Sustainable Development and Management of Groundwater in Varanasi, India

Padam Jee Omar, S. B. Dwivedi and P. K. S. Dikshit

Abstract Groundwater is the main source of drinking water for half of the world's population. Therefore, it is very important to conserve and manage this resource. Sustainable development and management of groundwater resource mean to the efficient management of the existing groundwater resources to meet the requirement of the present and future demand without affecting the risk associated with the damage to aquifer physical characteristics. In this paper, Varanasi was taken for the study of groundwater and its sustainable development. Varanasi is the oldest living city, situated on the bank of the holy river Ganga. Varanasi is the third most congested city of the Uttar Pradesh as per census 2011. Due to its religious importance, groundwater extraction is increasing day by day. A steady state of groundwater model was developed for the study area using groundwater flow modelling programme. This model was built in three layers to simulate the different type of soil layers. For conceptualization of the model, different layers and maps were prepared in GIS environment. Data collection was done in the field, and aquifer data was provided by different government organizations. For preparing maps, Landsat 8 satellite imagery was used and for DEM SRTM data was used. Modelling results were also calibrated and validated with the field data. Results reveal that Kashi Vidya Peeth block of the Varanasi is the most groundwater vulnerable regions. Results of this study are very helpful in applying sustainable development and management strategies for the groundwater.

Keywords MODFLOW · Sustainable development · GIS · Groundwater · Varanasi

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1 Introduction

Groundwater is the main source of water for drinking and other daily use purposes. It is locked up in the ground and extracted with the help of pumping techniques. It becomes extremely significant due to its good quality and easily availability. But in recent years, it is getting depleted as extraction of groundwater increases. Groundwater model can simulate the real field condition of the system which can help in the understanding the behaviour and performance of the groundwater system. This can be done using mathematical equations. Groundwater model estimates the changes in the water balance due to pumping and other modes. Various researchers worked on the groundwater modelling. A dynamic steady-state groundwater model was developed by Graffi et al. [3], in which specific yield was estimated considering one unconfined layer. Capillary rise of water table was ignored in this study which can affect the soil moisture and evapotranspiration. A groundwater fluctuation study was done by Zare and Koch [11] from 2007 to 2009. They simulated a groundwater model using MODFLOW and results revealed that after 10 years of pumping and irrigation action in the study area groundwater table keep on rising, and it will lead to water logging in the 50% of the plain area. Some studies were also done on the interaction of surface and groundwater [2, 4, 5, 8, 9]. Singhal and Goyal [7] conceptualized a three-dimensional flow model using MODFLOW. In this model, random distributed recharge values were used as an average of recharge that is in general find by method of water budgeting. Groundwater flow model can be further used in transport modelling [6]. Zheng and Wang [12] developed three-dimensional transport model, Wels [10] done study on flow model and reviewed benefits of modelling and its application mainly in transport modelling, Anderson [1] described the difficulties involved in the groundwater flow modelling and mass transport modelling. He explains the behaviour of movement of flow in advection and dispersion medium.

In this study, groundwater flow model was developed for Varanasi district using MODFLOW, and the regions are identified which is susceptible for the groundwater vulnerable. This model was used to predict the corrective measures for enhancing the groundwater resources and safe groundwater abstraction.

2 Area of Study

The area selected for this study is Varanasi district of Uttar Pradesh, India. Study area is situated on a bank of river Ganga, a sacred river for Hindus. Varanasi is a holy city with minimum elevation of 43 m above mean sea level (msl) and maximum elevation of 99 m above msl. City had population of 1,201,815, according to 2011 census, and in 2018, estimated population is 4.1 million. Varanasi district consists of eight blocks and 1329 villages. Varanasi district stretched between latitudes 25° 09′N–25° 35′N and longitude 82° 40′E–83° 11′E which covers an area of 1535.28 km^2. Location map of the study area is shown in Fig. 1. The average annual rainfall over the Varanasi

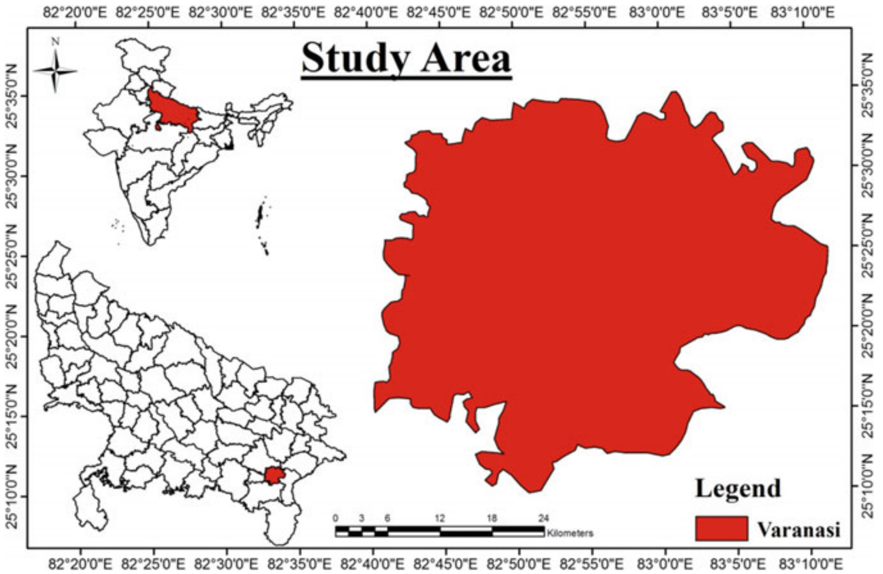

Fig. 1 Location map of the study area

is 1200 mm. There is large variation between summer and winter temperature. In the summer, temperature variation is 22–46 °C, and in the winter variation is 7–17 °C. The monthly rainfall variation is 96–290 mm in rainy seasons. Between the driest and wettest months, the difference in the precipitation is 296 mm. Crops of Rabi and Kharif are main crops in the study area. As study area lies in the gangetic plain, the soil of this area is very fertile. In recent years, the water head of the river Ganga has decreased significantly. This may happen due to construction of unregulated water extraction, upstream dams and dwindling glacial sources.

3 Data Used and Model Development

Groundwater flow model requires various types of data for conceptualization of the MODFLOW. For this, required data was type of soil strata, topography of the area, river stage, groundwater initial head, precipitation, infiltration rate of the soil, climate data, land use and land cover, water demand. Table 1 shows the data used in this study and from where it was collected.

Table 1 Data used in the study

Data	Type of data	Organization
Climate data	Rainfall, temperature and humidity	India Meteorological Department (IMD) Pune
Digital elevation model (DEM)	Shuttle Radar Topography Mission (SRTM) data of 90 m resolution	United States Geological Survey (USGS)
Satellite imagery	LANDSAT 8	United States Geological Survey (USGS)
Groundwater head and river stage	Groundwater level and top level of river	Field Survey
Census data	Population and livestock population	Office of the Registrar General & Census
Soil data	Soil type and vertical soil strata detail	National Bureau of Soil Survey and Land Utilisation Planning (NBSS & LUP), Nagpur

3.1 DEM and LULC Map Preparation

For this study, Shuttle Radar Topography Mission (SRTM) data of Varanasi district was used as a DEM. DEM data contains elevation data on a near-global scale at 90 m resolution. For the present analysis, DEM data was projected to WGS_1984 and UTM_Zone_44 N coordinate system was used. Figure 2 shows the DEM of the study area.

The term land use can be explained as use of land by people habitually with importance upon the functional role of land in economic activities and land cover can be explained as the vegetative and non-vegetative blanket, either natural or man-made of the earth's surface. In the present study, land use and land cover map was prepared using image classification. For this purpose, three bands of LANDSAT 8 imagery were used. Band 5, band 4 and Band 3 were stacked using image processing software, and region of interest (ROI) was delineated. After that, using supervised classification algorithm final map was prepared.

3.2 Model Development

A simplified model of the groundwater flow of Varanasi district was developed. To process the GIS-based data such as river digitization, pumping well location, DEM of Varanasi district, and recharge rate map, ArcGIS was used. In the study area, groundwater recharge occurs due to precipitation and some water inflow from the Ganga River. Actual estimation of groundwater recharge rate is very tedious and time taking task, so 30–40% of the precipitation was taken as the recharge rate for

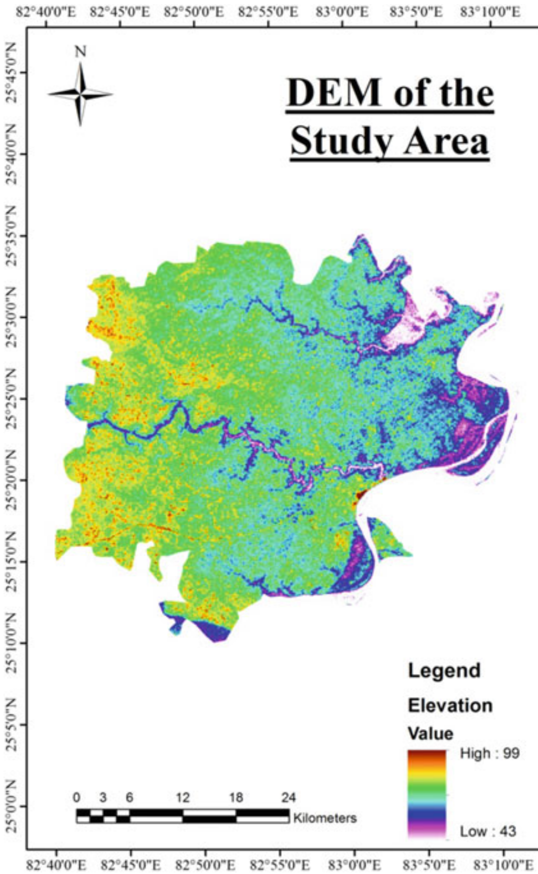

Fig. 2 Digital elevation model of the study area

the study area. The rainfall is a major aspect for the estimating recharge rate in the area. For assigning the pumping wells, water demand was calculated for the whole study area. This water demand decides the number of pumping wells and location was decided by the field survey. Water from the wells is extracted throughout the year, and the extraction rate of the pumping well was taken 600 m^3/day based on the aquifer capacity. Initial groundwater head level data and observation head data were collected from the CGWB Varanasi.

For the hydraulic property, results of the aquifer pumping test were used in this study. Hydraulic parameters play a very important role in the movement of the groundwater flow. Hydraulic conductivity (K) and transmissivity (T) are not uniform over the study area. The variation in the hydraulic property is due to the heterogeneity nature of the soil. To avoid the complexity in the model hydraulic property was taken as constant in one strata of the soil. In the first layer of the soil, horizontal hydraulic conductivity (K_x and K_y) in x and y direction are taken as same and equal to 2.17×10^{-5} m/s, and vertical hydraulic conductivity (K_z) is taken as 2.17×10^{-6}

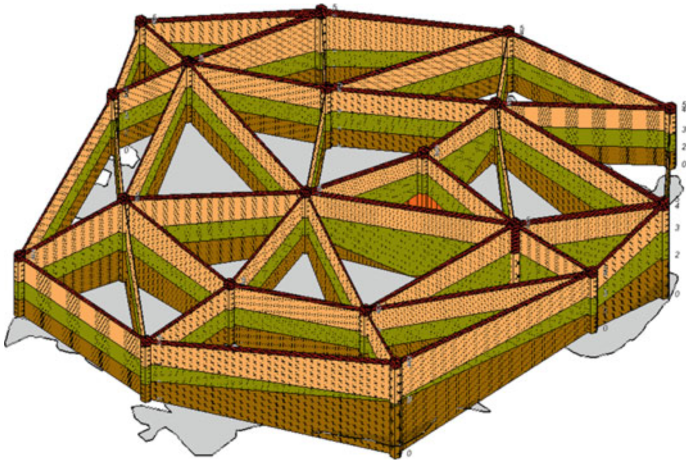

Fig. 3 Fence diagram of the study area

m/s. Porosity and specific yield (S_y) of the soil are taken as 0.30 and 0.11, respectively. Initial groundwater head for the Varanasi district approximately ranges from 6 to 30 m below ground level (bgl). Model was build up in three layers of uniform thickness of 40 m.

To know the vertical soil profile and characteristics of the soil strata, fence diagram was prepared. Fence diagram, as shown in Fig. 3, was prepared using the lithology data. Fence diagram reveals the vertical and lateral disposition of aquifers in the study area down to depth of 120 m below groundwater level. Top layer of the study area consists of surface clay with variation in depth of 3–8 m. Second layer made of fine sand and vary spatially in the nature. Below this layer clayey soil and sandy clay layer were found. Underneath, a relatively hard and impervious bed is encountered. Study area is spread over 53.45 km × 47.56 km, and this area is discretized into a three-dimensional grid with a single grid cell size of 500 m × 500 m. This grid cell size was selected to maintain a balance between the accuracy of the model and the computational time taken by the model to run. For the model, the boundary condition was taken as specified flow boundary.

3.3 Calibration and Validation of the Model

Calibration of the model was carried out by providing the approx values of the model parameters in such a way that it behaves like a real field condition. To minimize the error in the model PEST tool was used. Parameter estimation tool provides the most accurate values of the model parameters. After the model calibration, validation of model was done. For validation, three years of data was taken. Figure 4 given below explains briefly the methodology and steps followed in this study.

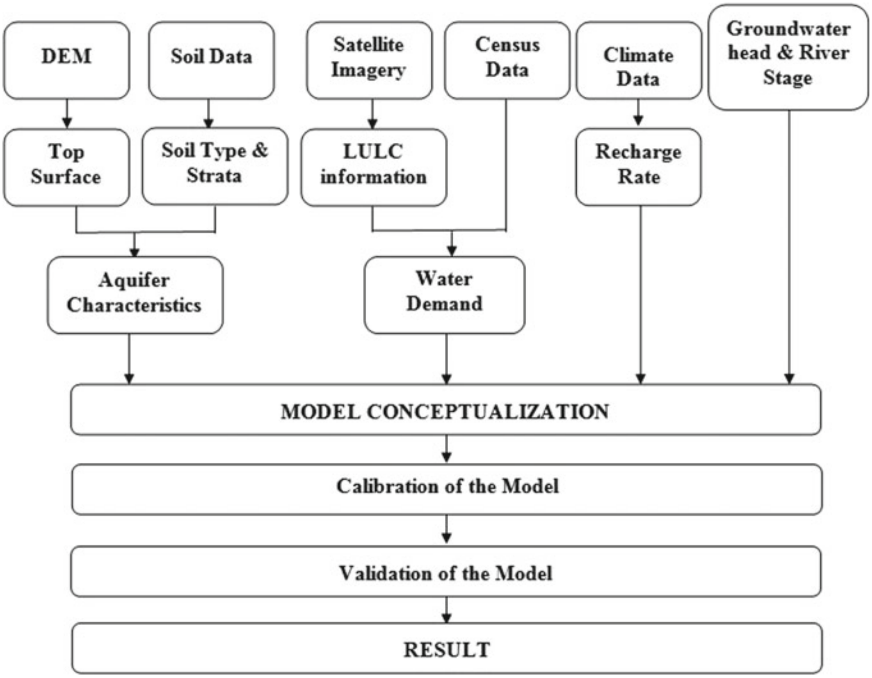

Fig. 4 Flow chart of methodology

4 Results and Discussion

The computed groundwater head in Varanasi district has shown the satisfactory results. The water level accuracy was judged by comparing the mean error, mean absolute and root mean square error calculated by the model. Root mean square (RMS) error is the square root of the sum of the square of the differences between calculated and observed heads, divided by the number of observation wells. Groundwater flow pattern obtained from the model represented almost accurate movement of the groundwater. But at some places, groundwater flow pattern was poorly represented by the model. It may be due to some pumping wells, small drainages and lake were not incorporated in the model and might have influenced the pattern of groundwater flow. In the calibration of the model, it was kept in the mind that model water level reasonably matches with the observed water level. Result of groundwater model for Varanasi district reveals that the computed groundwater level shows a decreasing trend of water level in Kashi Vidya Peeth block and near surrounding area, while the other blocks are shown the increasing trend of the water level. This result came may be due to the rapid increase in the population of the Kashi Vidya Peeth block and careless use of the water resource. Figure 5 shows the graph between the observed head and the head computed by the model. This result shows that the

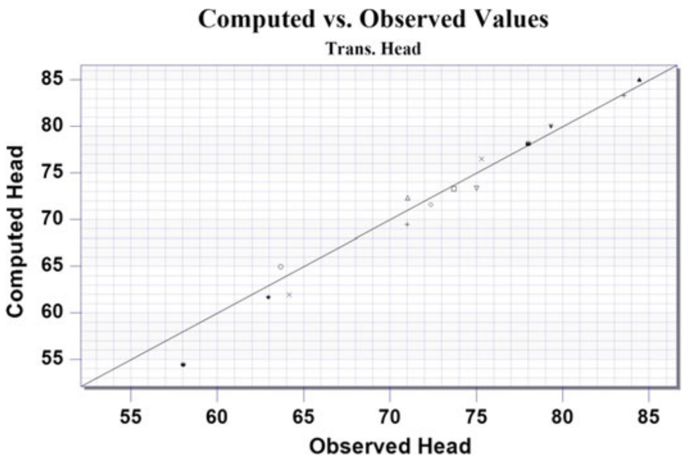

Fig. 5 Graph between computed head by the model and observed head

computed values of the water head are in good-fitness of the measured data, which indicate that the model is reliable.

5 Conclusion

Anthropogenic activities and natural processes affect the groundwater systems. This requires sustainable development and management strategies to keep groundwater resource in good condition. For this, groundwater flow modelling has become more popular and useful among researchers for various purposes. Due to overexploitation of the groundwater, it becomes essential to locate the groundwater scare regions and apply a strategic management plan to conserve this resource for future water demand. For this reason, a groundwater flow model was developed for the Varanasi district with known boundary conditions and known field observation values. This model was very helpful to estimate the groundwater level and the direction of the groundwater flow for the Varanasi district. GIS tools were used for pre-processing of the data such as geological data, climate data and hydrological data. Methodology presented here can be proved superior tools for a conceptual model development to deal with the groundwater modelling problems. Results of this study show large fluctuation in the groundwater head, and in Kashi Vidya Peeth block, there is huge water depletion. This fluctuation may be due to rising agricultural and domestic water demand. The maximum groundwater in the study area is exploited for agricultural purposes. To conserve this natural resource, more water conservation techniques are needed to keep the sustainable groundwater in the study area. Hence, this study can be very helpful in application and the management strategies for the sustainable development of the groundwater.

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