



Three-dimensional numerical model to simulate regional groundwater flow in Thirukkazhukundram block, Southern India

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Abstract

Three-dimensional mathematical representation of territorial subsurface water flow is a worthwhile contribution to the regulation and governing of underwater reserves as they provide the components of hydrological processes as well as the flow of water in an aquifer. An attempt is made in applying this type of modeling study in the Palar river basin, Thirukkazhukundram block, southern India, which is chosen as the study area. The research area is signalized by multiple aquifer system consumed for agrarian and intake purposes. This model is having two vertical layers of the zonal type which prompts subsurface water flow over an area of 229 km² with 34 rows and 40 columns with a size of 500m² grids for elaborate study. The model was initiated in a steady and intermittent state utilizing a finite difference approximation of the three-dimensional partial differential groundwater flow equation in the concerned aquifer from Jan 2017 to Dec 2019. The pattern is designed in calibrating constant and transitory conditions. There is always a sensible match between the worked-out and spotted heads. As per the obtained modeling output, the aquifer is noted to be stable with the acquired pumping rate. The transient model is expected to work out until the period 2022. This model is helpful in forecasting the active groundwater flow under various pumping tests also, in monitoring the release and recharge of water.

Keywords Three-dimensional model · Groundwater flow · Aquifer system · MODFLOW · Sustainable management

Introduction

Groundwater modeling is a significant management tool that has the ability to work on multiple purposes. It is a framework

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to organize and compile the hydrologic data, quantifying the properties and characteristics of the system and predicting the responses of the system. A three-dimensional groundwater model is an empirically functional tool. Many researchers have studied groundwater management in various places around the world (Corbet and Bethke (1992); Strom and Mallory (1995); Gomboso et al. (1996); Strom (1998); Gnanasundar and Elango (2000); Senthilkumar and Elango (2001) and (Senthilkumar and Elango 2011); Selroos et al. (2002); Lamsoge et al. (2014), Pawan Kumar Neupane et al. (2020)). Such a kind of research work was approached in the lower Palar river basin located in southern India. The Palar river flows only for a few days a year, so, the groundwater from the source of this river has been substantially used to meet the up surging demand for domestic, irrigational, and industrial requirements. The groundwater model will be significantly important in managing the aquifer system as the need for groundwater has increased in all needed scenarios. Hence, the present study is aimed at evolving a regional groundwater flow model for the lower Palar river basin with an ultimate focus on groundwater management.

Based on the geological models, the groundwater models were made with high-quality data. Over the last decades, meticulous strengthening of databases for geological and groundwater-related geophysical data at the national and regional level was done by Szalkai et al. (2007). Generally, efforts were made to set up databases for the purpose of preservation and recovery of recorded geological models by Gunnink (2007). Simultaneously, greater focus is given to general guidelines for groundwater flow modelling, (Middlemis (2000); Refsgaard et al. (2005); Jakeman et al. (2006)), complexity tests (Refsgaard et al. (2007), van der Keur et al. (2008)), and usages of templates for social understanding and compatible management were done by Tidwell and van den Brink (2004). Gnanachandrasamy et al. (2018), using remote sensing and GIS, found the way out for groundwater potential zone mapping.

In this study, a three-dimensional, block-centered, steady-state, finite difference model, MODFLOW by McDonald and Harbaugh (1998), is utilized to quantify groundwater in Birjand Plain, South Khorasan, Iran. In recent years, Groundwater Modeling System (GMS: MODFLOW) has been evolved and broadcasted in many of the groundwater studies because of its user-friendly methods without any complications, modular program structure, and distributed assortments to elucidate hydro-geological issues by Hogeboom et al. (2015), Panagopoulos (2012), and Sar et al. (2015). This model, with a GUI (graphical user interface), can be interspersed with GIS (geographic information system) for monitoring the evolution of groundwater resources and management Wang et al. (2008). According to USGS, MODFLOW is considered an international standard for vitalizing and predicting groundwater interactions and their condition. In some research, MODFLOW has been applied for Birjand Plain in the real conditions; the following were not considered in detail such as source, recharges, extractions, return flows, and soil coverage. Also seepage and groundwater flow has been studied by Rushton and Redshaw (1979). In GMS: MODFLOW, the steady state and transient are the two accesses used predominantly. The variation in parameters during the study period is determined by using semi-transient method.

Study area

The study space, Thirukkazhukundram coastal block aligned at intervals 12°00" N and 12°10" N latitudes and 80°00" E and 80°10" E longitudes with Survey of Asian nation toposheet nos. 66 D/2, 66 D/3, and 66 D/6, categorized as semi-critical area as per CGWB (2010), is circumscribed by East Bay of Bengal, West Maduranthagam, North Kattankolathur, Thiruporur, and South Lattur with the regional extent of 352.82 km², and geological depiction includes recent

alluvium followed by epoch and crystalline rocks (charnockite or gneiss) earth science. Sand-gravel-silt-clay proves to be the alluvium and beach sands lithography with Archaean age succession comprising of mixed gneisses-charnockites. Flood plain, pediments (inselberg, shallow, moderate, deep, and dissected), mudflats, coastal plains, and structural and denudational hills form the geomorphological litho units. The places which can hold and yield water cover weathered, fractured, jointed, and faulted portions of granite rocks. The research area has semi-arid climatic conditions with more or less uniform pre-monsoon showers throughout the entire district. Generally, this block situated on the coast gets more rainfall than those areas situated in the interior part. The total annual rainfall relies on the Northeast and Southwest monsoons. Very often, the rainfall recorded is in the range 1213mm. Temperature of the range 36 °C prevails between April and June, while in December and January, the minimum temperature recorded is of the range 19°C. Relative humidity varies between 58 and 84% throughout the year. Relative humidity is higher between November and January and is lowest throughout June. Brown soil and alluvial soil are the soil types present in the study area (Agriculture Officer, SMS Agronomy, O/O JD, Agri, Kpm). Agriculture is the prime occupation of the people with paddy being the prime crop of cultivation. Groundnuts, sugarcane, cereals, millets, and pulses are the other major crops cultivated. Palar river along with tanks and wells is the main source of irrigation in this district. The average pre-monsoon and post-monsoon water levels of the area under research are 5.9m and 4.2m respectively. Groundwater is developed by 9275 dug wells and 2881 bore wells (Fig. 7a).

Methodology

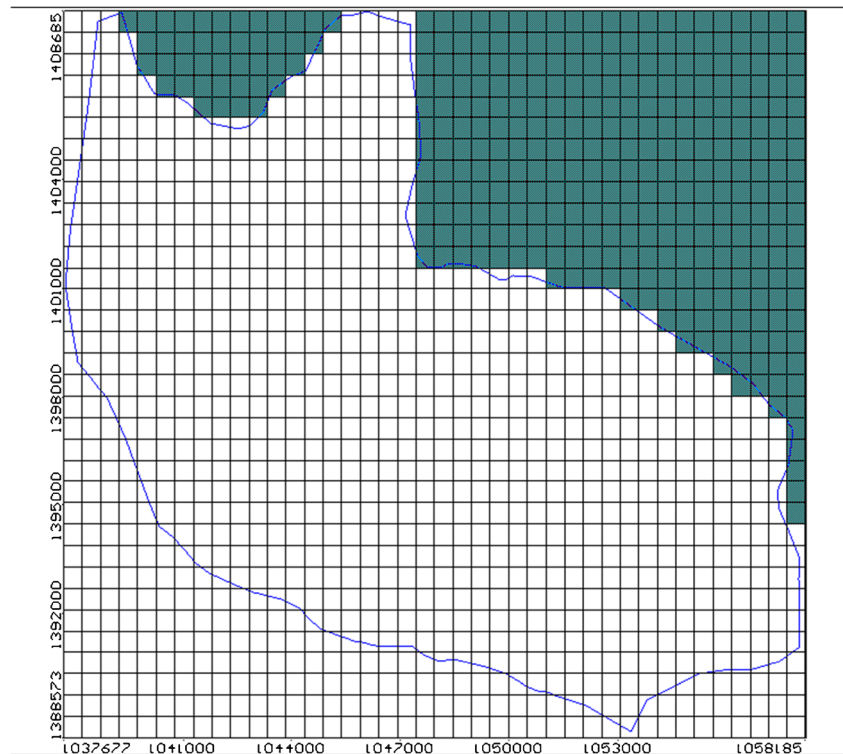
Model postulation

The abstract pattern of the system was obtained by a deep examination of the hydrogeology of that area. The groundwater is found to prevail in the weatherworn structures and fresh alluvia in our study area as well as in confined and semi-confined conditions. The northern portion has weathered formation underlain by fractured/jointed formation. The southern and central part of our study space having alluvium within the high area unit is underlain by arduous rock structure PWD (2000).

Boundary constraints

The survey space makes a locality of the Palar geographic area and contains a watershed boundary (Fig. 1). The flow from the northern boundary is the least, and so, absolutely, it was sculptured as a no-flow boundary. In our study space, the Palar

Fig. 1 Boundary conditions of the study area



stream flows from the northwestern to the southern boundary and was sculptured with this stream package. As the system flow starts from the eastern part of our study space, it is sculptured as a general head boundary.

Grid design

Using the GIS map module, nearly 229 km² of the geographic boundary of our study area has been mapped as a grid pattern. The map was imported into the MODFLOW method after the map has been projected using the metric coordinate system. Based on the physical aspects of the subsurface water system, the concept of a finite difference array was imposed on the research space. The constant spacing of each grid in the network is 0.5 km by 0.5 km from every other grid. The grid was dissected into 3120 cells with 34 rows and 40 columns and 2 vertical layers (Fig. 2). In our study area, along the east-west, the length of the cell is 500 m, and along the north-south, it is found to be 500 m.

Result and discussion

Initial groundwater head

The primary undersurface water head of our examining area is displayed in Fig. 3. It is pronounced that the subsurface water head details of Jan 2017 depict the spatial subsurface water

distribution of the research area as the results obtained after the meticulous analysis of the hydrographs, water level fluctuations, and rainfall. The rainfall and groundwater fluctuations were also found to be normal in this period.

Aquifer geometry

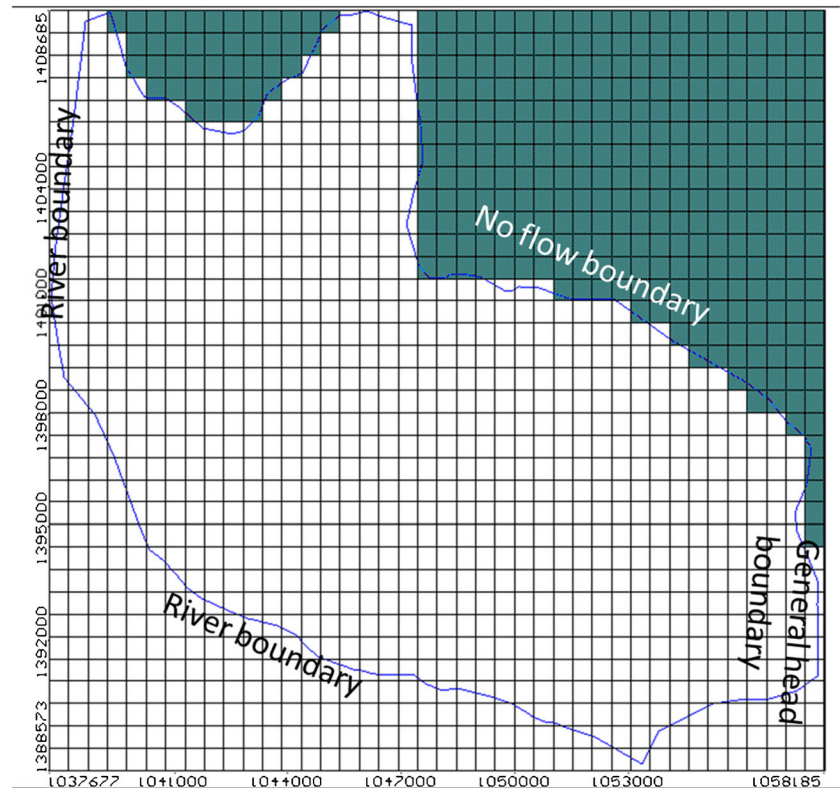
The aquifer geometry incorporates the meticulous study of lithology and geology of the fieldwork, so that we can easily interpret the geometry of the aquifer present in our study area.

The top and bottom of Ist and IInd strata for all the cells are shown in Fig. 4 a, b, and c. With these values, the entire area was extrapolated with the consideration of well sections and lithological variations. The Ist layer is comprised of young alluvium having an upper limit thickness of 40 m and is emphasized by fractured charnockite. Cross-section along the west-east direction is shown in Fig. 4d and that along north-south direction is given by Fig. 4e.

Aquifer characteristics

Horizontal conductivity and specific yield are the aquifer characteristics that were given as input to the model obtained from the results of 09 pumping tests and are depicted in Table 1. The hydraulic conductivity value of the river extends from 40 to 42 m/day. The alluvium hydraulic conductivity limit extends from 14 to 18 m/

Fig. 2 Grid discretization of the study area



day (Fig. 5). The weathered formation is observed in the northern portion and has its hydraulic conductivity extension from 6 to 8 m/day. The fractured and jointed formation has a hydraulic conductivity limit ranging from 4 to 6 m/day. Specific yield ranges from 0.08 to 0.12% for alluvium while for the weathered formation from 0.04 to 0.06%, and for the fractured formation, the specific yield ranges from 0.02 to 0.04% (Fig. 6).

Groundwater abstraction

The subsurface water in our research area finds varied usage such as irrigation, drinking, and for domestic purposes. Since there is a very nice canal network in the examining area, the available water resource is used predominantly in agricultural activity. From the analyzed period of flow of the river, land use, and drainage pattern, it is also found that the groundwater

Fig. 3 Initial groundwater head of the study area during Jan 2017

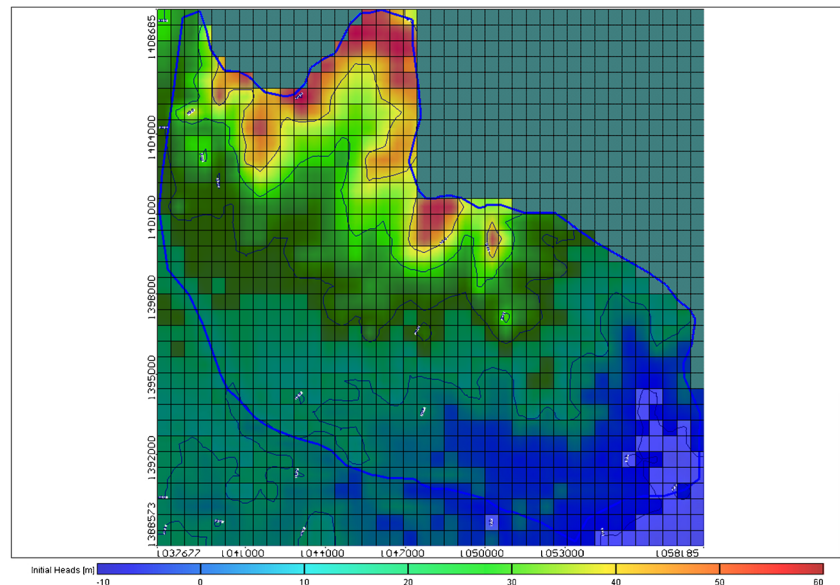
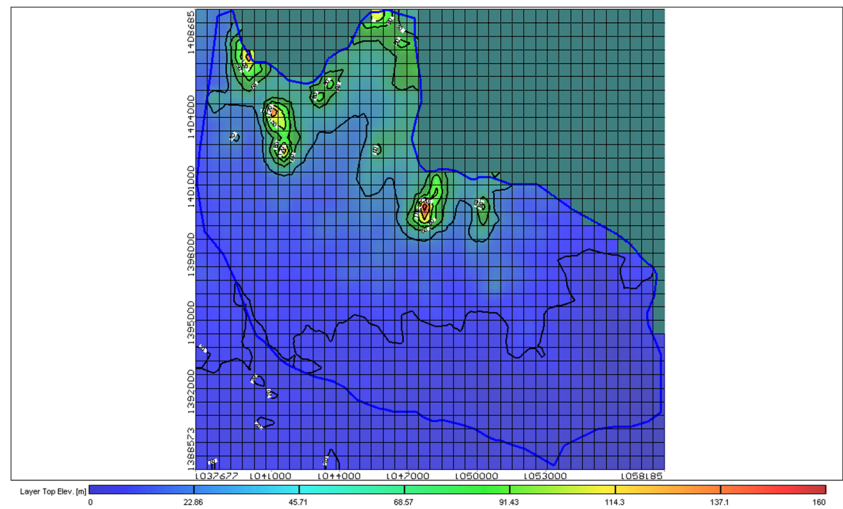
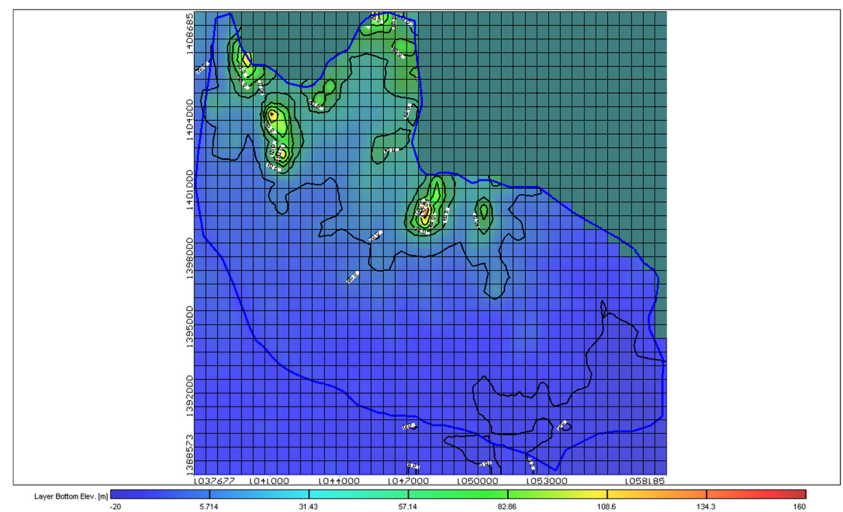


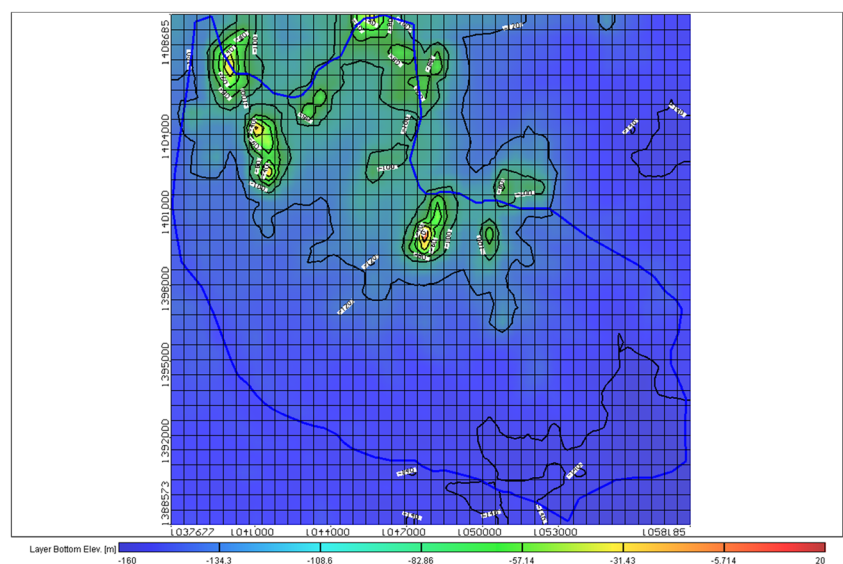
Fig. 4 **a** Top elevation of the study area. **b** Bottom elevation of the Ist layer of the study area. **c** Bottom elevation of the IInd layer of the study area. **d** Section along west-east direction. **e** Section along north-south direction



a



b



c

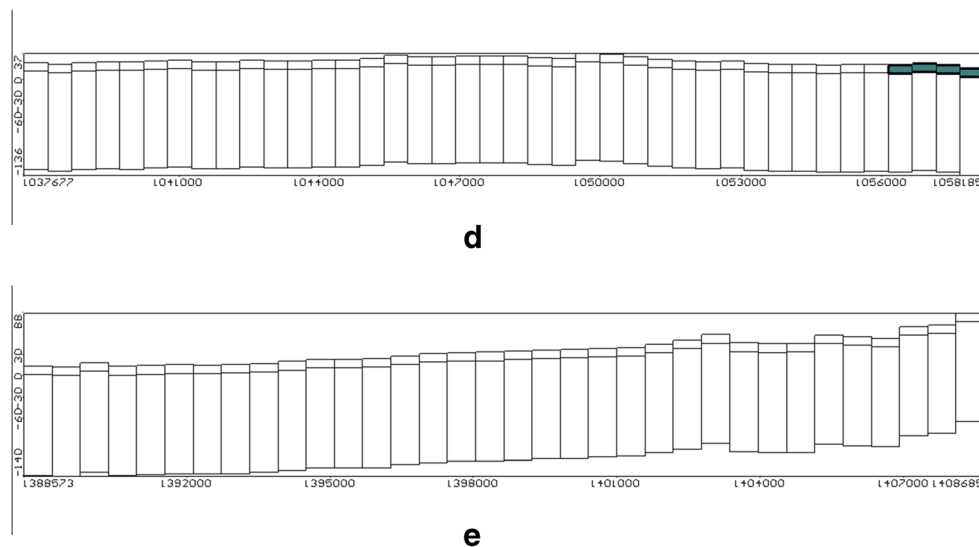


Fig. 4 continued.

in the study area is used only during the summer period. Based on the thickness of the population, the requirement and need for domestic and drinking water were calculated.

As aquifer is an integral part of the river and its basin, no-flow in the Palar river for the past 2 decades has adversely affected the irrigation by surface water in the region. As a result, farmers had to totally depend on groundwater for irrigation. This led to an increase in the withdrawal of groundwater by the farmers adding stress to the aquifer system. Groundwater is developed by dug wells (9275 nos.) and bore wells (2881 nos.) (Fig. 7a). The thickness of weathered formation values varies from 8 to 17 m and is followed by a fractured aquifer (2 to 3 sets of fractures) which extends up to 140 m bgl. The groundwater height ranges from 3.5 to 18.3 m underground level during the dry period and 1.3 to 13.4 m bgl during the wet period. The specific yield and hydraulic conductivity of the weathered formation value range from 0.002–0.01 and 0.5–12 m/day.

Out of total of 229 km², 89 km² is intensively irrigated. Paddy, sugarcane, and other cash crops are being cultivated. Groundwater contributes to about 88 km² of irrigation area and surface water, which is mainly rain-fed tanks (3–4 months) contribute to 44.34 km² of irrigation area. Paddy is

the main crop of the region (68 km²). Sugarcane (13 km²) is a year crop and requires a huge quantity of water. The farmers of the study area are small to marginal landholders and totally depend on agriculture for their livelihood. Farmers in the study area have a free power supply for 8 hours and hence have the privilege to withdraw groundwater at their ease. This indiscriminate groundwater withdrawal has lead to a declining trend in groundwater level, and many regions show an alarming decline from 4 to 5 m in a decadal. Pumping wells along west-east (Fig. 7b) and north-south (Fig. 7c) are vertically distributed.

Groundwater recharge

The refilling of the aquifer system has its sources from the downpour, river contribution, irrigation return flow, and

Table 1 Pumping test results

Formation	Hydraulic conductivity (k in m/day)	Specific yield
River alluvium	40	0.12
Alluvium	14 to 18	0.08 to 0.10
Weathered formation	6 to 8	0.04 to 0.06
Fractured/jointed formation	4 to 6	0.02 to 0.04

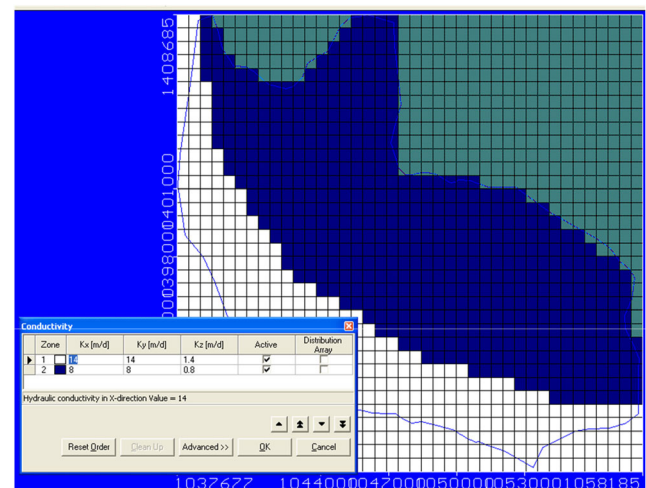


Fig. 5 Hydraulic conductivity for layer 1 of the study area

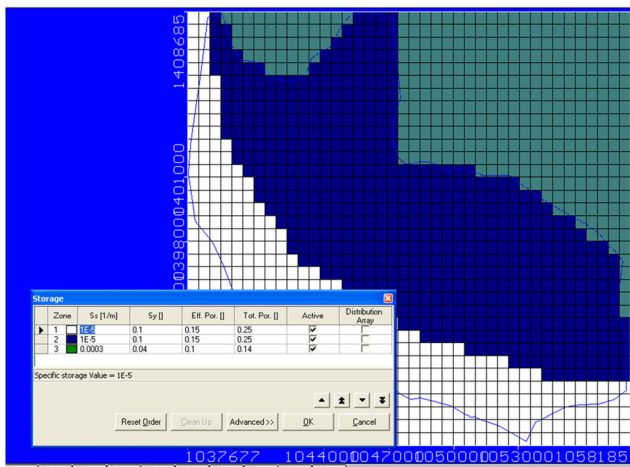


Fig. 6 Specific yield for layer 1 of the study area

storage tanks. Based on various parameters such as geology, lithology, relief, and topography, the potential and capability of the aquifer show variation. To realize the recharge pattern in our work out area, the rainfall hydrograph was studied, since the rainfall is one of the major sources of groundwater recharge. The water table gets replenished, and groundwater level rises when precipitation is beyond 60 mm. Geologically, our examining area is veiled by alluvial, sandstones of Cuddalore, and the Eocene period. The invasion capability of subsurface values ranges from 0 to 20% as per groundwater resources estimation committee report, (1997). Table 2 shows the precipitation infiltration factor employed in modeling for groundwater reload calibration.

Depending on the fluctuation between the river head and subsurface water head, the rate of leakage was found between the river and the aquifer. Based on the variation between the head in the adjoining wells and reservoir head, the sharing of rivers in the research area to the groundwater refilling was elucidated. The data of the river head was given as an input in the model.

Two refilling zones have been marked in the work out area, and they contain alluvium and river alluvium forming zone 1 and weathered formation forming zone 2 on the northern side. The recharge zones of the research area are shown in Fig. 8.

Model calibration

Initially, the calibration action plan was used to alter the parameters from familiar, poorly known, and unknown values to get the total agreement between simulated and ascertained. In our study area, the steady-state evaluation was carried out to minimize the difference between the computed and field water level conditions with the water level data of Jan 2017 obtained from various 09 wells. Out of all other input parameters, the hydraulic conductivity value alone is found to be poorly

known, as an impact of only 04 pumping tests performances in this work out space. Depending on the lithological fluctuation and borehole lithology of the well, it was determined to alter hydraulic conductivity values up to 10% of the pumping test outcomes, for subsurface lithology is beneficial to acquire a satisfactory tally of the calculated and noted heads (Fig. 8a). From the acquired results, it is indicated that there is a remarkable coincidence between the estimated and noted water heads in most of the wells present in our research space. Root mean square error and the mean error were reduced through innumerable test runs. Through several trial runs, the root mean square error and the mean error were minimized.

For a period of 3 years, the transient state simulation was undertaken from Jan 2017 to Dec 2019 with monthly stress periods and 24-h time step. From Jan 2017 to Dec 2019 measurement findings at various 09 observation wells and based on the close agreement between measured and computed heads, the transient models were considered to be calibrated satisfactorily (Fig. 8b). The input parameters of the model were tested by altering the parameter of interest over a range of values. The response of the model can be monitored by determining the root mean square error of the simulated heads compared to the measured heads.

Simulation results

For 3 years of time duration, the transient condition of the design was simulated from 2019 to 2022. There was a satisfactory correspondence between the calibrated and noted heads (Fig. 8b). The northern side of the study area results with the highest heads, from the outcome of the initiated potentiometric surface study of the water table as the groundwater head, which follows the general topography (Fig. 9 a and b). A spatial comparison of the simulated and observed groundwater head is shown in Fig. 9c which clearly shows a good match to the field conditions. The groundwater flow direction is from North to the South and towards the eastern side in the regional areas. For the month of June and December 2018, the groundwater flow vectors are put up in Fig. 10 a and b, respectively.

The vertical distribution of the regional groundwater flow is shown in Fig. 11 along the north to south direction and also the flow is laminar and steady. In the summer period, the flow is laminar which shows that groundwater movement is controlled by natural flow and groundwater pumping. During the monsoon recharge period, the flow is irregular and not uniform, which is due to the recharge process taking place in the study area.

Model forecast

Various responses of input and output fluxes of the aquifer were studied to assess the consequences of the aquifer system

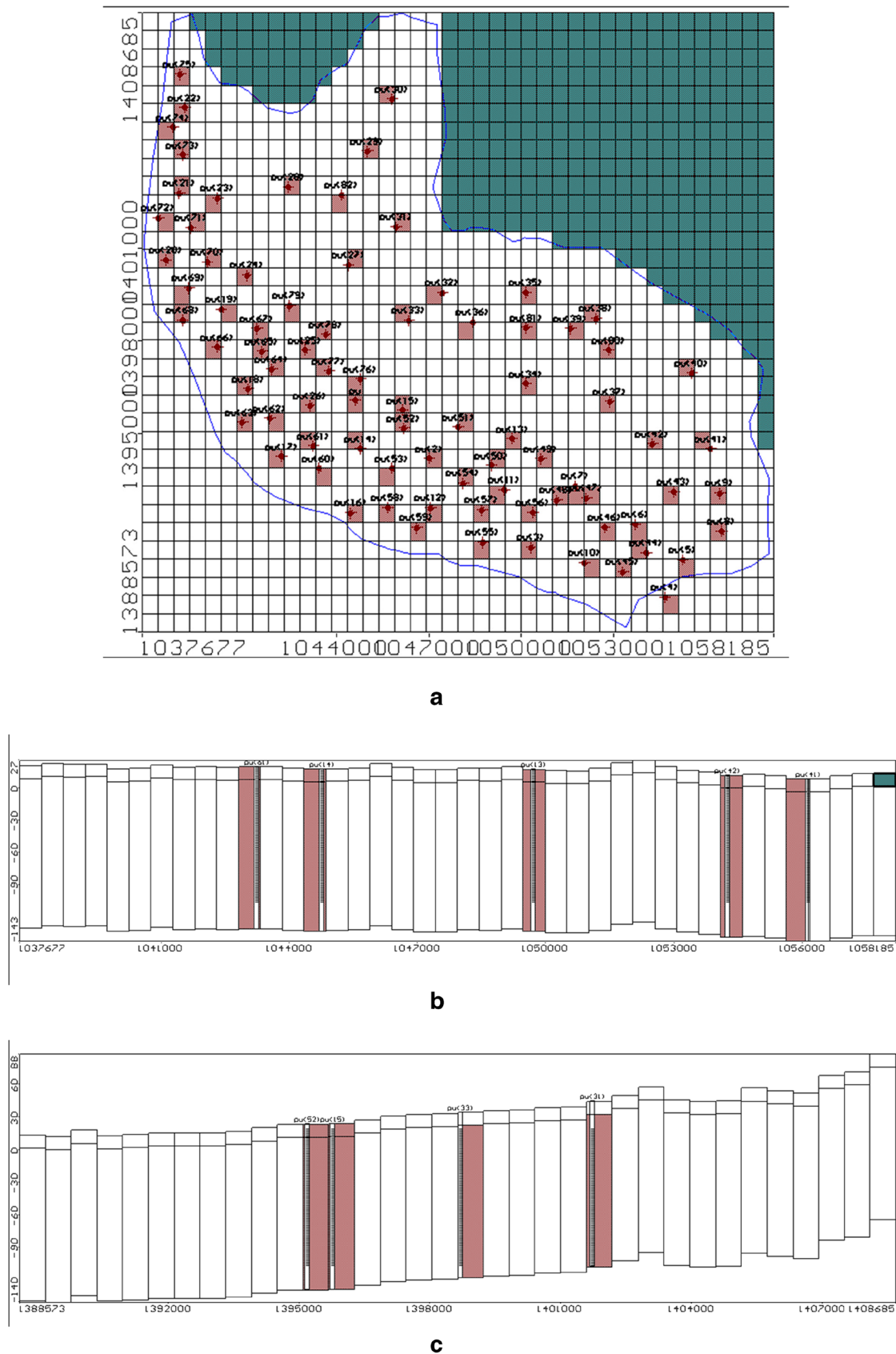


Fig. 7 **a** Distribution of pumping wells of the study area. **b** Pumping well section along west-east direction. **c** Pumping well section along north-south direction

Table 2 Rainfall vs infiltration factor used in groundwater recharge calculations

S. no	Rainfall (mm)	Infiltration factor (%)
1	0–60	0
2	60–100	10
3	100–200	12
4	200–300	14
5	300–400	12

because of varied hydrological pressures, like increase in pumping and reduction in recharge rates to durably manage this water table system. The model will be further run for a time duration of 03 years from 2020 to 2022. Prior to the initiation of simulation, the data of average rainfall, groundwater pumping, water level in the tanks, flow in the river, and sources of quantum of recharge was supplied to the model up to 2022. For the evolution of optimal management schemes, two prediction runs were planned.

(1) Normal Rainfall Condition

In the regional areas, until the year 2022, the model was run to find out the water table head. Twenty years of monthly average rainfall data were utilized to run this model. The simulated regional groundwater head for September 2022 is depicted in Fig. 12. The aquifer is stable, and there is no abundant increase or decrease in subsurface water level with time. Similar observations were done in most of the locations of the study area.

(2) Increase in Groundwater Pumping

The regional groundwater head in the study area was predicted using this model till 2022 with a 10% increase in annual groundwater pumping. Twenty years of monthly average rainfall data were also given as input for the prediction model. The present annual groundwater withdrawal for the alluvium aquifer and for the weathered aquifer was increased by 10%. The first scenario predicted the groundwater head in 2022 with the current pumping condition, while in this scenario, the possible increase in annual groundwater draft was taken as 10%. The predicted model (Fig. 12) indicates that the major portion of the groundwater potential lines moves towards the western side (Fig. 12). The predicted model indicates the steady

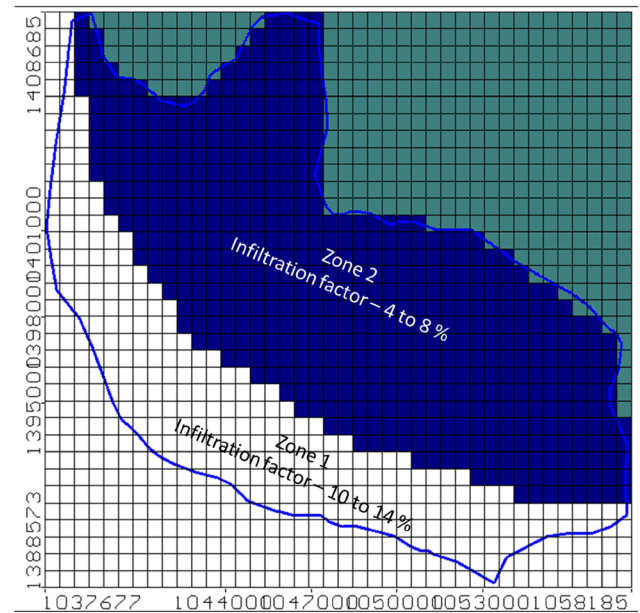
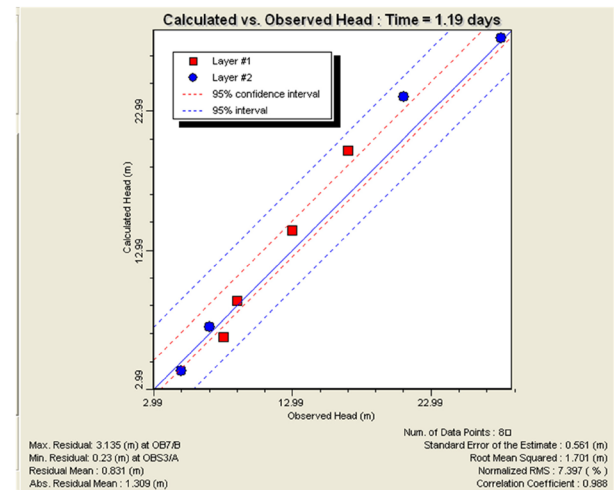
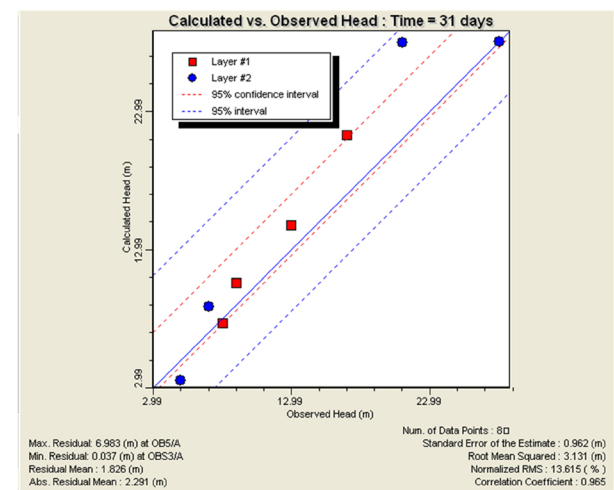
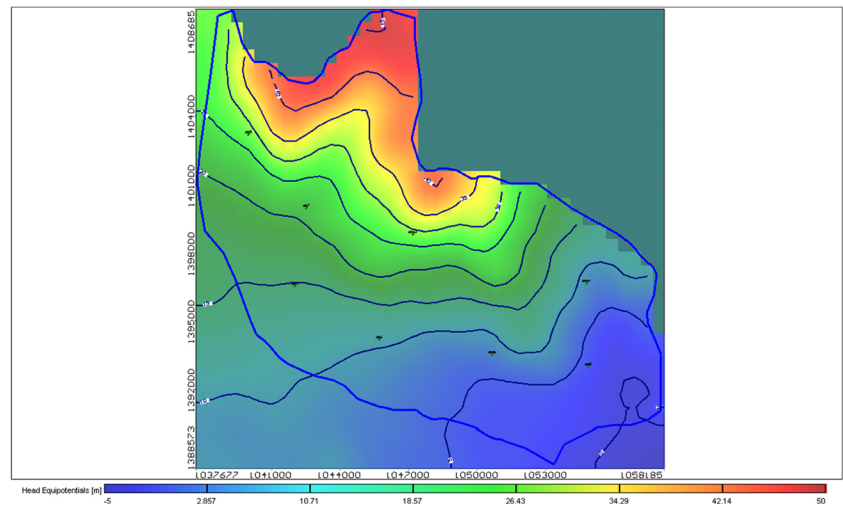
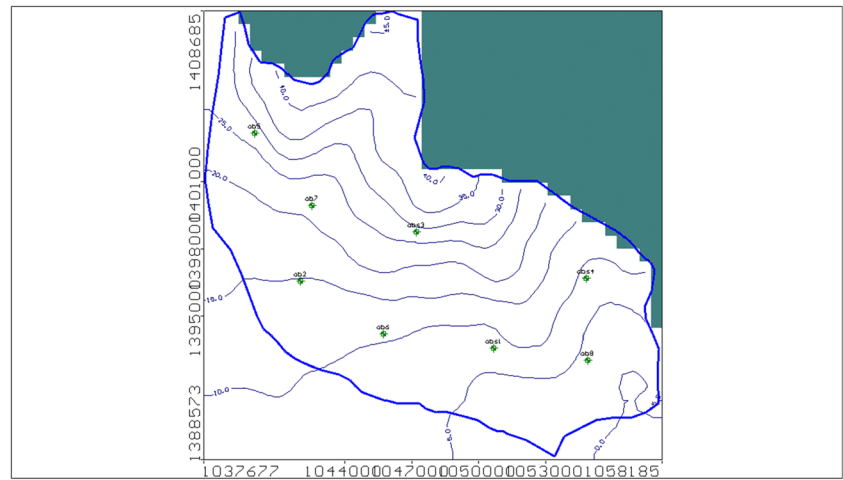
**a****b****c**

Fig. 8 Recharge zones of the study area. **a** Comparison of computed and observed groundwater head under steady-state and transient state condition. **b** Comparison of computed and observed groundwater head under steady-state and transient state condition

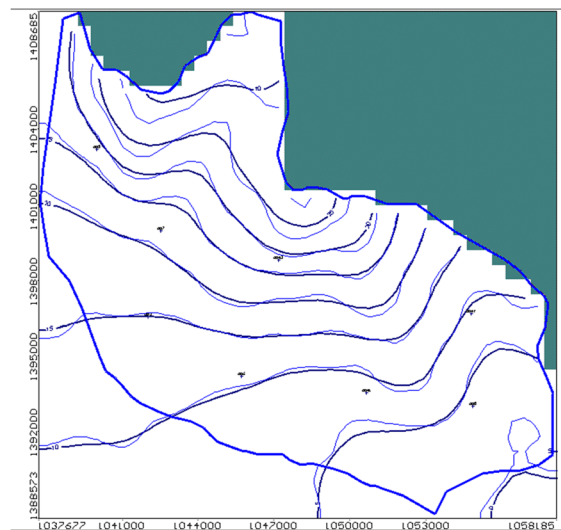
Fig. 9 **a** Simulated groundwater head during July 2018. **b** Simulated groundwater head during July 2018. **c** Simulated and observed groundwater head during May 2018



a

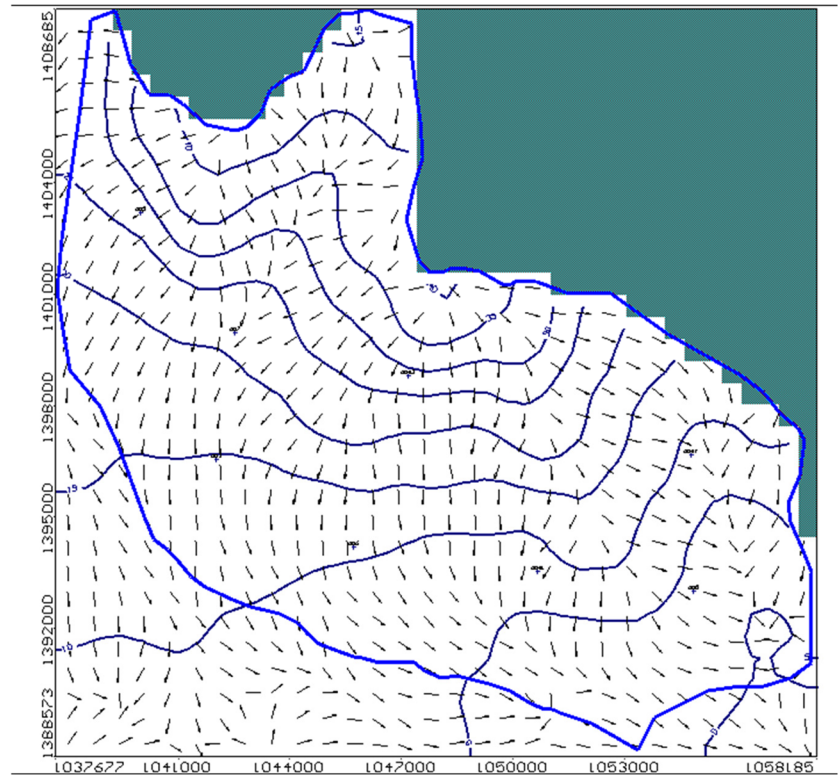


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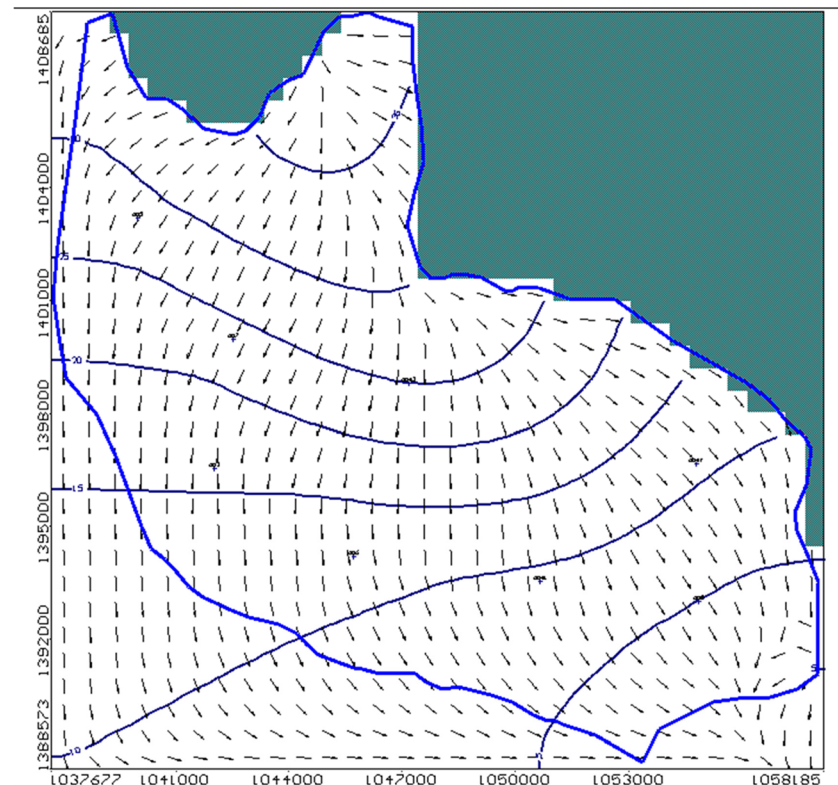


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Fig. 10 **a** Groundwater flow vectors during October 2018. **b** Groundwater flow vectors during June 2018

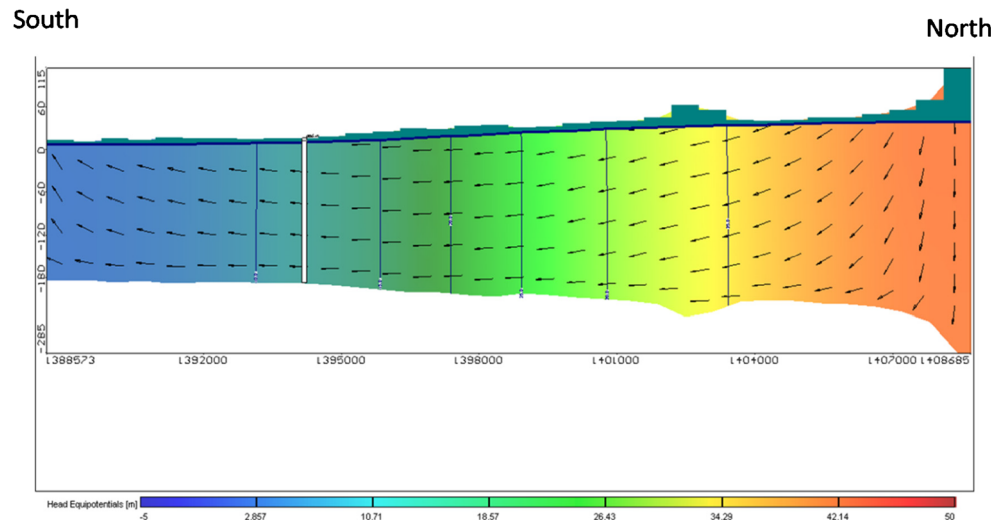


a



b

Fig. 11 Section view of groundwater flow from west to east during May 2009



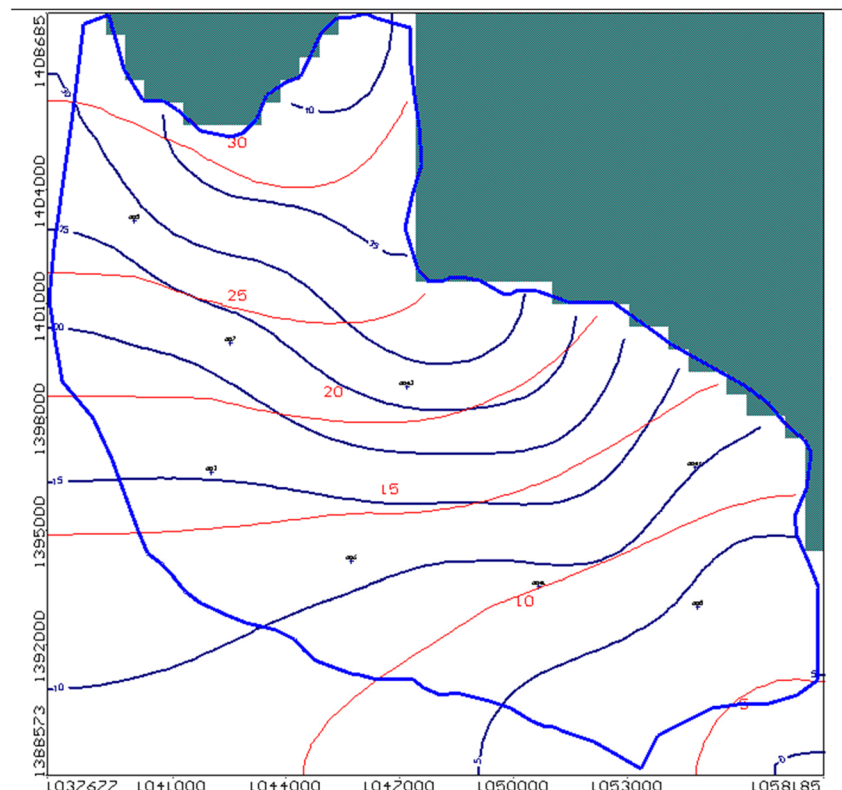
deterioration in the groundwater head with intensive pumping. The impact of the decline with a 10% rise in pumping shows groundwater head lowering at a rate of 0.3 to 0.6 m in certain locations in the central part of the study area.

Conclusion

Groundwater simulation modeling was evolved to prompt the groundwater head in parts of the Palar river basin, Thirukkazhukundram watershed region for a time duration

of 3 years (2017–2019) for improved management of the aquifer. From the present groundwater pumping conditions, it is obvious that the aquifer system is stable. The groundwater flows from the northern part towards the southern riverside and finally towards the eastern side, and also it follows the topography. The groundwater contributes to the river system. The model is also advantageous to forecast the variations in groundwater head from the hydrological conditions like change in time with existing pumping and hike in pumping rate by 10% for another 03 years, i.e., 2020–2022. In 2022, the aquifer system is stable, and there is not much change in the

Fig. 12 Predicted groundwater head (m msl)—during 2022 with **a** present annual groundwater draft (black colored contour line) and **b** 10% increase in annual groundwater draft (red colored contour line)



groundwater head with existing pumping conditions. But with the hike in pumping, the groundwater head moves towards the west side to increase by 10% of groundwater pumping, and a decline in groundwater heads is observed in a few locations in the range of 0.3 to 0.6 m. The groundwater from the aquifer flows substantially to the Palar river boundary.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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