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GIS Based Groundwater Modeling Study to Assess the Effect of Artificial Recharge: A Case Study from Kodaganar River Basin, Dindigul District, Tamil Nadu

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ABSTRACT

Groundwater is a dynamic and replenishable natural resource. The numerical modeling techniques serve as a tool to assess the effect of artificial recharge from the water conservation structures and its response with the aquifers under different recharge conditions. The objective of the present study is to identify the suitable sites for artificial recharge structures to augment groundwater resources and assess its performance through the integrated approach of Geographic Information System (GIS) and numerical groundwater modeling techniques using MODFLOW software for the watershed located in the Kodaganar river basin, Dindigul district, Tamil Nadu. Thematic layers such as geology, geomorphology, soil, runoff, land use and slope were integrated to prepare the groundwater prospect and recharge site map. These potential zones were categorized as good (23%), moderate (54%), and poor (23%) zones with respect to the assigned weightage of different thematic layers. The major artificial recharge structures like percolation ponds and check dams were recommended based on the drainage morphology in the watershed. Finally, a three-layer groundwater flow model was developed. The model was calibrated in two stages, which involved steady and transient state condition. The transient calibration was carried out for the time period from January 1989 to December 2008. The groundwater model was validated after model calibration. The prediction scenario was carried out after the transient calibration for the time period of year up to 2013. The results show that there is 15 to 38% increase in groundwater quantity due to artificial recharge. The present study is useful to assess the effect of artificial recharge from the proposed artificial structures by integrating GIS and groundwater model together to arrive at reasonable results.

INTRODUCTION

Groundwater is one of the prime sources of fresh water. Groundwater serves as an important source of water for various purposes like domestic needs, industries and agriculture, which needs to be managed carefully, especially in drought prone and hard rock areas (Selvam, 2012a). Groundwater has become crucial not only for targeting of groundwater potential zones, but also for monitoring and conserving this important resource (Narendra et al. 2012; Selvam and Sivasubramanian, 2012b). Besides targeting groundwater potential zones, it is also important to identify suitable sites for artificial recharge. The recharge rate is low in hard rock areas therefore cannot meet the demand for water, the balance is disturbed and hence it calls for artificial recharge on a watershed basis. Effective groundwater management requires good understanding of the aquifer system and quantification of its responses under different input and output stresses. Groundwater modeling is an important tool for proper planning and management of aquifer system. In recent years Geographic Information System (GIS) has been used for groundwater studies and also utilized for assessment of groundwater potential zones (Kumar et al. 2008). GIS and remote sensing applications have widely been used to demarcate the groundwater prospects zones (Akram et al. 2009). Krishnamurthy et al. (1996) have demonstrated the capabilities of GIS for demarcation of different groundwater potential zones, especially in diverse geological set up. Phukon et al. (2004) applied multi criteria evaluation technique in GIS environment for groundwater resource mapping in Guwahati city areas. Nagarajan et al. (2009) demarcated the groundwater potential zones for the Kattankulathur block, Tamil Nadu using GIS technique. Pradeepkumar et al. (2010) carried out demarcation of groundwater resources potential in Kurmapalli Vagu basin in Andra Pradesh, India using remote sensing and GIS techniques. Sinha et al. (2012) delineated the groundwater potential zones in Bilari watershed, Madhya Pradesh using remote sensing and GIS.

GIS offers data management and spatial analysis capabilities that are useful in groundwater modeling. Sekhar et al. (2004) developed a regional groundwater model to analyze groundwater flow in a hard rock aquifer in the Gundal sub-basin of the Kabini river basin for the assessment and management of groundwater by the integration of GIS and groundwater flow model. Mondal and Singh (2005) developed a numerical model in the tannery belt of Dindigul town, Dindigul district, Tamil Nadu using the finite difference technique coupled with method of characteristics. MT3D is a 3D solute transport model for simulation of advection, dispersion, and chemical reactions of dissolved constituents in ground-water systems. MT3D computer code was used to simulate mass transport in groundwater system. The model uses a modular structure similar to that implemented in MODFLOW. Abdulla and Assad (2006) built a groundwater flow model to simulate the behavior of the flow system under different stresses for Mujib aquifer, Jordan using MODFLOW software. Singhal and Goyal (2011) applied GIS tools for development of groundwater flow model for Pali Area, India. GIS is utilized for preprocessing of hydrological, hydrogeological and geological data. Sohrabi et al. (2013) presented the results of a mathematical groundwater model (Groundwater Modeling Software (GMS & MODFLOW-2000 code) developed for Evan sub-basin the semi-arid region at northwestern Khuzestan Province (Iran). The source/ sink coverage, recharge coverage, extraction coverage, return flow coverage was considered for the development of groundwater model. Pradeep Kumar and Anil Kumar (2014) developed a steady state finite difference model using

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MODFLOW to quantify groundwater in Choutuppal Mandal, Nalgonda district, Andhra Pradesh using groundwater data from 19 observation wells. Ajami et al. (2015) integrated hydrologic models to characterize catchment responses by coupling the sub-surface flow with land surface processes. Kulkarni (2015) developed the numerical groundwater model to simulate groundwater recharge from an injection well using Explicit Finite Difference Model (FDFLOW) and Galerkin Finite Element Model (FEFLOW). These models were validated with reported analytical solutions for a test run period of 210 days.

In Tamil Nadu nearly 73% of the area is of hard rocks. These hard rocks are occurring at Salem, Erode, Kanyakumari, Coimbatore, Madurai, Thoothukudi and Dindigul districts. In Dindigul district, surface water is being utilized for irrigation through minor and major tanks (PWD report 2002). In this context, the present study was carried out to identify the suitable sites for artificial recharge structures to harvest the available surface runoff resources and assessing its effects through the development of a groundwater flow model combined with GIS in a hard rock aquifer of watershed located in the Kodaganar river basin of Dindigul district, Tamil Nadu.

STUDY AREA

The watershed is located in the Kodaganar river basin of Dindigul district, Tamil Nadu, India. It is one of the hard rock and drought prone regions. The upper part of the Kodaganar river basin with an aerial extent of 107.6 Sq.km was selected for this study. The watershed is located between 10°25'55"N to 10°33'10"N latitude and 77°50'23"E to 77°57'14"E longitude. The location map of the study area is shown in Fig.1. The study area is covering parts of Reddiarchattram and Vedasandhur blocks in Dindigul district. The river Kodaganar constitutes eastern boundary of the watershed. The river is ephemeral. The Kodaganar river originates from the eastern slopes of the lower Palani hills. The mean annual rainfall in watershed area is about 720 mm. The rainfall distribution in the study area is uneven. The area experiences semi arid tropical climatic condition and falls in the east coast plains as classified by the Indian Council of Agricultural Research (ICAR). The climate of the watershed is influenced by the monsoon winds and northeast monsoon accounting for the maximum amount of rainfall. The temperature varies from 26°C to 34°C in winter and 32°C to 39°C in summer. The elevation of the area ranges from 210 m to 300 m above Mean Sea Level (MSL). The study area is characterized by undulating topography with hills located in the western side of the watershed. The main source of water supply is only through groundwater. The wells will be recharged only during monsoon and it is used mainly for irrigation, drinking and domestic purpose. It has been found that there is a significant rise in water level due to rainfall during the month of October to December. During non-monsoon periods, the groundwater is depleted due to heavy pumping for irrigation purpose which has resulted in acute scarcity of water. In order to improve groundwater resource in the study area, implementations of artificial recharge structures are essential. But it is also important to know the effects of artificial recharge structures in groundwater development, well in advance through some numerical modeling techniques.

PHYSIOGRAPHIC CHARACTERISTICS

Several land use patterns impede runoff, reduces recharge, evaporation of surface and groundwater and hence have an impact on groundwater resources (Selvam et al. 2013a and 2014a,b,c). Field verification along with acquired land use pattern map is used to classify the land use pattern of the study area. Most of the inhabitants in the watershed depend on agriculture and the major part of the land is under agriculture. Mostly dry crops such as cannels, pulses, groundnuts, tobacco, tomato and chilies are being cultivated. Five types of land use pattern were identified in the watershed such as Built up lands (0.997%), Cultivable lands (1.14%), Fallow/harvested land (28.7%), agricultural crop land (67.16%) and water bodies (1.99%). The land use pattern map is depicted in Fig.2a.

The water holding capacity of an area depends upon the soil type and their permeability. From the field study it was observed that, the study area is predominantly covered by red sandy soil and black cotton soil. Based on these field observation and soil type map, the hydrological soil group B and D was identified in the study area and is shown in Fig.2b. The maximum area of watershed was observed to be under hydrological soil group B (93.32%) followed by hydrological soil group D (6.67%). The geology of the study area consists of two different types of rocks namely charnokites and hornblende biotite gneiss. Based on the field observation of borehole lithology and acquired geological map, the geological map of study area is prepared

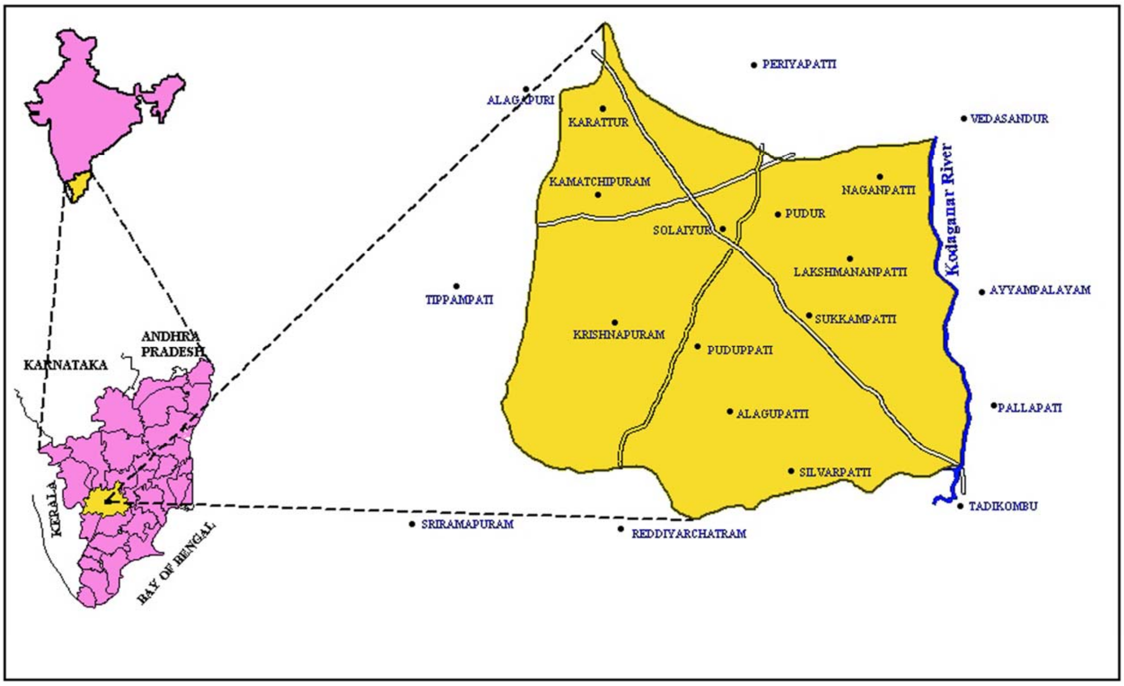

Fig.1. Location map of the study area.

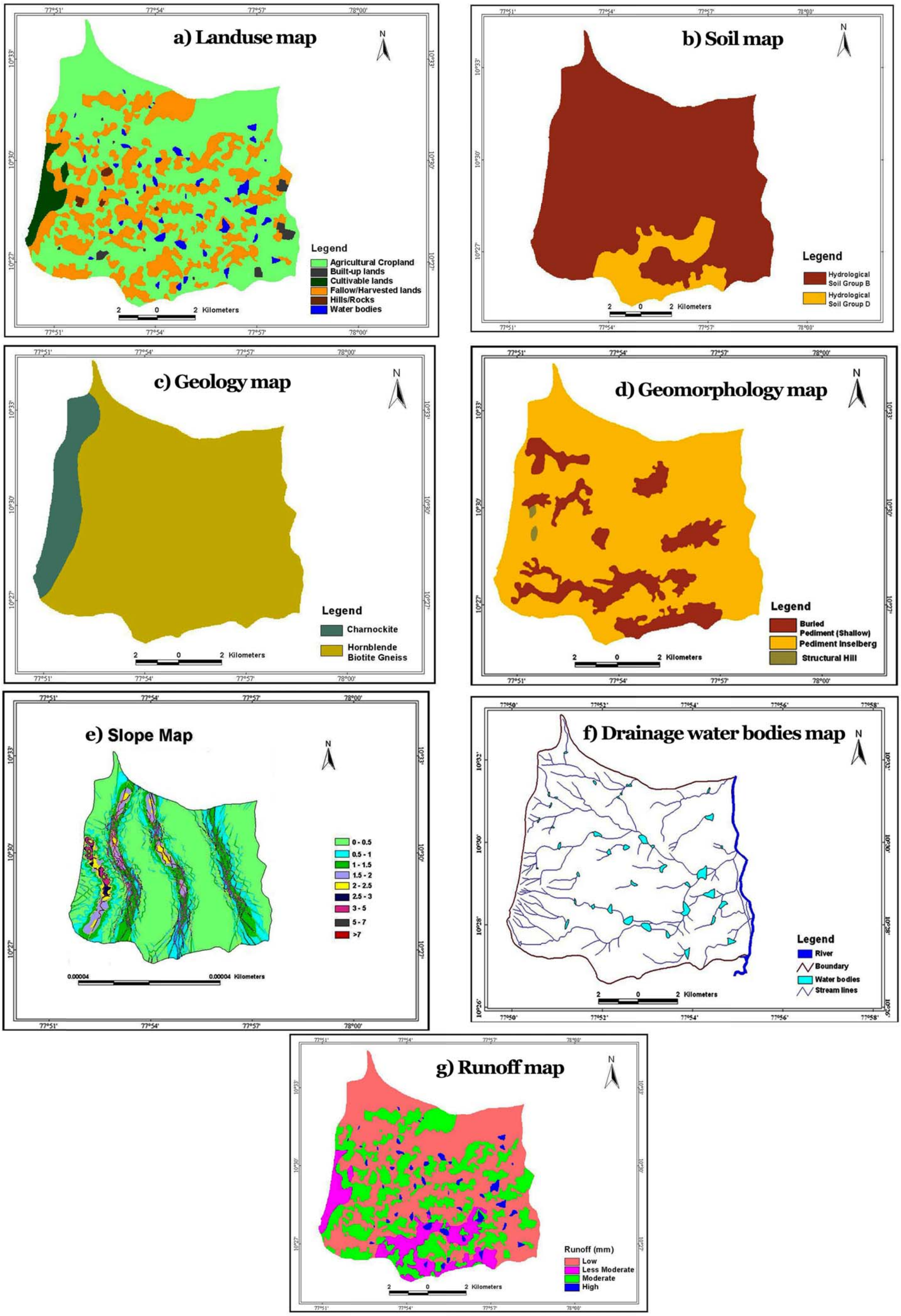

Fig.2. **(a)** Land use, **(b)** Soil, **(c)** Geology, **(d)** Geomorphology, **(e)** Slope, **(f)** Drainage water bodies, **(g)** Runoff map of the study area.

and represented in Fig.2c.

Geomorphology is one of the main controlling factors of groundwater. The geomorphic features can be considered as surface indicators for identification of sub-surface water conditions (Selvam et al. 2013b and 2015a). The major geomorphic units identified in this study area are pediment-inselberg complex followed by buried pediment (shallow) and structural hill. The shallow buried pediment is found at relatively less sloping areas with moderate soil cover. Ridge type structural hill is the only geomorphic unit classified under the structural origin and is found in the western part of the study area. The geomorphological map of study area is illustrated in Fig.2d. Slope has a direct control on the runoff and therefore on infiltration. Slope map on a scale of 1:50,000 was generated by the contour lines. The slope map of study area is shown in Fig.2e. The drainage map has been prepared from watershed map on 1:50,000 scale. The drainage network and location of tanks were digitized and converted into thematic map as presented in Fig.2f.

Database Used

Groundwater recharge potential depends on watershed characteristics like land use pattern, soil type, geology, geomorphology and slope (Sankar, 2002; Selvam et al. 2013c and 2015b). These thematic maps were collected from the Institute of Remote Sensing, Anna University, Chennai on 1:50,000 scale that can be integrated in GIS for evaluation of groundwater resources. All these thematic maps were georeferenced and digitized by using Arc GIS software. Ancillary data like SOI (Survey of India) topomap of 1: 50,000 scale was procured from Survey of India Office, Guindy, Chennai. The non-spatial data such as rainfall, water level details and aquifer parameters were also collected from Institute for Water Studies, Public Works Department (PWD), Chennai. In addition, monthly wise water level details from the 8 observation wells spread over the study area were monitored for model validation.

MATERIALS AND METHODS

The present study was carried out in five phases. In the first phase, all the resource maps were converted into thematic maps using GIS software and the surface runoff was estimated. In the second phase, groundwater recharge potential zones were delineated with the aid of GIS. In the third phase, suitable artificial recharge structures were located in the watershed using GIS based methodology. In the fourth phase, numerical groundwater flow modeling was developed for the study area using MODFLOW software. In the fifth phase, effect of artificial recharge through the proposed artificial recharge structures was assessed by the integration of GIS and numerical groundwater flow modeling. In the present study GIS is used as a pre-processor and post-processor to generate model input data and display output.

Assessment of Surface Runoff

Soil Conservation Service-Curve Number (SCS-CN) method was used to assess the surface runoff of the study area using the rainfall data, soil type and land use pattern. The daily rainfall data was taken into account for the calculation of runoff. The thematic maps such as land use pattern and hydrological soil group were geo-referenced by latitude and longitude and digitized using map info software. Then the digitized maps were exported to Arc GIS software for identification of curve number and estimation of runoff. The spatial variation map of surface runoff for the study area is shown in Fig.2g.

Groundwater Recharge Potential Zones

All the thematic maps were overlaid through weighted index overlay method for demarcating groundwater recharge potential zones. In weighted index overlay method, weights have been assigned to various classes of different themes like land use pattern, soil type, geology, geomorphology, runoff and slope according to the importance of these classes supporting groundwater estimation. The weightages assigned to different classes of all the thematic layers are given in Table 1. In this study, the weightages are derived from Saraf and Choudhury, 1998; Ramalingam & Santhakumar, 1999; Selvam et al. 2015c results and the same is adopted for the study area. The various thematic maps are given suitable weightages and ranks based on the relative importance. Suitable sites were selected by integrating the maps with their corresponding weighted index. Finally, while integrating the thematic maps, the respective weightages and ranks are multiplied to get the integrated value for each polygon. Then it is reclassified into groups such as good, moderate and poor.

Table 1. Ranks and weightages of different parameters for groundwater recharge potential zones

Sl. No	Criteria	Classes	Rank	Weightage (%)
1	Geology	Hornblende Biotite Gneiss (HBG)	3	20
		Charnockite (CH)	4	
2	Geomorphology	Buried Pediment Shallow (BPS)	2	25
		Pediment Inselberg (PI)	3	
		Structural Hills (SH)	4	
3	Hydrological Soil Group	B	2	15
		D	4	
4	Slope	0-5°	1	10
		5-7°	2	
		7-10°	3	
		>10°	4	
5	Runoff	Moderate	1	15
		Less Moderate	2	
		Low	3	
		High	4	
6	Land use	Wet crop, Plantation	1	15
		Dry crop, Fallow/harvested land	2	
		Scrub, barren	3	
		Rock outcrops, Forest & others	4	

Selection of Suitable Sites for Artificial Recharge

The drainage pattern map is superimposed over the groundwater recharge potential map and used to identify site-specific mechanism for artificial recharge of the watershed (Ravi Shankar and Mohan, 2005). From the groundwater recharge potential map, the hydro-geomorphic parameters of good and moderate groundwater recharge zones were considered as favourable sites for the adoption of artificial recharge techniques. This would effectively exclude regions with very low groundwater recharge potential where artificial recharge techniques cannot be employed. Percolation ponds and check dams were adopted based on the drainage morphology in the areas demarcated as favourable for artificial recharge.

Groundwater Model Input Data and Boundary Conditions

The numerical groundwater flow model was developed for the study area using Visual MODFLOW 4.1 software. The digitized map of the Kodaganar watershed is taken as input for the groundwater flow modelling. The model domain was discretized using 45 rows x 40 columns with each grid of size 330 by 350 m. The aquifer parameters, hydraulic conductivity and storage coefficient were estimated through pumping tests. It involves the measurement of the fall and rise of water level with respect to time. The change in water level is caused due to pumping of water from the well. The change in water level with time is then interpreted to arrive at aquifer parameters. The eastern boundary of the study area was considered as inflow boundary due to the Kodaganar river located on the eastern side of the model. The ridgelines along the west, north and southern boundaries were taken as no flow boundaries in the groundwater model.

RESULTS AND DISCUSSION

Groundwater Recharge Potential Zones and Selection of Suitable Artificial Recharge Structures

Groundwater occurrence and its assessment is based on indirect analysis of some directly observable terrain features like geological, geomorphological, structural features and their hydrological characteristics (Mondal et al. 2011). Based on this the features like land use pattern, geology, geomorphological, slope, runoff and soil types have been taken into consideration for weighted index overlay analysis. With this integrated GIS analysis, groundwater recharge potential map of the watershed was prepared. The groundwater recharge potential have been classified quantitatively as good, moderate and poor depending on the final weight values assigned to polygons in the final layer and is shown in Fig.3a. The areas falling under different categories of groundwater recharge potential zones are shown in Table 2. The groundwater recharge potential zones were delineated as good, moderate and poor zones with the area of 24.47 km^2, 58.50 km^2 and 24.63 km^2 respectively. The field study was conducted in the study area to check the three different groundwater recharge potential zones. The wells located in zones favorable for good groundwater potential have a depth of water level which varies from 1 - 12 m below ground level in a year. The wells located in moderate groundwater potential zones have the depth of water level which varies from 2 – 18 m below ground level in a year. The wells located in poor groundwater potential zones have the depth of water level which varies from 3 – 20 m below ground level in a year. Hence the demarcated groundwater recharge potential zones have good correspondence with the observed field groundwater level data in the study area.

From the groundwater recharge potential map, the hydrogeomorphic parameters of good and moderate groundwater recharge zones were found to be favorable sites for the adoption of artificial recharge techniques and would effectively exclude regions with very low groundwater recharge potential where artificial recharge techniques cannot be engaged. The drainage pattern map is superimposed over the groundwater recharge potential map, to identify favorable locations for implementing artificial recharge structures in the study area. Finally, suitable recharge structures such as percolation ponds and check dams were recommended which have been proved to be a good measure of artificial recharge by accumulating surface runoff and augmenting the infiltration capacity in hard rock terrains. The recharge structures were adopted based on the drainage morphology. The located structures and their locations in the study area are shown in Fig.3b. The recharge wells, recharge pits and recharge shafts are the minor artificial recharge structures and they can be adopted with the major artificial recharge structures.

Table. 2 Classification of groundwater recharge potential zones

Sl. No.	Groundwater recharge potential zones	Area (km^2)
1	Good	24.47
2	Moderate	58.50
3	Poor	24.63

Groundwater Flow Model

Groundwater modeling can be used to simulate the flow of groundwater in an aquifer. To represent the layers in the model, lithology data arrived from bore well were used to develop the surface by interpolating the layer thickness values. After analyzing the lithological data, the study area was conceptualized as three layers. The upper layer represents the shallow topsoil with a thickness ranging from 2 to 6 m below groundwater level. The middle layer represents the weathered rocks with a thickness ranging from 2 to 20 m below the top layer, and the bottom layer represents the crystalline bedrock with joints and fractures with a thickness ranging from 20 m to 40 m below the middle layer. The vertical cross section of the model is shown in Fig.4a. The coordinates of wells used for monitoring water level by the PWD is identified by plotting the wells in the GIS. The wells are located in the field by the identified coordinates with the help of Global Positioning System (GPS). For monthly water level study, six observation wells were selected in the month of January 1989. The water levels were given as input to the well for every stress period. Monthly rate of groundwater withdrawal and recharge estimated by SCS curve number method were applied for every stress period. The designing the model domain, the model was run for steady state condition for January 1989.

Groundwater Model Calibration

The monthly water level data collected by PWD in six observation wells in the study area for the period January 1989 to December 2008 has been taken for model calibration. In addition, groundwater levels from the 8 wells spread over the study area were monitored on monthly basis from the month January 2009 to May 2012 for model validation.

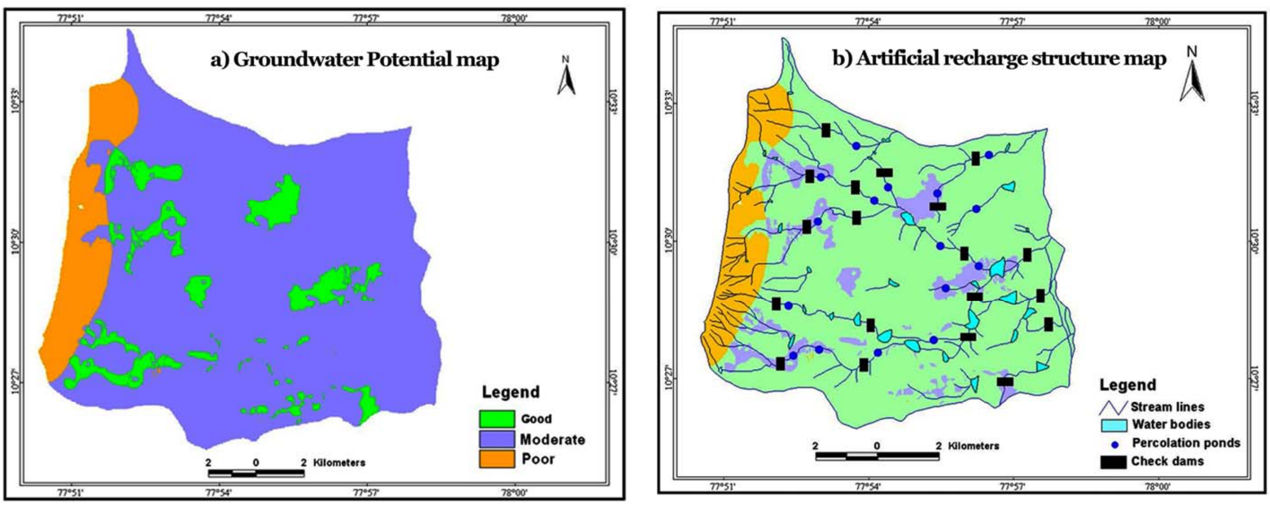

Fig.3. (a) Groundwater recharge potential map and **(b)** Artificial recharge structures map of the study area.

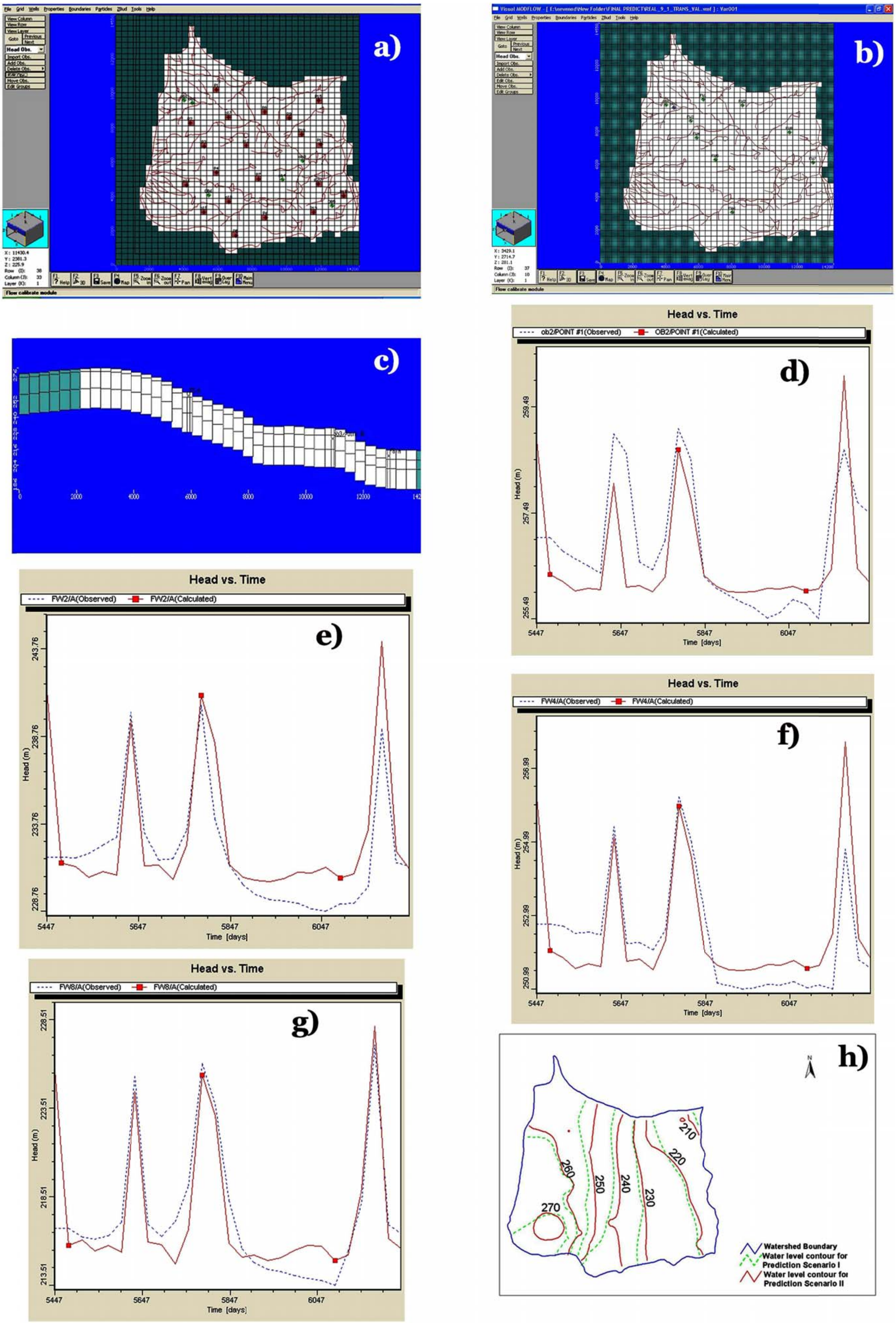

Fig.4. (a) Vertical cross section of the groundwater model, **(b)** The locations of observation wells along with pumping wells, **(c)** The locations of observation wells along with the field monitored wells, **(d)** Hydrograph map of observation well OB2, **(e)** Hydrograph map of observation well FW2, **(f)** Hydrograph map of observation well FW4, **(g)** Hydrograph map of observation well FW8, **(h)** Computed water level contour map of water level in scenario I and II.

Aquifer parameters including hydraulic conductivity, specific yield and specific storage were assigned for each layer of the model based on the hydrological formation and pumping tests conducted in the field. The locations of observation wells along with pumping wells are shown in Fig. 4b. The recharge rates are found to vary from 8% to 16% of rainfall and were assigned as input to the model and then calibrated. The model was calibrated in two stages, which involved a steady state condition and a transient state condition.

In steady state simulation a number of trial runs were made by varying the hydraulic conductivity values for all the three layers to minimize the difference between the observed water level and computed water level. The resulting calibration graph shows very good agreement with observed value, and the percentage of normalized root mean squared error is 2.69. The residual mean and absolute residual mean error was found to be 0.31 and 0.95 m respectively. The simulated and observed values of hydraulic head for all of the observation wells had a correlation of 0.99. Most of the predicted values are located within the edge of 95% confidence interval. The calibration resulted in a very good agreement between the computed and observed water levels. The transient calibration was carried out for the time period from January 1989 to December 2003. The hydraulic conductivity, storage coefficient and boundary conditions are finalized through steady state model calibration, which is used as initial condition to the transient model. The storage coefficient and the recharge values are adjusted reasonably in the transient state model until good correlation was obtained between the computed and observed water levels. From this transient simulation, the residual mean and absolute residual mean were found to be 1.28 and 1.30 m respectively and the normalized root mean squared error is 5.12. The correlation obtained as a result of comparison between the simulated and observed values of hydraulic head for the six observation wells is 0.99. A very good correspondence of computed water levels and observed water levels in the basin exists. The computed well hydrographs for these wells show a good agreement and hence the model reasonably represented the true aquifer system. The water level contours and velocity vectors showed that the flow was predominantly towards eastern side of river Kodaganar.

Model Validation

The groundwater model was validated after model calibration. The water level data collected from the two observation wells (OB1 and OB2) and monthly water level monitored from the eight monitoring wells (FW1 to FW8) spread over the study area was utilized for model validation. The locations of observation wells (OB1 and OB2) along with field monitored wells (FW1 to FW8) are shown in Fig.4c. The general trend of the calibrated water level matches reasonably well that of the observed measured water level. The hydrographs of the observation wells OB2, FW2, FW4 and FW8 shows a very good correlation between the observed and calibrated water levels and is shown in Fig. 4d to 4g.

Prediction Scenario

The transient model was used to perform predictive stimulations in order to assess the sustainability of groundwater system. The prediction scenario was carried out after the transient calibration for the time period up to 2013. Two different scenarios were considered to predict the changes in water level in the aquifer system, which are given below.

i) The calibrated model run up to 2013 without any artificial recharge structures and corresponding aquifer response were analysed.
ii) The calibrated model run up to 2013 and effects of recharge from the proposed artificial recharge structures were analysed.

Comparison of Scenarios

The water level contours from scenarios I (without recharge structures) and II (with recharge structures) for the year 2013 were exported from MODFLOW to Arc GIS to compare the effect of recharge from the proposed artificial recharge structures. The computed water level contour map shows that the water level is significantly improved in scenario II when compared to scenario I. The water levels contours were exported from MODFLOW to Arc GIS and the changes compared in water level between these two scenarios are shown in Fig. 4h. The comparison of results revealed that the artificial recharge structures such as percolation ponds and check dams proposed in this region are better equipped in improving the groundwater level when compared to the existing condition of the watershed. The results show that the water level in the central part of the watershed has a good improvement when compared to the other sides of the watershed. This change in water level is due to the presence of considerable thickness of weathered rocks in that area and it is capable of storing more amount of recharge water. The eastern boundary shows marginal improvement in water level when compared to western boundary of the watershed. This is due to the presence of charnockite in western side of the model area and the depth of top soil and weathered thickness are shallow in nature, which is not capable of storing more quantum of recharge water.

CONCLUSION

The study has utilized the benefits of GIS and visual MODFLOW to model the groundwater flow in a hard rock aquifer of the Kodaganar watershed. The weighted index overlay method is used to delineate the groundwater recharge potential zones of the Kodaganar watershed. The various thematic maps such as land use pattern, soil type, geology, geomorphology and slope were integrated and the groundwater recharge potential zone was generated and is divided into three different zones such as good, moderate and poor. Good potential zone (23%) and moderate potential zone (54%) are due to the presence of permeable soil group B and buried pediment and poor potential zones (23%) are dominated by pediment-inselberg and charnockite hard rocks in the area. The groundwater recharge potential map will be an important tool in understanding the groundwater availability and can be used for any groundwater development and management programs. The integrated approach of GIS and MODFLOW software used to develop numerical groundwater model of the Kodaganar watershed system. Prediction scenario results shows that there is a 15 to 38% increase in groundwater quantity due to artificial recharge and the central part of the watershed has marginal increase in groundwater level when compared to other part of the watershed. So, more number of artificial recharge structures can be implemented in the central portion of watershed. The implementation of artificial recharge structures on the western side of the model area does not have much effect due to the presence of charnockite which is impermeable in nature. The study has shown that the identified zones of good and moderate areas can be utilized to implement artificial recharge structures. The development of numerical groundwater models is useful in determining the recharge pattern of water through artificial recharge structures into groundwater aquifers and may serve as a guideline in planning and implementation of artificial recharge structures especially in semi-arid regions of hard rock aquifers.

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