Numerical Modeling as an Effective tool for Artificial Groundwater Recharge Assessment

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Abstract
Quantification of distribution of groundwater recharge in spatial and temporal scale is a precondition for operating groundwater system effectively. Groundwater in aquifers depends on rainfall-recharge and percolation from water storages. Groundwater extraction at rates higher than its recharge rates, results in receding water tables at alarming rate. The study is to assess groundwater recharge capability of various structures in the Cuddalore aquifer, Tamil Nadu, India. The groundwater flow model was developed using MODFLOW, a finite-difference model with the support of GMS graphical user interface. Calibration, validation and the $\chi^2$ test proved that there is no significant difference amid observed heads and modeled heads. Modelling results indicate that artificial recharge could augment groundwater levels in the area by 2 m.

Key words: Numerical modelling, Ponds, Recharge, Simulation, MODFLOW

1. Introduction

Groundwater has important role in water balance and water quality of surface water bodies in addition to meeting the demand. Artificial recharge is the process of refilling groundwater by enhancing the natural infiltration of surface water into sub-surface formations using appropriate methods depending on the soil, topographic, and lithologic conditions.

Artificial recharge can save water during surplus period for use in the deficit period and also there is quality improvement due to the filtering mechanism of formation. There is limited scope for storing water in dams now, due to the various economic and social problems. Also surface storages have drawbacks, such as huge evaporation losses and sediment accumulation, chances of structural failure, adverse ecological, environmental and socio-economic effects.

Groundwater modeling integrates hydrogeological system with mathematics. Its two key components are a conceptual model and a mathematical model. The conceptual model includes hydrogeological flow processes and the mathematical model includes equations, which quantifies the physical processes in the system being modeled to
approximates the functioning of an aquifer. The model represents the groundwater system and helps to quantify the impacts of particular stresses due to hydrological, pumping and recharge on the system. Recharge systems act as natural filters and are also effective in controlling seawater intrusion in coastal zones [1, 2].

Water level fluctuation method is accurate but frequent monitoring of groundwater levels is difficult [3]. Mass balance approach is a common and fundamental method for estimating recharge [4, 5, 6]. A water balance study of recharge ponds revealed that in favorable hydro-geological conditions 96% of the water was recharged and in the worst scenario 45% was recharged and 55% was evaporated [7]. Water balance study was carried out and proved effective for estimation of groundwater recharge after calibrating with water level fluctuations of a basin in Tamil Nadu [8]. In India, rainfall-recharge varies from 5% to 20% [9]. Rainfall-recharge was computed as 19% for the study area [10]. Ponds had a strong influence zone of 400 m from the ponds [11]. Numerical models were used by several researchers worldwide to simulate groundwater head under different hydrogeological scenarios using MODFLOW [12, 13, 14, 15, 16]. MODFLOW is effective in simulating recharge of groundwater in arid and semi-arid regions [3]. Spatial and temporal distribution of groundwater recharge was assessed by [17].

Due to highly complicated hydro-geological conditions studies on aquifer groundwater recharge in spatial and temporal scales are necessary. For the present study artificial recharge structures such as recharge wells, check dams, ponds etc. were used. The ability to predict the response of any system is an inherent part of the procedure for determining optimal management policy.

2. Study Area

The study area falls in Cuddalore basin in South Arcot District of Tamilnadu, India. The locations suitable for recharge structures were identified from electrical resistivity survey conducted in the study area [18]. Study area with structural arrangements and initial head contours are shown in Figure 1. The recharge from this area feeds the deep-water table and confined aquifers. The confined aquifer is exploited for irrigation, industrial needs and drinking water supply. To augment the groundwater resources, it is essential to replenish the groundwater through artificial recharge after studying the hydrogeology and effectiveness of artificial recharge systems. Artificial recharge is a necessity for the sustainable management of the groundwater resources in an aquifer. The present study is aimed at studying the recharge zone of artificial recharge structures.

3. Methodology

Different artificial recharge arrangements constructed for the recharge study with numerical modeling are

- Check dams and one recharge wells
- Pond & 3 percolation wells
- Combined structure area with recharge well, pond & 3 percolation wells and check dam
Location of wells, water levels and pumping details were collected. Daily water level observations were made in 15 observation wells. Individual and combined effect of various structures were evaluated using numerical model. Daily rainfall, aquifer parameters, well details were collected. Effectiveness of the structures was studied individually and in a combined way with spatial and temporal recharge effects from numerical model.

3.1 Numerical modeling
Numerical modeling was carried out using MODFLOW, with GMS as graphical user interface [19]. Data files for MODFLOW were generated in GMS [20]. The physical processes of flow in the system were modeled by mathematical model using a governing flow equation for anisotropic, heterogeneous, transient flow which is given below.

$$\frac{\partial}{\partial x}(k_{xx} \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(k_{yy} \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(k_{zz} \frac{\partial h}{\partial z}) - w = S_s \frac{\partial h}{\partial t}$$

where:
- $h$ = hydraulic head for the aquifer
- $x$, $y$, and $z$ = cartesian coordinates of the hydraulic conductivity
- $w$ = volumetric flux per unit volume
- $k_{xx}$, $k_{yy}$, and $k_{zz}$ = hydraulic conductivities in the principal directions
- $S_s$ = specific storage

Finite-difference techniques were used to resolve the groundwater flow equations. The solver selected was strongly implicit procedure. The finite-differences compute the average value of head for a cell at the node.

3.1.1 Model design
Numerical groundwater model development for field problems involve constructing, calibrating and validating the model. Model construction comprises of designing the model, creating finite-difference grids and running the simulation. In the conceptual model design the base map was imported and then the system boundaries were defined, and the boundary conditions were assigned based on the generalization of the conceptual model. A model layer spreading from 80 m above mean sea level (MSL) to 45 m below MSL was divided into 36 rows and 39 columns.
Figure 1. Study area map with recharge arrangements
3.1.2 Data Input

The study area consists of water table and deep-water table aquifers. Constant head boundary conditions were used to represent the model boundaries. Hydraulic head contour of the aquifer was established from the interpolation of heads from observation wells. Initial water levels measured for the observation wells were taken as initial condition. Hydraulic conductivity of the aquifer, hydraulic head of aquifers, estimated recharge values and aquifer thickness were given as input to the model. Hydraulic property values were allocated according to the earlier hydrogeological investigation. Vertical hydraulic conductivity was taken as 10% of the horizontal conductivity. Based on an infiltration study saturated hydraulic conductivity values in the principal directions were considered as $K_{xx}$ - 10m/day, $K_{yy}$ - 10m/day and $K_{zz}$ - 1m/day.

Natural rainfall-recharge rate was taken as 19% of rainfall for the study area based on water balance model studies conducted in the area [10]. Evapotranspiration values were calculated for the region according to Penman-Monteith method [21]. Boundaries were given as dirichlet boundaries (head boundaries). Constant head boundary was given for the pond area as per the available water table contours.

3.1.3 Model Calibration and Validation

Calibration is carried out to verify whether the model predictions matched observed data to the desirable degree. To calibrate the flow model, hydraulic conductivity and specific yield were varied repeatedly to produce modeled head contours matching the observed values. Monthly water levels for sixteen months were used for calibration. During the calibration process, the effects of hydraulic conductivity were noted, and the model values were modified within limits for further runs. The model was considered calibrated when field water level data approximated the modeled head obtained from numerical model. The hydraulic conductivity was varied within reasonable limits during calibration and found as 12m/day. Without changing the parameters, the model was validated for the monthly water levels for the next fourteen months data. Further by using the $\chi^2$ test the sampling distribution of field water level and modeled heads were compared for all the three cases to check whether there is any significance difference between the two heads.

$$\chi^2 = \sum \frac{(Simulated-Observed)^2}{Observed} = \sum \frac{(S-O)^2}{O} < \text{Table value}$$

4. Results and Discussions

The numerical model for recharge was developed for transient condition and the estimated responses due to the development were obtained. The modeled head contours give the overall groundwater head in the region obtained from the flow model (Figure 2). The numerical model simulates the allocation of hydraulic head and aid to quantify recharge and its effects on the spatial and temporal scale. Observed head and modeled head in representative wells adjoining check dam, pond and combined structure are shown in Figure 3, Figure 4 and Figure 5 respectively.
Figure 2. Modeled head contours after two years of recharge

Figure 3. Observed and modeled heads near Check dam (CS 5)
Further by using the $\chi^2$ test the sampling distribution of observed head was compared with modeled head for all the three cases. $\chi^2$ obtained were 0.011, 0.010, and 0.013 respectively for wells near check dam, pond and combined structure area. The Table value of $\chi^2$ at 0.01 with degree of freedom 4 is 7.796.
Since $\chi^2 = \sum \frac{(\text{Observed head} - \text{Simulated head})^2}{\text{Observed head}} < \text{Table value}$

Thus, the statistical test also proves that observed head and modeled head are fitting for all the three cases and there is no significant difference.

**Spatial disparity**

Recharge varied significantly with time and location. For the overall study area, the combined spatial variation in artificial recharge was obtained from the groundwater head contours obtained from the model. The spatial variation in head for the individual structures in the study area were obtained from the model developed. Figure 6 shows the spatial disparity in head in pond with 3 percolation wells. Figure 7 shows the spatial disparity in head for a single percolation well in the pond area. The area of influence of the pond area is around 500m radially. Wells had a radial influence area of 125m.

![Figure 6. Spatial variations in head in pond with percolation wells](image-url)
The Maximum rise in groundwater level on account of artificial recharge and zone of influence is given Table 1. Pond had maximum influence in recharging the aquifer in a consistent manner. Check dam could recharge only for 3 months after rains where as pond could recharge the aquifer throughout the year and had a radial influence zone of 600 m. combined structure was also effective due to the pond available in the combination of structure area.

Table 1. Maximum rise in groundwater level on account of artificial recharge

| Sl. No. | Location              | Maximum water Level reached, *bgl (m) | Rise in WL (m) | Zone of influence after 2 years |
|---------|-----------------------|---------------------------------------|----------------|---------------------------------|
|         |                       | Start period                          | After 1 year   | After 2 year                    | After 1 year | After 2 year |                      |
| 1       | Check dam area        | 17.28                                 | 16.05          | 13.47                           | 1.23         | 3.81         | 450 m - DG and 300 m - UG |
| 2       | Pond area             | 7.86                                  | 6.47           | 5.38                            | 1.39         | 2.48         | 650 m - DG and 600 m - UG |
| 3       | Combined structure area | 23.20                           | 22.13          | 19.25                           | 1.07         | 3.95         | 500 m - DG and 450 m - UG |

*bgl – below ground level
DG – down gradient
UG – up gradient
5. Conclusions

A numerical model can effectively represent the hydrogeological setup of an area using mathematical equations to quantify the effects of various stresses such as pumping and recharge. The numerical model was developed from the conceptual model and calibrated using borehole data collected. The model was refined based on calibration and used to test scenarios for artificial recharge. The validity of the model was tested by statistical analysis and was found to be fitting. Wells had a radial influence zone of 125 m. The rise in water levels were 3.81 m, 2.48 m and 3.95 m respectively at the center of check dam, pond and combined structure following two years recharge. The present study concludes that an increase in water level around 2 m was noticed owing to artificial recharge in the study area after 2 years of recharge. The study concludes that artificial recharge can be considered as an appropriate option for the sustainability of groundwater and numerical modeling is a very effective tool for assessing the impact of artificial recharge.

6. References

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