumetric flux per unit volume and represents sources and/or sinks of water ($t^{-1}$); $S_s$, is the specific storage of the porous material ($L^{-l}$); and t is time (t). In general, $S_S$, $K_{XX}$, $K_{yy}$, and $K_{ZZ}$ may be functions of space ($S_S$= Ss(x,y,z), $K_{xx}$= $K_{XX}$(x,y,z), etc.) and $W$ may be a function of space and time ($W$ = W(x,y,z,t)). Equation 1 describes ground-water flow under non-equilibrium conditions in a heterogeneous and anisotropic medium and provided the principal axes of hydraulic conductivity are aligned with the coordinate directions.

## 4. Methodology

Figure 2 shows the flow diagram form groundwater modeling using MODFLOW.

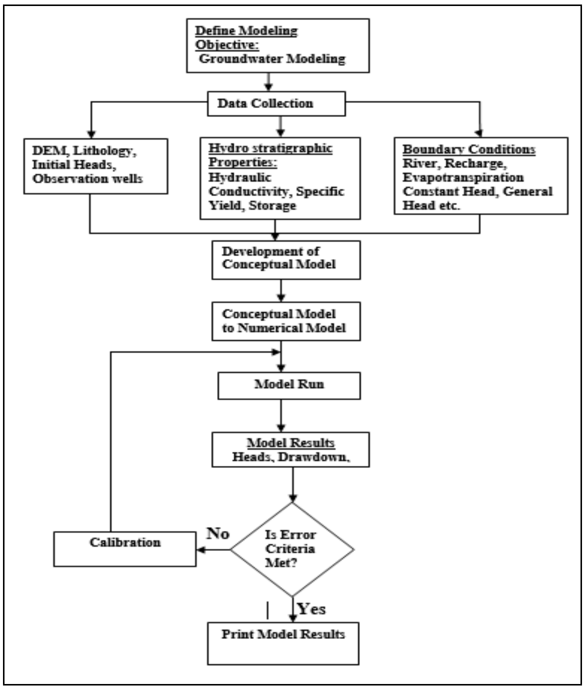


***Figure 2:*** *Work flow diagram form groundwater modeling using MODFLOW*

## 4.1 MODFLOW Setup

Setting up of a model has been carried out in two steps, data processing and data assembly.

## 4.2 Data Requirement and Processing

Various data are required to carry out groundwater modeling. The data such as Precipitation and Recharge, Hydraulic Conductivity, Observation wells and River stage and Discharge aren’t available in a single department and were collected from various sources. Data that have been used to carry out the modeling are described briefly.

#### 4.2.1 Precipitation and Recharge

Precipitation data for the Belgaum district was obtained from statistical department, Bangalore whereas, for regions coming under Maharashtra state and for Bagalkot district precipitation value was directly adopted from the literature [6]. In hard rock area of southern India, approximately 12- 37% of average annual precipitation contributes to groundwater recharge [3] and 3 -13 % in basaltic terrain. According to NIH report [6], the attempted to model groundwater level in Ghataprabha sub-basin whereby they have considered 15% of average annual precipitation as groundwater recharge, same was adopted for this study.

Figure 3 represents the monthly variation in precipitation and groundwater recharge in the study area from year 2008 to 2012.

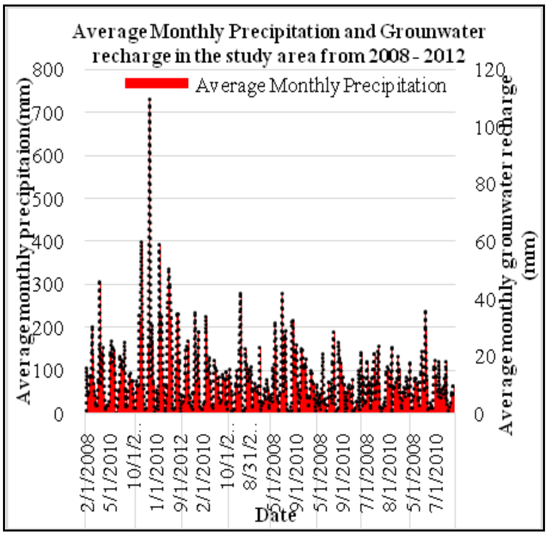


*Figure 3: Average monthly precipitation and groundwater recharge in the study area from the year 2008 -2012*

#### 4.2.2 Hydraulic Conductivity

Data on hydraulic conductivity has been derived from the CGWB report on Karnataka state. Taluka wise bore wells havebeen drilled by CGWB to study the hydrogeological formations. CGWB carried out various pumping test to calculate the transmissivity of the geological formations underlying the area. Transmissivity ranges between 0.22 m2/day to 2220 m2/day in the basin. Visual MODFLOW Flex requires the conductivity values as an input parameter which was calculated dividing transmissivity with the depth of drill. However, specific yield and storage coefficient has not been registered in the Karnataka CGWB report. Specific yield and storage coefficient was adopted from NIH report [6]. Figure 4 displays the location details of bore wells in the study area.

#### 4.2.3 Observation wells

CGWB, Bangalore has been collecting taluka wise groundwater level data at different period for the entire Karnataka state. Groundwater level is recorded in mbgl (meters below ground level). For the present study, groundwater level data from 2008 to 2013 were taken for the talukas coming under Ghatapraha sub-basin. Observation wells falling under the study area were clipped using ArcGIS ver. 10.1. Data on observation wells then was transformed into the required format by Visual MODFLOW Flex. Figure 5 displays the distribution of observation wells in the study area.

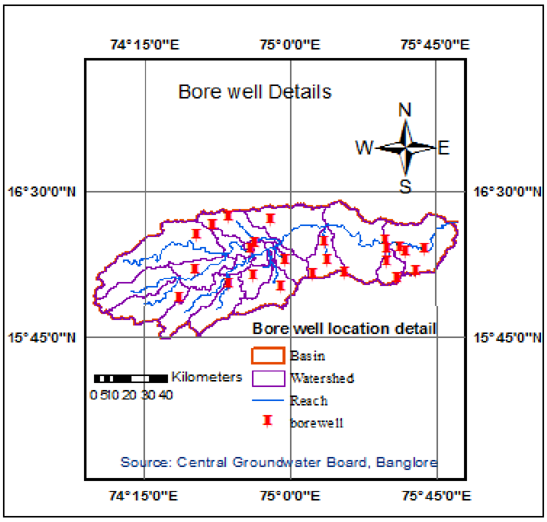


***Figure 4:** Bore well details*

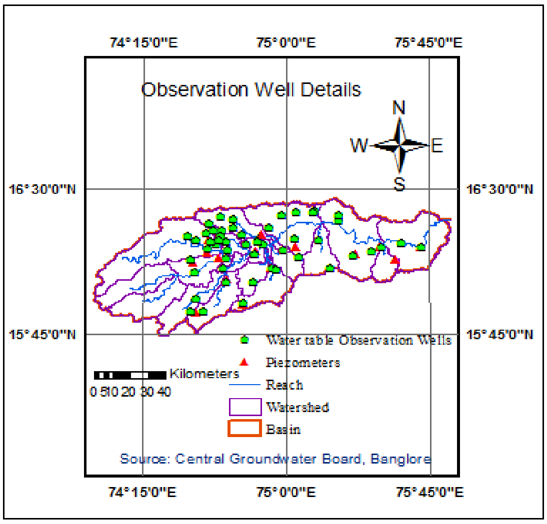


***Figure 5:** Location of Observation wells in the study area*

#### 4.2.4 River stage and Discharge

Visual MODFLOW Flex software, used in this study, has the specific requirement of River or stream properties to assess the river aquifer interaction. River stage, bottom, bed thickness and its hydraulic conductivities are the major requirements. River discharge and stage data were obtained from Water

Resource Information System (WRIS ver. 4.0). The obtained river stage data were analyzed and on an average of 3 m river stage was taken. River width was obtained from DEM processing under ArcGIS environment. River bed thickness of 0.6 m has been adopted.

### 4.3 Groundwater Modeling

Groundwater models are, by definition, a simplification of complex reality which have been extensively used to address the groundwater problems and to support the decision making [14]. Hence, it is used to make predictions about the subsurface system's response to stresses. Modeling further helps to increase our understanding on the hydrological system of the catchment. In this case, modeling has been carried as a single layered unconfined model assumed based on the literature, that the hard rock aquifer extends first few tens of meters and groundwater occurs in unconfined to semi confined condition [15].

To carry out this study, a single layered unconfined aquifer was conceptualized with appropriate boundary conditions.

#### *4.3.1 Boundary Condition*

Boundary conditions are the key components in conceptualizing the groundwater flow system or model [16] [17]. Various boundary conditions used in this study are described briefly.

#### River Boundary Condition

Visual MODFLOW Flex uses the river package to incorporate streams and rivers into the groundwater model. Surface water bodies such as stream and rivers may act as recharging and discharging boundary condition based on the gradient between the surface water and groundwater. Interaction between surface water and groundwater was simulated by assigning stage of water in the stream, stream bed thickness and conductivity values of streambed. Figure 6 describes the stream boundary condition in MODFLOW. Blue region in the figure 6 indicates the active cells where river aquifer interaction takes place.

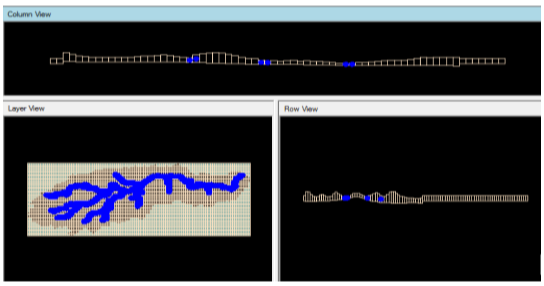

***Figure 6:*** *Stream boundary condition*

#### Recharge

MODFLOW recharge package was used to incorporate recharge into groundwater model. Recharge values for the single layered is tabulated in table 1. Recharge in this case was assigned taluka wise as 15% of the precipitation.

***Table 1:*** *Taluka wise precipitation and corresponding recharge for the year 2008*

| Taluka | Year | Precipitation | Recharge |
|---|---|---|---|
| Belgaum | 2008 | 1297.88 | 194.68 |
| Gokak | 2008 | 520.04 | 78.00 |
| Hukkeri | 2008 | 687.23 | 103.08 |
| Sayandatti | 2008 | 525.88 | 78.88 |
| Bailhongal | 2008 | 828.43 | 124.26 |
| Chikkodi | 2008 | 732.38 | 109.85 |
| Raibag | 2008 | 437.66 | 65.64 |
| Ramdurga | 2008 | 608.06 | 91.20 |
| Chandgad | 2008 | 2814.00 | 422.10 |
| Gadinglaz | 2008 | 644.00 | 96.60 |
| Bagalkot | 2008 | 456.00 | 68.40 |
| Bigli | 2008 | 395.00 | 59.25 |
| Mudhol | 2008 | 334.00 | 50.10 |

### 4.4 Groundwater Calibration and Validation

Calibration refers to the fine tuning of the model parameters such that model simulated results properly matches the field conditions. So, for this purpose, it is necessary that field conditions should be properly characterized. Improper characterization may results in a model, which is not representative of real field conditions [18]. Parameter ESTimation (PEST) was to calibrate the model in the current study.

Doherty and Johnston in 2003 [19] developed the PEST, which is a non-linear parameter estimation and optimization package. It offers model independent optimization routines. PEST uses Levenberg-Marquardt algorithm (i.e. gradient-based methodology) to search for the optimal solution. The objective in case of groundwater model calibration is to minimize the sum of squared residuals. Residual are differences between observed and simulated groundwater heads.

### 4.5 Sensitivity Analysis

Prior to calibration, it is necessary that sensitivity analysis is performed. It helps to understand the effect of parameters on the model performance. In this study, PEST was used to perform sensitivity analysis. Figure 7 describes the sensitivity of parameters. It is noticed that the specific yield is highly sensitive parameter.

After the sensitivity analysis, model calibration was performed. Initial value of the objective function was 656286.00. The objective function is the sum of square of the residuals (i.e. sum of squares of simulated- observed head). Based on the parameter alteration the value of the objective function was lowered to 6823.8. Values of objective functions over iterations are tabulated in table 2 and displayed in graphical form as shown in figure 8.

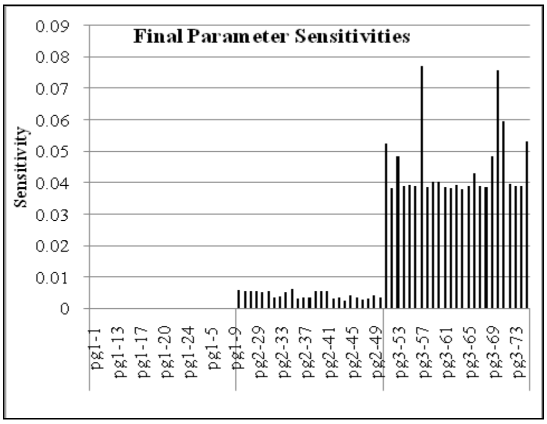


***Figure 7:*** *Results of Sensitivity analysis*

***Table 2:*** *Showing Iteration vs. Phi*

| Iteration | Phi |
|---|---|
| 1 | 656286 |
| 2 | 126402 |
| 3 | 43216 |
| 4 | 22732 |
| 5 | 15607 |
| 6 | 14817 |
| 7 | 14646 |
| 8 | 13144 |
| 9 | 10174 |
| 10 | 8712.9 |
| 11 | 7510.3 |
| 12 | 7113.1 |
| 13 | 7062 |
| 14 | 6977 |
| 15 | 6914.5 |
| 16 | 6891.7 |
| 17 | 6878.8 |
| 18 | 6850.8 |
| 19 | 6843 |
| 20 | 6832.8 |

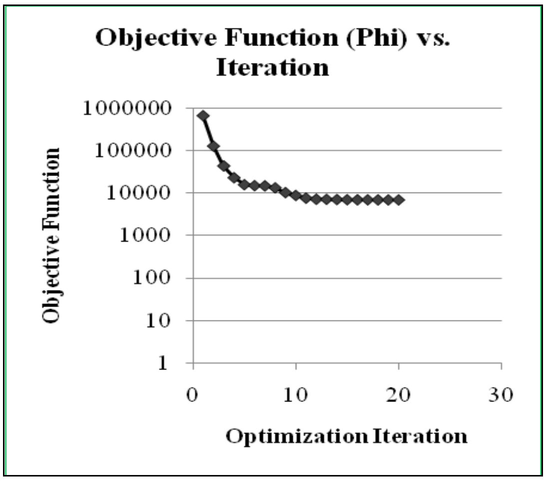


***Figure 8:*** *Plot of objective function values vs. iteration*

## 4.6 After Calibration

After optimization of parameters, model was once again run with the optimized parameters which yielded a very good result. Observed and simulated head shows a near perfect correlation with $R^2$ of 0.99. Comparison between observed and simulated head is displayed in figure 9 by line graph.

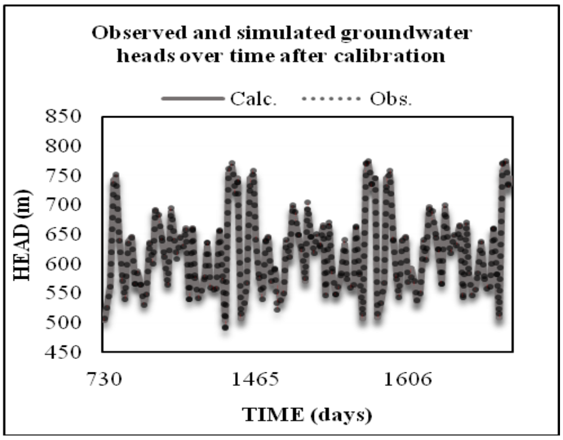


***Figure 9:*** *Line graph for observed vs. simulated heads after calibration*

## 4.7 Evaluation of Calibration

Anderson and Woessner [18] suggest evaluating the results of calibration both quantitatively and qualitatively. In this study, three methods of error quantification techniques (mean error, root mean square error, and normalized root mean square) and coefficient of linear regression were used to evaluate the results of calibration. Table 3 describes the values of model evaluation criterion before and after calibration. A drastic change in model performance can be seen before and after calibration.

***Table 3:*** *Model evaluation criteria and their respective values before and after calibration*

| Evaluation Criterion | Before Calibration | After Calibration |
|---|---|---|
| Minimum residual (m) | 0.16 | -0.0083 |
| Maximum Residual (m) | 156.38 | -15.4 |
| Residual mean (m) | 22.88 | 0.43 |
| RMSE (m) | 45.8 | 6 |
| NRMSE (%) | 16.17 | 2.13 |
| Regression Coefficient ($R^2$) | 0.65 | 0.99 |

## 5. Results and Discussions

## 5.1 Groundwater Modeling Results

Figure 10 - 12 represents the spatial distribution of simulated hydraulic head over different period.

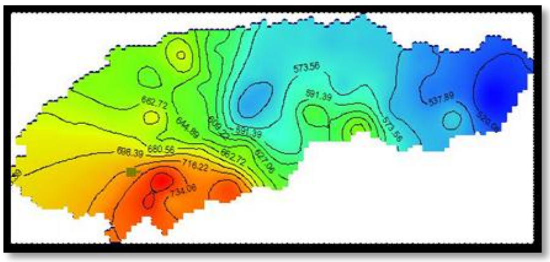

***Figure 10:*** *Distribution of Hydraulic head (Time of simulation: 5 years)*

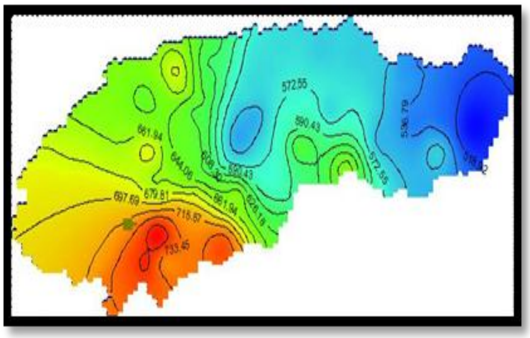

***Figure 11:*** *Distribution of Hydraulic head (Time of simulation: 1 year)*

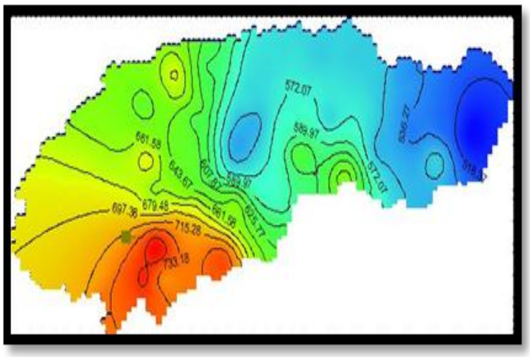

***Figure 12:*** *Distribution of Hydraulic head (Time of simulation: 0 days)*

Spatial groundwater head distribution profile indicates the movement of groundwater along the topographic profile from higher elevation to lower elevation. In the present, study only the effect of recharge on the groundwater level with stream as the only source of groundwater discharge is highlighted. Groundwater level profile for different period of simulation has been shown in figure 10-12. The simulated head indicates the increasing water level, with a head increase of 0.46m for the first 1 year of simulation and approximately 1.46 m for the simulation period of 5 years. Model simulation complies with the observed groundwater level trend. Table 4 shows the groundwater balance rate under transient case from 2008 to 2014, where recharge exceeds the discharge rate indicating increase in groundwater level.

***Table 4:*** *Daily groundwater balance rate under transient condition for the month of October*

| Year | Rates [m^3/day](IN) | Rates [m^3/day](OUT) | In- out |
|---|---|---|---|
| 1/10/20088 | 1066443.88 | 1066523 | 78.75 |
| 1/10/2009 | 1061585 | 1061862 | 276.75 |
| 1/10/2010 | 1057806.38 | 1057997 | 190.37 |
| 1/10/2011 | 1054671.25 | 1054771 | 100 |
| 1/10/2012 | 1051778.63 | 1051866 | 87.62 |
| 1/10/2013 | 1049150.25 | 1049172 | 21.75 |
| 1/10/2014 | 1046766.13 | 1046849 | 83.31 |

Figure 13 shows the daily groundwater balance rate from year 2008 to 2012.

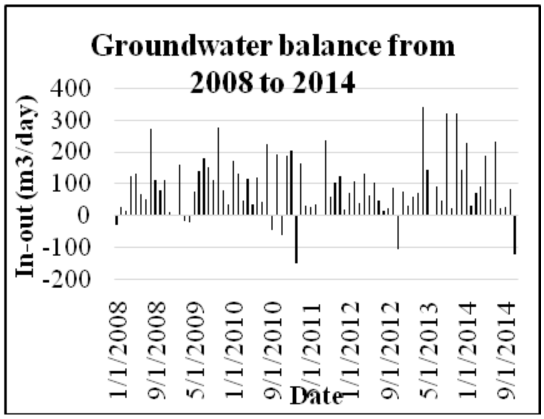


***Figure 13:*** *Daily groundwater balance in the study region from year 2008 – 2014*

## 6. Conclusion

Groundwater modeling showed an increase in groundwater level in the study area. Groundwater model was calibrated for the period of 2008-2013. $R^2$, NRMSE and RMSE were used to evaluate the model performance. Model behaved well with $R^2$, RMS and NRMS for 0.99, 2.13 % and 6m respectively. Increases in groundwater level possess a severe threat of creating waterlogging condition and groundwater flooding in low lying areas. Incorporating these results in planning the water resource in the study area would be advantageous.

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