CHAPTER 5

MODEL SETUP

5.1 General

Before establishing a groundwater model, one has to understand the definition of a groundwater model. The definition of groundwater model has been suggested by many researchers and scientists. According to Anderson et al. 1992, the groundwater model is the computational technique that attempts to simplify the sophisticated groundwater system by approximation. In 1995, Bredehoeft and Hall suggested that a groundwater model makes available a quantitative framework for synthesizing field information and for conceptualizing the hydro-geologic processes. In a simple manner, it can be defined, as a groundwater flow model is a mathematical formulation of groundwater flow through an aquifer, which is composed of saturated sediment (soil particles) and rock. In order to solve the mathematical equations that constitute the flow model, it is required to make simple assumptions about the groundwater aquifer system and the physical processes governing groundwater flow. The most important of these assumptions are embodied in the conceptual model of the aquifer.

Recently, due to advancement in the field of computational capacity, groundwater modeling becomes very popular for the groundwater management and prediction, as well as modeling also helps in the groundwater protection and remediation. Groundwater models can be categorized into two classes as analogue models, and numerical (mathematical) models as discussed in the chapter 02. Mathematical models are extensively used as it is widely accepted by the groundwater modelers and researchers. In mathematical models, the groundwater equation is solved either analytically or numerically.

Analytical solution methods do not involve so much data that is why the applications of AEM methods are restricted to the straightforward groundwater problems. Whereas, numerical solution methods have the potential to solve more complex groundwater flow problems. These models have become more efficient and easier to use due to the advancement in the field of computational capacity and processing speed of the computer processors. The most well-known numerical methods to solve the groundwater flow problems are the Finite Difference Method (FDM) and Finite Element Method (FEM). The appropriate approach to the modeling method can be selected, according to the problem concerns and modeling objectives, as each method have its advantages and limitations. The outputs of any groundwater flow problem are influenced by the chosen modeling approach, initial, and boundary conditions, type of discretization, and the quality and quantity of the collected data (Husam, 2009).

Before conceptualization of the groundwater model, it requires knowledge and detailed information about the area, for which model has to be develop. All these requirements can be summarizes in the following points.

1. Development of the conceptual model is the main stage for a numerical groundwater flow model.
2. Selection of the model code (MODFLOW) that can efficiently simulate groundwater flow problem.
3. Discretization of the grid layout, demarcation of the boundaries, arrangement, and number of layers of the model.
4. Input of the groundwater aquifer characteristics such as hydraulic conductivity, storage, porosity, and others.
5. Input of the transient data for river water head, recharge rate, well pumping data, evapotranspiration rate etc.

6. After providing the all input data and model setup, model simulation starts and then model calibration, validation of the model was done to match the water head with the real field condition.

5.2 Groundwater Model Conceptualization of the study area

For developing the accurate groundwater flow model, six steps as discussed above, must be taken. Detailed knowledge about the groundwater aquifer and characteristics of the study area, groundwater solving techniques should be known to the modeler. Steps to be followed for the conceptualization of the groundwater flow model are presented in the form of a flowchart in Chapter 04 (Figure 4.1).

In GMS (Groundwater Modeling System) software, conceptualizing a groundwater flow model mainly requires the insertion of input files of the study area with hydro-geological characteristics, all boundary conditions in GIS format (.shp), run the model, visualize and check the output of the model, model calibration (manually or automatic), and after all these steps, finally finding the predictive groundwater flow model for the study area. The methodology adopted in the study has been presented in Figure 5.1.

The groundwater flow model was conceptualized on the basis of geological, climatic, and hydro-geological characteristics of the study area. In the study area, to conceptualize the groundwater aquifer system, it needs software that can deal with the simulation process of the model precisely and effectively. Hence, GMS 10.2 program which is designed by Aquaveo is used. GMS version 10.2 was released in October 2016. In 2006, a report has been prepared by Buseman and Alexander, which stated GMS "the most sophisticated groundwater modeling software available" (Buseman and Alexander Y., 2006). GMS has the capability to integrate with the GIS files and it can also export the files in the GIS formats. It can build a high-level representation of a model using known GIS features such as points, lines, and polygons and easily update the model as needed.

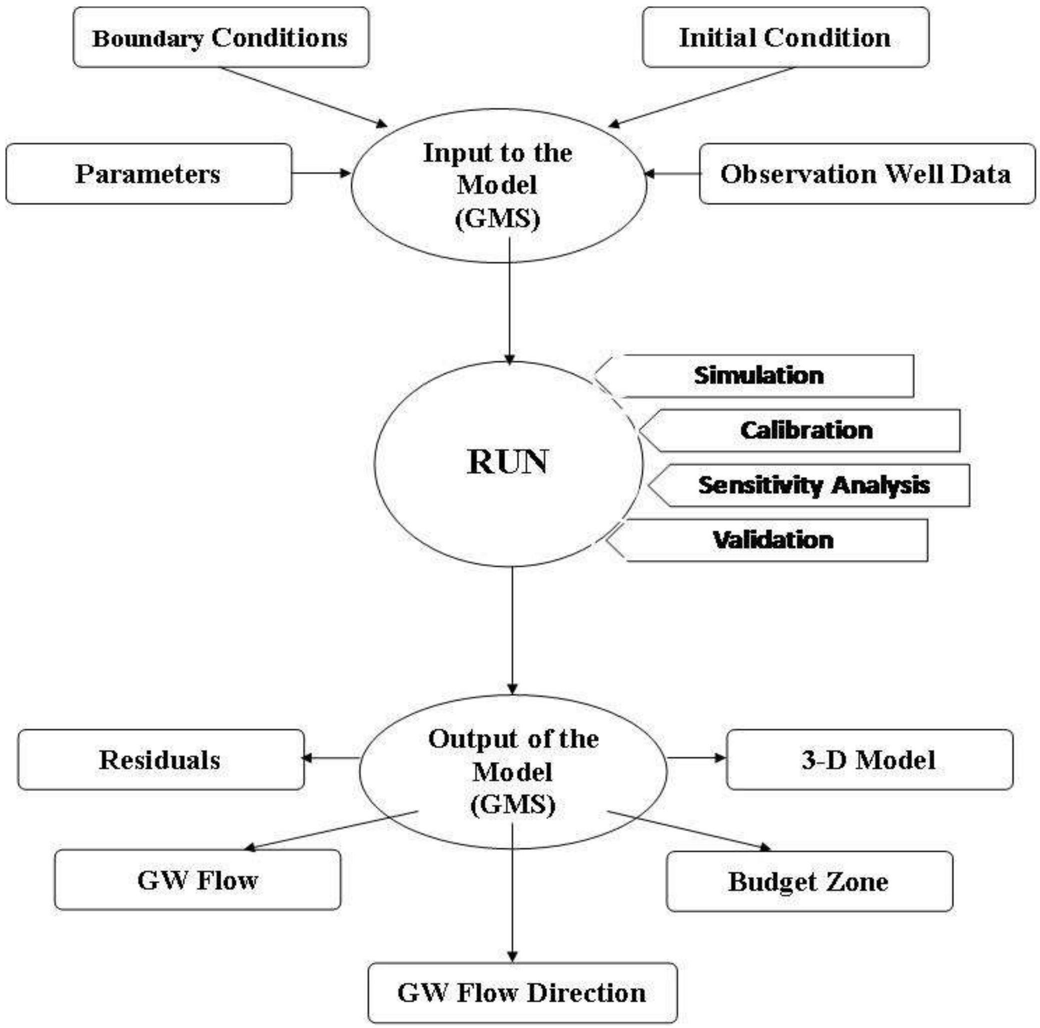


Figure 5.1 Adopted methodology for Groundwater flow Model using GMS

Thus, the GIS based conceptual groundwater model was developed using MODFLOW based software GMS 10.2 (Aquaveo, 2010). MODFLOW can solve the steady and transient groundwater flow equation and can simulate single or multiple aquifer layers with different boundary conditions (Tamma Rao et al. 2012; Surinaidu et al. 2013; Senthilkumar, and Elango, L., 2004).

The area of the aquifer is about 2,785 $km^{2,}$ and the thickness of the aquifer varies up to 222 m. Transient state simulation of groundwater model was done using five layers in the computational grid. The computational grid for the study area consists of 210 rows and 210 columns, where each cell measures 250 m × 250 m on ground as shown in Figure 5.2. Based on the geological and hydro-geological analysis discussed in chapter 3, it can make the groundwater flow model with five layers and known hydraulic conductivity as shown in the Figure 5.3. In the model, approximately 1,38,000 grid cells were created for the numerical solution, which increased the complexity and computational runtime for the numerical flow model. The topographic elevation of the ground surface is imported from the 30 m SRTM data based on the downloaded DEM. DEM data were imported in ASCII (American Standard Code for Information Interchange) file and interpolation was done using scatter points created from DEM and feature files available in the dataset in GIS.

The bottom elevations of each layer were found from the borehole data that was drilled in the study area. The aquifer in the study area is unconfined with five layers (as shown in Figure 5.3) that symbolize the geological features of the study area. To calculate hydraulic conductivity for the entire study area, hydraulic conductivity was interpolated from the collected samples. For the top layer, hydraulic conductivity was set at 16 m/day from the interpolation. From the surface profile of the area and field observation, it is observed that the movement of the groundwater is from west to east. The recharge rate in the groundwater is derived from the calculations as discussed in Chapter 4 and the value is 0.0005 m/day.

For transient state conditions, ten years of data were taken from the Central Ground Water Board (CGWB), Varanasi from January 2006 to December 2017. Transient data were entered with great caution in the conceptual model using time values, where the time at the beginning of the first MODFLOW stress period was assumed to be the reference time.

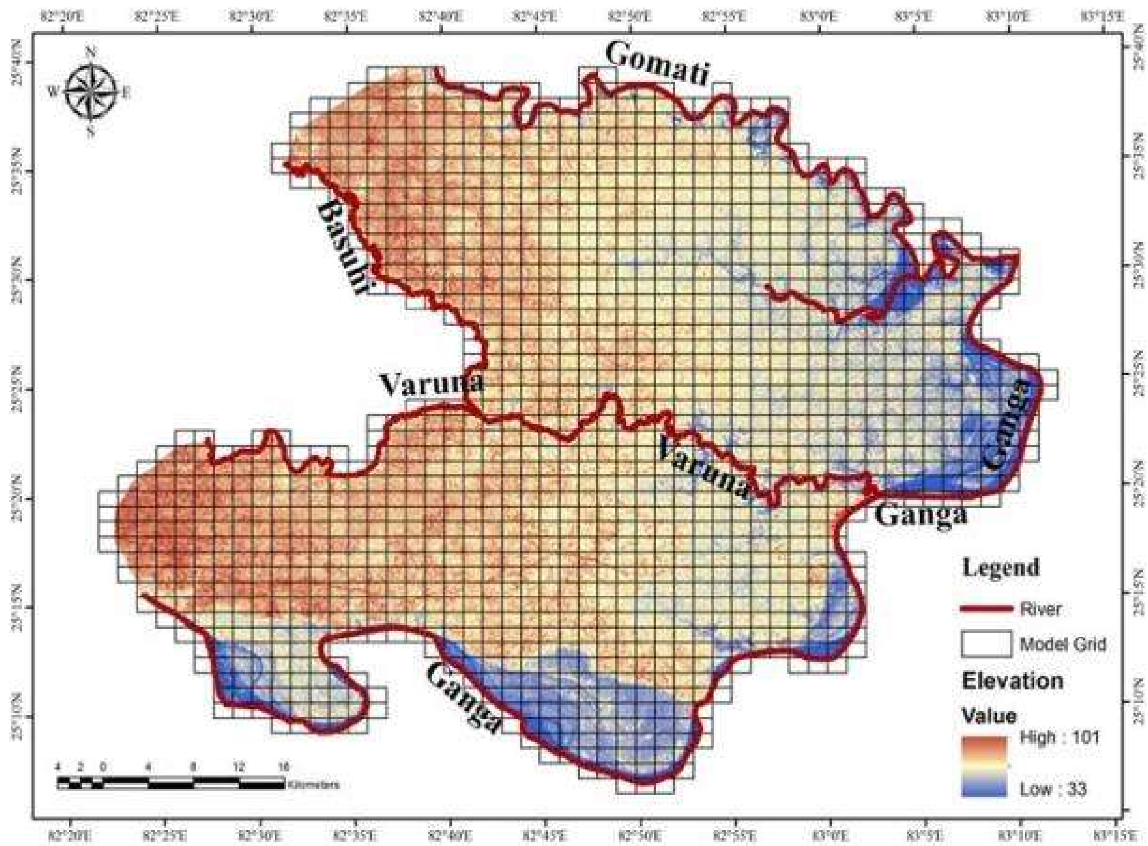


Figure 5.2 Computational Mesh with the River boundary conditions

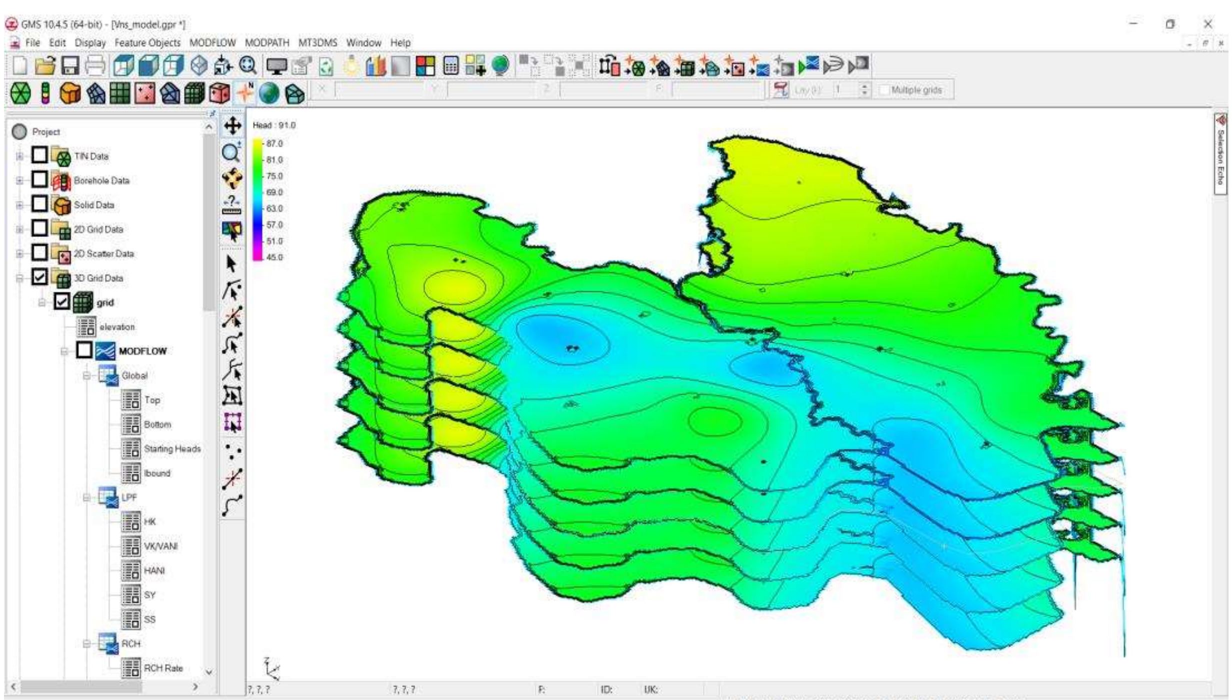
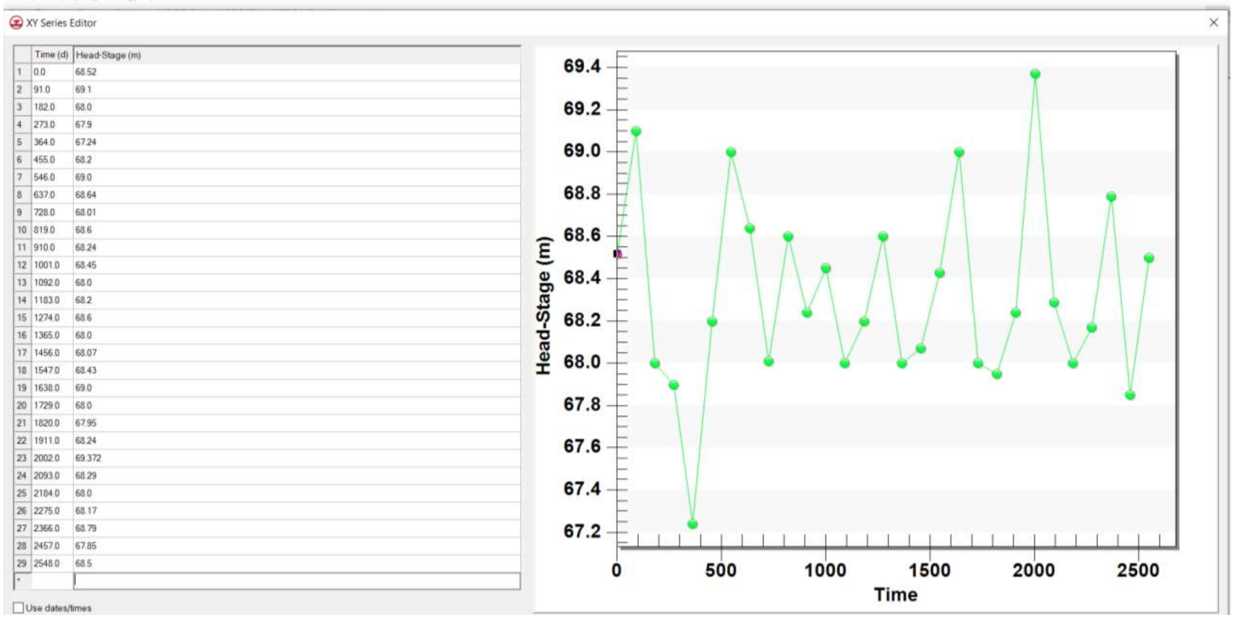


Figure 5.3 Groundwater model with five layers

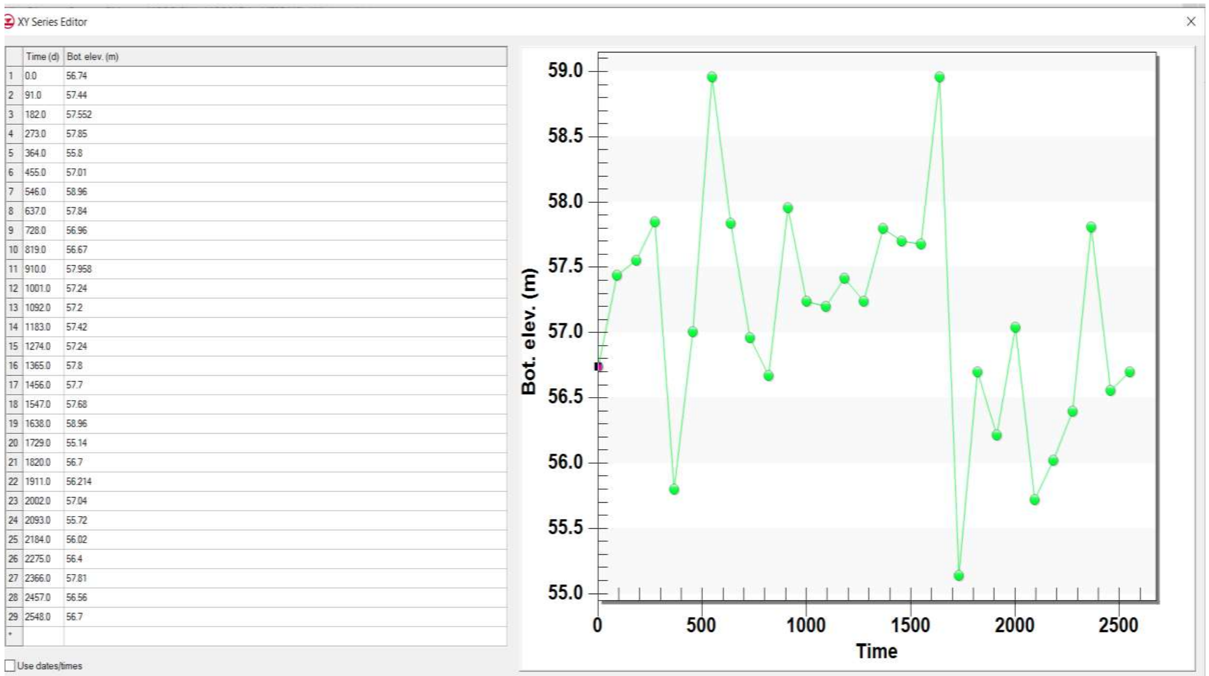
In the model, the data were recorded at an interval of 91 days, starting from January 2006, i.e., pre monsoon Ravi to December 2013 i.e., post monsoon kharif. Thus, there were a total of 28 stress periods, for which river head stage, bottom elevation for rivers, specified flow and recharge rates were recorded. Figure 5.4, 5.5 and 5.6 shows the variation in the river head stage, bottom elevation of the River Ganga, and recharge rate values with different time duration starting from January 2006 to December 2013, respectively.



	Time (d)	Head-Stage (m)
1	0.0	68.52
2	91.0	69.1
3	182.0	68.0
4	273.0	67.9
5	364.0	67.24
6	455.0	68.2
7	546.0	69.0
8	637.0	68.64
9	728.0	68.01
10	819.0	68.6
11	910.0	68.24
12	1001.0	68.45
13	1092.0	68.0
14	1183.0	68.2
15	1274.0	68.6
16	1365.0	68.0
17	1456.0	68.07
18	1547.0	68.43
19	1638.0	69.0
20	1729.0	68.0
21	1820.0	67.95
22	1911.0	68.24
23	2002.0	69.372
24	2093.0	68.29
25	2184.0	68.0
26	2275.0	68.17
27	2366.0	68.79
28	2457.0	67.85
29	2548.0	68.5

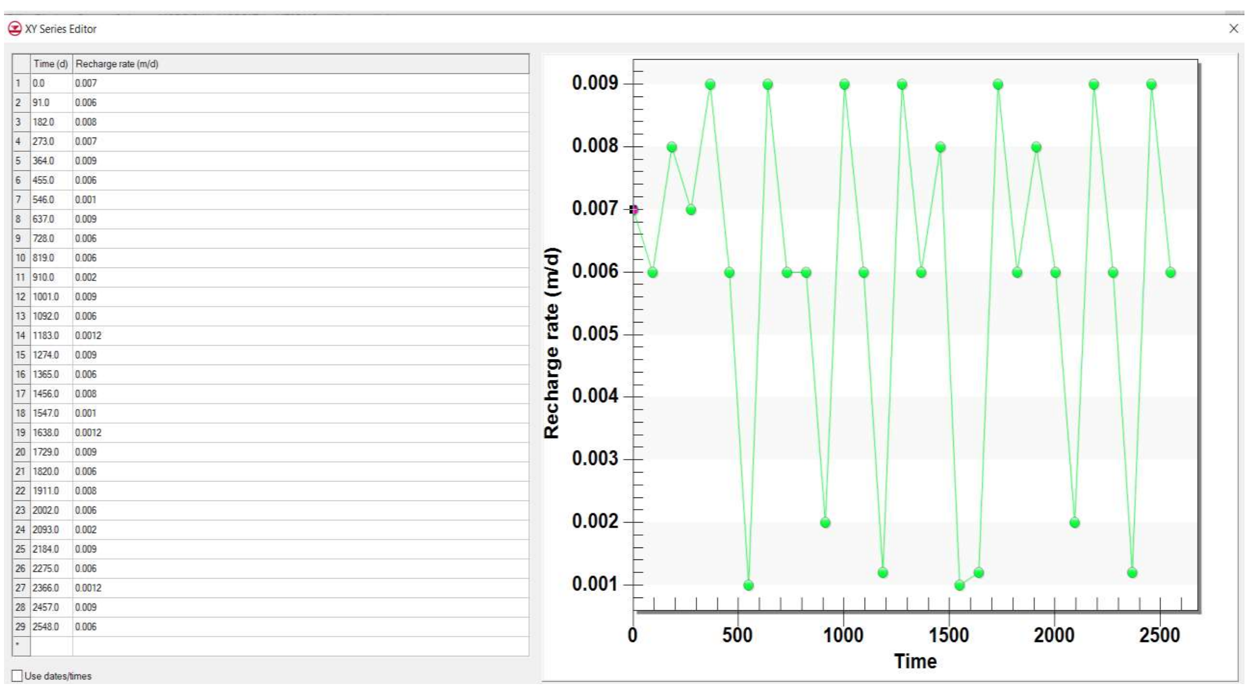
Figure 5.4 Values of River Head stage (m) in transient condition

From Figure 5.4, it is observed that the starting head stage for the Ganga River is 68.52 m, and bottom elevation is 56.74 m. This indicates that at this point, the depth of River Ganga is 11.78 m. Similarly, head stage value and bottom elevation values were recorded for Gomati River, Varuna River, and Basuhi River. All this data was collected by the field surveying. For this, cross-sections of the rivers were collected. In taking cross-sections, River depth was measured with the help of Eco-Sounder equipment and elevation data were measured using DGPS. 25 cross-sections were taken in the 148.67 km length of the Ganga River. In Gomati River (length 94.768 km), 15 cross-sections were taken, and ten cross-sections were taken in the 47.698 km length of the Basuhi River.



	Time (d)	Bot. elev. (m)
1	0.0	56.74
2	91.0	57.44
3	182.0	57.552
4	273.0	57.85
5	364.0	55.8
6	455.0	57.01
7	546.0	58.96
8	637.0	57.84
9	728.0	56.96
10	819.0	56.67
11	910.0	57.958
12	1001.0	57.24
13	1092.0	57.2
14	1183.0	57.42
15	1274.0	57.24
16	1365.0	57.8
17	1456.0	57.7
18	1547.0	57.68
19	1638.0	58.96
20	1729.0	55.14
21	1820.0	56.7
22	1911.0	56.214
23	2002.0	57.04
24	2093.0	55.72
25	2184.0	56.02
26	2275.0	56.4
27	2366.0	57.81
28	2457.0	56.56
29	2548.0	56.7
*		

Figure 5.5 Values of River Bottom Elevation (m) in transient condition



	Time (d)	Recharge rate (m/d)
1	0.0	0.007
2	91.0	0.006
3	182.0	0.008
4	273.0	0.007
5	364.0	0.009
6	455.0	0.006
7	546.0	0.001
8	637.0	0.009
9	728.0	0.006
10	819.0	0.006
11	910.0	0.002
12	1001.0	0.009
13	1092.0	0.006
14	1183.0	0.0012
15	1274.0	0.009
16	1365.0	0.006
17	1456.0	0.008
18	1547.0	0.001
19	1638.0	0.0012
20	1729.0	0.009
21	1820.0	0.006
22	1911.0	0.008
23	2002.0	0.006
24	2093.0	0.002
25	2184.0	0.009
26	2275.0	0.006
27	2366.0	0.0012
28	2457.0	0.009
29	2548.0	0.006
*		

Figure 5.6 Recharge rate value (m/d) in transient condition

For the development of conceptual model, different layers (as shown in Figure 5.7) were developed in vector data format. The different layer includes data of boundary conditions, elevation of the top and bottom layers, recharge rate, hydraulic conductivity, total water draft through pumping well, agriculture pattern, river characteristics, canal layout, surface water bodies etc. Data for the preparation of these files have been gathered by conducting the field surveys. Data collection had been an exciting task. It has to be very careful, sometimes had to jump in the river too. Pictures from the time of the data collection are shown in Appendix C. Compilation of the collected data requires a lot of care and sophisticated data management.

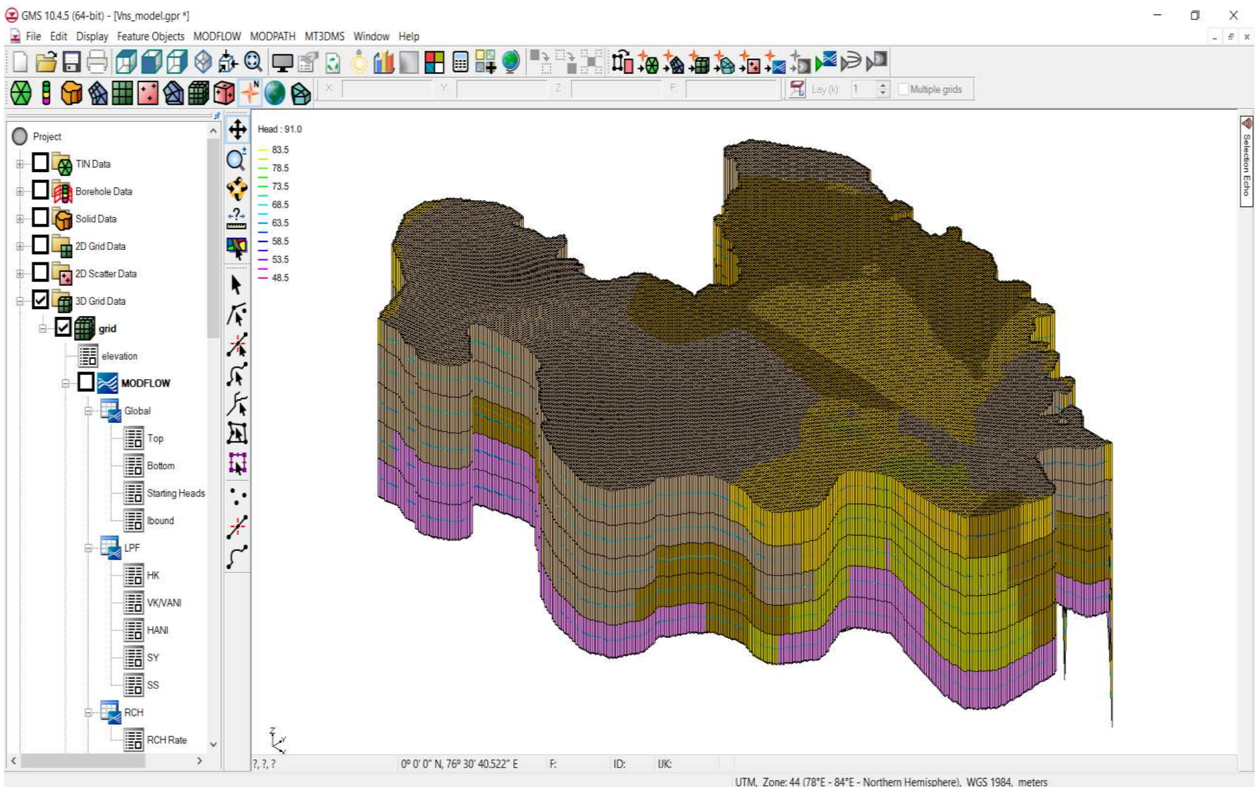


Figure 5.7 Model discretization with five layers of the model

For managing the draft through wells, data of water consumption for population, irrigation and livestock have been collected intensively by carrying out the field survey. The Landuse classification of satellite imageries was also been done to calculate total agricultural area and other areas, which are discussed in the subsequent heading.

5.3 Borehole Module

Three-dimensional cross-sections of the groundwater aquifer has been developed using the borehole data, collected from the field survey, as discussed in Chapter 3, under aquifer geometry heading. The collected borehole data had too much category of the soil types. This would have greatly complicated the aquifer geometry, and would have led to a complex groundwater flow model. To reduce this problem, soils with similar characteristics were intermingled with each other to reduce the number of soil types. After normalization of soil layers, borehole data were recorded in the borehole editor in GMS as shown in Figure 5.8. Thus, data for all boreholes were recorded in the borehole editor, and a network of borehole data was framed for the study area as shown in Figure 5.9. On checking the boreholes in three dimensions (3-D view) it looks like as shown in Figure 5.10. As already discussed, the top surface of the groundwater aquifer is surface clay, and the last layer (bottom) is hard kanker (rock strata). The characteristics of each soil type were recorded in the material editor.

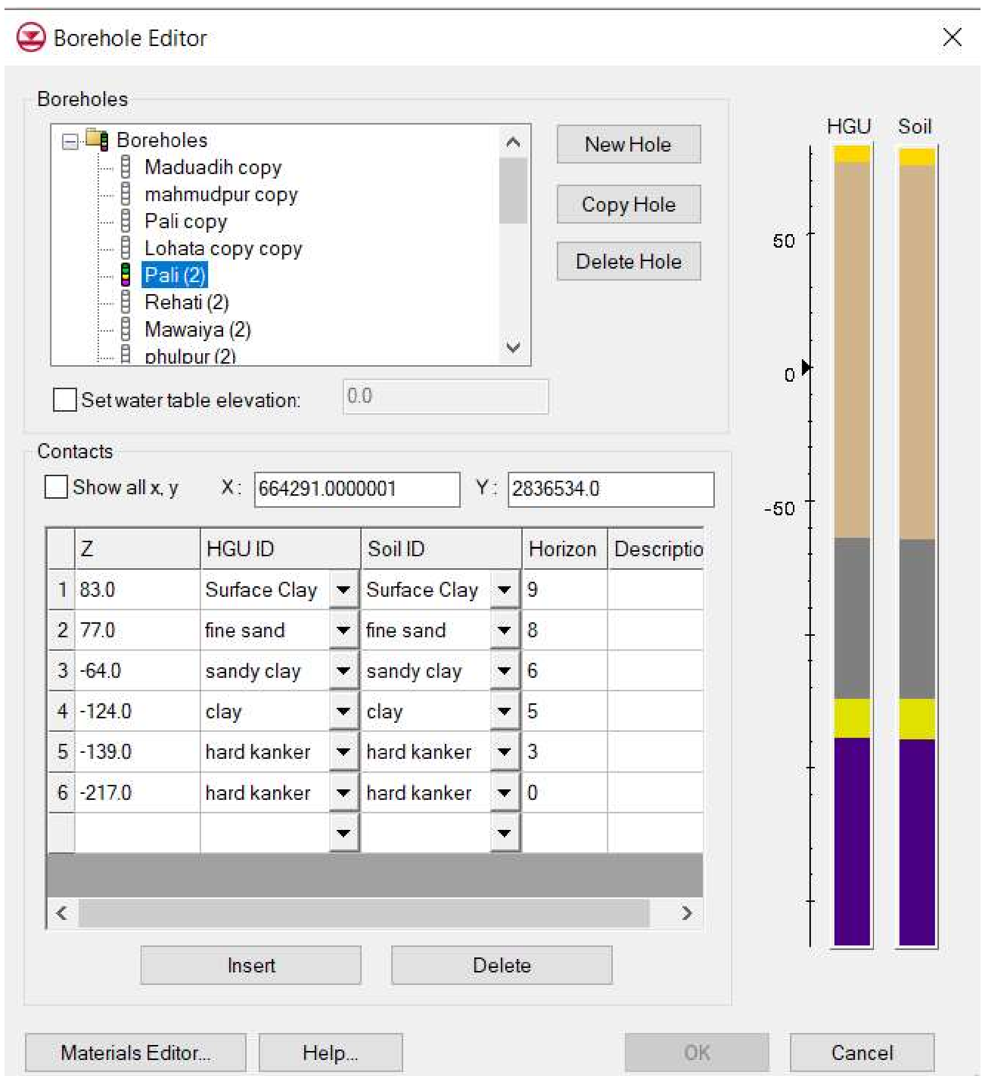


Figure 5.8 Borehole data entry into the Borehole editor of GMS

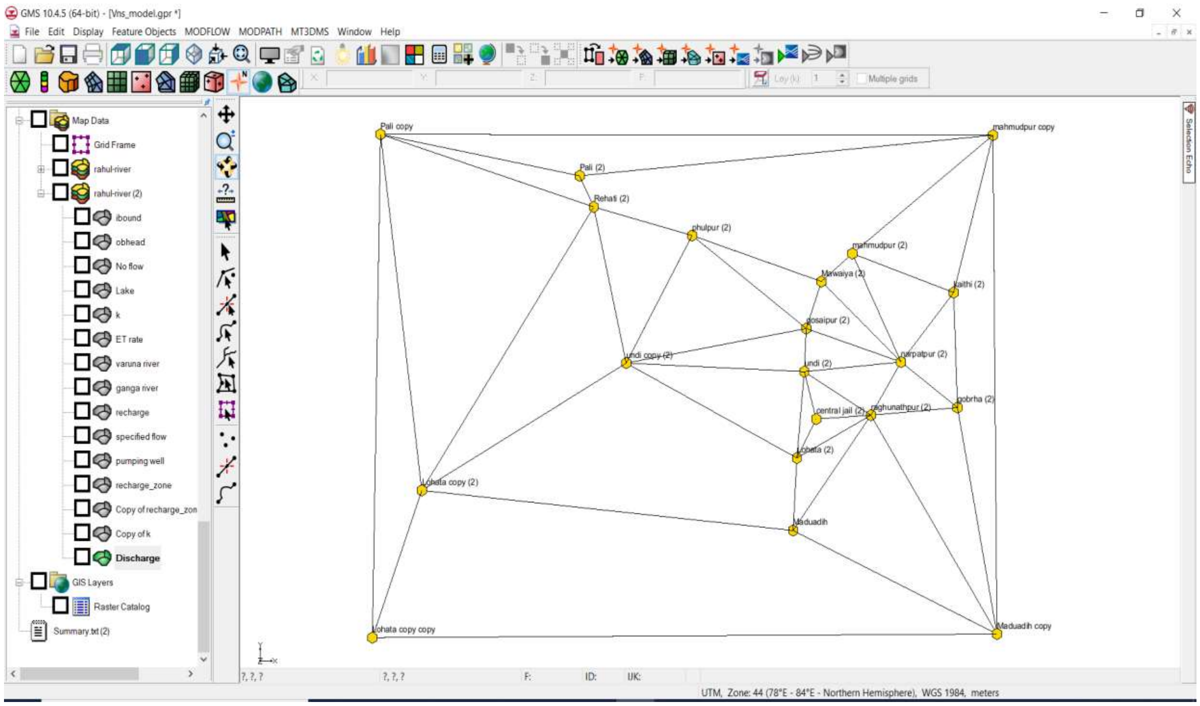


Figure 5.9 Network of borehole data in the study area.

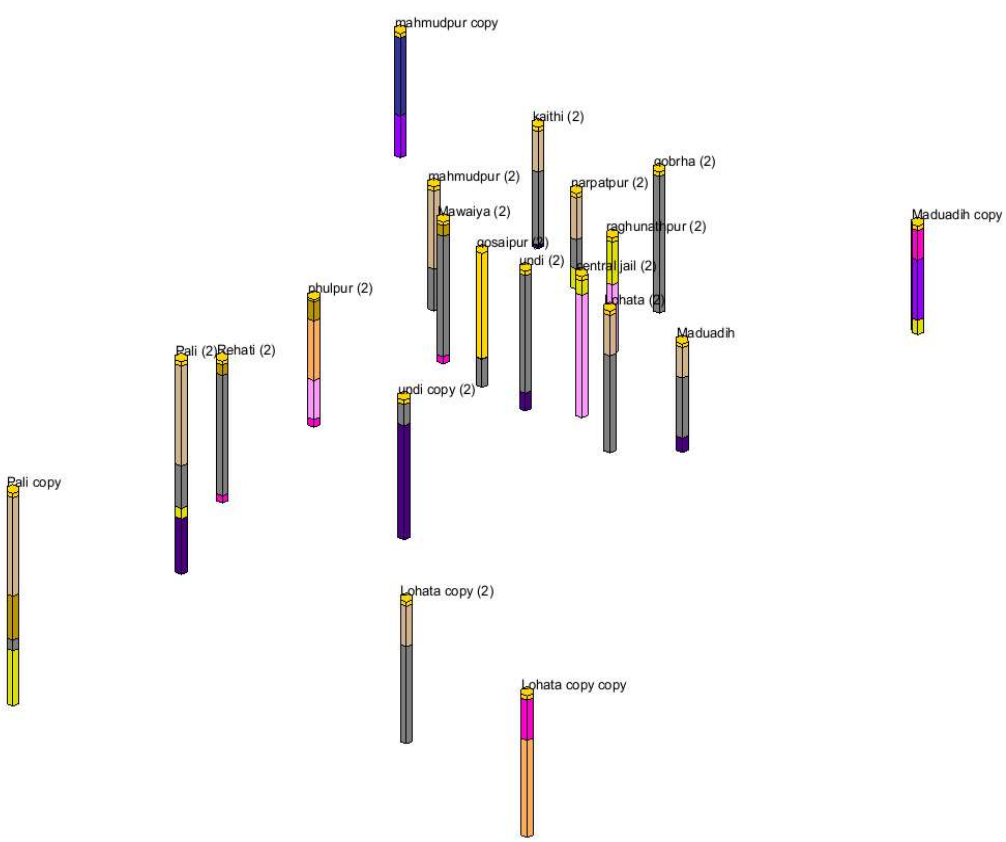


Figure 5.10 Borehole data representation in the GMS

After preparing the borehole network and providing the aquifer characteristics to the Borehole Editor, solid structure of the groundwater aquifer has been developed for the study area. This solid data has maximum depth up to 222 m and interpolation of this solid data has been done into five layered model as shown in Figure 5.11.

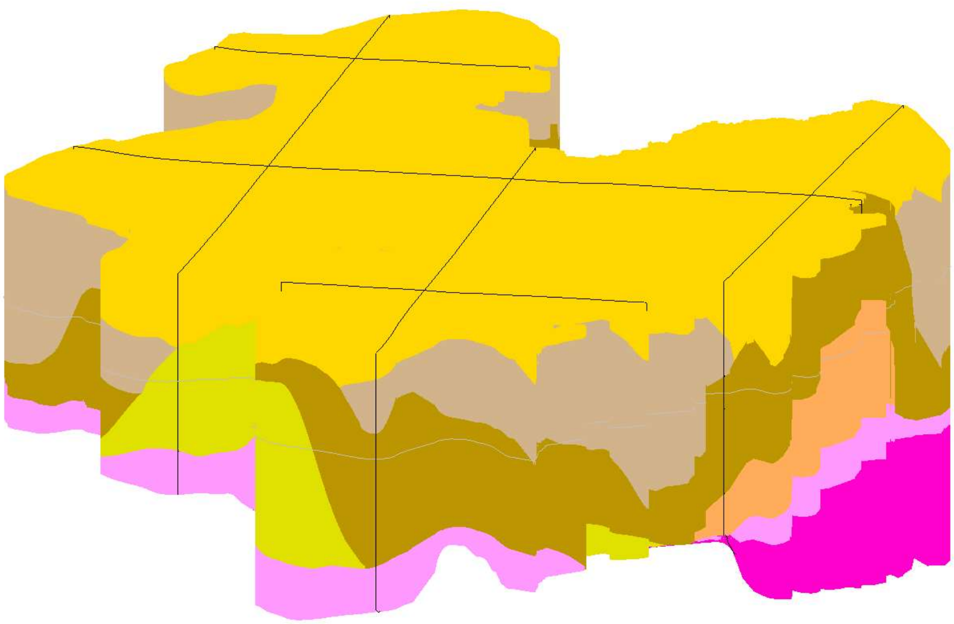


Figure 5.11 Interpolation of Solid data into the Model

5.4 Boundary Conditions

The boundary condition of the aquifer was considered as time invariant. In the study, two types of boundary conditions have been considered as river boundary and Specified flux boundary. Detailed discussion about the boundary conditions is discussed here.

5.4.1 River Boundary

Study area has a vast network of rivers. It is surrounded by River Gomati in North, River Ganga in the South and East, Varuna and Basuhi River in the West. Varuna River divides the study area in almost two equal parts as shown in Figure 5.12. Intensive river survey was carried out on the River Ganga, Varuna, Basuhi, and Gomati to measure the head stages and cross-section of the Rivers. The survey was conducted at different locations for the year

2015, 2016 and 2017. In the cross-section measurement, echo-sounder and DGPS (Differential Global Positioning System) instrument was used. Echo-sounder gives the bottom elevation of the River bed. The Echo-sounder device works on the sonar technique and is used to determine the depth of water by transmitting acoustic waves into the water. The time interval between pulse emission and return is recorded, which is then used to determine the speed of sound in the water as well as the depth of the water.

For the year of 2006 and onwards, data were collected from the Central Water Commission (CWC), Varanasi. The data were used as input in the model as River boundary. River bed conductance values ranging from 30 to 150 m^2/d were adopted for the different Rivers (Maheswaran et al. 2016).

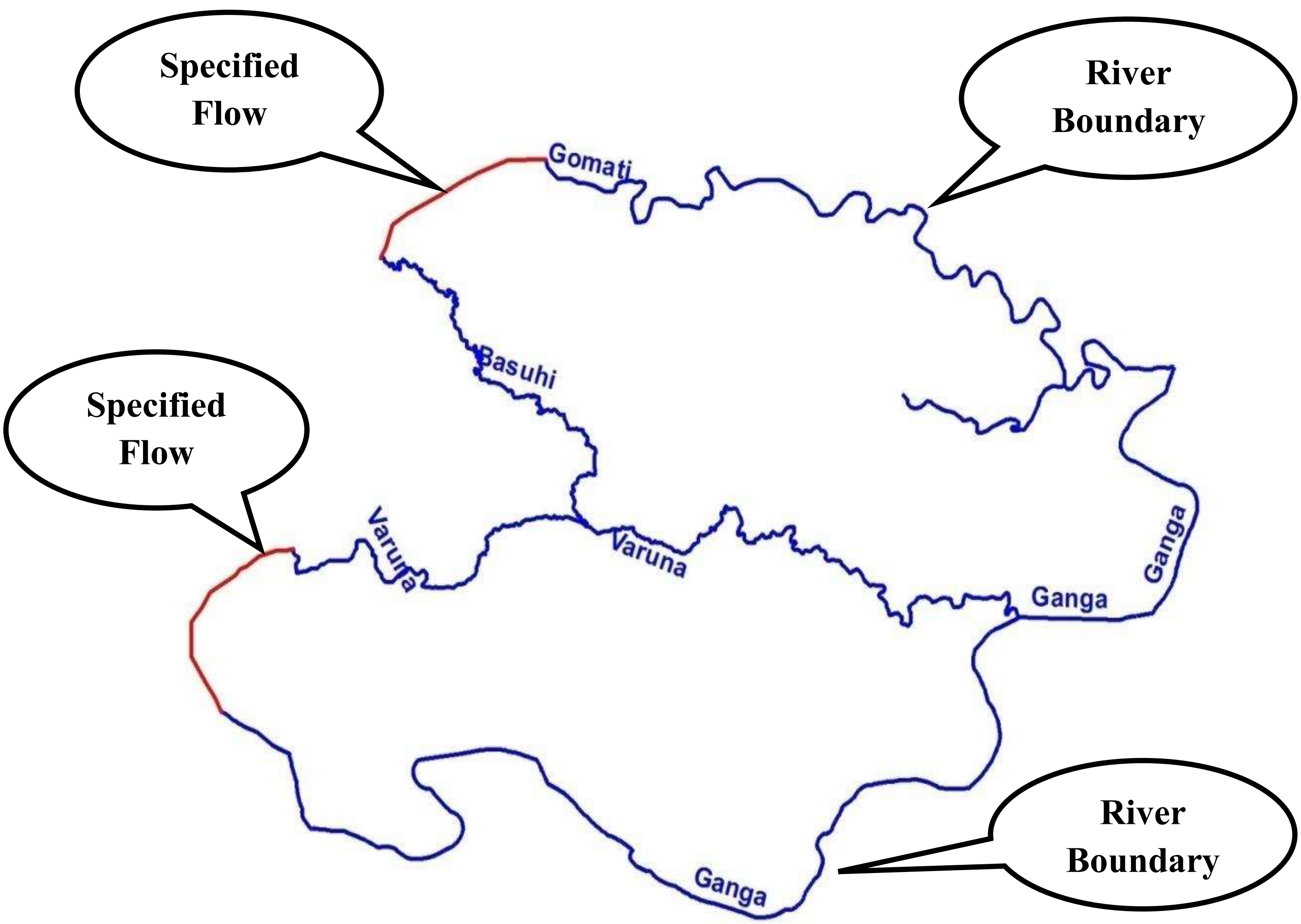


Figure 5.12 Model Boundary conditions in the study area

The starting head at the inlet of the model boundary was taken as 66.279 m, whereas at the downstream end, constant head was taken as 60.78 m. Starting constant head at the Gomati River entering the study area was taken as 68.23 m, and at the downstream end, constant head was taken as 60.78 m. Starting constant head at the Varuna River and Basuhi River were taken as 73.17 m and 69.83 m, respectively. All input data were prepared in the ArcGIS and provided in the model as a vector layer.

5.4.2 Specified flux Boundary

Two boundaries of the study area were taken as specified flux boundaries where one boundary is situated between Gomati River and Basuhi River and another boundary is situated between Varuna River and Ganga River. The length of specified flux boundaries is 16.72 km and 18.56 km, respectively. The specified flux from the contributing regions was estimated through groundwater contour data. The specific flow entering the study area, from Basuhi River, was taken as 5.0×10^{-6} m^3/day and the specific flow, from Varuna River, entering the study area was taken as 3.8×10^{-6} m^3/day. The specified flux from the contributing regions were estimated from the SWAT model as groundwater recharge (Maheswaran et al., 2016).

5.5 Top and bottom layers

The topography of the study area is largely even with the low relief and less undulation. Realistic representation of the top and bottom surfaces in the model is a difficult task, and the accuracy of the model result depends on these surfaces. The top surface of the model was determined by DEM of the study area. In this study, Shuttle Radar Topography Mission (SRTM) DEM was used, which was taken from the USGS site (https://earthexplorer.usgs.gov). Scatter points were prepared by converting from a DEM to an ASCII file. Scatter points helps in the preparation of the top layer of the groundwater aquifer. Surface elevation for each grid was computed and recorded it into the top surface in

GMS 10.2. Figure 5.13 shows the values of top surface elevation recorded in the GMS. These values were provided for the active grid cells of the model, while inactive grid cells (that are outside the study area) were kept blank. The bottom layer was defined with the help of well log data collected from Uttar Pradesh Jal Nigam, as discussed in Chapter 3. Evenly distributed data over the entire area were taken and interpolated to generate the bottom surface. Similar to the top surface, the bottom surface elevation was computed for each grid cell and recorded in the bottom elevation editor of GMS, as shown in Figure 5.14. After giving the top elevation and bottom elevation of the groundwater aquifer, the elevation of the second, third, and fourth layers was computed by the GMS itself. From the multi-layer geometry, it can be said that the bottom elevation of the first layer is the top elevation of the second layer; similarly, the bottom elevation of the second layer is the top elevation of the third layer. Thus, top and bottom elevation data for all the five layers was recorded in the GMS.

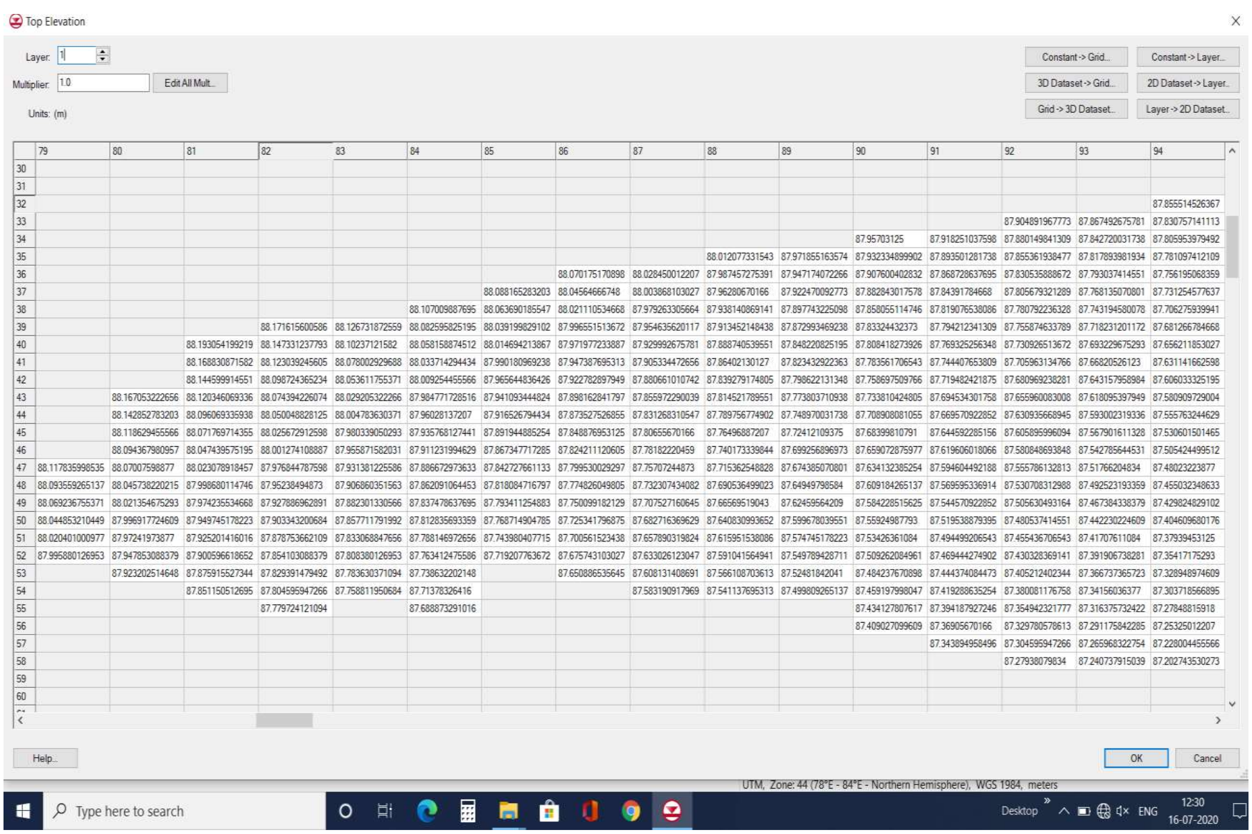


Figure 5.13 Elevation values for the top surface of model

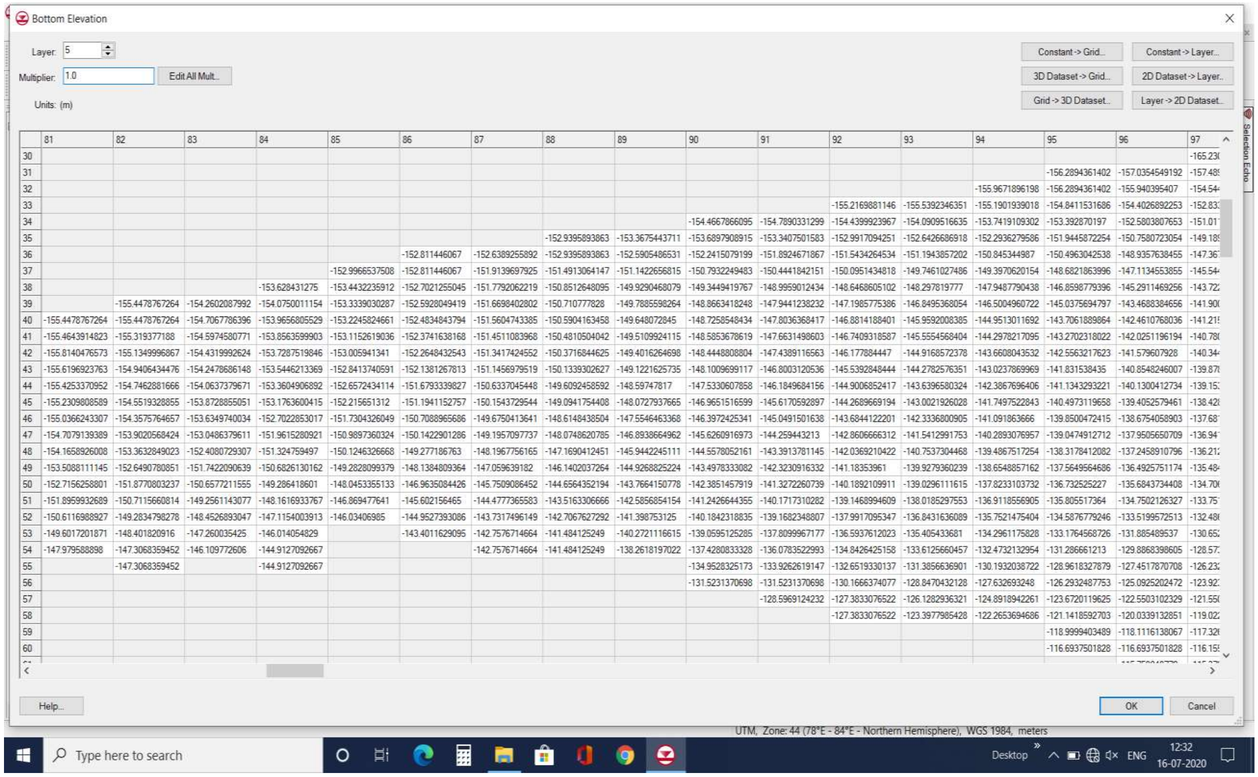


Figure 5.14 Elevation values for the bottom surface of the model

5.6 Depth of Groundwater Level

The groundwater level in the study area is obtained from site India-WRIS (Water Resource Information System of India) portal (http://www.india-wris.nrsc.gov.in). From India-WRIS, the groundwater level is obtained at different location within the study area. In pre-monsoon seasons i.e., June 2015 and June 2016 the depth to water level ranges from 2.5-15 meter and 1.8-13.48 meter below ground level, respectively. The deeper water level viz. 11.03, 13.48, and 15.0 meters were recorded at Pali, Rustampur, and Thatra, block respectively. Similarly, in monsoon season i.e., June 2015 and June 2016 range of water level depth is 2.23-19 meter and 2.34-20.1 meter, respectively. In post-monsoon season i.e., November 2015 to November 2016 depth of water level is in range of 2.36 - 18.2 meter and 2.78 - 19.45 meter respectively.

5.7 Well Discharge

Water demand for agriculture was calculated by the classification of satellite images and then calculating the area covered by agricultural field. Further classification for each type of crop was done and corresponding area was calculated for the each crop. The imageries were classified in five groups, i.e., *Vegetation*, *Urban/Built-Up land*, *Water*, *Sand/waste Land*, *Agricultural field*. Table 5.1 shows the block wise LU & LC details for the whole study area. Intensive field survey was done throughout the study area to know the agriculture pattern from the natives and field truthing of the satellite imageries. Out of all the 10 administrative division of the study area, Arajiline have the maximum agricultural area (57.55%), and minimum built-up land (17.22%). Kashi Vidya Peeth (KVP) division contains maximum area of water bodies (4.05%).

Table 5.1 Details of LULC of the study area

LAND USE/ LAND COVER							
BLOCK		**Agriculture**	**Water**	**Vegetation**	**Urban/ built- area**	**Soil/waste Land**	**Total**
Pindra	Area (km^2)	110.058	1.4463	8.952	50.2704	32.9607	**203.68**
	Area (%)	54.0327	0.7100	4.3951	24.6801	16.18195	
Sevapuri	Area (km^2)	85.5342	1.3788	14.397	30.8997	29.9304	**162.14**
	Area (%)	52.7531	0.8503	8.8795	19.0573	18.45956	
Kashi Vidya Peeth	Area (km^2)	67.4955	5.3226	3.7845	29.5002	25.4052	**131.50**
	Area (%)	51.3242	4.0473	2.8777	22.4322	19.31837	
Baragaon	Area (km^2)	78.921	1.5111	9.2034	36.6831	29.1861	**155.50**
	Area (%)	50.7515	0.9717	5.9184	23.5897	18.76863	
Cholapur	Area (km^2)	54.0612	3.8394	14.110	58.8663	28.6938	**159.57**

	Area (%)	33.879	2.4060	8.8425	36.8903	17.98185	
Chiraigaon	Area (km^2)	96.660	7.8597	13.928	45.9054	39.2193	**203.57**
	Area (%)	47.482	3.8608	6.8419	22.5497	19.26541	
Arajiline	Area (km^2)	137.837	5.9976	9.0585	41.2425	45.3573	**239.49**
	Area (%)	57.5538	2.5042	3.7823	17.2207	18.93884	
Harahua	Area (km^2)	103.164	7.8885	5.1948	55.1079	44.6067	**215.96**
	Area (%)	47.7696	3.6527	2.4054	25.5173	20.65486	
St Ravi DasNagar	Area (km^2)	320.558	22.578	140.96	196.410	47.7882	**728.29**
	Area (%)	44.0148	3.1001	19.354	26.9685	6.561643	
Jaunpur	Area (km^2)	206.323	3.7701	139.83	105.447	17.9127	**473.29**
	Area (%)	43.5933	0.7965	29.545	22.2796	3.784718	

Based on the type of crops that were harvested in the area, the water requirement for each crop was calculated for per meter square area. As the area irrigated by the particular crop is known, water requirement for the entire area for that crop can be calculated. In this fashion, water requirement for agriculture for the entire study area was calculated.

There are 'n' numbers of crops that are harvested in the study area. Where "w" denotes water requirement of each crop planted in per m^2 and the different crop is planted in an area of "A". Therefore, the total water required for agriculture in the study area was calculated as:

$$\boldsymbol{w_A = \sum_{i=1}^{n} w_i A_i} \quad (5.1)$$

Where 'i' is the no. of crops planted in the study area, 'W_A' is the total water required by agriculture. After calculating the total agricultural area, individual area for each type of crops was calculated. This exercise was done by field survey and discussion with the farmers of different villages to understand yearly cropping pattern in the area. The major crops in the area were found as rice, wheat, and pulses, vegetables. Then the agricultural area of a particular type of crop was multiplied by per m^2 water requirement of that crop, according to the season, to estimate the total water requirement. In the study area, three types of crops were found, as *Rice*, *Wheat*, and *Pulses*. The duty of Rice, Wheat, and Pulses were taken 1250 mm, 550 mm and 350 mm, respectively (Garg, 2016). The duty of individual crops was multiplied by the total area of that crop, and this provides the total water demand for that area, as shown in Table 5.2. Thus, the total water required for agriculture was found to be 225.86 Mm^3 (million cubic meters) per month.

Table 5.2 Agricultural Groundwater demands in the study area

BLOCK	Area (km^2)	Water Demand by RICE (m^3)	Water Demand by WHEAT (m^3)	Water Demand by PULSES (m^3)	Total groundwater Demand used in irrigation (m^3)
Pindra	110.06	1320,69,960	605,32,065	385,20,405	**2366,25,345**
Sevapuri	85.53	1026,41,040	470,43,810	299,36,970	**1838,98,530**
KVP	67.50	809,94,600	371,22,525	236,23,425	**1451,15,325**
Baragaon	78.92	947,05,200	434,06,550	276,22,350	**1696,80,150**
Cholapur	54.06	648,73,440	297,33,660	189,21,420	**1162,31,580**
Chiraigaon	96.66	1159,93,080	531,63,495	338,31,315	**2078,20,935**
Arajiline	137.84	1654,05,240	758,10,735	482,43,195	**2963,51,055**
Harahua	103.16	1237,97,160	567,40,365	361,07,505	**2218,03,245**
St Ravi das	244.60	2935,24,949	1345,32,268	856,11,443	**6892,00,560**
Jaunpur	206.32	2475,87,840	1134,77,760	722,13,120	**4435,94,880**

The water requirement for domestic demand was calculated by multiplying the per capita demand by the population of the area. The total population of the study area was taken from the Census of India, as shown in Table 5.3. The water demand for the rural and urban areas was calculated separately. Per capita demand for the rural and urban population was taken as 135 liters/person and 170 liters/person, respectively (Modi, 1998). In this way, water demand of the study area was calculated as:

$$W_D = 135*P_r \textbf{ or } W_D = 170*P_u \quad 5.2$$

Where,

'W_D' is the total water demand in the study area,

'P_r' is the total population in the rural area, and

'P_u' is the total population in the urban area.

Thus, total water required for the domestic demand was found to be 15.13 Mm^3 per month. Table 5.3 shows the distribution of water demand in each administrative block.

Table 5.3 Total Population and Groundwater demand in the study area

Block	Rural Population	Urban Population	Water Demand Rural (Litre/Day)	Water Demand Urban (Litre/Day)	Total Water Demand (Litre/Day)	Total Water Demand (Cum)	Total Monthly Population Demand By Gw (M^3)
Pindra	393264		53090640	0	53090640	**1592719**	**1274175**
Sevapuri	323209		43633215	0	43633215	**1308996**	**1047197**
Kvp	398349	327380	53777115	55654600	109431715	**3282951**	**2626361**
Baragaon	280188	28383	37825380	4825110	42650490	**1279514**	**1023611**
Cholapur	296422		40016970	0	40016970	**1200509**	**960407.2**

Chiraigaon	337670	80328	45585450	13655760	59241210	**1777236**	**1421789**
Arajiline	399700	48359	53959500	8221030	62180530	**1865415**	**1492332**
Harahua	333669		45045315	0	45045315	**1351359**	**1081087**
St RaviDas	1087620	23878	146828700	4059260	150887960	**4526638**	**3621311**
Jaunpur	627890	11012	84765150	1872040	86637190	**2599115**	**2079292**

Groundwater was the main source of the livestock withdrawals (Dieter et al. 2018). That's why groundwater demand for livestock was explored. Different livestock consume different amount of water for fulfilling their thrust. Considering their average water demand, total water demand for livestock at blocks level was calculated. The average drinking water demand of cow, buffalo, goat, pig, sheep and poultry were taken as 30, 35, 3, 3.5, and 1 liters/day respectively (http://upenvis.nic.in). The total population of livestock was derived for each block from the ENVIS Centre of Uttar Pradesh, as shown in Table 5.4.

Table 5.4 Livestock Population in the study area

BLOCK	Cow Population	Buffalo Population	Goat Population	Pig Population	Sheep Population	Poultry Population
Pindra	35109	21349	18764	1855	3067	64581
Sevapuri	14224	15475	8275	294	945	27926
KVP	11799	8845	10261	307	222	61621
Baragaon	20350	12169	9283	972	2398	41941
Cholapur	18572	22937	12773	1164	1539	22170

Chiraigaon	17990	22315	10748	1153	1874	21363
Arajiline	32068	21224	13623	246	4859	68299
Harahua	17319	13198	11999	570	968	27735
St Ravi Das	34768	64578	44123	6977	18096	70652
Jaunpur	40657	34499	47452	8982	12555	49593

After obtaining, the livestock population, for each block of the study area, the average drinking water demand of each livestock was multiplied, and the water demand of livestock was obtained. The Table 5.5 shows groundwater demand for the livestock. Total water demand for livestock was calculated as 0.253 Mm^3 per month.

Table 5.5 Livestock Groundwater demand in study area

BLOCK	Cow Water Demand (l/d)	Buffalo Water Demand (l/d)	Goat Water Demand (l/d)	Pig Water Demand (l/d)	Sheep Water Demand (l/d)	Poultry Water Demand (l/d)	Total Livestock Demand (Cu M)	Total monthly livestock demand by GW (m^3)
Pindra	1053270	747215	56292	6492.5	13801.5	64581	58249.56	**29124**
Sevapuri	426720	541625	24825	1029	4252.5	27926	30791.325	**15395**
KVP	353970	309575	30783	1074.5	999	61621	22740.675	**11370**
Baragaon	610500	425915	27849	3402	10791	41941	33611.94	**16805**
Cholapur	557160	802795	38319	4074	6925.5	22170	42943.305	**21471**
Chiraigaon	539700	781025	32244	4035.5	8433	21363	41604.015	**20802**
Arajiline	962040	742840	40869	861	21865.5	68299	55103.235	**27551**

Harahua	519570	461930	35997	1995	4356	27735	31547.49	**15773.7**
St Ravi Das	1043040	2260230	132369	24419.5	81432	70652	108364.28	**54182.1**
Jaunpur	1219710	1207465	142356	31437	56497.5	49593	81211.755	**40605.8**

Thus, the total monthly water demand for agriculture, population and livestock was calculated for the each block of the study area. Combination of these demands is comprised of the total monthly water demand for the study area, as mentioned in Table 5.6. The total monthly water demand for St. Ravi Das block was found maximum (1,76,777,029 m^3), whereas the minimum was found for Cholapur block (272,88,059 m^3). The total water demand was used to distribute the water demand in the pumping wells of the study area.

Specific yield of the aquifer in the study area was found between the range of 20 liter per second (1,728 m^3/day) to 25 liter per second (2,160 m^3/day). Based on the specific yield of the aquifer, the maximum well capacity per day was calculated for the study area. For this, the total monthly water demand (as shown in Table 5.6) was divided by 30 and converted into daily water demand, as shown in Table 5.7.

Table 5.6 Total monthly water Demand for the study area

BLOCK	**Total Water Demand by Agriculture**	**Total population water demand**	**Total livestock water demand**	**Total Water demand for the area**
	1	2	3	1+2+3
Pindra	584,54,164	12,74,175	29,125	597,57,464
Sevapuri	468,40,239	10,47,197	15,396	479,02,831
Kvp	395,13,216	26,26,361	11,370	421,50,947
Baragaon	416,70,288	10,23,612	16,806	427,10,706

Cholapur	263,06,180	9,60,407	21,472	272,88,059
Chiraigaon	542,90,561	14,21,789	20,802	557,33,152
Arajiline	798,16,299	14,92,333	27,552	813,36,183
Harahua	558,63,468	10,81,088	15,774	569,60,330
St. Ravi Das	1,73,101,536	36,21,311	54,182	1,76,777,029
Jaunpur	99,035,136	20,79,292	40,606	1,01,155,034

This daily water demand was used in calculating the maximum number of wells for the study area. To get the number of pumping wells in the study area, the total daily water demand was divided by per day well capacity. For the calculation of the maximum number of wells, the minimum well yield was considered, i.e., 1,728 m^3/day (20 lps). Table 5.7 shows the total number of wells required for each block of the study area to meet their water demand by the groundwater.

Table 5.7 Total Number of pumping wells required for the study area.

BLOCK	**Total daily water Demand (m^3)**	**Well Yield (m^3/day)**	**Max. No of Wells**
Pindra	19,91,915.48	1728	1,153
Sevapuri	15,96,761.05	1728	924
Kvp	14,05,031.57	1728	813
Baragaon	14,23,690.19	1728	824
Cholapur	9,09,601.96	1728	526
Chiraigaon	18,57,771.74	1728	1,075

Arajiline	27,11,206.10	1728	1,569
Harahua	18,98,677.66	1728	1,099
St Ravi Das	58,92,567.63	1728	3,410
Jaunpur	33,71,834.46	1728	1,951

5.8 Observation wells

The groundwater level at different locations in the study area was taken from India-WRIS website (www.india-wris.nrsc.gov.in) and Central Ground Water Board (CGWB), Varanasi. Usually, observation wells are used to monitor and measure the groundwater level. The groundwater table data was taken for four different seasons of the year namely: pre-monsoon rabi, pre-monsoon, monsoon, post-monsoon kharif. Duration of four periods of the year has been presented in Table 5.8. Observed groundwater head data has been collected for the model validation, in which observed head will be compared with the simulated (computed) water head. Fourteen wells have been chosen as observation wells, which were uniformly distributed over the study area as shown in Figure 5.15. For each observation well, the groundwater level changes were measured monthly. Observed groundwater head data was categorized at 180 days interval. This data was also recorded in transient state condition.

Table 5.8 Duration of four periods

S No	Period Name	Duration
01.	Pre-monsoon ravi (POMR)	January-March
02.	Pre monsoon (PRM)	April-June
03.	Monsoon (MO)	July-September
04.	Post monsoon kharif (POMK)	October-December

Figure 5.15 Location of observation wells in the study area.

Observed head data of four observation wells situated at Jakkhini, Varanasi, Kakrahwan, and Babatpur, have been presented in Table 5.9, 5.10, 5.11 and 5.12, respectively.

Table 5.9 Observed water head elevation in Jakkhini Observation Well

JAKKHINI								
YEAR	POMR		PRM		MO		POMK	
	S	**RL**	S	**RL**	S	**RL**	S	**RL**
2006	12.28	**72.72**	11.65	**73.35**	9.2	**75.8**	11	**74**
2007	9.75	**75.25**	11	**74**	10.28	**74.72**	9.82	**75.18**
2008	9.6	**75.4**	8.45	**76.55**	6.05	**78.95**	7.28	**77.72**
2009	8.19	**76.81**	9	**76**	11.3	**73.7**	10.9	**74.1**
2010	11.6	**73.4**	0	**85**	13.45	**71.55**	12.23	**72.77**

2011	12.2	**72.8**	13.95	**71.05**	11.88	**73.12**	8.87	**76.13**
2012	9.3	**75.7**	11.75	**73.25**	0	**85**	0	**85**
2013	8.28	**76.72**	11.3	**73.7**	11.6	**73.4**	10.6	**74.4**
2014	10.6	**74.4**	12.34	**72.66**	11.9	**73.1**	0	**85**
2015	0	**85**	10.48	**74.52**	10.48	**74.52**	10.21	**74.79**
2016	0	**85**	12.8	**72.2**	0	**85**	0	**85**

'S' is the drawdown. It signifies the depth of groundwater table from the ground surface level. In the Table, the drawdown is mentioned '0' at some places. The reason for this is non-availability of the data from CGWB.

'RL' is the reduce level of the groundwater table. It signifies the elevation of the groundwater table from mean sea level (msl). RL was computed by subtracting the drawdown from the RL of the ground surface at that point, for which drawdown is provided.

Table 5.10 Observed water head elevation in Varanasi Observation Well

VARANASI								
YEAR	POMR		PRM		MO		POMK	
	S	**RL**	S	**RL**	S	**RL**	S	**RL**
2006	12.6	**67.4**	11.6	**68.4**	10.4	**69.6**	10.9	**69.1**
2007	11.88	**68.12**	12.17	**67.83**	9.4	**70.6**	9.8	**70.2**
2008	11.35	**68.65**	10.86	**69.14**	5.3	**74.7**	8.4	**71.6**
2009	8.96	**71.04**	9.4	**70.6**	10	**70**	9.9	**70.1**
2010	11.2	**68.8**	12.26	**67.74**	10.3	**69.7**	8.35	**71.65**
2011	10.43	**69.57**	12.85	**67.15**	11.36	**68.64**	10.13	**69.87**

2012	11.43	**68.57**	13.72	**66.28**	0	**80**	0	**80**
2013	11.75	**68.25**	11.9	**68.1**	8.6	**71.4**	8.5	**71.5**
2014	9.25	**70.75**	10.6	**69.4**	10.2	**69.8**	0	**80**
2015	0	**80**	9.4	**70.6**	9.4	**70.6**	12.2	**67.8**
2016	0	**80**	12.8	**67.2**	0	**80**	0	**80**

Table 5.11 Observed water head elevation in Kakrahwan Observation Well

KAKRAHWAN								
Year	POMR		PRM		MO		POMK	
	S	**RL**	S	**RL**	S	**RL**	S	**RL**
2006	17.09	**64.91**	16.7	**65.3**	14.59	**67.41**	15.51	**66.49**
2007	17.57	**64.43**	18.25	**63.75**	8.87	**73.13**	17.59	**64.41**
2008	17.19	**64.81**	20.09	**61.91**	14.35	**67.65**	14.2	**67.8**
2009	14.97	**67.03**	17.67	**64.33**	17.49	**64.51**	17.84	**64.16**
2010	18.79	**63.21**	19.69	**62.31**	19.24	**62.76**	19.03	**62.97**
2011	19.22	**62.78**	0	**82**	17.67	**64.33**	16.29	**65.71**
2012	17.11	**64.89**	20.05	**61.95**	0	**82**	0	**82**
2013	16.68	**65.32**	20.34	**61.66**	17.65	**64.35**	0	**82**
2014	8.09	**73.91**	18.39	**63.61**	15.44	**66.56**	0	**82**
2015	0	**82**	15.99	**66.01**	15.99	**66.01**	18.21	**63.79**
2016	0	**82**	17.59	**64.41**	0	**82**	0	**82**

Table 5.12 Observed water head elevation in Babatpur Observation Well

BABATPUR								
YEAR	POMR		PRM		MO		POMK	
	S	**RL**	S	**RL**	S	**RL**	S	**RL**
2006	8.86	**74.14**	6.39	**76.61**	4.14	**78.86**	10.97	**72.03**
2007	11.2	**71.8**	11.08	**71.92**	7.21	**75.79**	7.16	**75.84**
2008	7.61	**75.39**	8.75	**74.25**	8.12	**74.88**	4.72	**78.28**
2009	5.11	**77.89**	8.31	**74.69**	7.1	**75.9**	8.45	**74.55**
2010	8.61	**74.39**	0	**83**	0	**83**	9.43	**73.57**
2011	0	**83**	0	**83**	0	**83**	7.42	**75.58**
2012	7.64	**75.36**	10.15	**72.85**	0	**83**	0	**83**
2013	8.22	**74.78**	10.15	**72.85**	8	**75**	7.55	**75.45**
2014	8.15	**74.85**	12.65	**70.35**	0	**83**	0	**83**
2015	0	**83**	6.77	**76.23**	6.77	**76.23**	12.8	**70.2**
2016	0	**83**	10.75	**72.25**	0	**83**	0	**83**

5.9 Model Calibration

Model calibration process is required to minimize the difference between model outputs with real field conditions up to acceptable limit. It is an important part of any groundwater modeling process. Before implementing the groundwater model in any type of role management, it must be proved that the groundwater model can successfully simulate the observed aquifer behavior. In this process, values of certain input parameters, such as hydraulic conductivity, recharge rate, are varied in a systematic way and run the model repeatedly, until the computed values corresponds the field observed values within an acceptable level of accuracy.

In this study, the model was calibrated for transient state conditions in which simulations involved the change in the head (groundwater head and river stage) with time. Initial values of hydraulic conductivities and recharge rate were introduced into the model. Further, residual error in the initial model solution was analyzed, and a new value for hydraulic conductivities and recharge rates were entered. After running the groundwater flow model, a new MODFLOW solution was generated, and again, a new error estimate was computed and plotted. This process was repeated until the error was reasonably small.

Fourteen observation wells were taken in the study area. For each observation well, the observed head data was categorized at 180 days interval, and model calibration was done at the same time interval with 90% confidence level. This confidence value represents confidence in the error estimate.

Residual error in the initial model solution (run 1) was analyzed. In run 2, a new value for hydraulic conductivity was entered by increasing this value by 10%, and recharge rate was decreased to 0.0004 m/d. After running the groundwater flow model, a new MODFLOW solution was generated, and again, a new error estimate was computed and plotted. This run reduced the difference between the observed head and simulated head. In run 3, the conductivity was further increased by 20%, and recharge rate was decreased to 0.0003 m/d. This run again reduced the root mean square error (RMSE). In run 4, the hydraulic conductivity value was increased by 15%, and recharge rate was further decreased to 0.0002 m/d. This run provided a better match as it gave very less standard error of estimate (SEE) to 0.002 m. The good calibration shows that this model is actually representing the real field conditions for the study area. The parameter values used in calibration of the model are listed in Table 5.13. In each run, RMSE, NRMSE, and SEE were calculated using the formulas discussed in heading 4.8 of Chapter 4.

Table 5.13 Parameters values used in the model calibration

Parameters	Initial (Run 1)	Iteration 1 (Run 2)	Iteration 2 (Run 3)	Iteration 3 (Run 4)
Hydraulic conductivity (m/d)	16	17.6	19.2	18.4
Recharge Rate (m/d)	0.0005	0.0004	0.0003	0.0002
RMSE (m)	2.598	1.842	0.954	0.524
NRMSE (%)	2.74	2.36	1.05	8.60
SEE (m)	3.2	2.1	1.6	0.002

A scatter plot was drawn between final values of computed head and observed head for fourteen observation wells as shown in Figure 5.16. Scatter plots show calibration targets versus simulated values and allow for a quick assessment of model fit. The scatter plots also visualize the bias in the calibration. Bias is absent when the points in the scatter plot are more or less equally distributed around the central line shown on the plot, which indicates a one-to-one correspondence between simulated and observed values. Plot shown in Figure 5.16 shows a good match between the observed head and computed groundwater heads. The observed root mean square error (RMSE) was found within the allowable limit i.e. 1 m. Scatter plot and RMSE suggested that the developed groundwater model is well-calibrated and it represents the actual groundwater aquifer conditions for the study area.

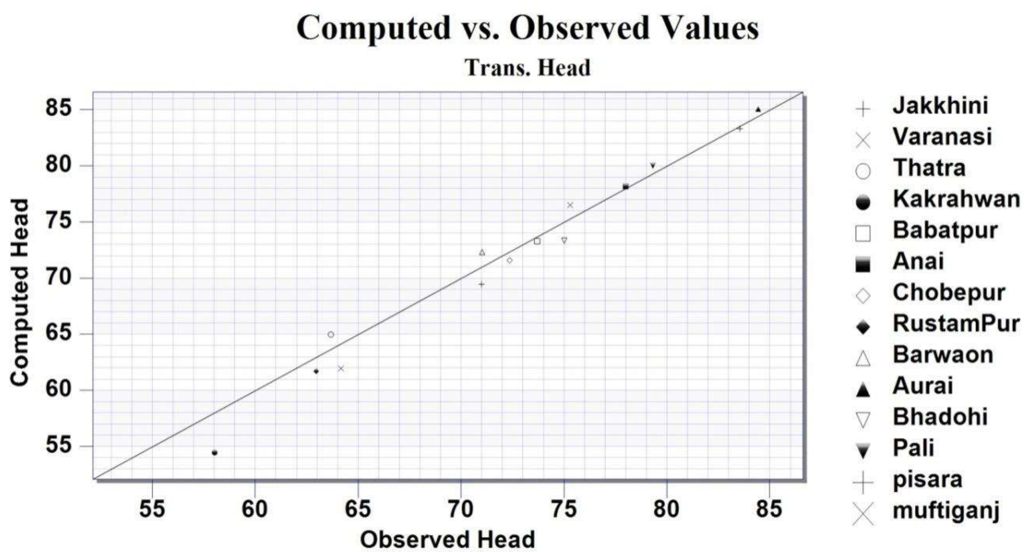


Figure 5.16 Comparison of computed and observed head for fourteen observation wells

5.10 Model sensitivity

Sensitivity analysis is important for calibration, optimization, risk assessment, and data collection. Regional groundwater models have a large number of uncertain parameters, which can affect the model accuracy. Dealing with these uncertainties is time-consuming and involves significant attempts in model calibration process. Sensitivity analysis indicates which parameter(s) has greater influence on the model output. Parameters that have a high impact on model output should get the most attention in the calibration process, and in the data collection for that parameter should give the most attention.

The sensitivity criterion is a good assessment for the uncertainty of any groundwater model. Usually, this uncertainty occurs in the aquifer parameters such hydraulic conductivity and sometimes in the boundary conditions of the model. The basic idea of applying the sensitivity analysis is to understand the impact on the groundwater aquifer system caused by variation in the model parameters and the hydro-geological stresses. This can be done through systematically changing the calibrated values, which ultimately helps to identify which parameter requires individualized attention in future studies (Anderson et al. 1992). In this work, the sensitivity approach is performed using a systemic change in the value of two input parameters of the model, i.e., recharge rate and hydraulic conductivity of the aquifer.

Figure 5.17 shows the relationship between the Standard Error of Estimate (SEE) (m) and recharge rate. The result shows that the developed model is less sensitive for the recharge rate value less than 0.0002 m/day and considerably sensitive for the recharge rate values higher than 0.0002 m/day as an overall trend. In transient state condition, values of SEE are decreased a little when the recharge rate values increase up to 0.0002 m/day. With recharge rate higher than 0.0002 m/day, the SEE values increase significantly, as shown in Figure 5.17. This shows that the model is more sensitive to recharge rate values greater than 0.0002 m/day and less sensitive to recharge rate values lower than that value. Furthermore, the values of SEE are range between 0.002 m to 3.2 m. As the error is reduced, this indicates that the values of the computed heads are more closed to the observation heads. The result signifies that extreme caution should be exercised in computing recharge rate values exceeding 0.0002 m. day.

Similarly, model sensitivity analysis has been done for another parameter of the model i.e. hydraulic conductivity of the aquifer. For this a series of model tests were performed with the variation of the values of hydraulic conductivity. A relationship between the value of hydraulic conductivity and the Standard Error of Estimate (SEE) has been found out which are implemented in the model.

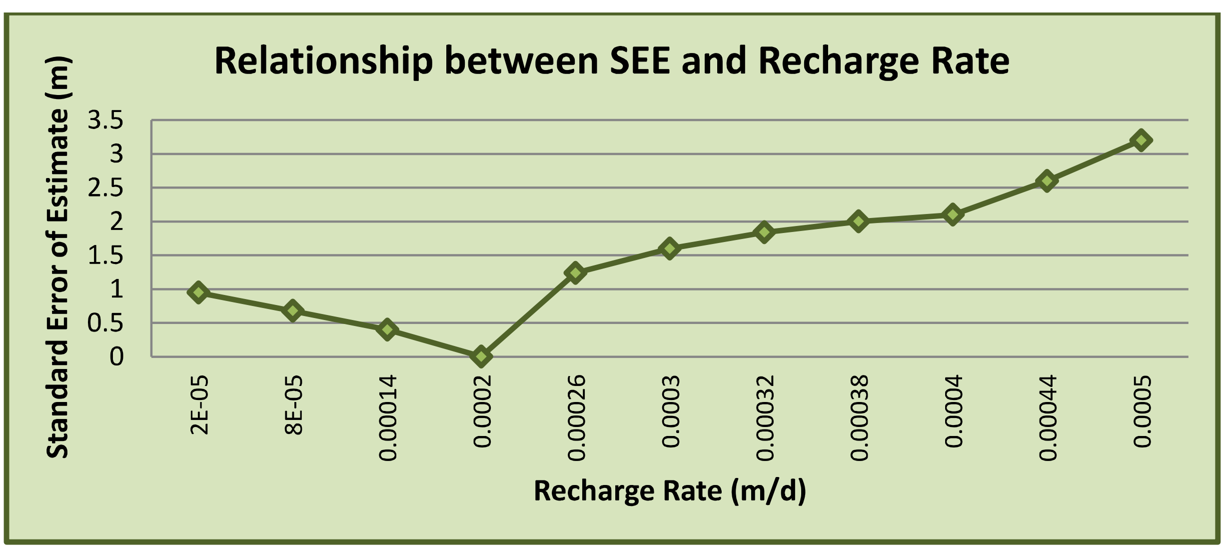


Figure 5.17 Relationship between the SEE and Recharge Rate

It can be concluded from the analysis that the hydraulic conductivity values that are greater than 18.4 m/day have a little impact on the Normalized SEE values. This suggests that the model is less sensitive to increase in the values of the hydraulic conductivity more than this value. Though, the sensitivity of hydraulic conductivity values to less than 18.4 m/day has been found to be very large and result in high values of Normalized SEE. The result of this analysis implies that the more care should be taken into the account in the determination of the hydraulic conductivity, when value is less than 18.4 m/day. Thus, in the sensitivity analysis, two parameters, hydraulic conductivity and recharge rate was found the most sensitive input model parameters.

5.11 Model validation

The objective of the model validation is to check if the calibrated model works well on any model dataset. The validation process verifies if the developed model is applicable for any dataset of the model. In this study, the data of 14 observation wells collected from the field has been used and a comparison of the calculated heads, resulted from GMS MODFLOW program was done. The calibrated model was validated for the period of January 2014 to December 2017. The groundwater recharge used for the validation process was 0.0002 m/d where this value has resulted in the best consistency between the computed output and observed field data. Figure 5.16 shows the fitting of the validation procedure for the computed and observed transient heads resulted from GMS MODFLOW code simulation when all of fourteen observation wells are being operated. From the same figure (Figure 5.16), a good fitting can be observed between the computed and observed heads which can be considered within the allowable limits and acceptable.

5.12 Soil Moisture Study

To cross check the output of the model, Soil Moisture map for the study area has been prepared. The area that has a high groundwater head value may have good moisture, while a low groundwater head value lacks moisture. For preparing the soil moisture map, Soil Moisture Index (SMI) value has been calculated for the whole study area. The formula used in the SMI calculation is mentioned in the equation.

$$SMI = \frac{T_{max} - T}{T_{max} - T_{min}} \qquad 5.3$$

Where, T_{max} and T_{min} are maximum and minimum surface temperature, respectively. SMI values range from 0 to 1, where 1 indicates extremely wet conditions (availability of moisture), while 0 indicates extremely dry conditions (lack of moisture).

The soil moisture content can be expressed in two manners, by weight, and by volume. If it is expressed by weight, it can define as the ratio of the present moisture weight of the soil to the dry weight of the soil. But if it is defined by volume, it would be the ratio of the water content in the soil mass to the total volume of the soil mass. The variable key in the climatic system is the soil moisture where it represents an important parameter for water and energy storage in the regional climatic system (Seneviratne et al. 2006). Furthermore, due to spatial and temporal variations in soil moisture, climate studies receive increased attention. Xi and Qi, (2004) postulated that soil moisture represents an essential element that is important in the biogeochemical and ecosystem cycles in the land-atmosphere system through participating in the derivation of energy fluxes and land-water surfaces.

From the Soil Moisture map of the study area, as shown in Figure 5.18, it can be seen that there are three large areas, which show higher soil moisture, content than the surroundings. One is in the south-west region of the study area, which lies in the St. Ravidas Nagar (Bhadohi). Second is in the east, belongs to Kashi Vidya Peth (KVP), Harahua and Chiraigaon administrative division of the Varanasi district. And, third one is in the north of the area, comes under Jaunpur division. The high soil moisture suggests that there is an abundance or surplus water in the soil mass. The soil moisture map helps in the validation of the developed groundwater model, as areas with high soil moisture have higher groundwater levels. Due to the high groundwater level, water can rise in the soil mass due to capillary action.

Capillary action (capillary motion or capillary effect) is a phenomenon in which liquid (water) can move upward through narrow spaces without the assistance against the force of gravity. In hydrology, it can be define as the attraction of water molecules to the soil particles. As soil mass consists of a number of interconnected voids that act as capillary tubes of varying diameter. Moreover, due to the capillary action water in the soil rises above the water table in these voids up to some height. As the capillary action is explained, it can be concluded that areas with high moisture content may have high groundwater table.

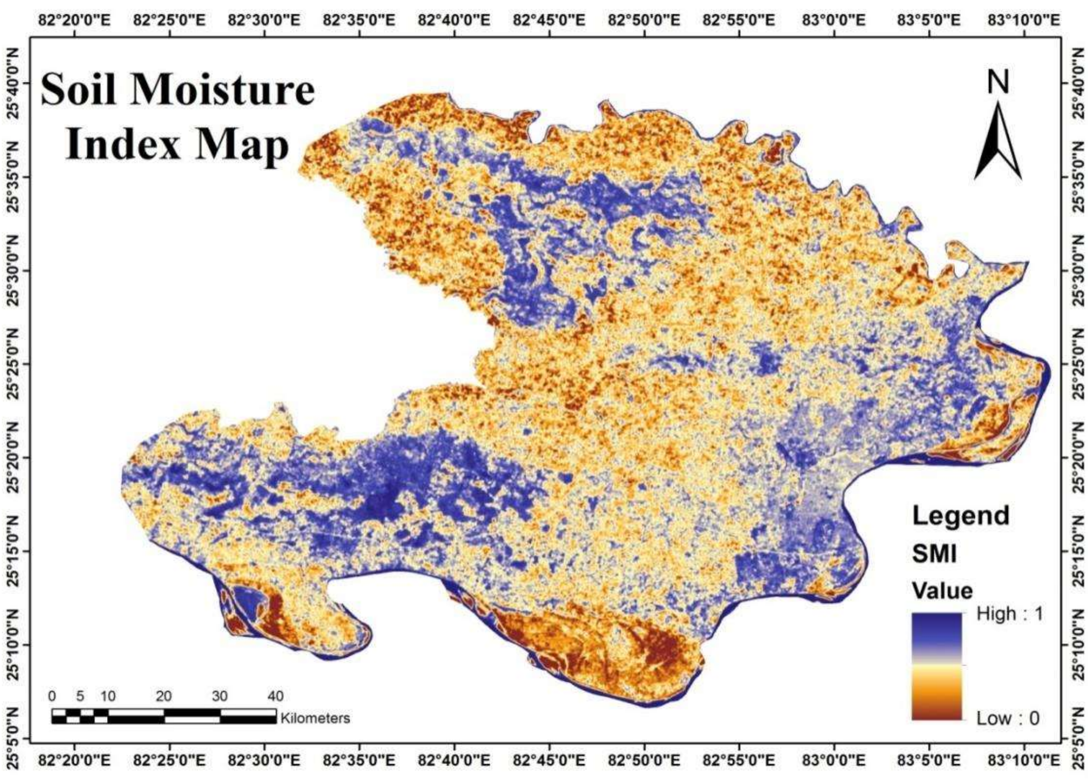


Figure 5.18 Soil Moisture Index Map of the study area.

5.13 Groundwater Model Development using AEM

In this study, for analytical simulation, AnAqSim software has been used. AnAqSim uses the AEM to perform groundwater modeling. For conceptualization of the study area, the basemap file was created in the DXF format in a GIS environment which includes river, discharge well and the boundary of the study area. The model domain was defined before inputting any model parameters. In AnAqSim, the term domain is referring to the regions within which the aquifer properties are constant.

5.13.1 Boundary conditions

In the AEM, boundary conditions are defined in the hydrological element itself as the head. Head specified boundary consists of river Ganga, Gomati and Basuhi, as used in FDM model conceptualization, and shown in figure 5.12. Digitization of the head specified boundary was done in a counter-clockwise direction starting from Ganga and end with Basuhi river. The far-field flow was taken as 5.0×10^{-5} m^3/day. This value of far-field flow was computed from the SWAT model (Maheswaran et al., 2016).

5.13.2 Recharge and discharge well

The recharge rate was taken same as the MODFLOW model. The recharge rate was considered to be uniform over the study area. The initial value of the recharge rate was taken as 8.0×10^{-5} m/day. The discharge wells were developed in ArcGIS, imported to excel and pasted in AnAqSim software. The value of good discharge was taken from the GMS which is -1728 m^3/day (negative sign indicates the extraction of the groundwater). By changing the discharge rate (increase or decrease), an effect on the groundwater level can be noticed.

5.14 AEM model calibration

AnAqSim software has a feature to check the line boundary conditions at any point or line in the study area. Head at the boundary line along Ganga River was checked in the upstream and downstream sides. In the AEM model calibration, the model was run using initial values. Residual error and line boundary conditions were checked, and in the next model run (run 1), the recharge rate value was taken 10 times the initial value and the hydraulic conductivity was taken 2 units higher. Similarly, in the consequent model run, recharge rate values were taken 10 times the initial value and hydraulic conductivity was taken 4 units higher, until the model run provides a good match between the computed head and the observed head. The parameter values used in AEM model calibration are shown in Table 5.14.

Table 5.14 Model Parameters values used in the AEM model calibration

S No	Iterations	Recharge Value	Hydraulic Conductivity
01.	Initial Run	$8*10^{-5}$	8
02.	Run 1	Initial * 10	10
03.	Run 2	Initial * 100	14
04.	Final Selected Value	0.008	18

Figure 5.19 shows the graph between observed heads and the simulated heads computed using a AEM flow model at the location of observation wells, after the model calibration. From the graph, it can be observed that the maximum number of points is positioned close to the best-fit line, which shows a good agreement between the observed head and simulated head. In the graph, there are some points, which are far from the diagonal line introducing some error in the model. The reason for this deviation of the head data from the actual head may be due to some inconsistency in the data.

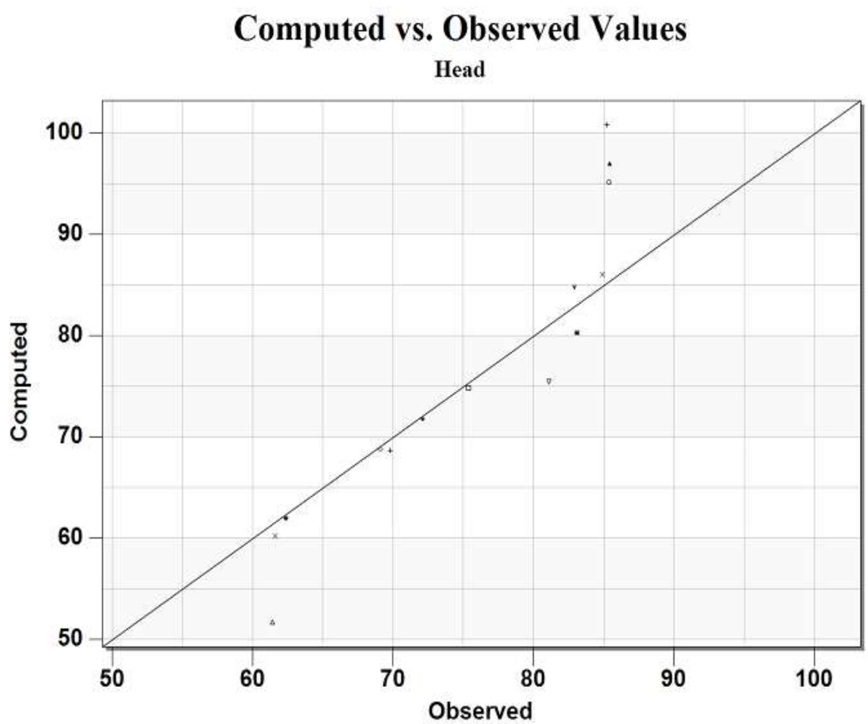


Figure 5.19 Observed head Vs Computed head (in m)

5.15 Summary

A three-dimensional conceptual groundwater flow model, with five layers, has been developed for Varanasi and adjoining areas in transient state by using MODFLOW GMS version 10.2. The total area of the study site is 2,785 km^2. An area of about 356 km^2 has been marked as an inactive area because this area was not represented as part of the groundwater aquifer, which is the aquifer considered under study in this research. The sensitivity analysis has been checked and examined for recharge rate and hydraulic conductivity. The 0.0002 m/d recharge rate and 18.4 m/d hydraulic conductivity applied on the study area. With these input parameters, the developed model is found to be the best as it achieves the good fitting between the computed and observed groundwater head. Whereas, in the case of model development using AEM approach, 0.008 m/d recharge rate, and 18 m/d hydraulic conductivity was found best suitable for the model. Model calibration and sensitivity analysis was also done for the developed model. The validation process has also been carried out where the results have led to an acceptable agreement.