Final Report

Development of Groundwater Flow Models and Preparation of Aquifer Management Plans (Bundelkhand Region)

Project Investigator

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Content

1. Rationale and motivation

Groundwater storage plays a vital role in domestic, agriculture, and industrial use. Nearly 60-70% of agriculture and 80-85% of domestic uses only depend upon groundwater (Tiwari et al., 2009). There are many other regions in the country where the impermeable subsurface and adverse climatic condition is a major reason behind the groundwater depletion. Groundwater depletion has now appeared as a strong challenge for our ecosystem, food security and economic prosperity in many parts of the world, particularly triggered by population growth and climate variability (Schewe et al., 2013). The continuous increase in population, agricultural and industrial growth causes high demand for groundwater (Hoque et al., 2007; CGWB, 2006, Wirsing et al., 2012). On the other hand, its over-use and over-draft can create a major problem for human beings and also for the environment. Subsurface groundwater is the major source for water; to this extent, intensive exploitation is the major issue for several parts of India.

The Bundelkhand region lies partly in Madhya Pradesh and partly in Uttar Pradesh and has a mixed terrain consisting of hard rocks and alluvial plains. A large tract of this region has an impermeable subsurface and adverse climatic condition. The Bundelkhand region of central India was once a prosperous region with ample forest covers which is now turning into a dessert. The average annual precipitation in this region is around 750 mm in the north-west and1250 mm in the south-east. Over 95% of the rainfall falls between June and September, with maximum rain generally in July-August. However, the average rainfall is slightly misleading as the general pattern of rainfall is in high bursts and the total rainfall of a given region may fall in just a few hours or days with intensity going up to 30 to 50 mm an hour. Thus, very little rainwater infiltrates into the sub-surface to recharge the groundwater. The problem of poor groundwater recharge is aggravated by the substratum of impermeable rock because of which most of the rainwater flows directly into the rivers. The recent, recorded history of Bundelkhand shows that the entire region suffers from severe crop loss every three years or so, either due to drought or flood. Four districts of Bundelkhand - Jalaun, Banda, Chitrakoot, Hamirpur and Mahoba - fall under the category of 'drought-prone area', as per the assessment of the 1981 National Committee on the Development of Backward Areas. There are numerous ponds in the region, but they are all degraded due to high siltation. This has further accelerated the groundwater depletion and its quality deterioration. This is adversely affecting agriculture, soil, water, forest and daily life of the people in the Bundelkhand region.

The Central Ground Water Board (CGWB) has done a rigorous subsurface study incorporating the hydrogeological, geological, geophysical, hydro-chemical aspects to achieve the objective of “KNOW YOUR AQUIFER, MANAGE YOUR AQUIFER” under the nationwide project of National Project on Aquifer Management (NAQUIM). All these studies are aimed at shifting the focus on “groundwater management” from the “groundwater development” (https://www.aims-cgwb.org).

Keeping in view the grim situation of groundwater availability in Bundelkhand, CGWB, New Delhi awarded a project to IIT Kanpur to take up groundwater modelling and to develop groundwater management plans for this region.

2. Objectives of the project

The main goal of the study is the development of groundwater flow models and preparation of aquifer management plans in the Bundelkhand region. This region is facing groundwater depletion at a high rate. The major reason behind this situation is due to impermeable subsurface, meteorological drought, low rainfall, soil erosion, deforestation. Given the unsustainable exploitation of groundwater, we need to develop plans for sustainable groundwater development to secure our future generations. The specific objectives for the study were envisaged as follows:

- Preparation of datasets in a GIS framework and data integration of various parameters required for groundwater modelling (Task 1).
- Preparation of a 3-dimensional conceptual model for alluvial and hard rock terrain separately. Development and calibration of a numerical groundwater flow model. (Task 2)
- Evolving aquifer management plans based on issues related to groundwater quantity and quality and projected scenarios (Task 3).

3. Study area description

Bundelkhand lies in central India, and a large part of this region consists of a hilly region covering the parts of southern Uttar Pradesh (UP) and northern Madhya Pradesh (MP). Figure 1 shows that the study area lies between latitude 23.15° and 26.44° N and longitude 78.05° and 81.55° E. The region occupies a geographical area of around 66,193 sq. Km and includes six districts of MP and seven districts of UP.

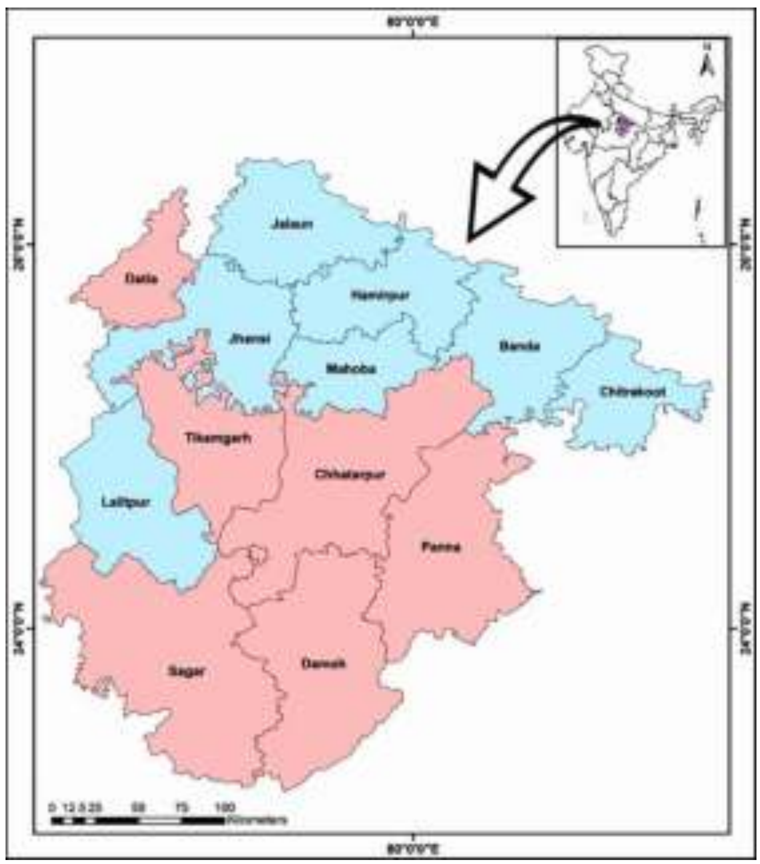
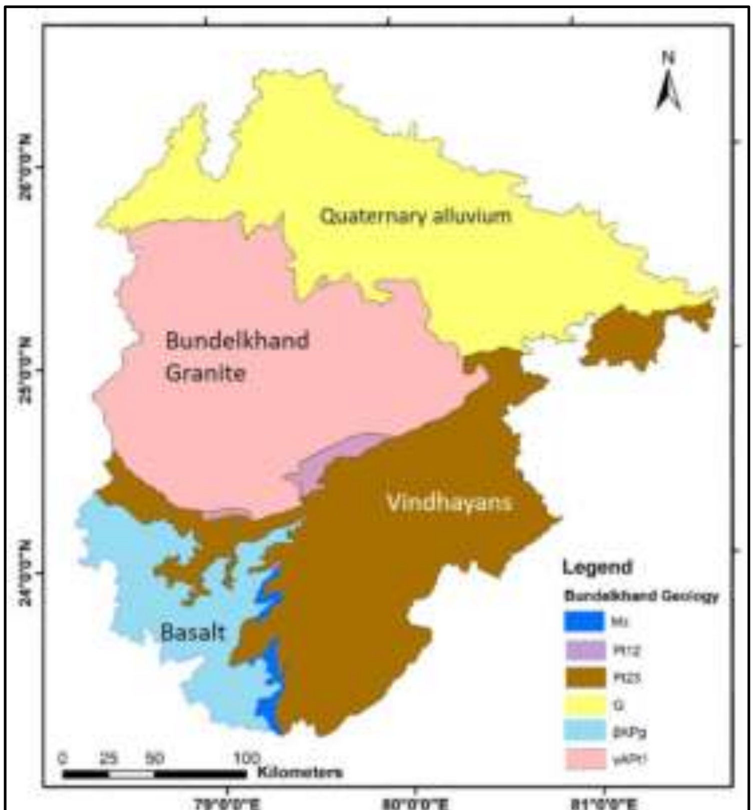


Figure 1: Map showing the study area of the Bundelkhand region. Blue and rose colours indicate the districts coming under U.P. & M.P. respectively.

3.1. Geology

The Bundelkhand region has a very complex geology. It is mainly studied under the Vindhyan Basin. The formations of the area range from Paleo Proterozoic Era to Recent. Different radiometric techniques suggest that its age range between 1721±90 Ma and 650 Ma (Ray S. J. 2006). Vindhyan basin is unconformably underlain by Bundelkhand granite of 2492±10Ma (Mondal et al., 2002). Most of the region under the districts of Jhansi, Lalitpur, Datia, Tikamgarh, Chhatarpur, Panna and Sagar districts, and southern portions of Mahoba and Chitrakoot have the granitic basement and exposed as an outcrop. Figure 2 shows the major outcrop in the study area.



Symbol	Bundelkhand Geology
Mz	Lameta Beds
Pt12	Gwalior and Bijwara Gps_L-M Proterozoic
Pt23	Vindhyan SGp_ M-U Proterozoic
Q	Alluvium_Quaternary
βKPg	Basalt
γAPt1	Bundelkhand Gr._ Archean-Lower Proterozoic

Figure 2: A general geological map of the Bundelkhand region showing major lithological units (GSI).

The Vindhyan basin consists of tectonically less disturbed, unmetamorphosed sedimentary sequence. It is further divided into (eastern) Son-valley and (western) Chambal valley sub-basins. The litho-stratigraphic succession of the Vindhyan basin is broadly divided into the Upper and Lower Vindhyan which are separated by an unconformity (Kumar and Sharma, 2012; Prasad et al., 2005; Sastri and Moitra, 1984). A generalised lithostratigraphy of eastern Vindhyan basin is presented in table 1. Sandstone (SSt.), quartzite (Qtzt.), limestone (LSt) and shale are the major rock types found in the Vindhyan supergroup. Vindhyan basin extends below the northern Ganga alluvial plain in the north (Ray S. J. 2006).

Table 1. Generalised Lithostratigraphy of Eastern Vindhyan basin (after Dayal et al., 2014; Rao et al., 2013; Bose et al., 2001)

Eastern Vindhyan Basin (Son valley)					
		Damoh-Rewa area		**Panna area**	
Group		**Formation**	**Thickness (m)**	**Formation**	**Thickness (m)**
Upper Vindhyan	Bhander	Lameta	--------	--------Unconformity------	----------
		----------Unconformity------			
		Maihar SSt.	87		
		Sirbu shale	80		
		Nagod LSt.	112		
		Gunurgarh Shale	45		
	Rewa	Upper Rewa SSt.	555	Upper Rewa SSt.	305
		Jhiri Shale	34	Rewa Shale	105
		Lpwer Rewa SSt.	64		
		Panna Shale	34		
	Kaimur	Dhandraul Qtzt.	185	Kaimur Qtzt SSt.	225
		Soman scarp SSt.	40	Kaimur Conglomerate	15
		Bijaigarh Shale	34		
		Domarkhoka Qtzt.	95	------Unconformity-------	
Lower Vindhyan	Semri	Rohtas LSt.	420	Pulkova Shale	210
		Basuhari Glauconitic SSt.	320	Dalchipur Conglomerate	40
		Mohana fawn LSt.	185	Hinota Shale	90
		Chakraria olive Shale	185	Semri LSt.	15
		Jardepahar		Semri SSt.	240
		Porcellanite		--------Unconformity------	
		Kajrahat Lst.	555		
		Basal conglomerate	235		
		----------Unconformity------			

Archean		Bijwara Group		Gwalior Group ------Unconformity-------- Bundelkhand Granite	

3.2. Geomorphology

The Bundelkhand region is bounded by Indo-Gangetic plain to the north and Vindhyan range to the south. It can be broadly divided into four sub-regions:

1. Bundelkhand Plain in the north,
2. Bundelkhand upland in the centre
3. Bundelkhand upland in the south, and
4. Sagar and Damoh (Vindhyanchal) plateau in the deep south.

The region is a gently sloping region having many isolated hills having sparse vegetation. The elevation is not more than 750 m above from mean sea level and have a master slope in the northeast direction. Sindh, Betwa, Dhasan, Ken are the major rivers of the region which flow from south to north as shown in figure 3. These streams are the tributary of river Yamuna.

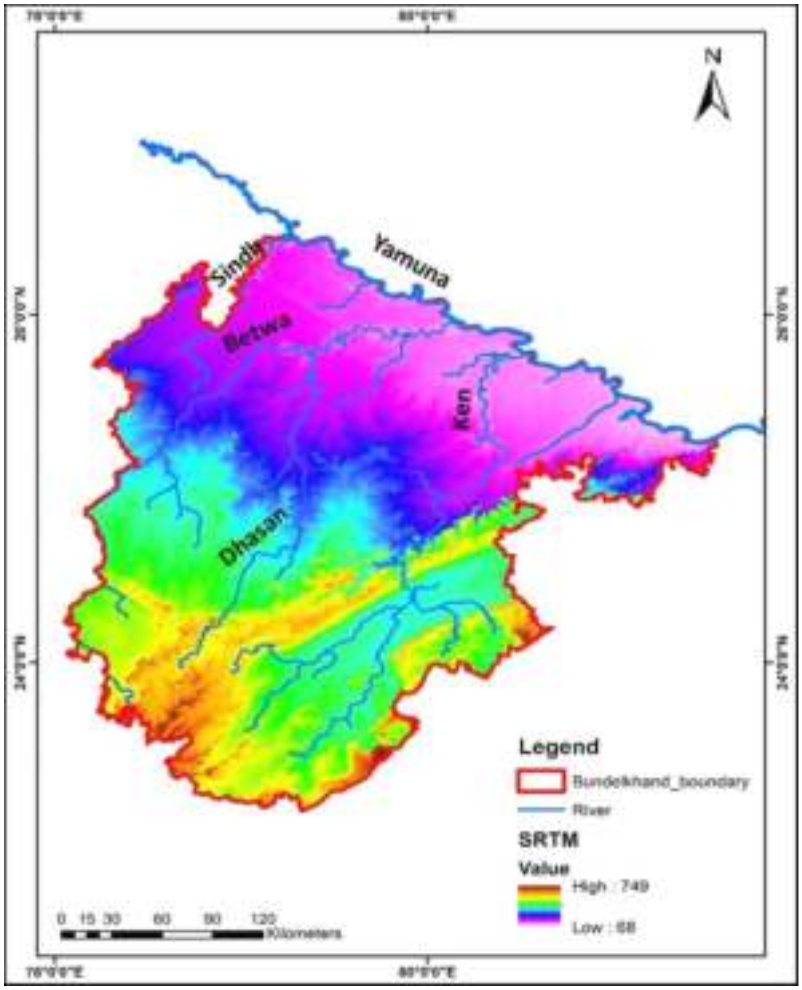


Figure 3: SRTM based digital elevation model showing the drainage network pattern of Bundelkhand region

It consists of two major geomorphic units (i) Central Ganga plains (ii) Bundelkhand plateau. The Central Ganga Plain is a thick repository of Quaternary alluvial deposits underlain by Precambrian basement. These alluvial sediments consist of different grades of sands admixed with clay, silt and Kankar. The Bundelkhand plateau area comprises of hard rocks of Bijawar and Vindhyan groups and lies south of the Central Ganga plain. The Bundelkhand Vindhyan plateau region is underlain by Precambrian formations, mostly granite and granite gneisses, Vindhyan sandstone, limestone & shale, under a thin alluvial cover or without alluvial cover.

3.3. Hydrogeology

The mode of occurrence groundwater in the Bundelkhand region depends on the type of hydrogeological units. It is broadly categorised into two units:

(1) **Unconsolidated:** This aquifer system is characterised by primary intergranular porosity and high groundwater potential. Lithologs show the presence of aquifer systems of variable thickness (0-150 bmgl). It is unconfined to semi-confined

condition. It is the main source of groundwater which is extensively exploited by private as well as government tubewells.

(2) **Consolidated:** This aquifer system is composed of hard and compact formation with cracks and fractures. Water-bearing properties are governed by the degree of weathering, presence of fractures, joints, and interconnected pore spaces available for the storage of water. The interconnections of joint and fractures govern the permeability. The groundwater moves under unconfined conditions in these formations. The weathered mantle over the entire unit also forms a potential aquifer.

The region is mainly occupied by basalt, Vindhyan sandstone and shale, Bundelkhand granite. alluvium, limestone and quartzitic sandstone are also found in a very small area. The prevailing water-bearing formation is listed district-wise in table 2.

Table 2: Hydrogeological units in the districts under the Bundelkhand region (Source: CGWB district profile, BDR and NAQUIM reports)

Sl. No.	District	Major Water-bearing Formation
Madhya Pradesh Region (36,794 km^2)		
1	Chhatarpur	Recent Alluvium, Deccan Traps, Vindhyans, Bijawar & Granite
2	Damoh	Alluvium, Shale, Limestone and Sandstone
3	Datia	Alluvium, Jointed and fractured granite sandstone and shale
4	Panna	Sandy alluvium, Jointed and fractured Sandstone, weathered Shale and solution cavity in Limestone
5	Sagar	Alluvium, Laterite, Intertreappean beds, Deccan traps, Vindhyans, Bijawars, Bundelkhand granites
6	Tikamgarh	Granite and Gneisses, Alluvium
Uttar Pradesh Region (29,399 km^2)		
1	Banda	Alluvium and Hard rock formation
2	Chitrakoot	Sand of various grades clay, silt, gravel Kaimur & Rewa sandstones & Shales, Tirohan limestone
3	Hamirpur	Quaternary Alluvium, Recent to sub-recent, Precambrian, Bundelkhand Massif
4	Jalaun	Sand and Gravel
5	Jhansi	Fractured and weathered granite
6	Lalitpur	Fractured and weathered granite
7	Mahoba	Fractured Bundelkhand granites

4. Approach and data requirement

Bundelkhand region is a terrain having alluvium as well as hard rock. The unconsolidated aquifers have a good amount of interconnected pores which are capable of receiving recharge from the surface water, whereas substratum of hard rock have very less primary porosity and degree of weathering of rock decides the volume of water to percolate down and get stored in the weathered zone. Also, the extraction of groundwater is more successful by using large-diameter wells rather than the tubewells.

Given the geological complexity of the Bundelkhand region, we have studied the soft rock and hard rock aquifers separately, and have developed independent models for these two regions even though the primary approach is same. We have used SRTM DEM data for understanding the surficial feature and the lithologs provided by CGWB are the most important dataset to delineate the different aquifers/ fractures zones.

In general, the data used for this study are as follows:

1. Remote sensing data: SRTM & DEM
2. Shapefile: District, blocks, rivers, geology, geomorphology, hydrogeological.
3. Lithology data
4. Hydrogeological parameters (hydraulic conductivity, transmissivity, specific yield, storativity)
5. Disposition of fractures and lineaments
6. Data related to groundwater draft, recharge, evapotranspiration, river stage etc.

The overall methodology for completing the objectives is described in figure 4.

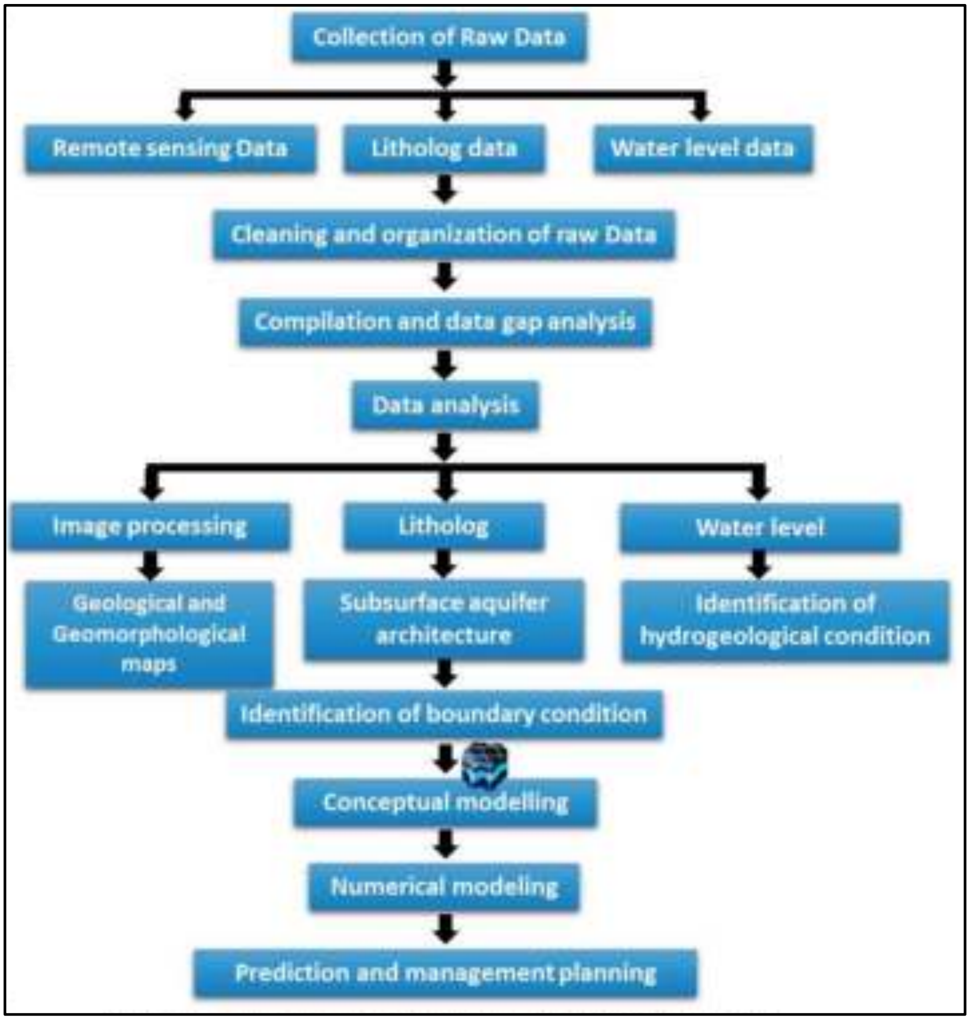


Figure 4: The major steps involved in data processing for flow modelling

5. Data Available

5.1. Remote sensing data

First-order geomorphic mapping of the region was carried out using the Landsat satellite images that are freely available. The Shuttle Radar Topography Mission (SRTM) digital elevation data of 90m resolution were also been downloaded from the USGS website. The area of Bundelkhand region comes under four tiles which were further processed to get a complete base file for the study area.

5.2. Borehole data

The borehole data have been made available by Central Ground Water Board (CGWB) in the form of different NAQUIM reports, BDR and Ms excel format for the Bundelkhand region. The data provided were in the form of an electronic copy of district reports and hard copy Basic Data Report (BDR). These data sets had to be digitised and formatted for GIS archival and for the modelling work.

5.3. Water level data

The CGWB has provided the water level for January, May, August and November for the year 1974 to 2017 for the M.P. part of Bundelkhand region (6 districts). A similar kind of water level data has been provided by the CGWB for U.P. part in pdf and excel format for the year 2000 to 2017. These data are arranged into different formats to understand the water level trend, hydrogeological condition, and feeding into the model etc.

5.4. Aquifer Parameters

Aquifer parameters such as hydraulic conductivity, transmissivity, storativity, specific yield etc. are the essential parameters to understand the groundwater and aquifer system. The CGWB has provided the BDR which has pumping test data analysed mainly using Jacobs and Theis recovery methods. Thus, most of the data pertain for the transmissivity. On the other hand, different groundwater resources assessment calculation sheet and NAQUIM reports provide some of these parameters at the block/district level.

5.5. Groundwater resources

The published dynamic groundwater resources and their detailed calculation sheets were provided from the CGWB, Lucknow and Bhopal. Data pertaining to groundwater draft at seasonal basis has been calculated using the draft rate and the number of different groundwater extraction units. The recharge rate has been calculated using GEC-97 norms from the available rainfall recharge and surface water resources. These data were needed for further computations as per the model requirements.

5.6. Evapotranspiration

The potential evapotranspiration and reference crop transpiration data have been downloaded from the site "https://www.indiawaterportal.org/met_data/" for the years 2000, 2001, and 2002 for districts falling under the Bundelkhand region. These data were studied for understanding its repetitiveness and applicability.

6. Data cleaning and Organization

VMOD Flex requires a huge amount of data to meet the desired accuracy and precision. For groundwater modelling the data type for this exercise includes remote sensing data, i.e. satellite imageries of LANDSAT, SRTM etc. and numerical data, i.e. borehole lithologs, aquifer depth extent, river stage, water level, aquifer parameters. These data need to be put on a single GIS platform to inform of shapefiles and raster files for different crucial analysis. The raw data from BDR and electronic copies were organised as per the

GIS format in electronic copies. The base file was also prepared for plotting the available data of the study area. The raw data needed to be cleaned and reorganised according to the requirement after getting the complete data of lithologs, and aquifer property of the study area was used for deciphering the aquifer geometry with more confidence.

6.1. Remote Sensing data

The SRTM data of 90mx90m resolution was downloaded for understanding the regional topography. In spite of the higher resolution of the data (figure 5a), the resolution didnot match with the proposed model grid size. Hence, this data was resampled at a coarser scale of 5km on the ArcGIS platform (figure 5b). Later on, this grid value was imported on point format to make the top surface in modelling work. Along with this, the new pixel values have been used as a reference for defining the litholog and water table elevation.

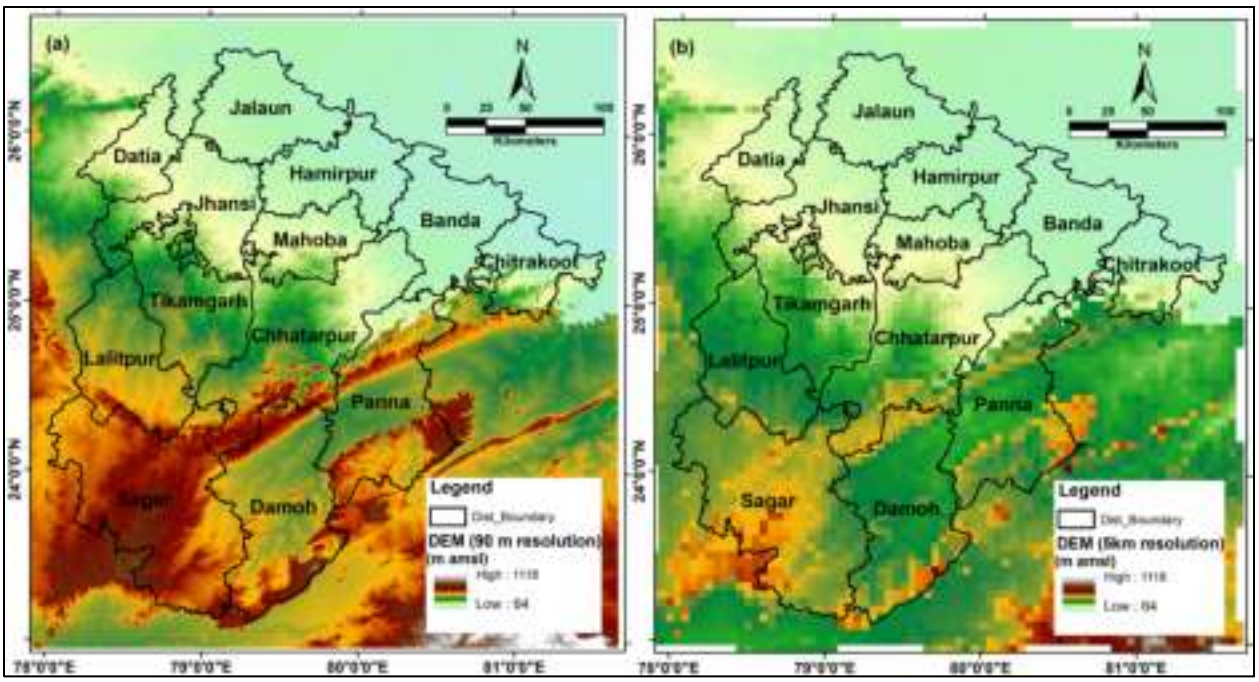


Figure 5. The topographic elevation of the surface at a resolution of (a) 90m and corresponding resampled values at (b) 5km.

6.2. Borehole data

A reasonable number of borehole litholog records that have been compiled from the basic data report (BDR), NAQUIM reports from CGWB for the Bundelkhand region. These lithologs represent subsurface sediments which were taken out during drilling of exploratory wells (EW) and observation wells (OW). The lithologs have been filtered based on the following conditions:

1) Due to the proximity of OW to the PW, some lithologs had the same geographical coordinates. Hence, less appropriate lithologs were discarded.

2) Depth of lithologs varies at a particular site in the range of 100-203m (approximately). In this situation, the deeper lithologs were selected for deciding the subsurface aquifer geometry.
3) The geographical location for the well falling outside the respective district boundary was adjusted by manually searching their names using Google earth. Those lithologs were summarily discarded whose geographical locations were not possible to retrieve.
4) The geographical location provided was in meter (UTM) and degree (Lat./Long.) coordinate system under different data sets (e.g. Litholog, location, etc.). The coordinates provided for the lithologs of Chattarpur and Damoh districts (M.P.) in the UTM system were not assigned correct UTM zone. So, the litholog points were falling outside of the study area (let's say in Jharkhand/Bihar). Therefore, in Chattarpur district, lithologs having there Lat/long values in other dataset were selected, and their coordinates were reconverted as the UTM (zone 44).
5) Similarly, the lithologs of Damoh district were matched with different database having coordinates in lat/long. About 15 lithlogs were found common. Their coordinates were converted into the UTM system. On comparing the new calculated UTM coordinates with old UTM an average error of 611733 m and 6412 m in Easting and Northing respectively were found. Thus, these values have been subtracted from other lithologs to retrieve all lithologs.
6) In the Tikamgarh districts, there were different datasets available with records of the zone tapped by wells (PW/OW) was available instead of the complete litholog. These wells were constructed in the different period under different schemes/years. Hence, lithologs dataset with more clear information was finalised.

Based on the above criteria, a total of 405 lithologs were finalised for delineating the aquifer / non-aquifer zone in the Bundelkhand region (Fig. 6).

Figure 6: Location of the finalised lithologs used for defining the aquifer/non-aquifer zone in the Bundelkhand region.

Table 3 shows the distribution of lithologs under different districts of the study area. From the acquired information, it is concluded that there are mainly three kinds of subsurface systems: (a) Granite and its fracture (b) Basalt and sandstone (c) Shale /Clay.

Table 3. shows the distribution of final lithologs data gathered from different BDR and NAQUIM reports for defining the aquifer/non-aquifer zones.

Uttar Pradesh			Madhya Pradesh		
S. No.	District	No. of litholog	S. No.	District	No. of litholog
1	Banda	31	1	Chhatarpur	22
2	Chitrakoot	36	2	Damoh	52
3	Hamirpur	24	3	Datia	20
4	Jalaun	20	4	Panna	31
5	Jhansi	67	5	Sagar	12
6	Lalitpur	57	6	Tikamgarh	25
7	Mahoba	8			

6.3. Water level data

Measurements of water level for a long period from the observation wells (OW) of CGWB are provided for the MP and UP part of Bundelkhand region. The data has been organised keepin in view the following constraints:

1) The water level data for the MP starts from the year 1974 whereas for the UP part it was from the year 2000. However, the water level data available on the WRIS (online data centre) is from the year 1996.
2) Water level data were discontinuous.
3) All observation points were not consistent with time, maybe due to hydrogeological conditions, abandoning old wells and establishment of new wells.

The water level data was subjected to the following processing:

1. The water level data were downloaded from the WRIS from the year 1996 to 1999 for the entire Bundelkhand region. The common well locations were identified, and their data were merged. The water level data of the finalised observation well were tabulated as given in table 4. Some of the OW whose data were available after the year 2012 or later have also been kept (considering their good data continuity). This may enhance the data density in the latest years, which could be useful in generation groundwater related maps and hydrogeological interpretation. The purpose was also motivated by the fact that these WL data could be further added year after year in the model for post-audit.

Table 4: Format of water level data of observation wells (OW).

STATE	DISTRICT	TEH_NAME	BLOCK_NAME	LAT	LON	SITE_NAME	SITE_TYPE	YEAR_OBS	1996	1997	......	2014	2015	2016	2017
MP	Chhatarpur	Bada Malhara	Bada Malhara	24.508	79.091	Ghuara	Dug Well	(May)PREMONSOON	9.32	8.57	------	6.75	7.25	-	10.15
MP	Chhatarpur	Rakswaha	Rakswaha	24.248	79.287	Buxwaha	Dug Well	(May)PREMONSOON	11.7	11.83	------	8.1	11.52	-	12
MP	Chhatarpur	Bijawar	Bijawar	24.65	79.498	Bijawar	Dug Well	(May)PREMONSOON	8.75	7.15	------	4.2	10.79	-	14.59
MP	Chhatarpur	Bijawar	Bijawar	24.639	79.482	Bijawar(D)	Bore Well	(May)PREMONSOON	-	-	------	8.7	13.84	-	19.2
MP	Chhatarpur	Bijawar	Bijawar	24.692	79.368	Gulganj	Dug Well	(May)PREMONSOON	9.12	9.96	------	7.3	11.83	-	9.52
MP	Chhatarpur	Eshanagar	Eshanagar	24.932	79.586	Chhatarpur	Bore Well	(May)PREMONSOON	-	-	------	8.2	8.17	-	9.1
MP	Chhatarpur	Eshanagar	Eshanagar	24.9	79.591	Chhatarpur1	Dug Well	(May)PREMONSOON	8.56	7.17	------	7.46	9.3	-	9.01

2. WL data were separated for the pre-monsoon and post-monsoon for the entire time series (1996-2017). Due to discontinuities in data, none of the years has all 308 OW data. Table 5 gives an idea about the data density of some of the particular year from which the figures (Figure 10, 11, 13, 14, and 19) related to water level, water table etc. are prepared in the GIS environment. Our compilation suggests that none of the available observation well has all year water level data (neither for pre-monsoon nor for post-monsoon):

Location having all 23 years (1996-2017) data: 0

Location having >19 years data (between 1996-2017): 72 (May); 111 (Nov.)

Location having 18 years data (between 2000-2017): 37 (May); 0 (Nov.)

Location having >14 years data (between 2000-2017): 146 (May); 119 (Nov.)

Table 5: Glimpse of variation in available water level data points in the Bundelkhand region.

Year	No. of OW (May)	No. of OW (Nov.)
1996	220	220
2000	233	257
2005	245	254
2010	192	177
2015	239	239

3. The water level data has been used for making regional groundwater level maps and water table contour maps and other decision support.
4. The final OW location (308) was plotted and is shown in figure 7.

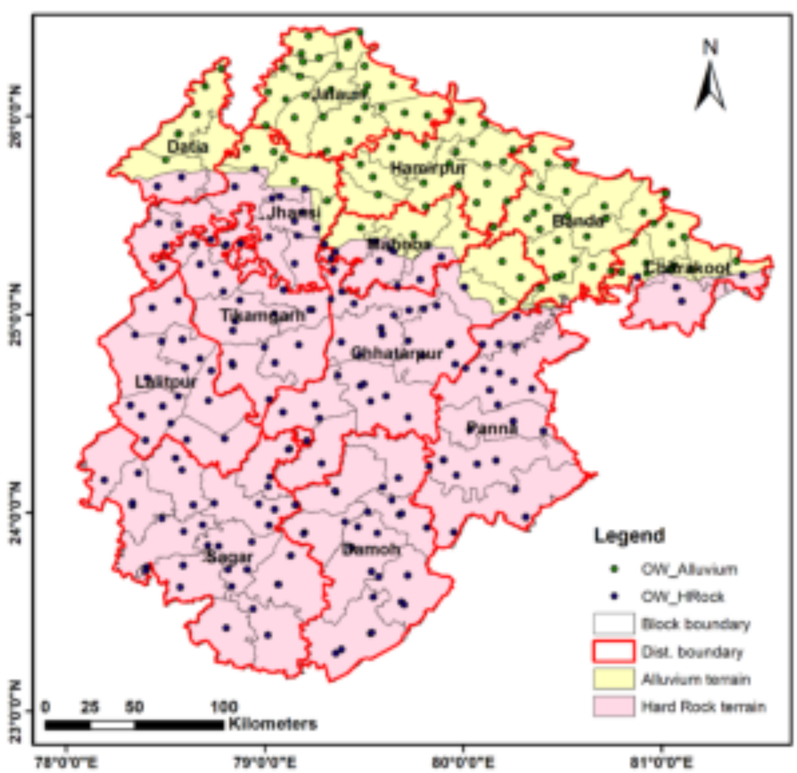


Figure 7: Location of observation wells (OW) in different aquifer settings in Bundelkhand region.

6.3.1 Water level time series

Water level data from the finalised observation wells of the study area have been plotted to understand the fluctuation through time. The water level fluctuation in the region for pre-monsoon and post-monsoon is shown as figure 8(a) and 8(b) respectively.

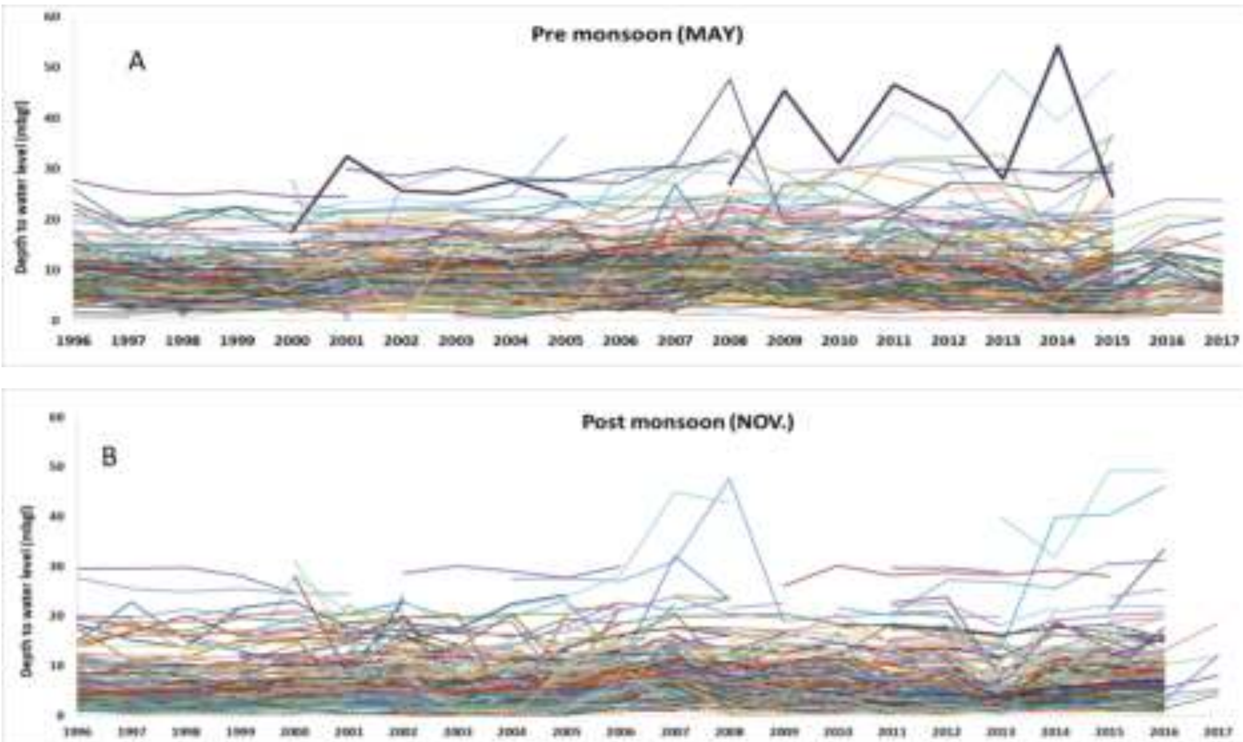
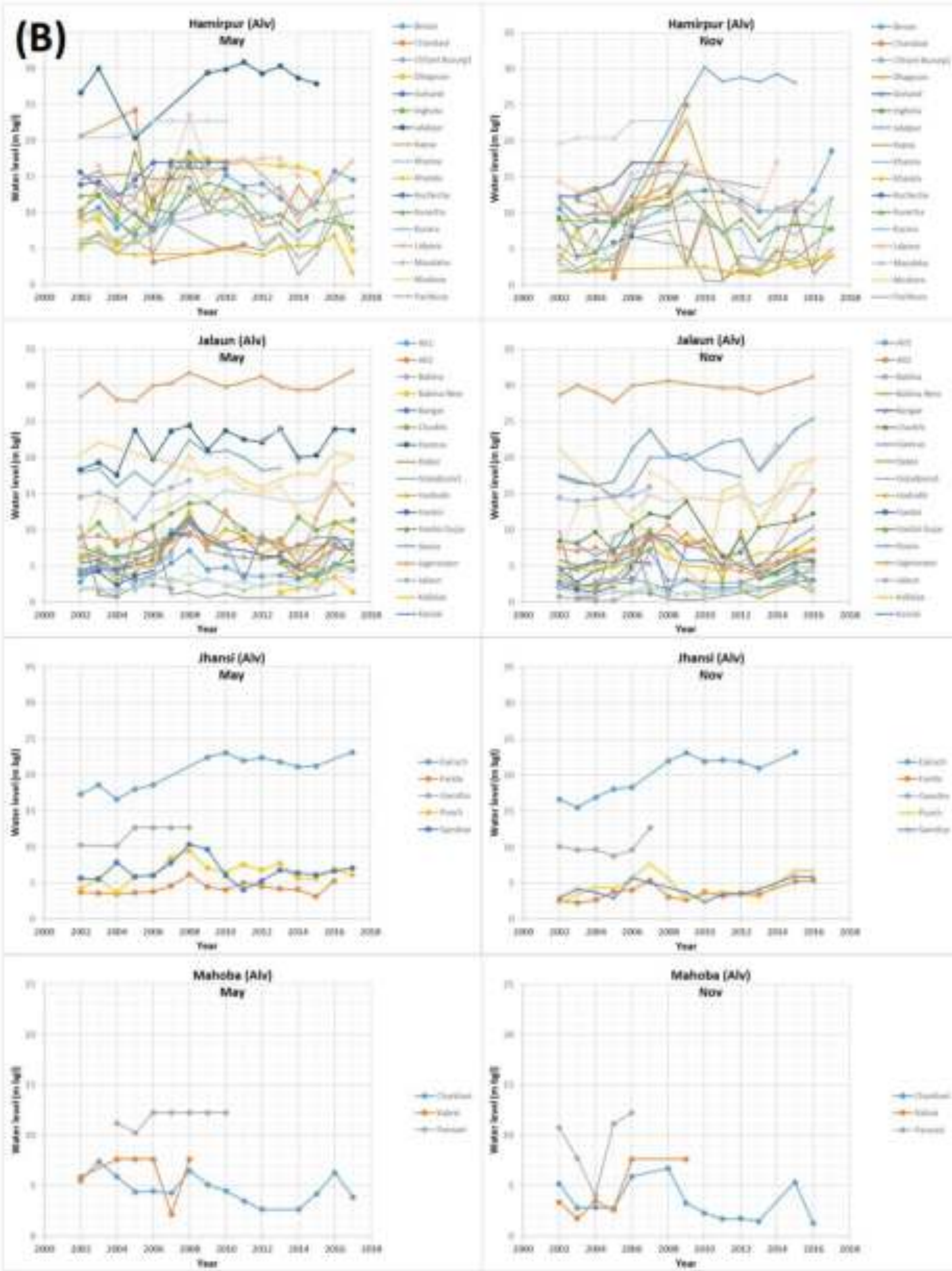


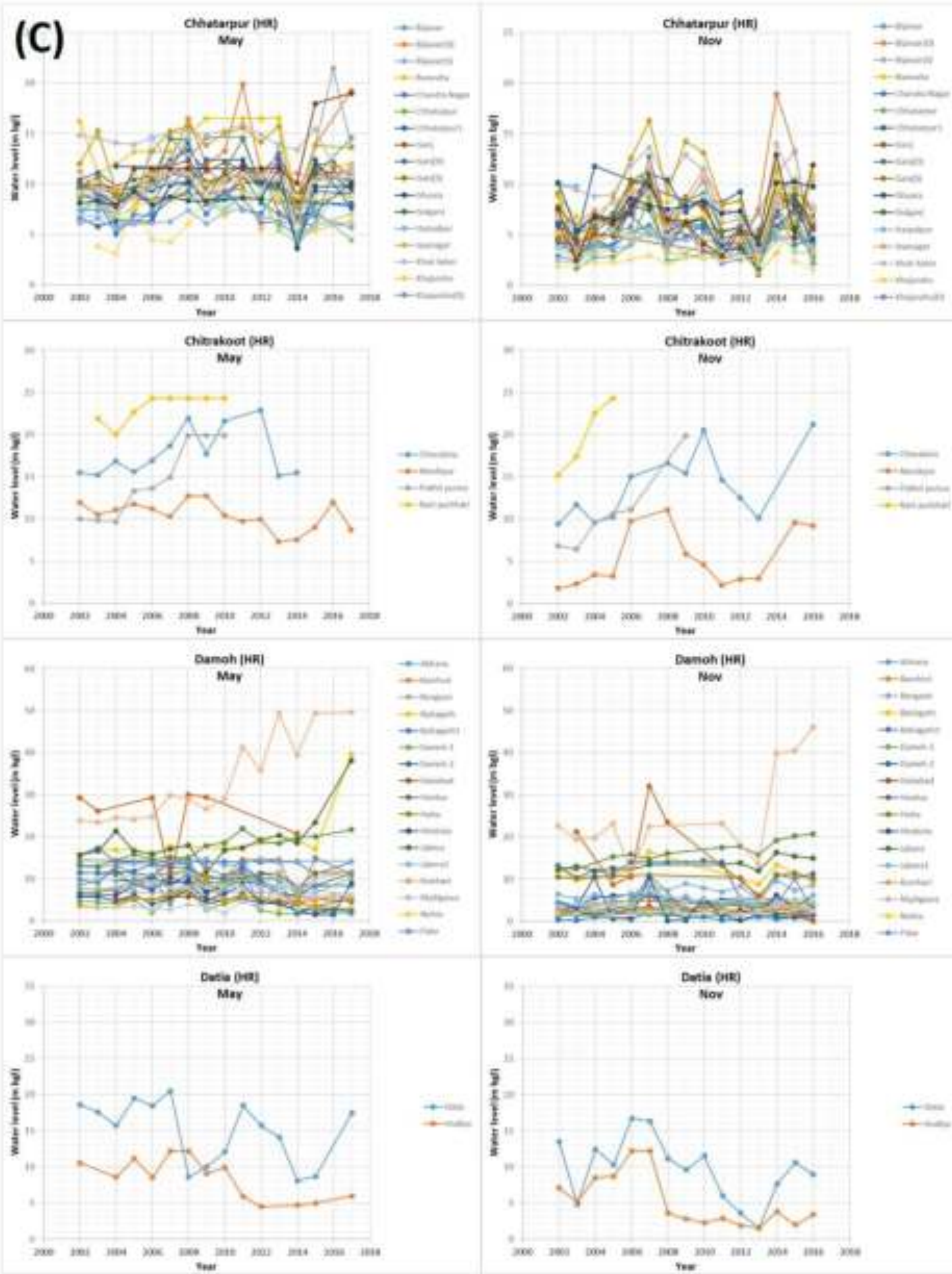
Figure 8. Temporal variation in water level in Bundelkhand region for (A) pre-monsoon and (B) post0-monsoon periods.

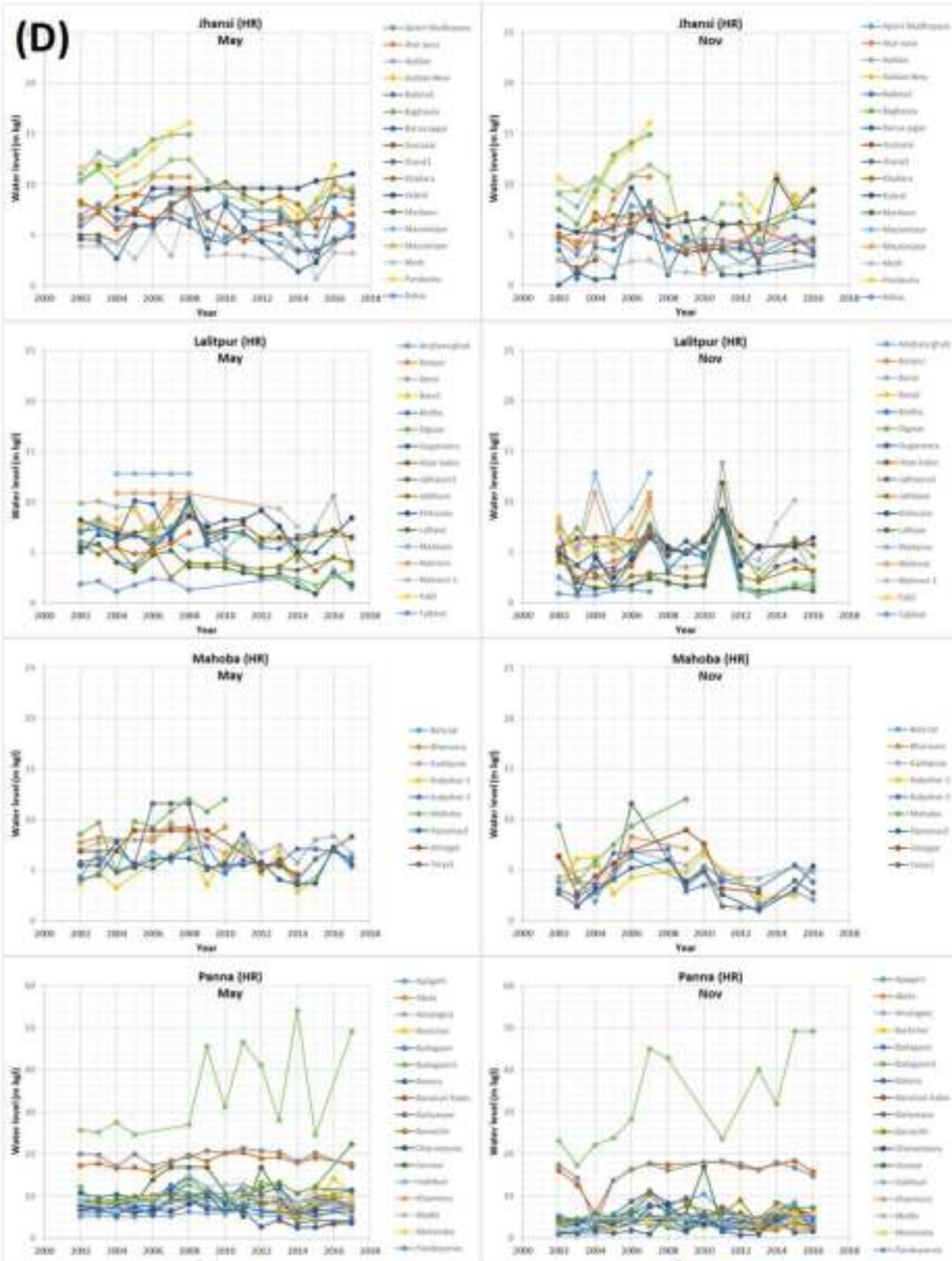
The water level data needs to be studied meticulously for each observation well to filter-out the anomalous behaviour in data to establish the trend. The hydrograph from each individual observation well of the study area was plotted, and the anomaly in the data has been observed. The rise/fall of 10m-20m in water level has been put on record from many sites (see figure 9). This kind of data has been cross-checked in reference to preceding and following years data for May and November months. In general, a maximum of 5 m of rising/fall in data has been considered. The long term fluctuation pattern of the individual OW is the key to filter the anomalous behaviour. In figure 9(a) and 9(b) hydrograph for the pre-monsoon and post-monsoon for the alluvial terrain has been plotted for different districts. Similarly, for the observation wells falling in the hard rock terrain of different district has been plotted as figure 9(c), 9(d) and 9(e).

After removing the anomalous water level records, the observation well hydrograph does not show a very continuous declining or rising trend. Most of the observation wells fluctuate between a certain range. The anomalous data might have been observed due to some strong local factors.


(A)
Banda (Alv)
May
Banda (Alv)
Nov
Chhatarpur (Alv)
May
Chhatarpur (Alv)
Nov
Chitrakoot (Alv)
May
Chitrakoot (Alv)
Nov
Datia (Alv)
May
Datia (Alv)
Nov
Year


(B)
Hamirpur (Alv)
May
Hamirpur (Alv)
Nov
Jalaun (Alv)
May
Jalaun (Alv)
Nov
Jhansi (Alv)
May
Jhansi (Alv)
Nov
Mahoba (Alv)
May
Mahoba (Alv)
Nov
Year


(C)
Chhatarpur (HR)
May
Chhatarpur (HR)
Nov
Chitrakoot (HR)
May
Chitrakoot (HR)
Nov
Damoh (HR)
May
Damoh (HR)
Nov
Datia (HR)
May
Datia (HR)
Nov
Year
Water level (m bgl)


(D)
Jhansi (HR)
May
Jhansi (HR)
Nov
Lalitpur (HR)
May
Lalitpur (HR)
Nov
Mahoba (HR)
May
Mahoba (HR)
Nov
Panna (HR)
May
Panna (HR)
Nov
Year

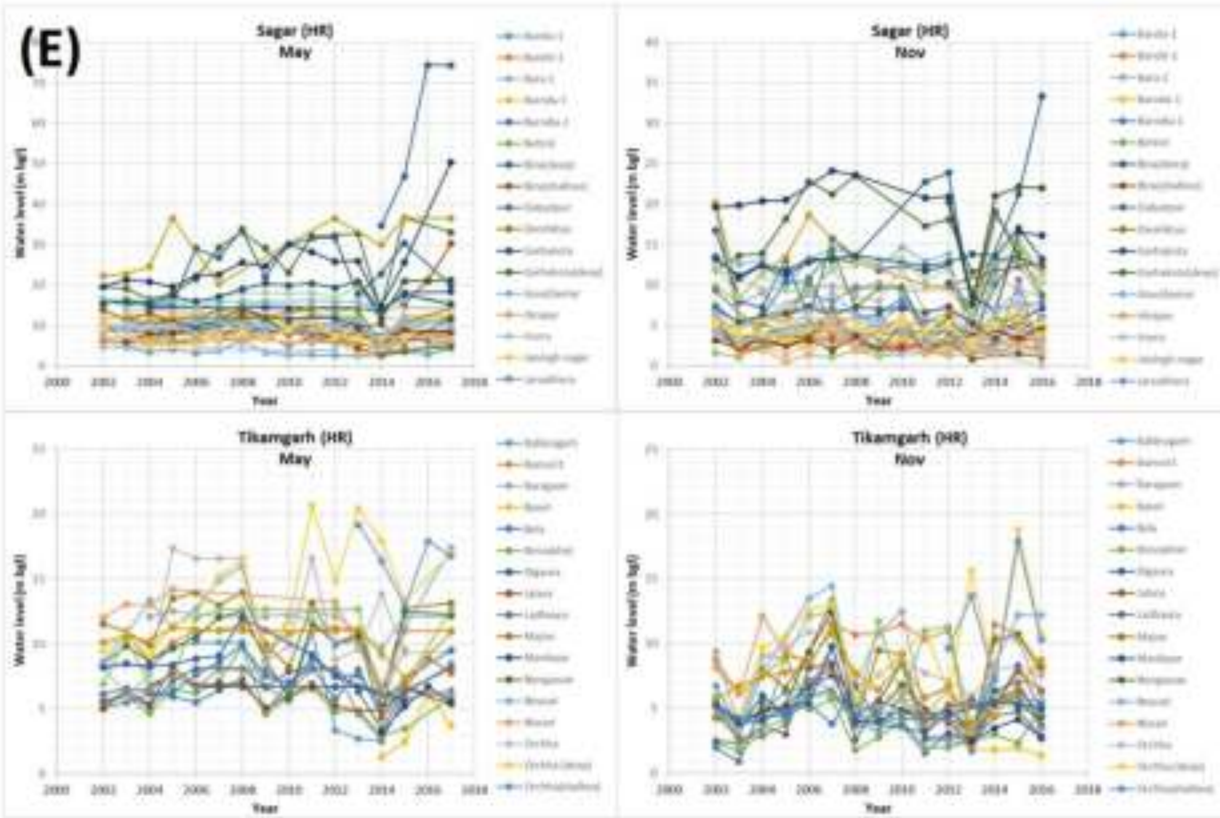


Figure 9. Comparative study of the observation well hydrograph plotted for the (A & B) alluvium, and (C to E) hard rock terrain for the different district of the Bundelkhand region. (Note: Alv and HR represents the OW/district falling under the Alluvium and Hard Rock terrain respectively for the sampling month of May and November).

6.3.2 Spatio-temporal variation in water level

The pre-monsoon and post-monsoon water level data for some selective years 1996, 2000, 2005, 2010, and 2015 have been imported in the GIS framework to prepare raster images. Figure 10 and 11 are very helpful in understanding the variation in depth of occurrence of groundwater during pre-monsoon and post-monsoon condition, respectively in the Bundelkhand region.

(A) Pre-monsoon:

Figure 10 shows the variation with time and space for the pre-monsoon condition of water level. The water level ranges between 3m to 19m below ground level. In general, the water level has been observed to be at greater depth in the northern and the southern region of the study area. It is also noted that whenever the water level is deepest in the northern boundary, water level occurs at intermediate depth range near the southern boundary (see for years 1996 and 2010) and vice versa (for years 2000, 2005, and 2015). Water level along the centre in northeast-southwest direction comprising Lalitpur, Tikamgarh, Mahoba and Banda has always been shallowest. Almost half of the Sagar and Damoh districts show very deep water level in year 2015.

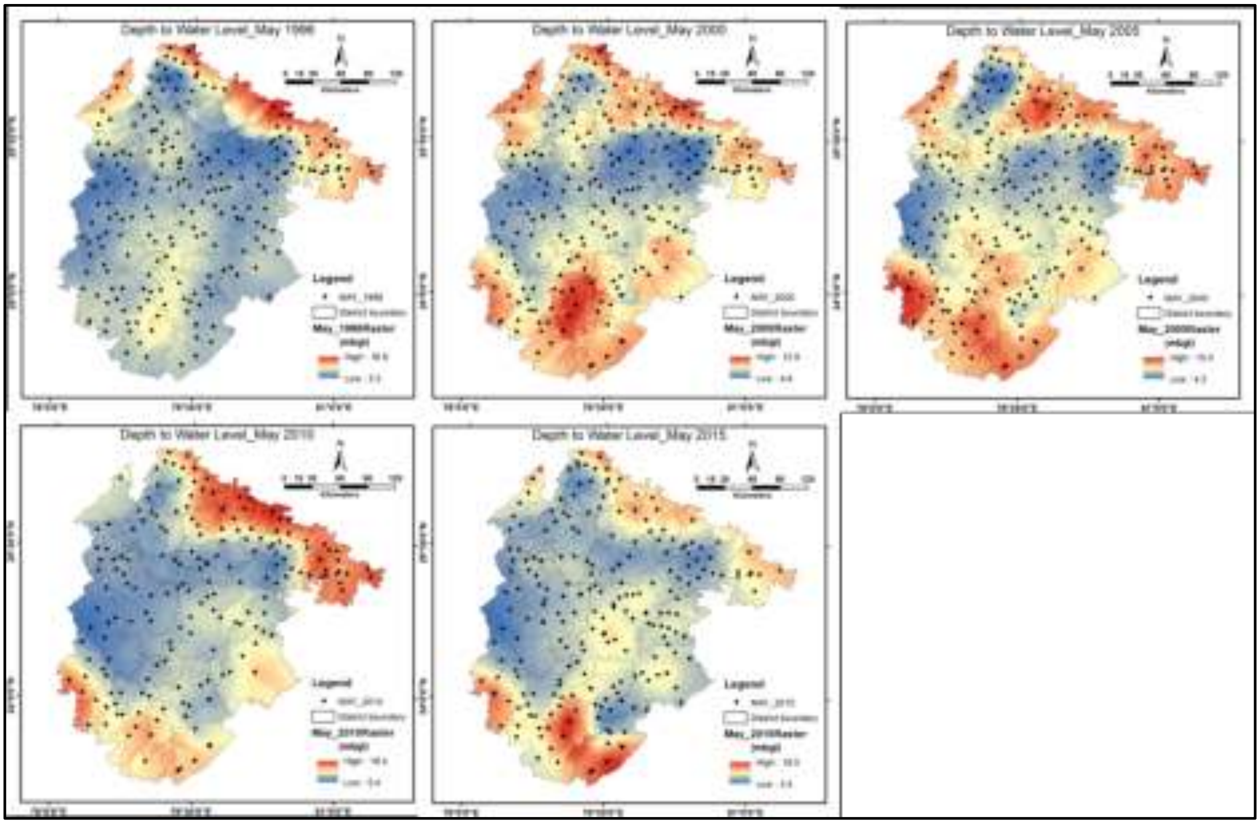


Figure 10: Pre-monsoonal variation of depth to the water level in the study area for different years.

Overall, the region is having a deeper water level condition along its border, whereas shallower condition is prevailing in central districts. Also, these images do not suggest a continuous decline of water level, because the year 2010 shows a rise in water level in most of the study area. However, we note a clear spread in groundwater depletion from peripheral to central districts between 1996 and 2015.

(B) Post-monsoon:

Figure 11 shows that most of the region is having shallow water level condition during post-monsoon season in the region. The depth to water level varies between 2m to 15m below ground level. The northern region and some small patches in southern part of the study area show an intermediate to deep water level condition. Datia, Hamirpur and Chitrakoot are three districts where intermediate to deep water level condition is noted throughout but with some variations in water level. The water level in southern part of Sagar and Damoh has declined sharply in 2015.

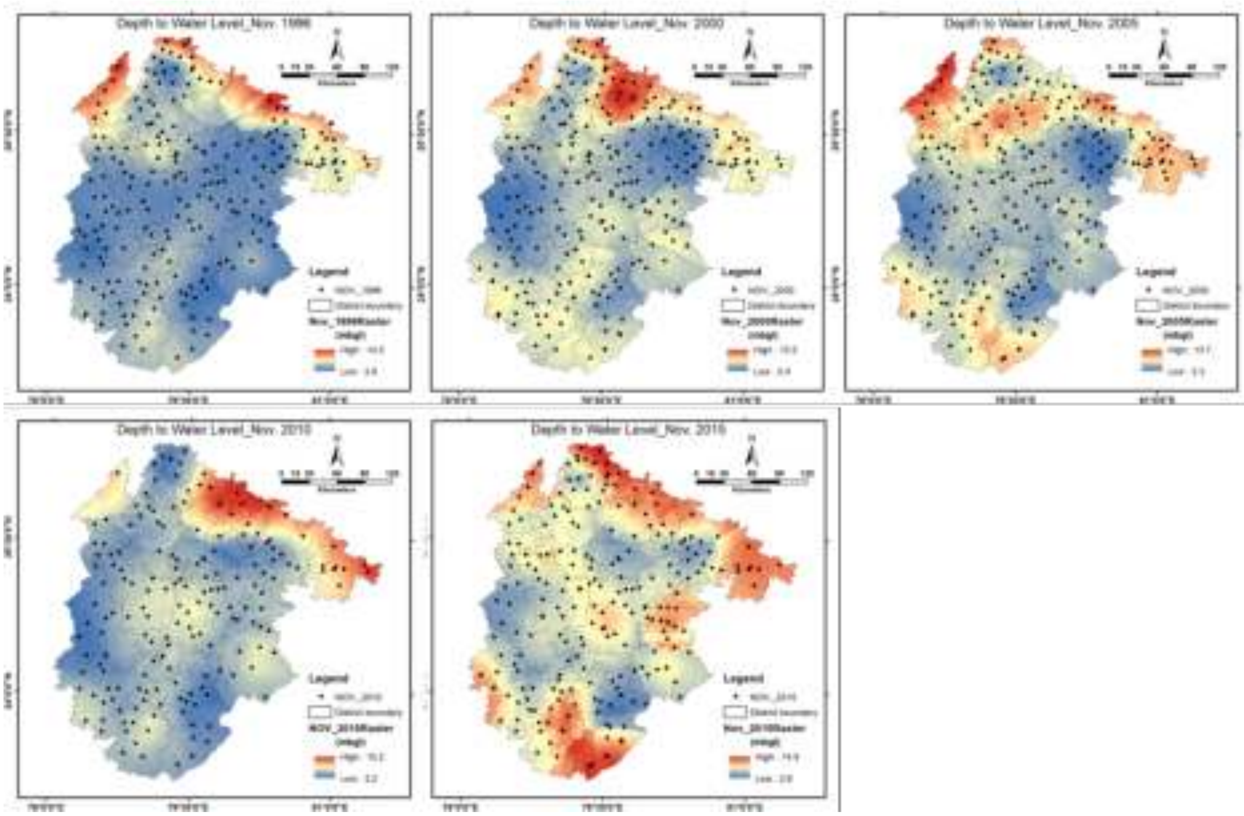


Figure 11: Post-monsoonal variation of depth to the water level in the study area for different years.

The deep water level is predominant in northern boundary (along Yamuna river), which is also observed in the southern part of Damoh district. Overall, shallowest water level condition can be observed for year 1996, and deepest condition is in year 2015.

(C) Seasonal water level fluctuation:

The depth of water level for post-monsoon and pre-monsoon has been compared for understanding the spatial recharge status in the study area. Figure 12 is basically a subtraction of figure 11 from figure 10 in ArcGIS. The image is varying from shaded of red to yellow to blue for declined, stabilised and increased condition respectively after post-monsoon.

There is a maximum increase in water level has been observed in northern-most and southern-most part of the Bundelkhand region in the year of 2010. The least change or further decline in respective post-monsoon can be observed in the middle or northwestern part of the study area. The overall scenario tells about the decrease in recharge after post-monsoon.

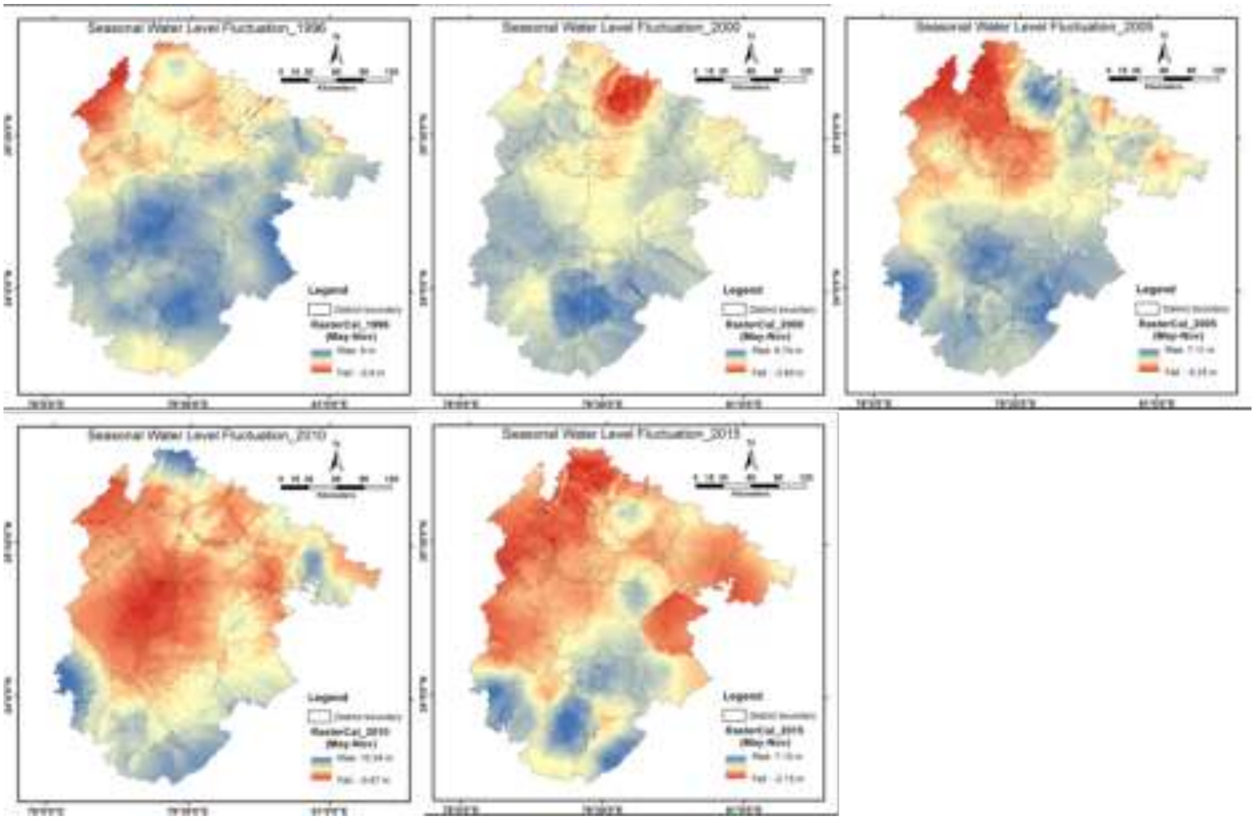


Figure 12: Seasonal water level fluctuation maps.

6.3.3 Spatio-temporal study of the water table

The ground elevation value for the water level observation points has been extracted from the DEM in ArcGIS. The depth to water level value has been subtracted from their respective point elevation values for all year’s available data. The water table map has been extrapolated outside the study area to understand groundwater dynamics at a wider scale.

The water table is important for studying the approximate direction of groundwater flow. The line drawn a perpendicular to the tangent on water table contour is key to know the direction of groundwater flow. Water table also indicates the recharge and discharge area, water divide, no flow zones etc.

(A) Pre-monsoon:

Figure 13 shows the water table contour map for May in and around the Bundelkhand region. The contour of the study area ranges between 560m in the southwest and 100m in along the northern border. The master slope of water table contour is towards north-east direction.

There is a concentric contour pattern in many places. That pattern is in the encircled by red line. The higher value towards the centre of the concentric contours circle suggests about the presence of water bodies. The red encircled zone could be generalised as recharge zone.

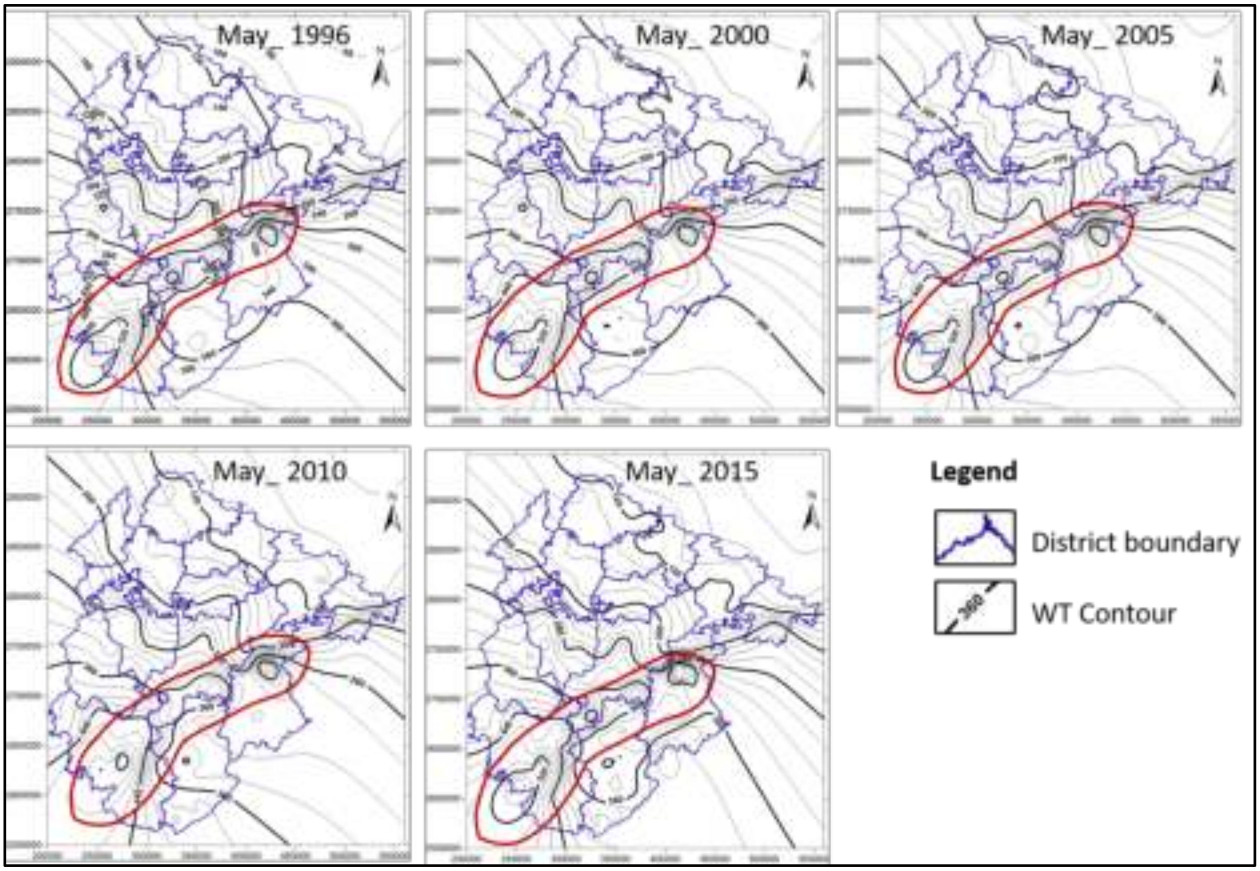


Figure 13: Pre-monsoon water table map extrapolated outside of the Bundelkhand region.

(B) Post-monsoon

Figure 14 shows the post-monsoon water table contour map for November in and around the Bundelkhand region. The contour of the study area ranges between 560m in the southwest and 120m in along the northern border. The master slope of water table contour is towards north-east direction.

There is a concentric contour pattern at many places similar to that in pre-monsoon condition. This region is encircled by red line and behaves as recharge zone.

The region southeast to this recharge zone is showing sparsely distributed contours. It indicates the increase in the water table due to monsoon. This finding could be rechecked with the water level fluctuation map (Figure 12) where this region has positive fluctuation in groundwater level.

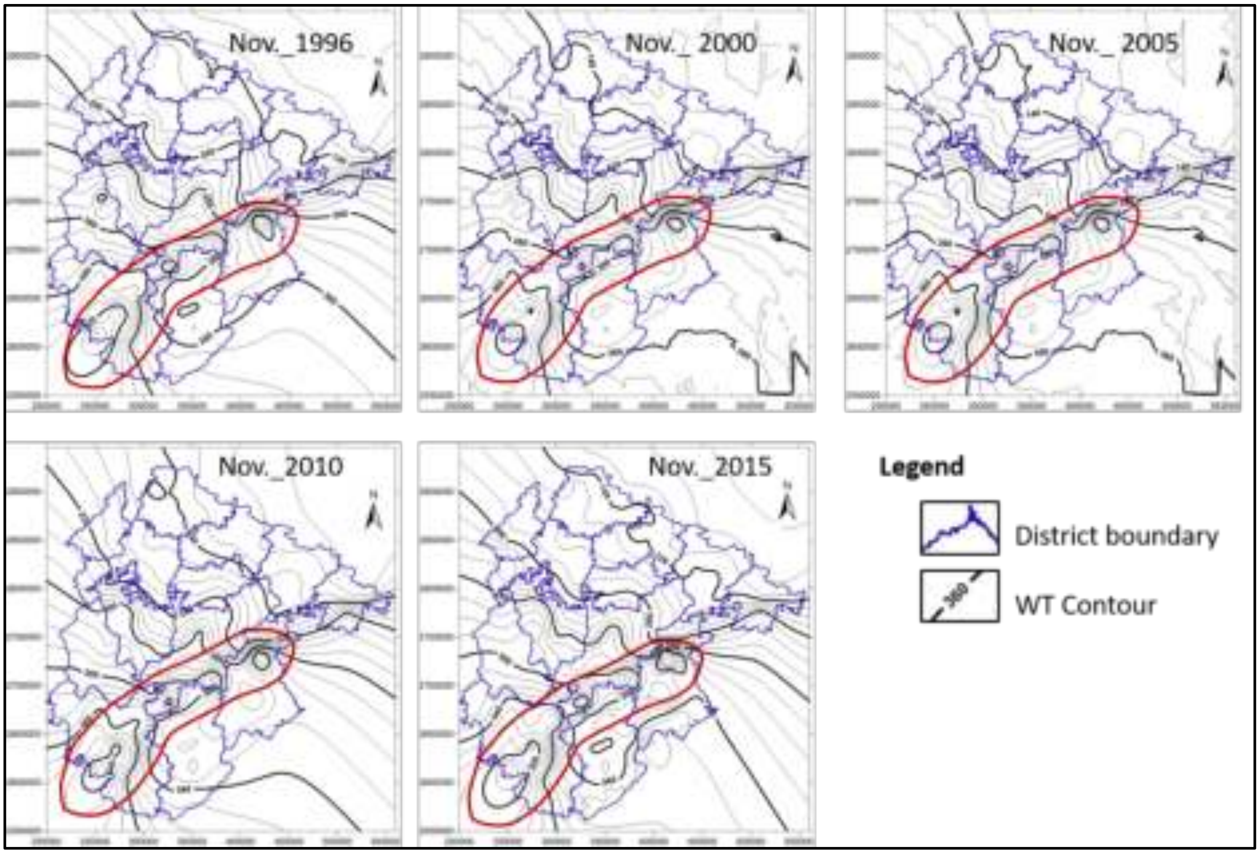


Figure 14: Post-monsoon water table map extrapolated outside of the Bundelkhand region.

6.4. Aquifer Parameters

A site-specific hydraulic property has been estimated using aquifer tests such as long and short duration pumping test and slug test. These values show the in-situ behaviour for the groundwater movement and its underground storage capacity. Table 6 shows the compilation of the aquifer parameter compiled from different Basic Data Report (BDR) of the CGWB. The hydraulic conductivity has been calculated by equation (1) and (2):

T=K*b … Eq. (1)

Where, T= Tramsmissivity (m/day)
K= Hydraulic conductivity (m/day)
b= saturated thickness (m)

b= Aquifer thickness- static water level (SWL) … Eq. (2)

The summary of the hydrogeological condition for other districts under the Bundelkhand region has been compiled from the respective NAQUIM reports and district groundwater information booklet as table 7.

Table 6: Hydrogeological condition compiled from the BDR of different inventory sites of Bundelkhand region

S. No	District	Location/ Village	LAT	LONG	Static Water Level (mbgl)	Aquifer thickness (m)	Transmissivity (m^2/day)	Saturated Thickness (m)	Hydraulic Conductivity (m/day)	Storage coefficient
A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I=G-F**	**J=H/I**	**K**
1	Banda	Banda	25.51	80.91	19.82	65	41	45.18	0.9	
2	Banda	Naraini	25.21	80.51	4.8	24.6	82.2	19.8	4.15	
3	Banda	Sunhula	25.6	80.79	21.17	78	1758	56.83	30.9	
4	Banda	Tangnamau	26.86	80.41	29.8	119	2776	89.2	31.1	
5	Banda	Para Bihari	25.45	80.56	1.4	73	2371	71.6	33.1	
6	Banda	Baberu	25.49	80.57	11	90	3257	79	41.2	$8.5x10^{-5}$
7	Jalaun	Bhagaura	26.01	79.46	24	93	613	69	8.88	
8	Jalaun	Etaura	26.01	79.43	20.62	114	907	93.38	9.71	
9	Jalaun	Nadigaon	26.1	79.02	16.95	93	1058	76.05	13.9	
10	Jalaun	Sirsakalan	26.29	79.43	17.64	100	1436	82.36	17.4	$4 x10^{-4}$
11	Jalaun	Bhuva	25.93	79.35	11.84	83	1390	71.16	19.5	
12	Jalaun	Bhadekh	26.37	79.47	10.59	130	2903	119.41	24.3	
13	Jalaun	Usargaon	25.99	79.38	8.39	81.79	1810	73.4	24.6	
14	Jalaun	Jagmanpur	26.35	79.46	30.39	133	2708	102.61	26.3	
15	Jalaun	Padluka	26.01	79.28	4.66	87	2263	82.34	27.4	
16	Jalaun	Bari Ka Purwa	26.4	79.43	18.72	168	4349	149.28	29.1	
17	Jalaun	Rajghat Kalpi	26.12	79.75	26.37	151	3717	124.63	29.8	
18	Jalaun	Orai	25.99	79.46	25.21	93	2406	67.79	35.4	$4 x10^{-5}$
19	Jalaun	Pithaupur	26.23	79.51	20.12	149	5755	128.88	44.6	
20	Jalaun	Chaunk	26.07	79.67	27.93	91	3154	63.07	50	
21	Jalaun	Konch	25.99	79.16	4.35	79.26	4100	74.91	54.7	
22	Jalaun	Konch	25.99	79.14	6.39	75	4117	68.61	60	
23	Jalaun	Bawali	26.14	79.01	13.91	68	3364	54.09	62.1	$8.34 x10^{-3}$
24	Jalaun	Kuthaund	26.35	79.42	23.94	80	3649	56.06	65	
25	Jhansi	Veerangana Nagar	25.45	78.61	2.75	9.93	84	7.18	11.6	
26	Jhansi	Pichhor	25.45	78.61	4	95	1324	91	14.5	
27	Mahoba	Mahoba 1	25.3	79.25	9	22	28.38	13	2.18	
28	Mahoba	Srinagar I	25.18	79.78	6.4	12.6	62	6.2	10	
29	Mahoba	Chakhari	25.4	79.76	4.5	8.5	57	4	14.2	
30	Mahoba	Jaitpur	25.2	79.56	**5**	5.7	13.5	0.7	19.2	
31	Mahoba	Srinagar Ii	25.15	79.76	7.9	12	177	4.1	43.1	

Table 7: Hydrogeological summary of the available NAQUIM reports for parts of the Bundelkhand regions.

District	Type of Aquifer	Formation	Depth Range (mbgl)	SWL (mbgl)	Thickness (m)	Discharge (lpm)	Sustainability	T (m2/d)	Sy/S
Jhansi	Shallow aquifer	Weathered Zone/ Alluvium	5-60	2-20	2-25	50-700	up to 10hrs	-	0.04
Jhansi	Deep aquifer	Fractured Granite	5-200	0.35-26	0.5-2.0	10-300	up to 8 hrs	25-500	$2.8x10^{-4}$
Lalitpur	Shallow aquifer	Weathered Zone/ Alluvium	10-30	2-15	2-20	50-200	up to 5hrs	-	-
Lalitpur	Deep aquifer	Fractured Granite	100-200	5-20	0.5-2.0	0-700	up to 5hrs	37-400	$7.5x10^{-5}$ to $1.57x10^{-3}$
Chhatarpur	Shallow+Deep	Weathered Zone/ Alluvium/fractured Granite	30-200	2.1 to 23.63	20-45	0.5 to 20	-	-	0.015
Damoh	Shallow+Deep	shale/sandstone/limestone	0-30-200	4.4 to 40	0-30	0.3-140	-	-	0.015
Datia	Shallow+Deep	Alluvium& fractured Granite, sandstone & shales	20-170	3.6-25.8	20-60	120-1800	2-6hrs	16 to 135	0.015-0.1
Panna	Shallow+Deep	Jointed sandstone, shale, granite	82-200	3.5-17	25-30	0-1020	16-24hrs		0.015
Sagar	Shallow+Deep	Bundelkhand massif/ Deccan traps	30-200	0-36	0-45	14-520	--	0.3-36-43	0.015
Tikamgarh	Shallow+Deep	Granite and Gneisses Alluvium	61-200	1.28-23.3	10-16.	60-375	2-3 hrs	13 to 145	0.015-$4.78x10^{-4}$

In addition to this, the calculation sheets for estimating the groundwater resources also have the data regarding the specific yield values at block level has been provided. In general, it ranges from 0.015 to 0.1 depending on the dominant lithology of the region.

6.5. Groundwater draft and recharge

6.5.1. Spatio-temporal variation

The annual groundwater draft and recharge rates are taken from the CGWB Dynamic Ground Water Resources reports for the assessment year 2004, 2009, 2011 and 2013 at district level for a quick understanding in the variation of stresses on the aquifer system. Furthermore, the detailed dynamic groundwater resources assessed at the block level by the CGWB has been provided for the previously mentioned years.

The reports provide a draft for irrigation and domestic and industrial draft annually for the entire district, whereas the recharge (from various sources) data has been provided for monsoon and non-monsoon period the year. These draft values have been compared and presented for different district under the Bundelkhand region graphically as figure 15(A) and 15(B) for the assessment years 2004, 2009, 2011, and 2013. Similarly, trend for the recharge from the rainfall and other sources has been summarised as figure 15(C) and 15(D) at district level for above said assessment years.

The draft for irrigation, and domestic and industrial purposes is generally in the range of 10-70 HaM and 0.5-4.5 HaM respectively, which indicates that agriculture is the major water-consuming sector. The recharge estimated from the rainfall and other sources (irrigation return flow, canal seepage etc.) is in the range of 10-110 HaM and 5-110 HaM respectively.

In general, the recharge from different sources is being calculated based on the GEC-97 norms (Ministry of Water Resources, 1997), which suggest that a certain fraction of the source volume could be the added to water table based on its depth and the prevailing cropping season. In general, it has been observed that rainfall is the major source of rainfall recharge. However, in Jalaun and Mahoba districts of U.P. recharge from other sources has been calculated equal to that from rainfall this is not the hydrological setup in all districts (see figure 15(C) & (D)). District groundwater brochure of Jalaun suggests the presence of good network canal system in all nine blocks, but it seems to be an anomaly w.r.t. other districts. Hence, the recharge from other sources has been compared with the total annual groundwater draft. The draft and recharge in terms of percentage with respect to the draft are plotted as line and Bar respectively in figure 16. It clearly shows that the Jalaun has always received recharge more than the groundwater withdrawal for all purposes. This kind of high recharge (except rainfall recharge) has not been reported from any district in this region except for Banda and Jhansi in the year 2004.

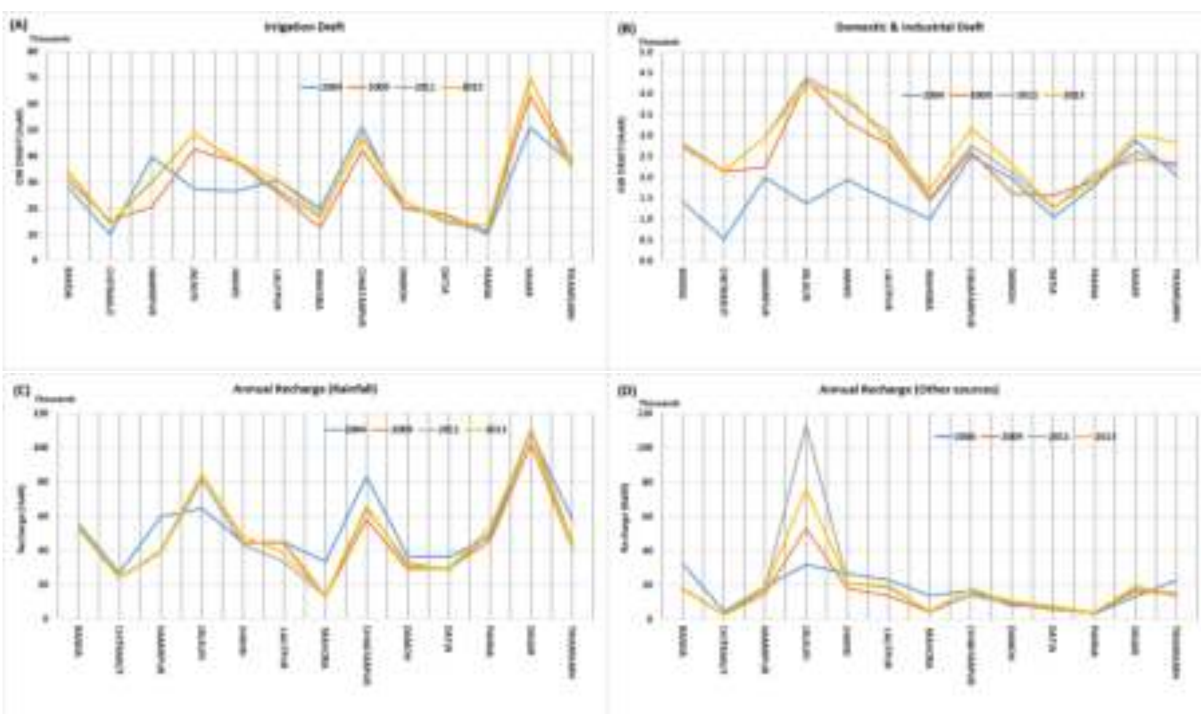


Figure 15: Dynamic Groundwater resource for the assessment years 2004, 2009, 2011, & 2013 for the different districts falling under the Bundelkhand region (Source: CGWB 2006, 2011, 2013 and 2017)

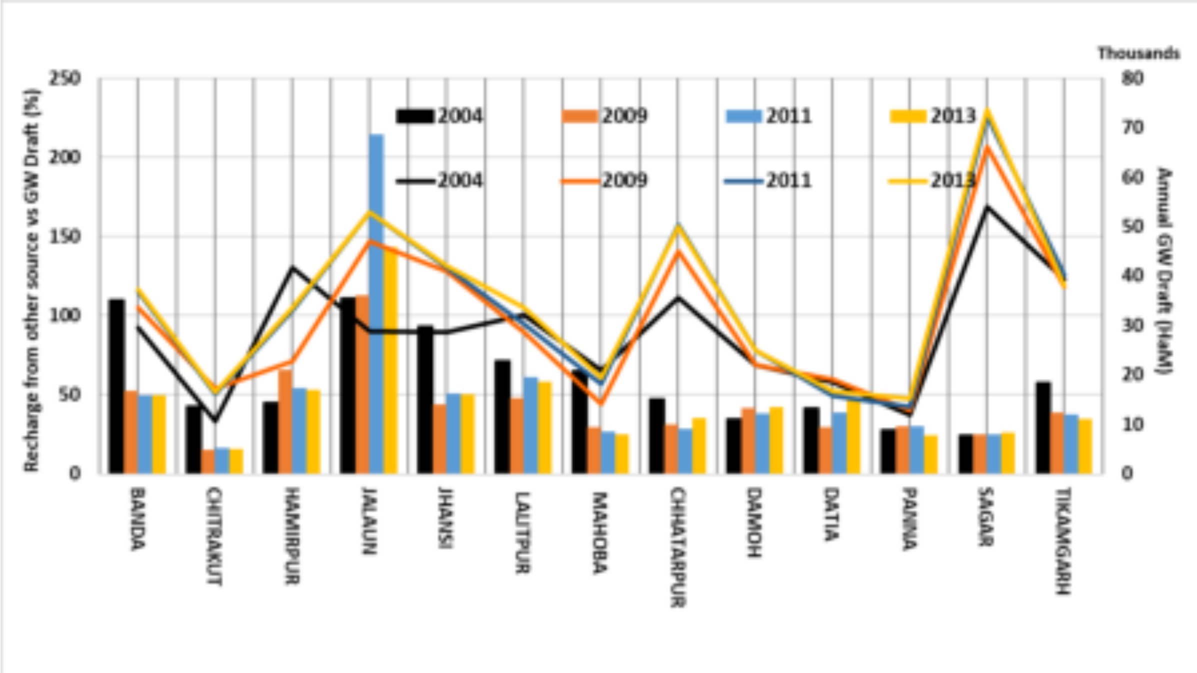


Figure 16: Comparison of annual groundwater draft for all sectors (line) with respect to the recharge to the groundwater from all sources (Bar) except rainfall.

The overall status of groundwater of the districts can be summarised in terms of its Stage of Groundwater development. It is accounted as the ratio of the total groundwater draft to net available groundwater resources. It can be mathematically expressed as equation (3):

$$Stage\ of\ GW\ Development\ (SoD)\% = \frac{Total\ Annual\ draft * 100}{Net\ available\ GW\ resource} \quad \ldots \text{Eq. (3)}$$

The perusal of the stage of groundwater development data at district (Table 8) reveals that presently it varies from 28% (Panna) to 111% (Mahoba). There are seven districts (marked in yellow) that have crossed 60% of groundwater development and are on the verge of moving towards the semi-critical category and we need to be cautious for future groundwater development in these districts. Rest of the districts can be categorised as safe zone where there no significant long term decline in water level is expected.

Table 8: Stage of Groundwater development (%) in districts of the Bundelkhand regions. (Source: CGWB, 2006, 2011, 2013 and 2017)

S.No.	State	District	2004	2009	2011	2013
1	UTTAR PRADESH	BANDA	36.70	53.00	54.63	53.85
2		CHITRAKOOT	36.80	72.00	66.13	64.32
3		HAMIRPUR	57.30	46.60	64.12	61.67
4		JALAUN	32.50	39.00	28.61	34.68

5		JHANSI	42.80	72.50	68.04	63.94
6		LALITPUR	51.70	53.60	61.62	60.68
7		MAHOBA	49.50	91.70	112.17	110.76
1	MADHYA PRADESH	CHHATARPUR	57	65.71	67	62.92
2		DAMOH	52	60.46	62	63.96
3		DATIA	44	57.34	48	46.31
4		PANNA	24	27.47	26	27.99
5		SAGAR	47	58.58	59	60.69
6		TIKAMGARH	51	71.39	72	72.95

Figure 17 shows a detailed block-level stage of groundwater development map for the assessment year of 2013 made from the data provided by the CGWB regional offices of Lucknow and Bhopal. The map is broadly classified into three zones:

Zone 1: Green colour, SoD < 70% (These regions are considered a safe zone, and the long term decline in water level could be insignificant.)

Zone 2: Rose pink colour, SoD=70-90% (These regions are considered as semi-critical zone)

Zone 3: Red colour, SoD=90-100% (These regions are considered as critical zone),

Zone 4: Brown colour, SoD >100% (These regions are considered as overexploited Zones)

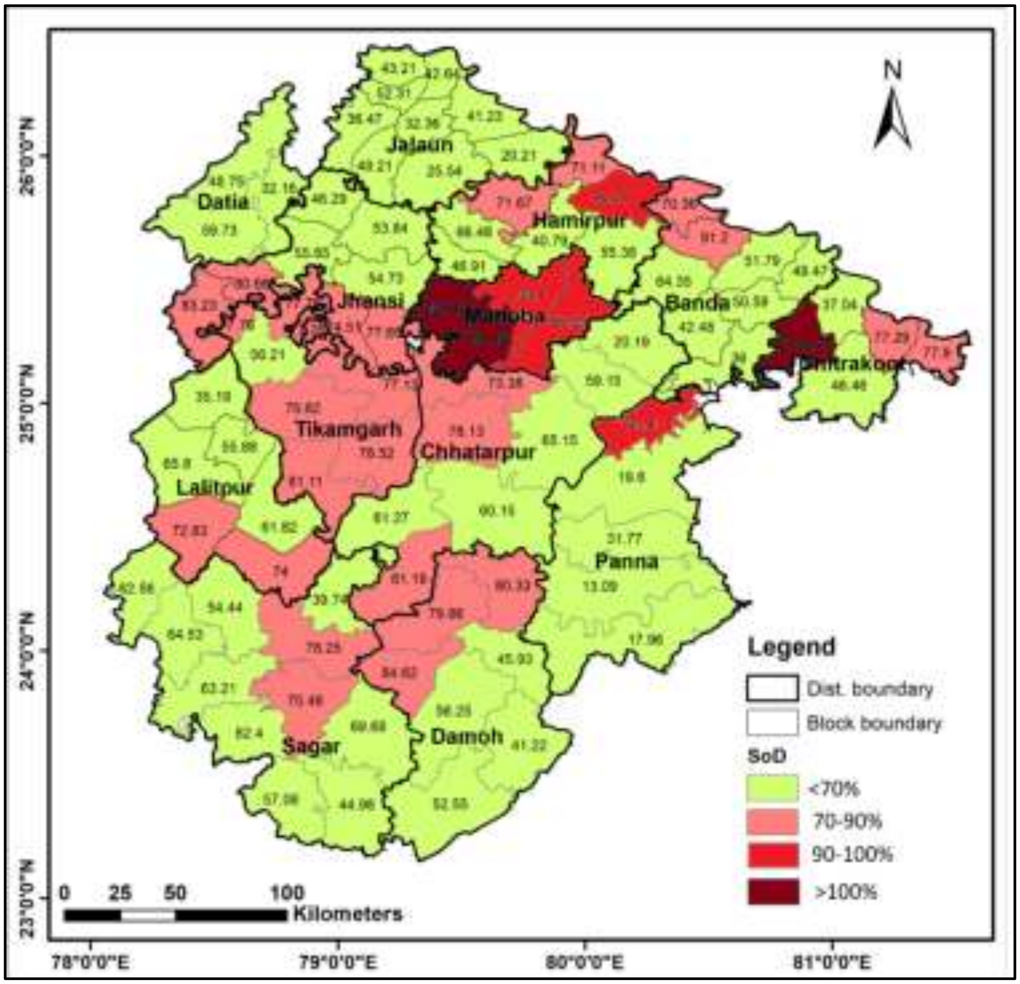


Figure 17: Spatial variation in stage of Groundwater development for the assessment year 2013 at the block level. (Source: CGWB)

As per the available resources for the year 2013, most of the region is falling under the safe zone, and only three blocks are extracting groundwater more than the recharge available from all sources. The zones having SoD > 70% (semi-critical, critical and Over -exploited) could be managed using different management strategies evolved in the different NAQUIM report of the respective districts. Overall, the status of Bundelkhand region is classified as SAFE except Mahoba.

6.5.2. Vertical variation

The data for the groundwater extraction was only available as the dynamic groundwater resources for the top unconfined aquifer. The distribution for the GW draft is not clearly mentioned with respect to the depth location/ disposition of different aquifer system. Based on the discussions with the regional office CGWB Lucknow & Bhopal, it decided to allocate the draft for unconfined aquifer system.

6.5.3. Stress period set up

The groundwater assessment year has been classified into two seasons: (1) monsoon (2) non-monsoon (GEC-97). The annual irrigation draft was bifurcated based on available draft calculation MS -Excel sheet for the assessment year 2009 for the districts falling in U.P state. Draft calculated for the monsoon/ non-monsoon season at block level is as equation (4):

Seasonal Draft = ∑(Season Wise unit Draft of different pumping structure)X (No. of different pumping Structure) … Eq. (4)

Based on the data related to Season wise unit draft and the number of total pumping structure, most of the blocks have used about 25% of the annual irrigation draft in monsoon period only, rest of the 75% irrigation draft is allocated for non-monsoon season. The blocks namely Chirgaon and Moth (Jhansi district) are exception in this observation having about 32% irrigation draft consumption in monsoon. This ratio has been used for bifurcating the irrigation draft for the other assessment years and the districts of M.P.

On the basis of normal rainfall and prevailing cropping pattern in the study area, the time duration for the seasons have been modified as follows to define the stress period:

(a) Monsoon stress- period: 15th June to 31st October (139 days)
(b) Non-Monsoon stress period: 1st November to 14th June (226 days)

NOTE: The annual domestic and industrial draft has not been divided according to the stress period because it is considered extracted consistently daily.

We have assigned a 5km*5km of area for running the numerical model. The extraction rate assigned for a grid has been calculated by equation (5):

$$Unit\ draft\ \left(\frac{m^3}{(day/25km^3)}\right) = \frac{Annual\ draft\ (HaM)*(0.25\ or\ 0.75\ or\ 1)*10000*25\ (km^2)}{(139\ or\ 226\ or\ 365)\ day*\ area\ (km^2)} \qquad \text{…Eq. (5)}$$

Where 0.25 and 139 days values are used for the monsoon irrigation draft, 0.75 and 226 days is used for the non-monsoonal irrigation draft. However, for domestic and industrial draft, value of 1 and 365 days are used for the unit draft calculation.

The final model input in the model is the sum of all types of draft prevailing during that particular stress period. Table 9 shows the calculation pattern of groundwater draft for the model input.

Table 9: Calculation format of groundwater draft for various stress period.

Area	Irrigation draft	Dom. + Ind. draft	Unit draft			Model input	
			Monsoon (Irrigation)	Non monsoon (Irrigation)	Dom.+Ind.	Monsoon draft	Non-monsoon draft
Shape file	Fig. 14(A)	Fig. 14(B)	15^{th} June to 31^{st} Oct. (139 days)	1^{st} Nov. to 14^{th} June (226 days)	(365 days)	15^{th} June to 31^{st} Oct. (139 days)	1^{st} Nov. to 14^{th} June (226 days)
A	B	C	D	E	F	G	H
Km^2	HaM	HaM	$m^3/day/km^2$	$m^3/day/km^2$	$m^3/day/km^2$	Draft per grid ($m^3/day/25km^2$)	Draft per grid ($m^3/day/25km^2$)
			(COL. B *10000*0.25)/ (139*COL A)	(COL B* 10000*0.75)/ (226*COL A)	(COLC*10000) / (365*COL A)	(D+F)*25	(E+F)*25

Since the model simulation starts from 1^{st} January 2002, the non-monsoon draft and recharge assessed for the year 2004 have been fed from 1^{st} January 2002 to 14^{th} June 2009, followed by monsoon draft and recharge in a cyclic pattern which is elaborated in Table 10. The model has been run up to 14^{th} June 2017 for calibration and validation purpose. The model has been further simulated for next 15 years for the prediction purpose.

Table 10: Repetition pattern of draft and recharge during model simulation.

Groundwater draft data	Using tenure in modelling
Assessment year 2004:	1^{st} January 2002 to 14^{th} June 2009
Assessment year 2009:	15^{th} June 2009 to 14^{th} June 2011
Assessment year 2011:	15^{th} June 2011 to 14^{th} June 2013
Assessment year 2013:	15^{th} June 2013 to 14^{th} June 2017
Assessment year 2017:	15^{th} June 2017 to 14^{th} June 2032 (for prediction)

6.6. Evapotranspiration

The term evapotranspiration is the combination of two different processes of evaporation and transpiration. Evaporation is the process of conversion of water (from the soil, pavement, waterbody, wet vegetation) into the vapour primarily due to solar radiation and ambient air temperature to a small extent. Whereas transpiration is the removal of water from the plant tissue (from the stomata of the leaves) in the form of vapour. Transpiration, like direct evaporation, depends on the energy supply, vapour pressure gradient and wind. Hence, radiation, air temperature, air humidity and wind terms should be considered when assessing transpiration (http://www.fao.org).

To obtain standard parameters and to develop a standard methodology is very challenging. Most of the ET model correlates the meteorological parameters with the evaporation statistically. The estimation of evaporation and ET is easier for the open water surface and wetlands rather than estimating ET from the crops/vegetative regions due to water acting as a limiting factor (Abtew & Melesse, 2012).

The data related to potential evapotranspiration (PET) and reference (crop) evapotranspiration (ET_o) is available online as annual mean and monthly mean for the year 1901 to 2002. Both data are frequently used interchangeably, which is not correct. Potential evapotranspiration at a site is the highest evapotranspiration that is recorded under the prevailing meteorological conditions whereas reference crop evapotranspiration is calculated as the evaporation with a reference well-watered crop (usually well-watered alfalfa of 12-cm height) with specified characteristic (Abtew & Melesse, 2012; http://www.fao.org).

For this study, monthly mean of reference crop evapotranspiration for the years 2000, 2001 and 2002 for each district of Bundelkhand region has been considered. The three-year data has been averaged for each month to understand the spatio-temporal pattern in data (table 11).

Table 11: Monthly averaged reference (crop) evapotranspiration (ETo) for Bundelkhand region (Source: http://www.indiawaterportal.org/met_data/, accessed on Feb. 2019).

UTTAR PRADESH							
	Banda	Chitrakoot	Hamirpur	Jalaun	Mahoba	Jhansi	Lalitpur
Jan	2.873333	2.87	2.87	2.793333	2.903333	2.87	2.993333
Feb	3.75	3.703333	3.76	3.716667	3.806667	3.773333	3.913333
Mar	5.44	5.383333	5.476667	5.43	5.45	5.413333	5.453333
Apr	7.056667	6.953333	7.14	7.1	7.06	7.01	6.936667
May	7.796667	7.693333	7.91	7.886667	7.786667	7.733333	7.586667
Jun	6.71	6.553333	6.846667	6.93	6.76	6.836667	6.666667
Jul	5.1	4.973333	5.243333	5.403333	5.096667	5.24	4.976667
Aug	4.456667	4.343333	4.586667	4.68	4.44	4.513333	4.243333
Sep	4.443333	4.283333	4.6	4.65	4.52	4.606667	4.486667
Oct	4.606667	4.47	4.736667	4.726667	4.703333	4.736667	4.706667

Nov	3.723333	3.68	3.73	3.706667	3.723333	3.706667	3.726667
Dec	2.893333	2.883333	2.91	2.826667	2.933333	2.9	3.03

MADHYA PRADESH						
	Chhatarpur	Datia	Damoh	Panna	Sagar	Tikamgarh
Jan	2.973333	2.813333	3.123333	3.04	3.116667	2.94
Feb	3.87	3.72	4.03	3.923333	4.026667	3.846667
Mar	5.443333	5.373333	5.496667	5.48	5.506667	5.426667
Apr	6.973333	6.98	6.94	6.983333	6.946667	6.963333
May	7.693333	7.713333	7.526667	7.65	7.496667	7.663333
Jun	6.68	6.876667	6.423333	6.556667	6.47	6.743333
Jul	4.953333	5.34	4.676667	4.823333	4.706667	5.073333
Aug	4.303333	4.58	4.066667	4.216667	4.07	4.363333
Sep	4.423333	4.646667	4.316667	4.34	4.373333	4.523333
Oct	4.65	4.73	4.593333	4.583333	4.67	4.706667
Nov	3.726667	3.69	3.753333	3.75	3.756667	3.706667
Dec	2.993333	2.856667	3.113333	3.046667	3.126667	2.98

7. Groundwater Modelling

The lithology, hydrogeological properties and geological set up of Bundelkhand region are very complex. The northern part is covered with thick alluvium which pinches out near the border of UP and MP. Whereas southern part is made up of hard rock having no or very thin layer of alluvium deposit. The major litho-units present in the region are granite, basalt, sandstone, quartzite, shale, limestone, and alluvium deposits (see table 1, 2 & 3; figure 2). It has been decided to consider the consolidated formation separately from the alluvium terrain.

A conceptual model has been developed and simulated using Visual MODFLOW Flex 6.1-GUI. This software uses a very popular MODFLOW code for simulating and predicting groundwater conditions and groundwater/surface-water interactions. It solves the three-dimensional groundwater flow equation (equation 6) using Finite Difference Method.

The general **governing equation** (differential equation) representing the three-dimensional transient groundwater flows in a heterogeneous and anisotropic medium is as following

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = S_s \frac{\partial h}{\partial t} - R^* \text{ … Eq. (6)}$$

where K_x, K_y, and K_z are values of hydraulic conductivity along the x, y and z coordinate axes, S_s is the specific storage of the porous material (L^{-1}); and h is the potentiometric head, and R* is source or sink.

The modelling process starts with the development of a conceptual model. The different layers of the model are decided based on the litho-units. For example, younger and older alluvium can be combined to form single layer, different fracture zones could be grouped under one aquifer system etc.

The modelling software dedicated to deal with the diverse and heterogeneous nature from the prospect of groundwater is not available. The density and orientation of fractures make the groundwater flow non-laminar. For developing a groundwater model using the MODFLOW needs either a very detailed data set or making a model equivalent to fractured aquifer system.

Hence, the basic principle remains the same for simulating the groundwater flow system in hard rock terrain and unconsolidated sedimentary rocks. The groundwater condition has been simulated using MODFLOW code for the Bundelkhand region with appropriate approximation of hydrologic properties. Some of the literature review regarding the hydraulic properties to be considered for modelling hard rock terrain are as following:

- Primary permeability: 10^{-2} to 10^{-16} cm^2/sec (K: 10^{-8} to 10^{-11}cm/sec) (Freeze and Cherry, 1979)
- Secondary permeability: Effective K may increase up to 5 order, depending on rock types, number of fractures and fracture intersections etc. (Gale et al., 1982)

However, if a solution occurs within the fractures, permeability can increase to a much larger magnitude.

- Fracture flow models (excluding conduit flow) assume that fracture apertures and flow velocities are small so that Darcy's law applies.
- Conceptually fractured rock can be modelled as (See figure 18).:

  (a) Equivalent porous medium (EPM) - used for very large-scale problems if there is no need for knowing the flow field in detail.

  (b) Discrete fracture (DF) - creates an exact representation of the fractured environment as possible by simulating particular fractures. These models can be used only for solution of the problems on relatively small domains (up to tens of meter).

  (c) Dual porosity (DP) - works with two connected continua – representing fractures and porous blocks.

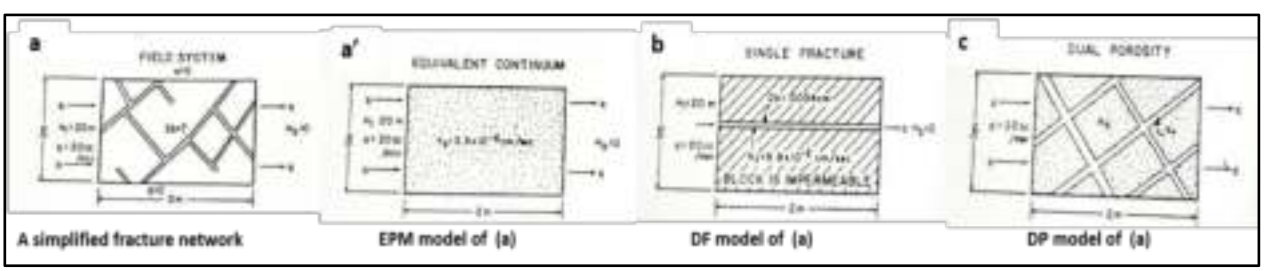


Figure 18: Representation of different conceptualisation methods of hard rock modelling.

The first approach to conceptualize a large modelling area is as EPM. Here, fracture zones of hard rock terrains are represented by equivalent porous medium (EPM). It needs either a gross simplification or a detailed description of aquifer properties controlling the flow.

For modelling hard-rock aquifers, the weathered zone, which is a true porous medium, can be represented by the continuum equation. For the weathered-fractured zone, it is usual to assume that the flow can be represented, by the same equation, for an equivalent continuous, possibly anisotropic, porous medium. This assumption is only valid at a certain scale, for a volume of rock including a sufficient number of fractures, so that the individual properties of each fracture are averaged out within the large-scale volume.

Discrete Fracture (DF) Model:

Water moves through fracture network only and hence DF model is useful for crystalline hard rocks having no primary porosity. The total quantity of flow (Q_f) is given by equation (7):

$$Q_f = 2b * w * K_f \, (dh/dl) \qquad \ldots \text{ Eq. (7)} \qquad \text{(Sahu, 1999)}$$

Where; 2b is fracture aperture;
w is fracture width;
K_f is hydraulic conductivity of fracture;
dh/dl is slope of hydraulic head (h);
l is length of flow

Dual Porosity (DP) Model:

In a fractured hard rock, whenever the stress is applied, viz., pumping, the fractures yield water first and becomes reduced due to pressure difference, the associated minor fractures called as block start yielding water.

Boundary Condition:

The boundary condition is probably the most important and critical in conceptualising the groundwater model. Improper selection may result an unresponsive model with respect to the stresses applied in real world. The selection of boundary condition for conceptual or numerical model needs to simplify the existing hydrogeological conditions prevailing in the model domain.

For modelling the regional model of Bundelkhand as a whole, the hydrological boundary could be conceptualised using the water table map of the region. The water table pattern variation with time is shown in figure 11 & 12 for both pre and post-monsoon respectively. The river Yamuna flowing along its northern boundary (Figure 19) can also act as boundary condition.

Figure 19 shows the proposed boundary condition for the regional level model based on groundwater flow lines and the presence of river Yamuna. The river Yamuna flows along the northern boundary of the study area (blue line for representation only). This can be considered as boundary (river package in MODFLOW) for simulating the model.

The flow line outside of the study area shows that the water is flowing from southwest- to northeast direction in a semi-circular path. The groundwater movement across the flow does not occur. Hence, the boundary in south, east and west can be considered as NO-FLOW boundary (shown with green line in figure 19).

Similarly, the contour pattern in the northern boundary of the study area is almost parallel with the water table contour values of 100m and 80m. Hence, the contour of 90m could be used as CONSTANT-HEAD OR SPECIFIED HEAD boundary in northern boundary of study area (if river-related data is not found available).

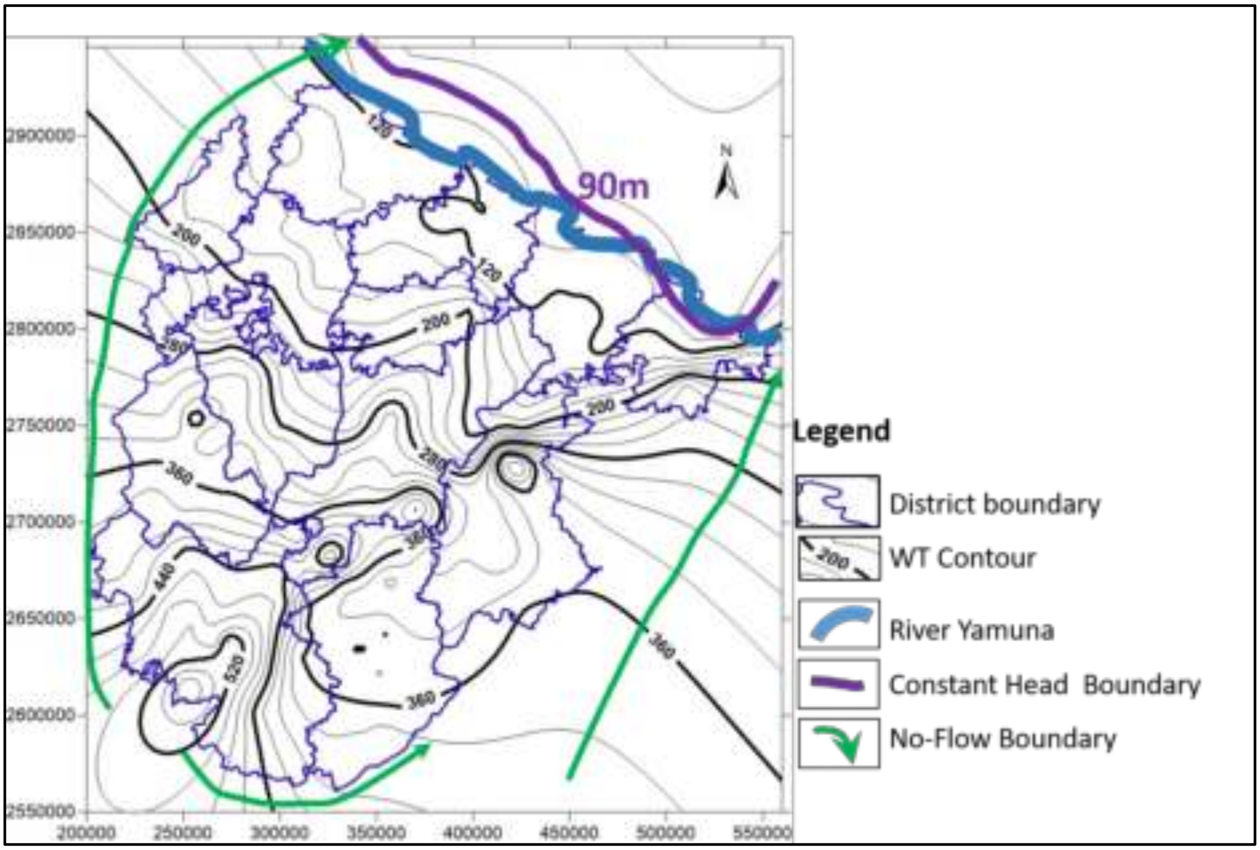


Figure 19: Probable Boundary Condition for GW modelling in Bundelkhand

The selection of boundary condition is a critical step in modelling, which requires a detailed hydrogeological study of the region, such as river stage data varying along its course and time, water level data, evapotranspiration etc. One boundary condition could be translated differently in the model.

7.1. Data organization and modelling protocol

The raw data were collected from different sources and in different formats. So, it was important to convert all of them in a format that is compatible to the model. Figure 20 describes the various kinds of data to be translated into a common platform to start the model. The modelling protocol consists of a series of steps that will aid in the construction of a calibrated and validated model which can be used or predicting the behaviour of the groundwater system with confidence. The data organisation and processes for making "ready to feed" has been discussed in inception report as well as in previous sections of this report itself. Here, the important steps for modelling will be discussed in brief. Figure 20 shows the protocol to follow for the execution of model.

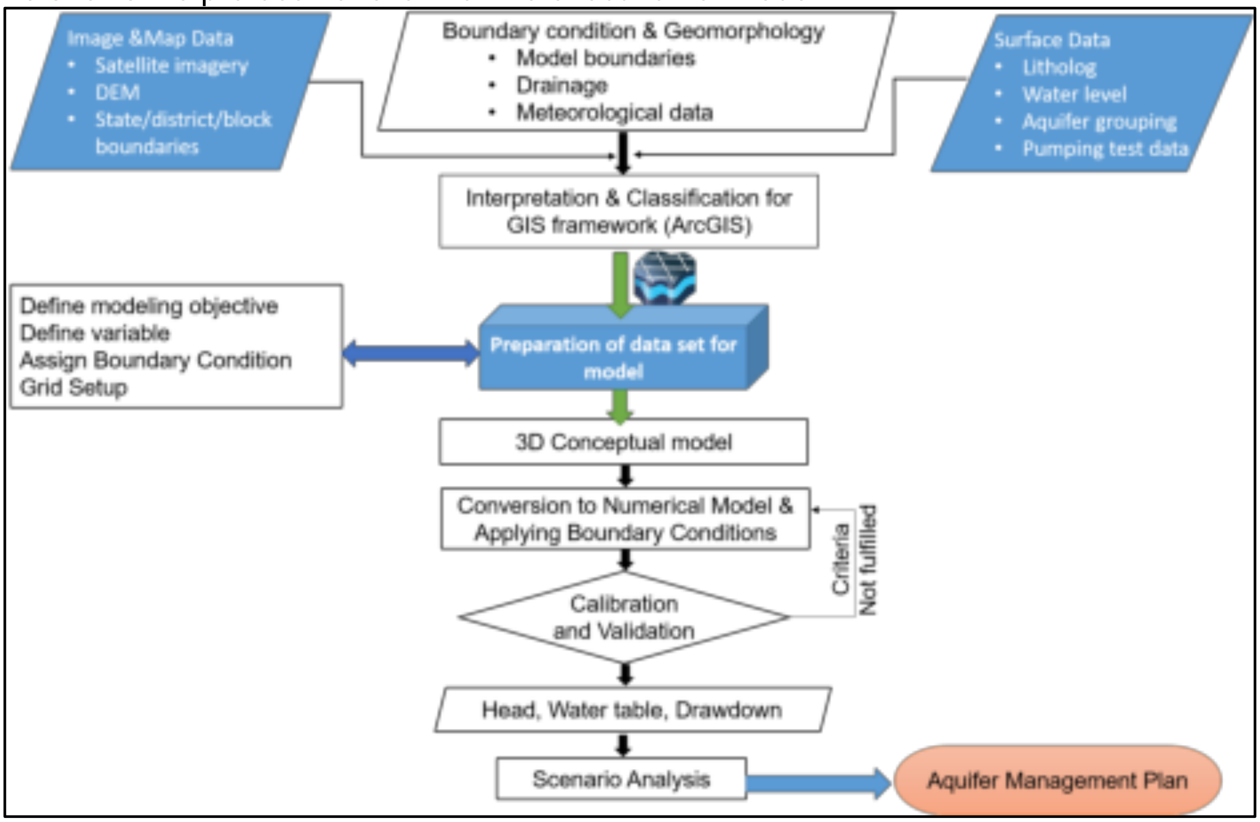


Figure 20: Steps in the protocol for Modelling

7.2. Model Conceptualization

The first important step here is the development of the conceptual model, which is based mainly on field investigations. It also includes the identification of hydrologic and boundary conditions. The main purpose of the conceptual model is to simplify the actual field conditions and to synthesise and organise all available set of data so that actual scenario can be visualised (Anderson and Woessner, 1992). Figure 21 shows the different steps and dataset required to make a conceptual model in VMOD Flex 6.1.

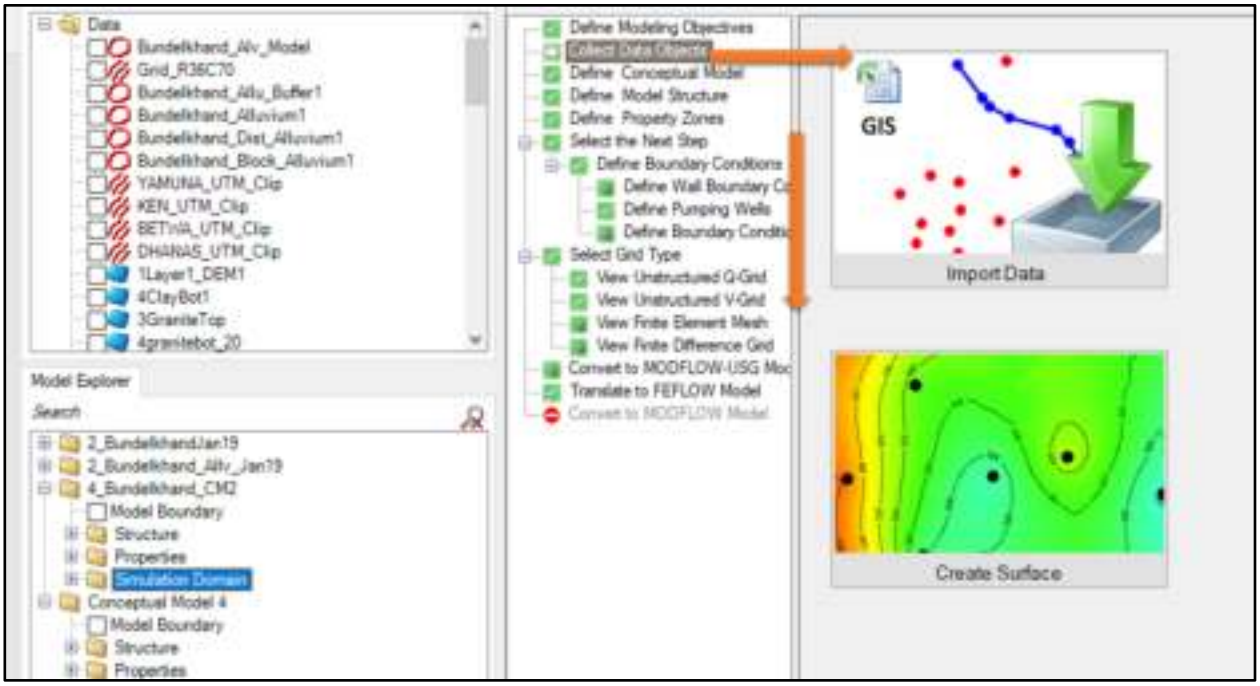


Figure 21: Workflow window for importing the various types of data in VMOD Flex.

7.3. Numerical Modelling

After the development of the conceptual model, different data sets such as groundwater extraction, recharge, observation wells, aquifer properties, initial head, simulation period etc. have to be fed. The steps and data involved to run a numerical groundwater model on the VMOD Flex 6.1 are shown in figure 22. The modelling could be done on a steady-state or transient state or both. When the water level data becomes insufficient to produce the initial head in each cell of the numerical model, then the initial head output from the steady-state model is imported into the transient model. Although it is a general practice to start with a steady-state model which is then converted into a transient condition model, we have been able to run the model with transient state directly (Maheswaran et al., 2016).

Figure 22. Workflow window for important steps involved to run a numerical groundwater model. The final run is analysed by comparing the simulated result with the observed water level data and maps.

In the following sections the model for alluvium region will be discussed separately. The model for the hard rock region will be presented in second part of this report.

8. Regional Modelling for Alluvium part of Bundelkhand region

8.1. Preparation of datasets in GIS framework and data integration of various parameters required for groundwater modeling

The data necessary for the modelling purpose are litholog, observed water level aquifer parameters, groundwater draft and recharge data. Most of them have been discussed in the earlier section. Important steps are discussed in the following sections.

8.1.1. Litholog/Aquifer grouping data

The litholog data were analysed and grouped into aquifer and non-aquifer horizons. The litholog data is not evenly distributed (figure 23), however they are sufficient to generate the different subsurface horizon. Although many of the lithologs are falling outside of the alluvial modelling domain, they have been incorporated to have a higher subsurface resolution. Figure 23 shows the model extent in terms of minimum to maximum lat/long which has been divided into 35 rows and 69 columns, having an equal spacing of 5km. The litholog data suggests overall presence of three layers from surface to drilling extend which in general varies from clay/overburden to sand to basement on moving from top to bottom. The type of basement encountered and their elevation with reference to the mean sea level has been shown using different symbols. Hence, it is clear from the figure 23 that the alluvium part of the Bundelkhand region is underlain by the Granitic basement except in Chitrakoot district where sandstone/ quartzite has been reported as basement rock. Somewhere at the border between Banda and Hamirpur, one BDR report has mentioned sandstone as basement rock which might be most probably due to an interpretational error.

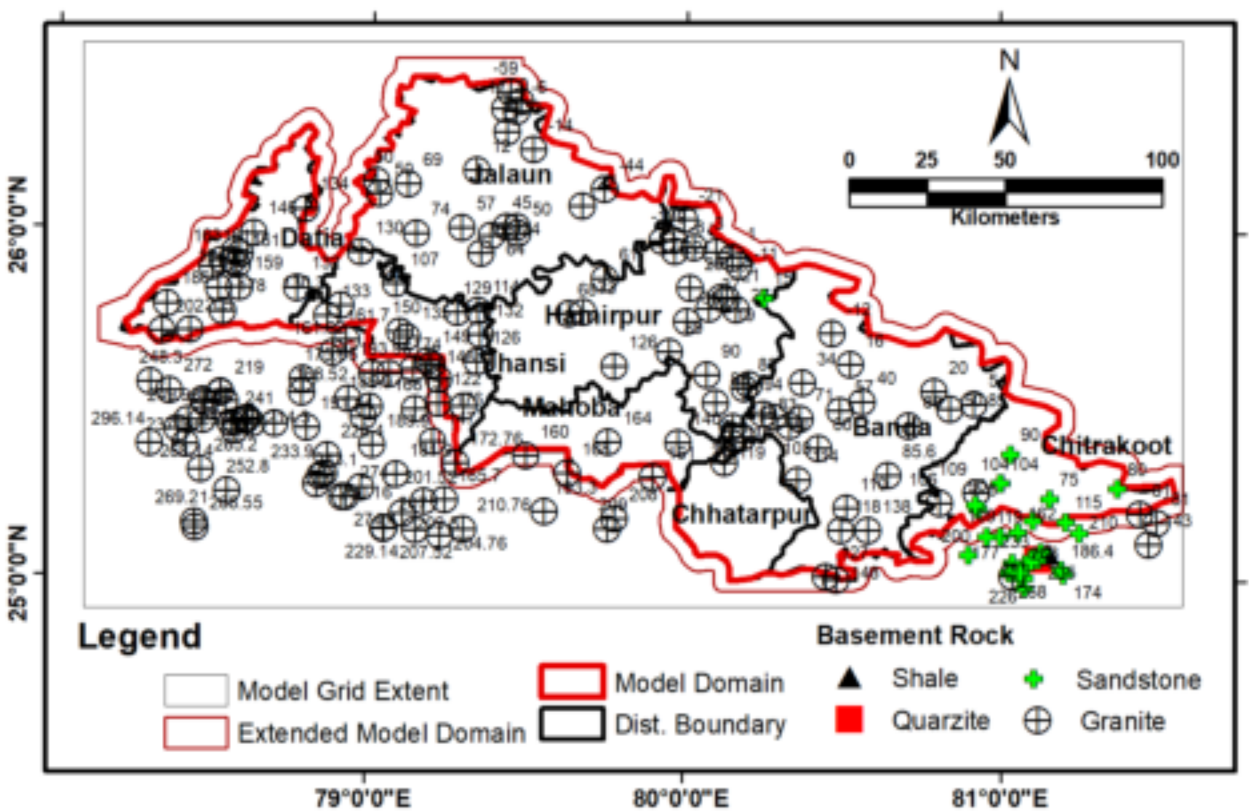


Figure 23: The spatial distribution of lithologs in the study area. The region is underlain by different rock, and their elevation is shown along with their location.

8.1.2. Observation Wells (OW) / Water level data

There are about 47 water level data has been used for assessing the model simulated water level head. The geographical location of those observation wells is plotted in figure 24. The observation wells are having data for the months of May and November from year 2002 to 2017. The latest water level data used is of May 2017.

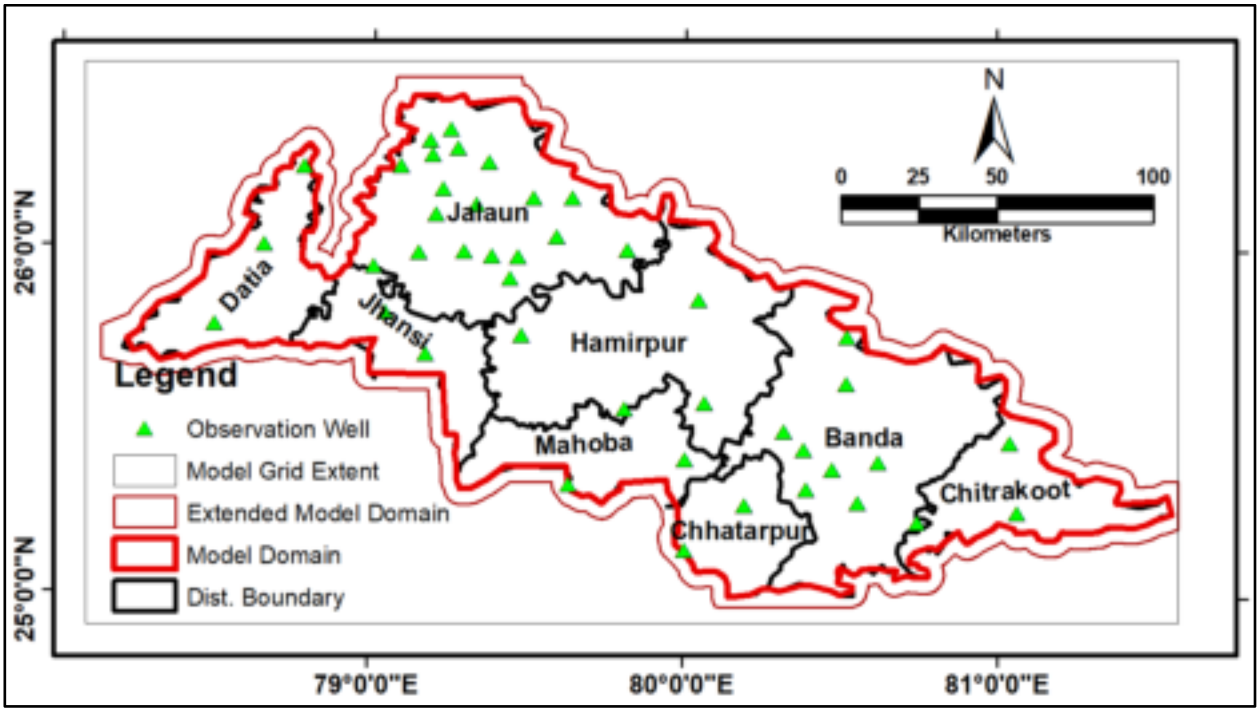


Figure 24: The spatial distribution of observation wells in the study area used for the model calibration.

The water level data has been arranged as per the required model input format. Table 12 shows the necessary attributes (column A to I) to be associated and preferable arrangement of the observation well data. "Well Id" is unique id assigned to each individual well. The "Well Id" assigned by in the CGWB data sheet was not directly relatable with its location. Therefore, the "Well Id" of the observation wells has been coded using the first three alphabets from the district's name, next four alphabets from the block name and rest part from the CGWB assigned code. Hence, **BanBadoW14734** represents the observation well from the district of "**Ban**da" (Column J) and "**Bado**khar Khurd**"** block (column K) and CGWB OW-code **W14734** . This coding scheme is subjective to the individual's choice.

The elevation and well bottom values are extracted from the SRTM and elevation of layer 3 i.e. top of bedrock respectively. The screen id is not an important parameter presently so it can be assigned any code. The values for observation point elevation (Column G) are assigned as 5-10m above to the well bottom the difference of about five meters with the well top and bottom has been assigned, however the observation well geometry has been rechecked by importing them in Visual MODFLOW Flex to validate it with the aquifer geometry.

Table 12: Required format to arrange the water level data for importing observation well option in Visual MODFLOW Flex.

Well Id	X	Y	Elevation	Well bottom	Obs. Point Id	Obs. Point Z	Observed Head	Head Observation Date	Dist.	Block
A	B	C	D	E	F	G	H	I	J	K
BanBadoW14734	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
BanBadoW14734	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
BanBadoW14734	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	118.3	[illegible]	[illegible]	[illegible]
BanBadoW14734	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
BanBadoW14734	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.	..	[illegible]	[illegible]
BanBadoW14734	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.	..	[illegible]	[illegible]
BanBadoW14734	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.	..	[illegible]	[illegible]
BanBadoW14734	421735	2212640	122	30	4734	27	...	....	Barda	[illegible]
BanBadoW14734	421735	2212640	122	30	4734	27	112.5	15 06 2015	Barda	[illegible]
BanBadoW14734	421735	2212640	122	30	4734	27	112.6	[illegible]	Barda	[illegible]
BanBadoW14734	421735	2212640	122	30	4734	27	[illegible]	15 06 2017	Barda	[illegible]

8.1.3. Wells (Groundwater draft)

To input, the draft data in the model, an evenly spaced pumping well (Figure 25) has been made using Fish Net method on ArcGIS platform. Since each pumping well was placed between a 5km*5km grid of the model, so they have been assigned an average unit draft for the 25 km^2 area of the respective block. The draft calculation and its variation with time have been mentioned previously in section 6.5 (table 9 and 10).

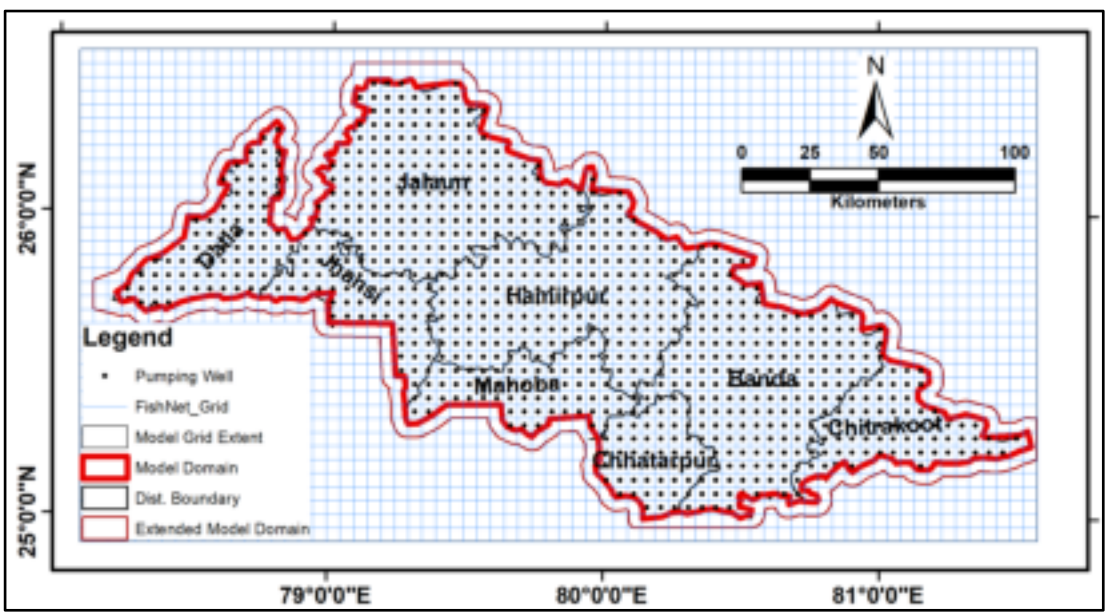


Figure 25: Generation of representative pumping well using Fish Net method in ArcGIS platform for the model input. A total of 857 representative pumping wells have been created in the model region.

The pumping well draft has been arranged as per the required model input format. Table 13 shows the necessary attributes (column A to K) to be associated and preferable arrangement of the pumping well data. “Well Id” is unique id assigned to each individual well. To understand directly about the locality of the P. Well, the Well Id has been coded using the first three alphabets from the districts name, next four alphabets from the block name and numerical value from the FiD assigned automatically in ArcGIS. Hence, **BanBabe**348 is pumping well from the **Ban**da district (Column L) and **Babe**ru block (column M). This coding scheme is subjective to the individual’s choice.

The pumping well elevation and bottom values are extracted from the SRTM and elevation of layer 3, i.e. top of bedrock, respectively. The screen id is not an important parameter presently so it can be assigned any code. The values for screen top and bottom are assigned as such that it should fall between the top and bottom of the well. In general, a difference of about five meters with the well top and bottom has been assigned, however the well geometry has been rechecked by importing them in Visual MODFLOW Flex several times to validate the well geometry with the aquifer geometry.

Table 13: Required format to arrange the draft input using Pumping Well option in Visual MODFLOW Flex.

Well Id	X	Y	Elevation	Well Bottom	Screen Id	Screen top Z	Screen bottom Z	Pumping Start Date	Pumping End Date	Pumping Rate	Dist	Block
A	B	C	D	E	F	G	H	I	J	K	L	M
BanBabe348	450422	2819900	125	57.61	1	124.5	82.02	15-06-2009	31-10-2009	-2730	BANDA	BABERU
BanBabe349	455422	2819900	125	50.302	2	124.5	75.75	15-06-2009	31-10-2009	-2730	BANDA	BABERU
BanBabe350	460422	2819900	123	53.453	3	122.5	77.27	15-06-2009	31-10-2009	-2730	BANDA	BABERU
BanBabe351	465422	2819900	123	59.376	4	122.5	78.7	15-06-2009	31-10-2009	-2730	BANDA	BABERU
BanBabe352	455422	2824900	120	37.775	5	119.5	69.34	15-06-2009	31-10-2009	-2730	BANDA	BABERU
BanBabe353	460422	2824900	121	37.787	6	120.5	70.05	15-06-2009	31-10-2009	-2730	BANDA	BABERU
BanBabe354	465422	2824900	119	40.52	7	118.5	73.87	15-06-2009	31-10-2009	-2730	BANDA	BABERU
BanBabe355	470422	2824900	119	39.189	8	118.5	78.12	15-06-2009	31-10-2009	-2730	BANDA	BABERU
BanBabe356	475422	2824900	115	31.729	9	114.5	92.4	15-06-2009	31-10-2009	-2730	BANDA	BABERU
BanBabe357	460422	2829900	117	27.289	10	116.5	65.99	15-06-2009	31-10-2009	-2730	BANDA	BABERU
BanBabe358	465422	2829900	114	27.549	11	113.5	68.79	15-06-2009	31-10-2009	-2730	BANDA	BABERU
BanBabe359	470422	2829900	117	23.602	12	116.5	73.11	15-06-2009	31-10-2009	-2730	BANDA	BABERU
BanBabe360	475422	2829900	115	18.553	13	114.5	76.50	15-06-2009	31-10-2009	-2730	BANDA	BABERU
BanBabe361	480422	2829900	115	18.175	14	114.5	79.52	15-06-2009	31-10-2009	-2730	BANDA	BABERU

8.1.4. Recharge

For simulating the groundwater model, the recharge values form the rainfall, and total recharge (rainfall + other sources) have been converted into “unit recharge” at the block level. The data for the different recharge sources, groundwater draft and water level suggests the overestimation of recharge. Hence, the recharge from the rainfall has been finalised for modelling exercise. The variation of recharge at block level are not found very high. Therefore, the recharge has been averaged to enter at district level.

To input the recharge data, the recharge values have to be mapped with the polygon. Therefore, a time schedule and corresponding unit recharge values for the different districts have been imported in the model. The format of time schedule for the recharge is presented below as table 14. It is necessary to note that separate polygon for each zone should be imported into the model for defining different recharge zones.

Table 14: Model input format for importing recharge (m/day) for different districts (zone).

Time schedule (Stress period)	BANDA	CHITRAKOOT	HAMIRPUR	JALAUN	JHANSI	MAHOBA	CHHATARPUR	DATIA
01-01-2002	0	0	0.000077	0.000061	0.000051	0.000000	0.000000	0.000000
15-06-2002	0.00085	0.00057	0.000827	0.000833	0.000510	0.000860	0.000495	0.000824
31-10-2002	0	0	0.000077	0.000061	0.000051	0.000000	0.000000	0.000000
…..	…..	…..	…..	…..	…..	…..	…..	…..
…..	…..	…..	…..	…..	…..	…..	…..	…..
…..	…..	…..	…..	…..	…..	…..	…..	…..
31-10-2031	0	0	0.000072	0.000086	0.000061	0.000000	0.000000	0.000000
15-06-2032	0.00078	0.00052	0.000505	0.001064	0.000470	0.000323	0.000552	0.000835

8.1.5. Evapotranspiration

For simulating the groundwater model, the reference crop evapotranspiration has been used. It is one of the important factors which controls the availability of water. The water loss due to evapotranspiration could be as good as a small tubewell depending upon the climatic conditions. The ET data is not available for the modelling period which leads us to use the monthly average values of the last three years (2000, 2001, & 2002) data for the study area. Figure 26 shows the plot for the three year average monthly data plotted for the different districts of the model area. Although the average of the total ET data considered (monthly data for three years for thirteen districts) is 0.00049 m/day (4.9 mm/day), the average of ET in April, May and June are 0.00072 m/day (7.2 mm/day) (approx.); however, it is 4.17mm/day (approx.) for rest of months.

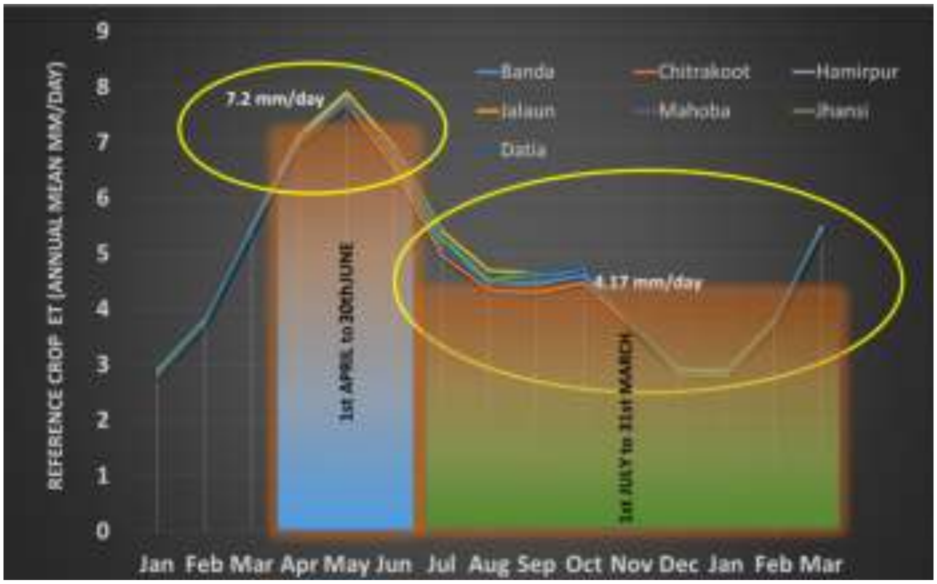


Figure 26: Variation in evapotranspiration in the model area. The different zones are demarcating the two broader prevailing ET rates.

The variation in the evapotranspiration data is not very high (figure 26) in the model area. This finding gives the liberty to assign one value in the entire model domain within the defined stress period.

To input the evapotranspiration data, the ET values have to be mapped with the polygon. Therefore, a “time-schedule” and corresponding ET values for the whole model region has been imported in the model. The format of time schedule for the ET is similar to that of recharge (table 14). It is necessary to note that a separate polygon should be imported into the model for defining ET zone.

8.2. Preparation of a 3-dimensional conceptual model

A conceptual model of the study area was developed based on the hydrogeological system, prevailing boundary condition, major stresses on the groundwater, and most importantly, through discussions with the experienced scientist from the CGWB.

8.2.1. Layer set up

The litholog data for shallow, intermediate and deep exploratory wells and observation wells were categorised into clay, sand dominant horizons and basement rock. The horizon boundary elevation has been interpolated in ArcGIS and Visual MODFLOW Flex platforms to get a relatively smooth layer which had been used finally for conceptualising of the model. The position and spatial reference of the layers interpolated in Visual MODFLOW Flex is given as figure 27.

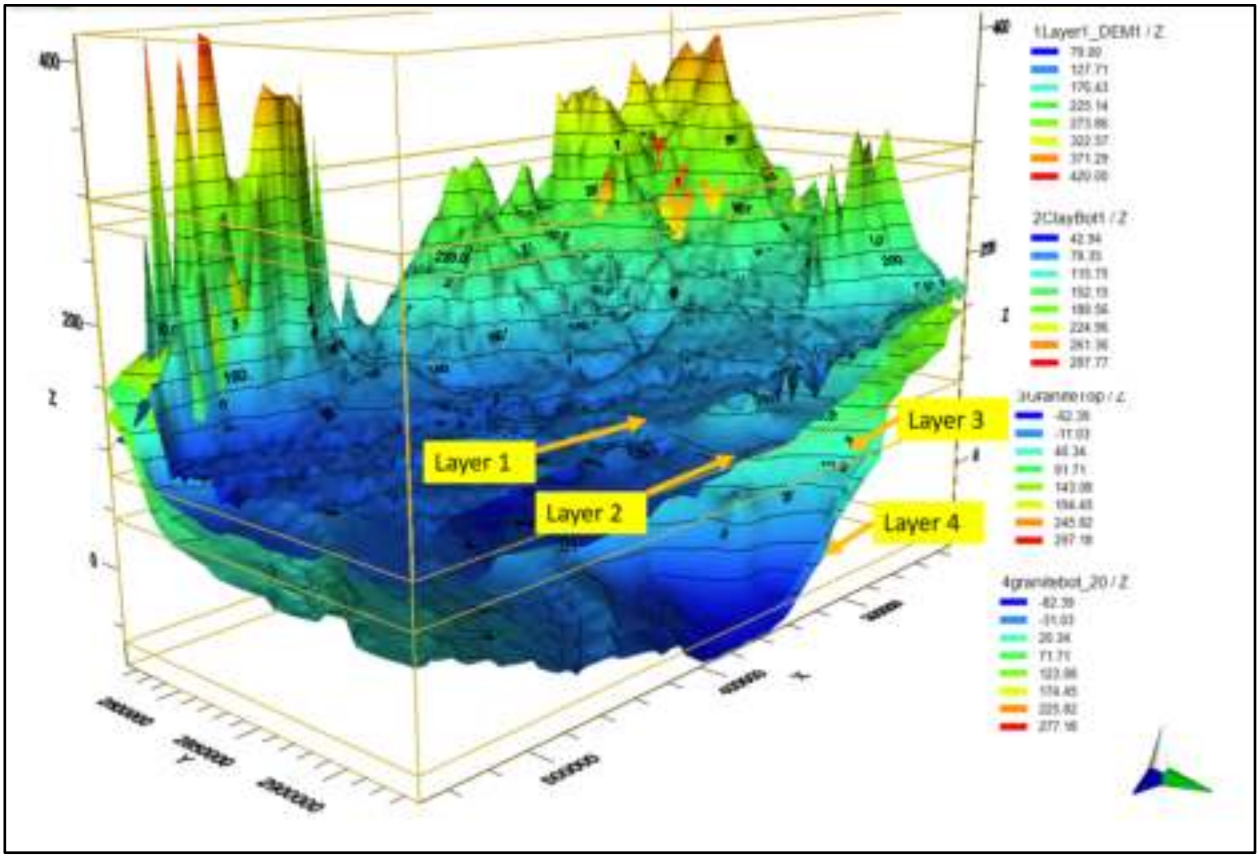


Figure 27: Different layers based on the CGWB lithologs. (Vertical exaggeration =500).

There are two aquifers delineated between layer one –layer 2 and layer 2-layer 3. The 1st aquifer is having clay, 2nd aquifer is silty sand which is underlain by the Granitic/sandstone basement.

8.2.2. Conceptual Model development

8.2.2.1. Horizontal Extent

The model covers alluvial part of the Bundelkhand region. It is bounded by the exposure of Bundelkhand granite in the south, sandstone in east, district boundary in the north and west. However, to avoid any probable boundary problem in simulating the region, the boundary has been extended with a buffer of 5km. Figure 28 shows the restriction of different layers (figure 27) up to the modelling domain. The data of different layers in the model domain is interpolated by setting the number of rows and column as 35 and 69 respectively.

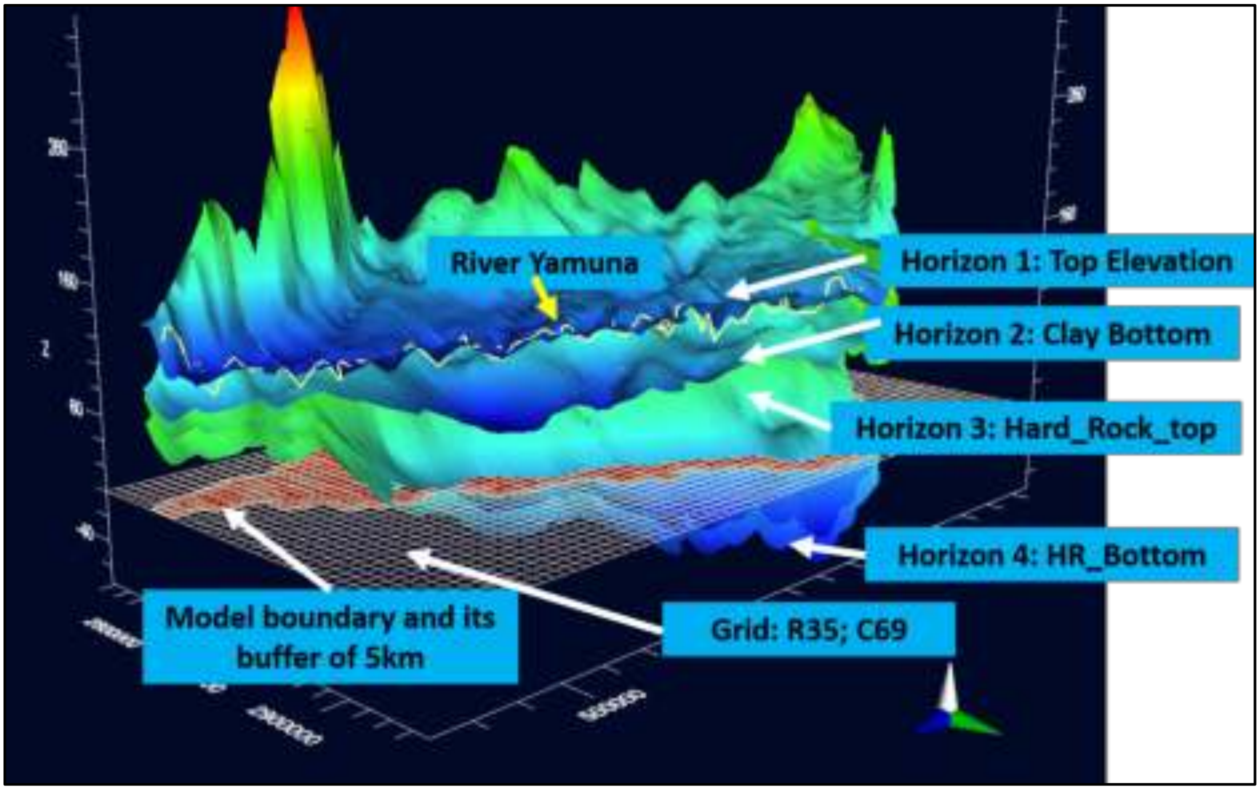


Figure 28: Horizontal extent of the model horizon with a 5km of boundary-buffer (Vertical exaggeration =500).

8.2.2.2. Vertical

Initially, the model was conceptualised with the three-layer system (figure 29 (a)). However, as per the suggestion of CGWB upon the good connectivity between the top clay and intermediate sand dominant layers, these layers were merged into one (figure 29 (b)). Since the basement is not to be considered for the groundwater resource evaluation, this layer was removed. Thus, the final model was conceptualised with a single aquifer system (figure 29c) with a mixed hydrological characteristics of clay, sand and silt. The model has incorporated three main rivers of the region, i.e. River Yamuna, Betwa, Dhanas and Ken.

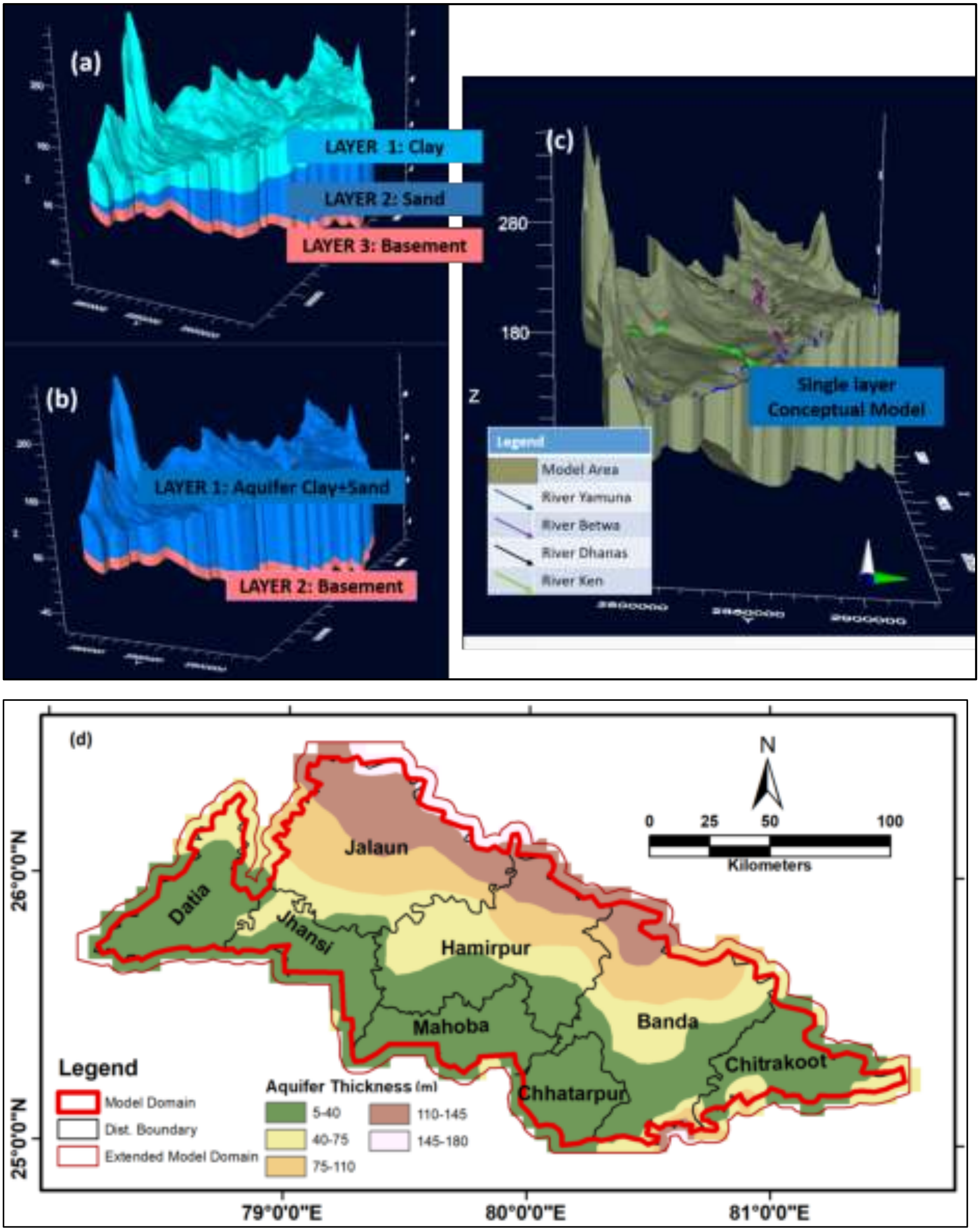


Figure 29: Development of a Conceptual model from three-layer to a single layer (a to c). A (Vertical exaggeration =500). Variation of the model thickness is plotted in figure 29 (d).

8.2.3. Defining Finite Difference Grid

The conceptual model has been discretised horizontally into finite-difference grid with 35 rows and 69 columns with an approximate distance of 5000m without any rotation (figure 30a). The grids outside the model area are assigned as inactive cells and inside cells are assigned as active cells. The properties and input parameters of the active cells of the modelling domain are used for the numerical calculation purposes whereas the inactive cell is by default assigned as no property zones by the modelling software.

In figure 30 (b), the vertical thickness of the aquifer has been discretized by defining the vertical grid as "DEFORMED". In the deformed grid, the top and bottom of the grid follow the defined elevation of layer surface. (https://www.waterloohydrogeologic.com/help/)

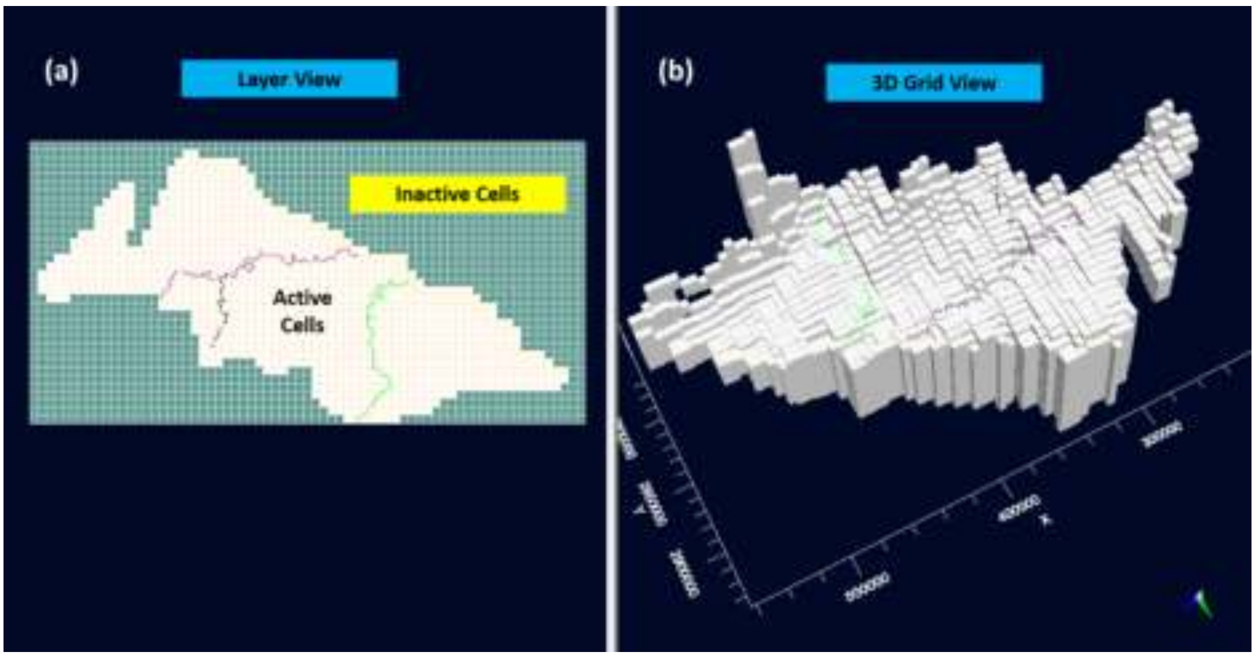


Figure 30: Defining the grids (a) layer view and (b) 3D grid for converting conceptual model to a numerical model.

8.2.4. Temporal discretisation of data

The simulation period starts from 1st January 2002 and ends 14th June 2017. As per the data input scheme for groundwater draft, recharge and evapotranspiration, the entire simulation period have been divided into 122 stress period in the visual MODFLOW Flex as following:

a) Calibration period: 01-01-2002 to 14-06-2009 (0-2722 days) => 30 stress period

b) Validation period: 15-06-2009 to 14-06-2017 (2723-5644 days) => 62 stress period

c) Prediction period: 15-06-2017 to 15-06-2032 (5645-11123 days) => 122 stress period

8.3. Development and calibration of the numerical groundwater flow model

The conceptual model has been translated into a numerical model. In numerical modelling, simulation is done on the basis value assigned to the particular boundary condition, or stress period or property. The study area is divided into 35 rows and 69 columns with an approximate distance of 5000m. The input parameters are described below:

8.3.1. Properties

8.3.1.1. Transmissivity (T) and Hydraulic conductivity (K)

Based on the pumping test carried out by CGWB (and WAPCOS) in the study area, the transmissivity value ranges between 13.5 m^2/da to 5755 m^2/day. The relation between the transmissivity and saturated thickness of the region suggests that hydraulic conductivity (K) ranges between 0.9 m/day to 65 m/day to 40 m/day corresponding dominance of weathered, fractured and clay dominance zone. The final value assigned after the calibration in the study area is shown in figure 31. Vertical conductivity in both the layers has been taken 10% of the horizontal conductivity values of the respective layers.

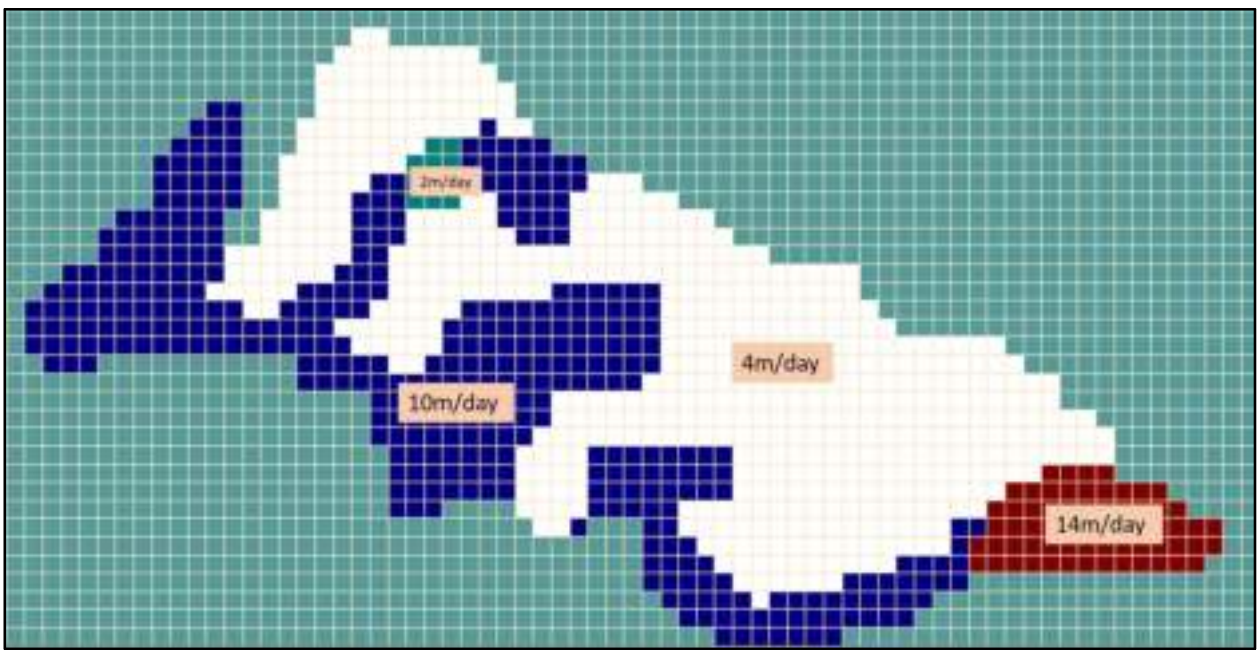


Figure 31: Conductivity values assigned in the model (calibrated model) active grid cells.

8.3.1.2. Storage parameter

The pumping test results in the different BDR and NAQUIM reports are summarised in table 6 and 7 under sub-section 6.4. The storage parameters available are very few which cannot produce a regional picture. Hence, these available values were used as a proxy by relating their prevailing aquifer material. Since, the clay is a very dominant in most of the parts of the aquifer, the resultant/equivalent values calculated for an aquifer comprising the silty sand overlain by thick clay layer as a unit system gets reduced. The distribution of the specific yield in the (calibrated) model is shown in figure 32. For the entire model, specific storage (S_s) has been kept constant i.e. $1 * 10^{-2}$.

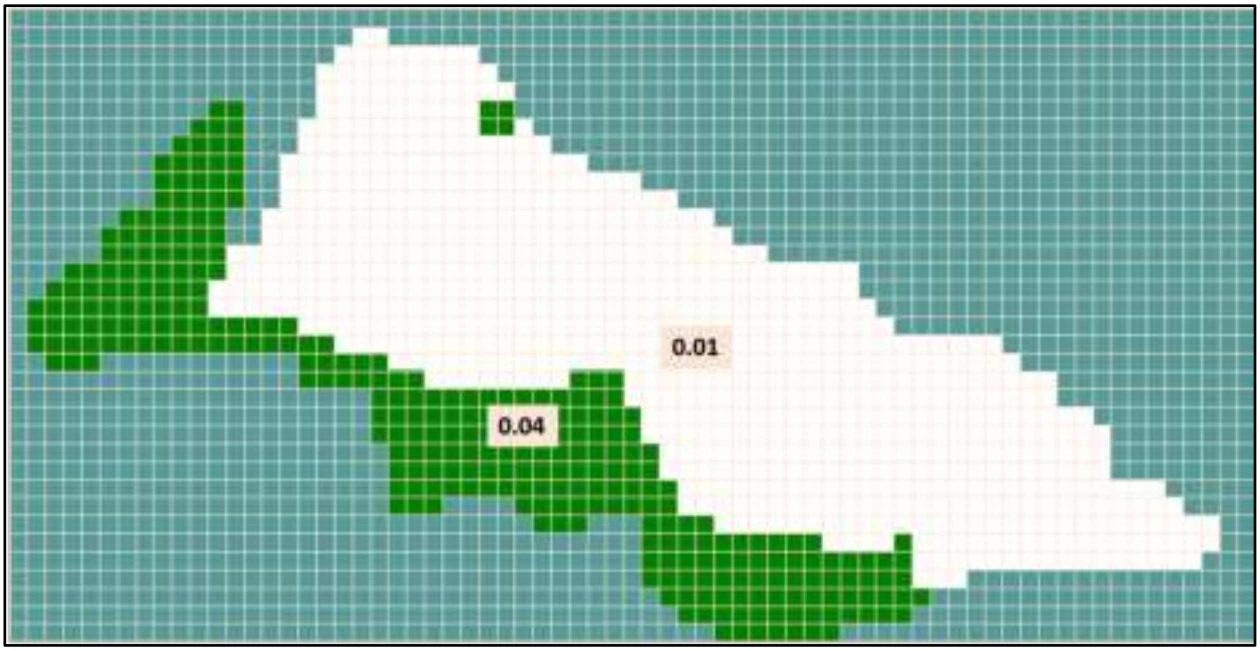


Figure 32: Specific yield values assigned in model (calibrated model) active grid cells.

8.3.1.3. Initial Head

The depth to water level form the observation wells have been interpolated in the ArcGIS platform with a resolution of 5km by 5km scale to match the model grid. This raster layer has been subtracted from the DEM resampled at 5km by 5km scale. Figure 33 shows the resultant initial water level condition assigned to the model.

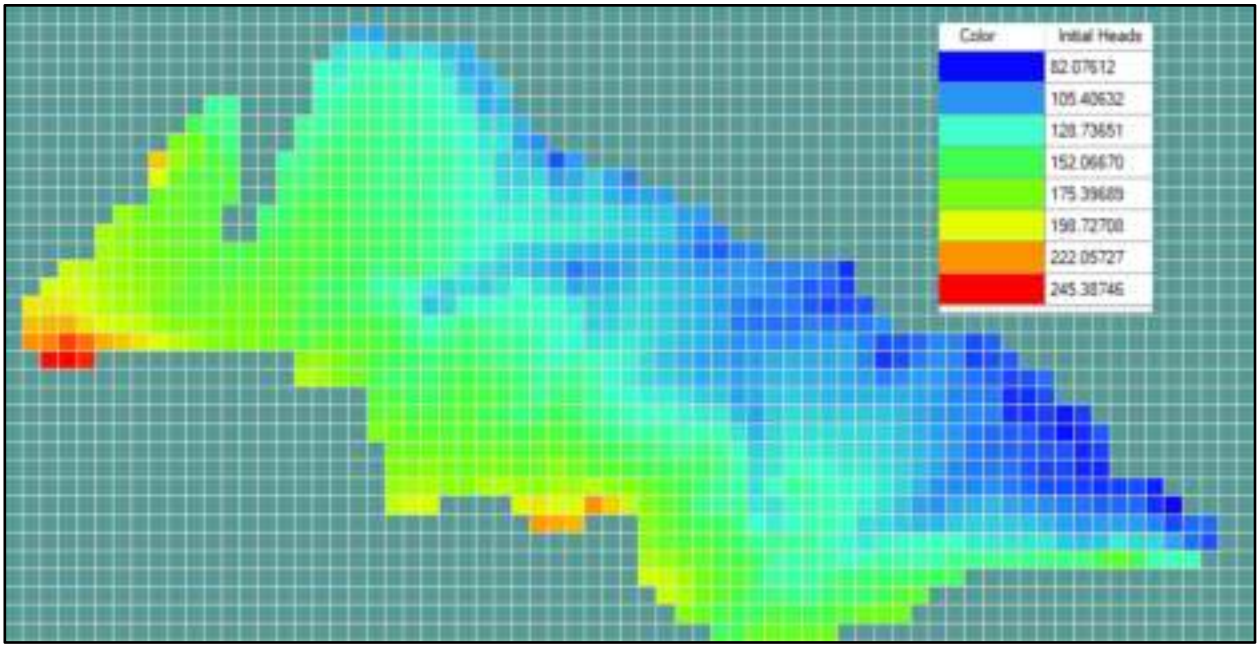


Figure 33: Distribution of initial head (IH) in model active grids.

8.3.2. Boundary condition

The Visual MODFLOW flex provides the following things to assign as the boundary condition:

- Constant Head
- River
- General Head
- Drain
- Wall (FHB)
- Well
- Recharge
- Evaporation
- Lake
- Specified_Flux
- Unsaturated Zone Flow (UFZ)
- Seepage Face
- Time-varying Material Properties

The boundaries assigned in the model is being discussed below in detail.

8.3.2.1. Assigning River boundary

The river boundary package (**RIV*) is used to simulate the effect on groundwater due to surface water body via seepage layer. These water body in general influence by adding water or discharging water to the groundwater.

The river boundary condition requires the following information regarding (a) River stage, (b) River bed bottom (c) river width (d) riverbed thickness (e) riverbed K_z and (f) Conductance. Figure 34 presents the cell realisation of river in MODFLOW. On the basis of the length of the reach (L) through a cell, the width of the river (W) in the cell, the thickness of the riverbed (M), and the vertical hydraulic conductivity of the riverbed material (K) , river bed conductance can be calculated using the equation (8) (www.waterloohydrogeologic.com/help):

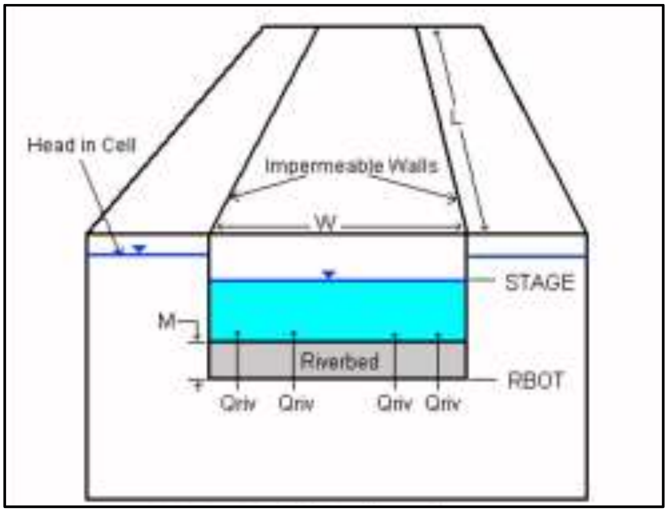


Figure 34: Schematic diagram of river boundary components (Source: www.waterloohydrogeologic.com)

$$C= (K*L*W)/M \qquad \ldots \text{Eq. (8)}$$

As per the discussion with the CGWB, the river Yamuna, Betwa, Dhanas and Ken have been incorporated into the model. The position of these rivers is presented in figure 29 (c). Since, different components for using the river as boundary were not available, based on the elevation and width observed in model and google earth imagery, the different such as river bottom, stage, width etc. have been decided. The river length (reach) and thickness used for the calculation of conductance are 5000m and 10m respectively. The parameters used were modified to get a better realistic result during calibration. These elements for the river boundaries have been tabulated below in table 15.

Table 15. The summary of data input for the different rivers in the model domain.

	River stage start (m)	River stage end (m)	Riverbed bottom start (m)	Riverbed bottom end (m)	River width (m)	riverbed conductivity (m/day) (Wojnar, A. J., 2008)	Conductance (m^2/day)
Yamuna	114	99	110	98	900	0.2	90,000
Betwa	178.3	97	177	95.6	360	0.1	18,000
Dhana	177.8	119.6	176.2	118	250	0.1	12,500
Ken	167	99.2	165.5	98.6	250	0.1	12,500

8.3.2.2. Assigning Pumping Well

The approach for assigning pumping wells, calculating groundwater extraction per unit grid, and their vertical position has been already mentioned earlier in detail (see section 8.1.3). There are about 857 pumping wells marked in the model domain for the aquifer whose position and screen position are shown in figure 35. The position of well is adjusted between the top surface and bedrock, whereas the screen has been positioned near the upper aquifer tapped zone.

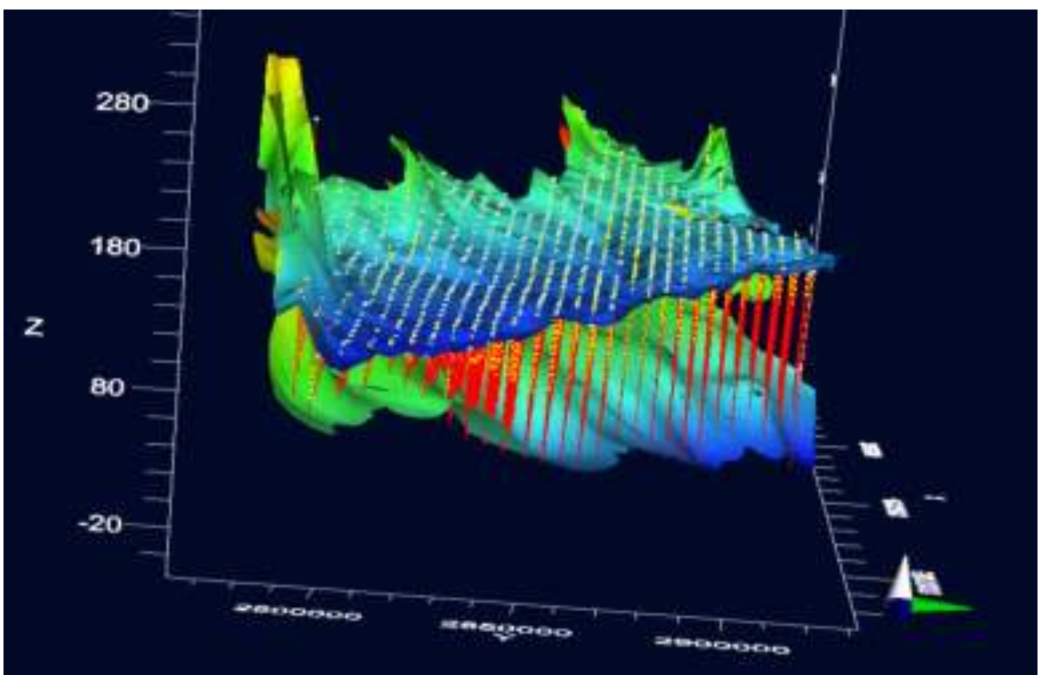


Figure 35: Pumping well and its screen position in single alluvium aquifer system of the Bundelkhand region.

The annual groundwater draft has been divided into two seasonal draft. The summary of the groundwater draft for the model input (each grid or each PW) calculated from the seasonal drafts assessed for different years is presented in table 16. The draft value for year 2013 has been repeated up to year 2017 for the during the validation period.

Table 16. Temporal variation in the numerical input for the pumping well for different block under the study area. Red-yellow-green shades highlight the value.

DIST.	BLOCK	M_04	M_09	M_11	M_13	NM_04	NM_09	NM_11	NM_13
BANDA	BABERU	-2930	-2730	-2772	-2819	-5231	-4693	-4759	-4845
	BAROKHAR	-2961	-3483	-4299	-4378	-5286	-6139	-7633	-7779
	BISANDA	-2613	-1750	-3829	-3896	-4665	-2818	-6641	-6764
	JASPURA	-3090	-3203	-3518	-3581	-5517	-5604	-6183	-6299
	KAMASIN	-2847	-2856	-3560	-3622	-5083	-4881	-6167	-6281
	MAHUA	-2896	-4486	-3558	-3620	-5171	-7900	-6178	-6293
	NARAINI	-2156	-3261	-2946	-2997	-4264	-6281	-5615	-5719
	TINDWARI	-4862	-5717	-6226	-5946	-8680	-10198	-11131	-10742
CHITRAKOOT	KARVI	-3462	-3213	-3970	-4036	-6176	-5371	-6735	-6856
	MANIKPUR	-530	-1590	-1565	-1591	-945	-2728	-2671	-2719
	MAU	-1926	-3661	-4071	-4140	-3439	-6262	-6994	-7122
	PAHARI	-2088	-3549	-2034	-2062	-3727	-5933	-3215	-3267
	RAM NAGAR	-880	-2902	-2269	-2305	-1570	-5002	-3810	-3877
HAMIRPUR	GOHAND	-7266	-3039	-4673	-4757	-12972	-5350	-8219	-8374
	KURARA	-2973	-2446	-4358	-4434	-5308	-4211	-7572	-7712
	MAUDAHA	-4567	-2454	-2583	-2629	-8153	-4179	-4548	-4634
	MUSKARA	-2796	-1741	-2708	-2754	-4992	-2998	-4663	-4748
	RATH	-3383	-3643	-3878	-3946	-6352	-6810	-7107	-7240
	SAREELA	-3180	-1797	-2970	-3022	-5971	-3282	-5446	-5548
	SUMERPUR	-7180	-2969	-5210	-5295	-12818	-4959	-8807	-8964
JALAUN	DAKORE	-1763	-3844	-3758	-3816	-3148	-6689	-6524	-6676
	JALAUN	-3578	-7922	-7399	-7533	-6718	-14691	-13656	-13992
	KADAURA	-2139	-3210	-3280	-3546	-4017	-5775	-5902	-6373
	KONCH	-2736	-5386	-6808	-6894	-5138	-9909	-12667	-12895
	KUTHOND	-4704	-5433	-7581	-6067	-8834	-9499	-13660	-10346
	MADHOGARH	-4869	-7270	-9451	-8978	-9143	-13170	-17399	-16607
	MAHEWA	-3156	-4894	-4810	-5010	-5635	-8543	-8378	-8836
	NADIGAON	-2323	-3945	-5483	-5348	-4363	-7056	-10039	-9974
	RAMPURA	-3597	-4040	-4463	-4765	-6754	-7205	-8014	-8448
JHANSI	BAMAUR	-972	-1688	-1822	-2474	-1619	-2795	-2995	-4330
	GURSARAI	-1427	-2999	-3169	-3075	-2460	-5229	-5472	-5275
	MOTH	-3289	-5585	-5683	-5274	-4377	-7438	-7536	-7049
MAHOBA	CHARKHARI	-3304	-2182	-2245	-2551	-5899	-3800	-3905	-4426
	JAITPUR	-4597	-2934	-3360	-3617	-8206	-5100	-5897	-6337
	KABRAI	-2298	-1859	-1791	-1940	-4102	-3157	-3014	-3275
	PANWARI	-4064	-2796	-5778	-5956	-7256	-4754	-10232	-10476
CHHATARPUR	GAURIHAR	-678	-1051	-1251	-874	-1054	-1717	-2076	-1366
	LAUNDI	-2131	-2403	-2465	-2782	-3697	-4182	-4287	-4881
DATIA	BHANDER	-1518	-3173	-2616	-2677	-2567	-5534	-4536	-4643
	DATIA	-6286	-3281	-2213	-2584	-11355	-5642	-3799	-4484
	SEONDHA	-1700	-4112	-3908	-3873	-2895	-7253	-6924	-6847

8.3.2.3. Assigning Recharge

The recharge values for the different blocks have been averaged at their respective district levels to assign it under different zone. The different zones assigned is shown below as figure 36 and their respective "time schedule" to be mapped is presented in table 17. The zone 1 is default assigned number by the software, and a "zero" value has been assigned in it.

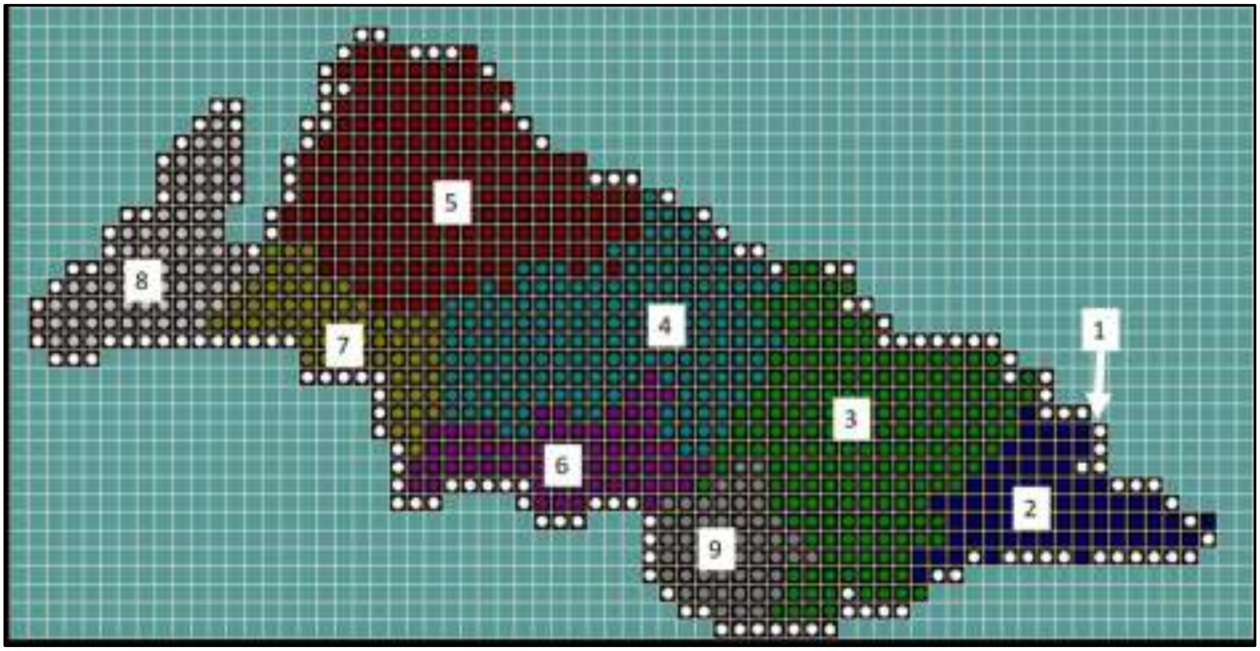


Figure 36: Recharge zone. The Zone 1 is a default zone assigned to any undefined grid.

Table 17: The recharge values for the different zones for different "time schedule".

Start time	Zone2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Season
01-01-2002	0	0	0.000077	0.000061	0.000000	0.000051	0.000000	0.000000	Non-Monsoon
15-06-2002	0.00057	0.00083	0.000827	0.000839	0.000860	0.000310	0.000824	0.000795	Monsoon
:::	:::	:::	:::	:::	:::	:::	:::	:::	:::
15-06-2009	0.00053	0.00076	0.000515	0.001032	0.000234	0.000450	0.000824	0.000795	Monsoon
31-10-2009	0	0	0.000073	0.000083	0.000052	0.000055	0.000000	0.000000	Non-Monsoon
:::	:::	:::	:::	:::	:::	:::	:::	:::	:::
15-06-2011	0.00053	0.00081	0.000538	0.001132	0.000332	0.000328	0.000833	0.000532	Monsoon
31-10-2011	0	0	0.000075	0.000093	0.000000	0.000057	0.000000	0.000000	Non-Monsoon
:::	:::	:::	:::	:::	:::	:::	:::	:::	:::
15-06-2013	0.00052	0.00078	0.000505	0.001067	0.000323	0.000470	0.000833	0.000532	Monsoon
31-10-2013	0	0	0.000072	0.000086	0.000000	0.000061	0.000000	0.000000	Non-Monsoon
:::	:::	:::	:::	:::	:::	:::	:::	:::	:::
31-10-2031	0	0	0.000072	0.000086	0.000000	0.000061	0.000000	0.000000	Non-Monsoon
15-06-2032	0.00052	0.00078	0.000505	0.001064	0.000323	0.000470	0.000835	0.000537	Monsoon

8.3.2.4. Assigning Evaporation

Due to non-availability of data at the block level, and little or no variation in it, reference (crop) evapotranspiration has been assigned under the evaporation boundary condition.

The Et0 value has been divided into two stress period of (April-June) and (July to March) for which 0.00722m/day and 0.00412 m/day value has been assigned throughout the model simulation period (see section 6.6. and 8.1.5. for detailed explanation).

8.3.2.5. Assigning Specified flux

The general contour pattern can be used for calculating the general hydraulic gradient near the boundary. The hydraulic property, along with the gradient, can be used to calculate the flow across the boundary.

Since the saturated thickness of the aquifer along the southern and eastern boundary of the model is very less, the flux across it was very less to be considered. On the other hand, the water table contours suggest the flow parallel to the model boundary in the western side.

8.3.3. Code Selection

The model was run using "USGS MODFLOW 2005 from WH" flow engine for the transient condition. In the transient condition, MODFLOW Flex prepares the data set for a transient flow simulation during which it automatically merges all data sets and creates a time-dependent flow solution. In the next step, LPF as property package along with Conjugate Gradient Solver (PCG) solver has been selected. PCG2 solver was run with maximum outer and inner iteration as 100 and 25 respectively. The head change and residual criteria for the convergence were chosen the default value of 0.01 with relaxation parameter of 1.

The layer type is also necessary to identify based on the groundwater and the hydraulic connectivity. Since the model layer is a numerical presentation of a combination of cay and sand layer in most of the region, it cannot be presented as a true unconfined layer. Hence, the layer type has been assigned as "Type 3- Confined/Unconfined, Variable S &T" In this setting the transmissivity is calculated on the basis of variable saturated thickness and storage coefficient may vary between the confined and unconfined values.

8.3.4. Calibration process and Results

The transient calibration of the system is to simulate the condition in which head changes with time. The region may have a steady-state condition in some part or another for a small time-periods, but it is near impossible to have an ideal steady-state hydrogeological condition region (Maheswaran et al., 2016). Hence, it has been chosen to run the model under the transient state.

8.3.4.1. Calibration

The model was calibrated to the transient state from January 2002 to June 2009 by diving a year in different stress period based on the draft/recharge and evapotranspiration data. The process of calibration involved changes in aquifer parameters and riverbed conductance under several runs. During calibration the rainfall recharge and irrigation-draft have been adopted to get a better match. The observed water level data for May and November has been compared with the corresponding computed head. The calibration statistics for the model run was judged based on the residual mean, absolute residual mean and root mean square.

The calibrated model has been further extended to 15th June 2017 to produce another set of water head which has been matched with the historical water level data for the month of May and November for years 2009 to 2017. This is known as "Model verification." During this period, the input data for groundwater draft and recharge has been changed as per the groundwater assessment years 2009, 2011, and 2013. The comparison between the model head and observed head is shown in figure 37. The overall correlation coefficient and coefficient of determination are 0.98 and 0.96 respectively.

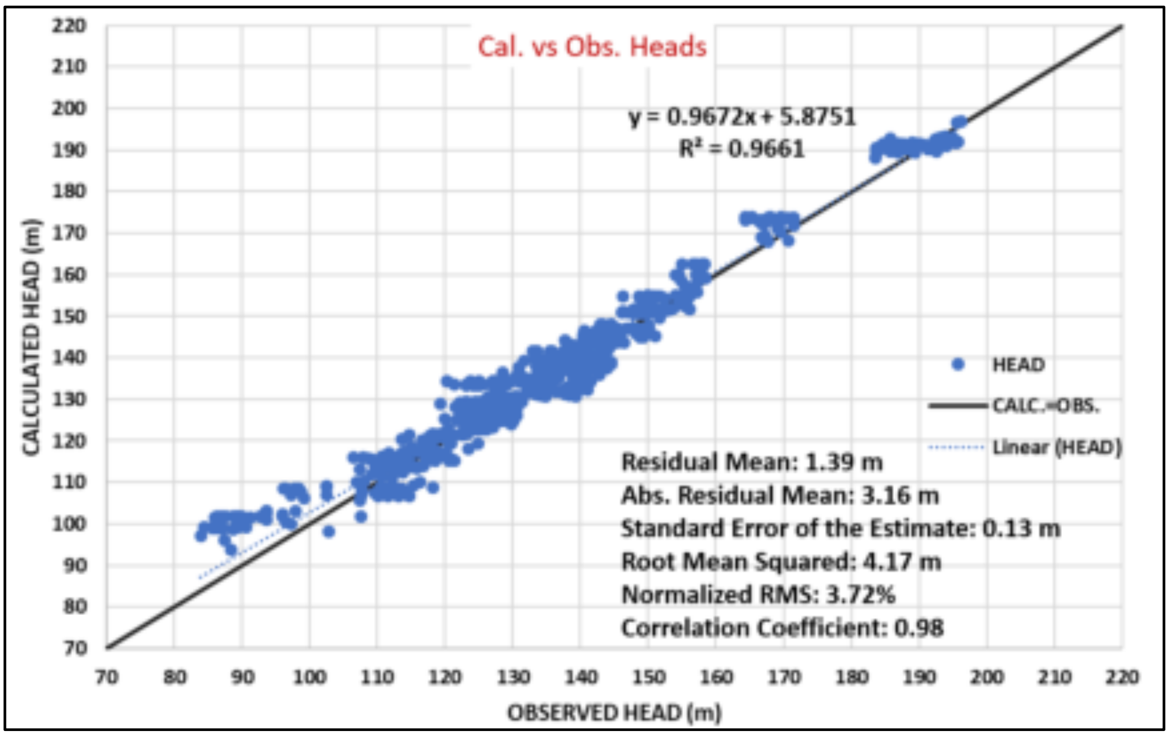


Figure 37: The scatter graph of calculated and observed heads for the alluvium part of the Bundelkhand region for the entire calibration and validation period (01/01/2002 to 15/06/2017).

The distribution of model generated head at the end of 62nd stress period (5644 days) is presented in figure 38 in the 3-D, and a cross-sectional view along the row and column number 24. The head in the study area varies in the range of 233 m to 90m above mean sea level.

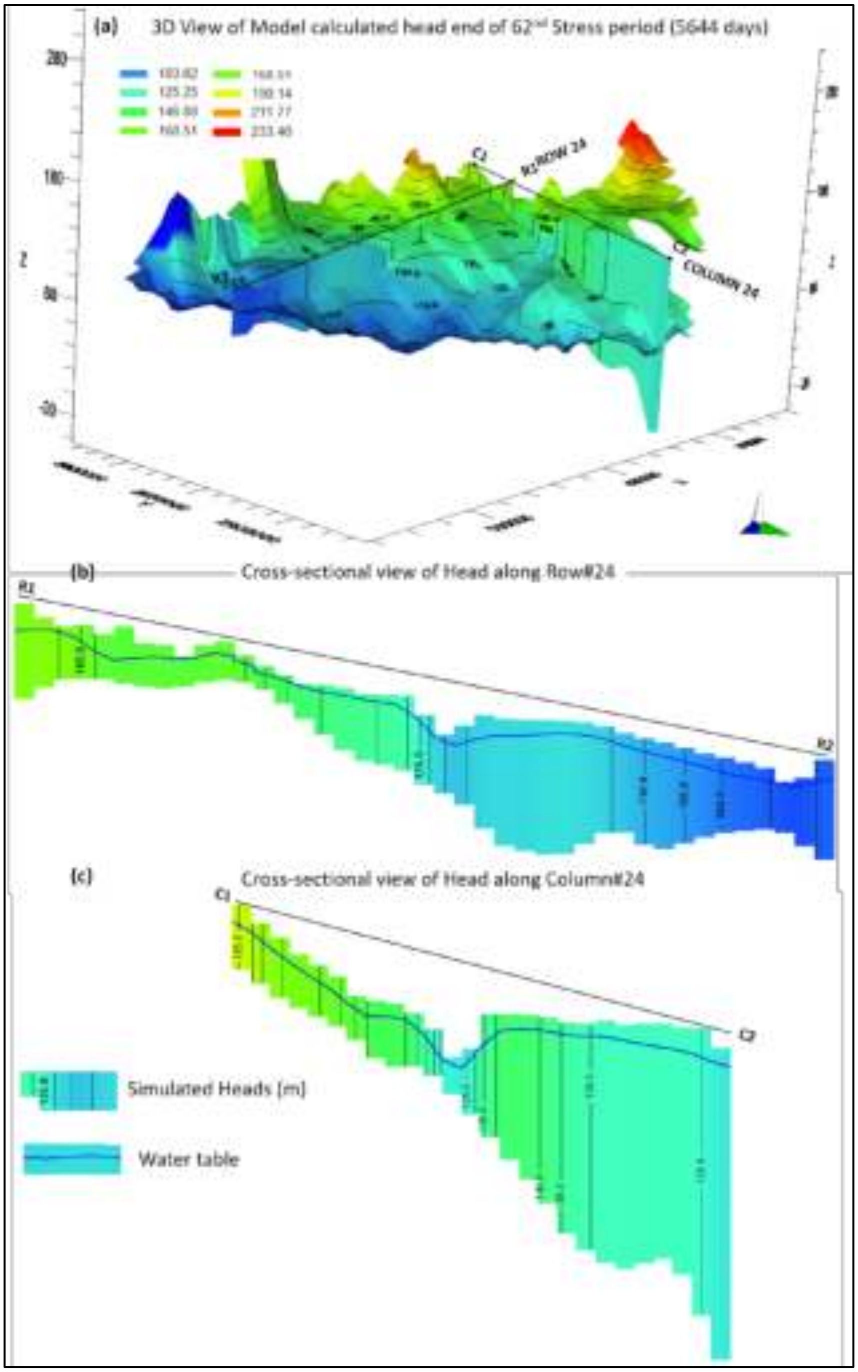


Figure 38: Model calculated head in the study area in (a) 3-D view, (b) along row# 24, and (c) along column#24 at the end of 62nd stress period (5644 days). Vertical black lines indicate the head and solid blue represents the variation of water table along the respective row/column.

The calibration statistics for a single time during the calibration and validation is shown in figure 39 and their respective comparison between model generated and field observed head is presented in figure 40.

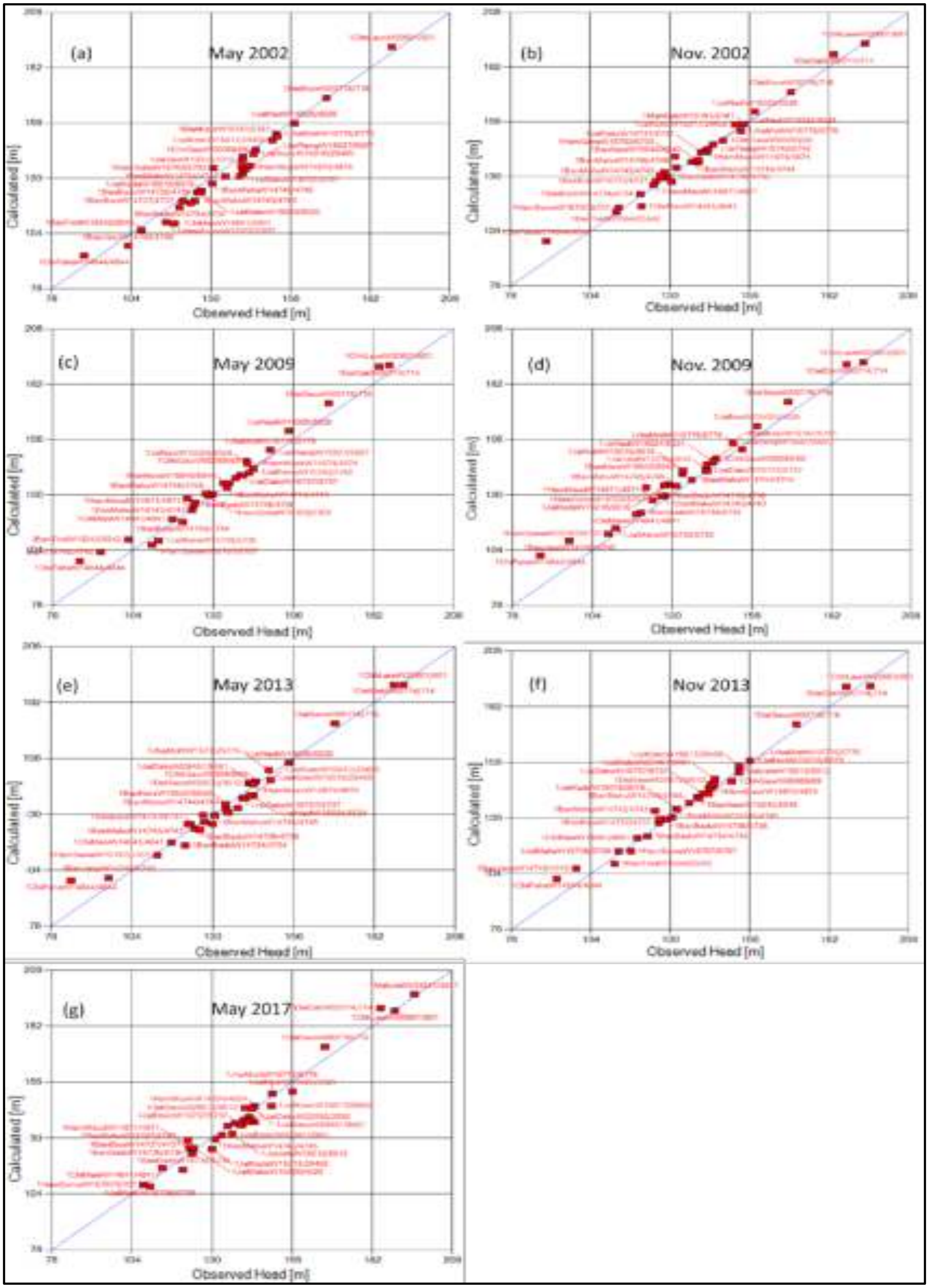


Figure 39: Calibration statistics for the different time during Calibration and validation stage in the model run.

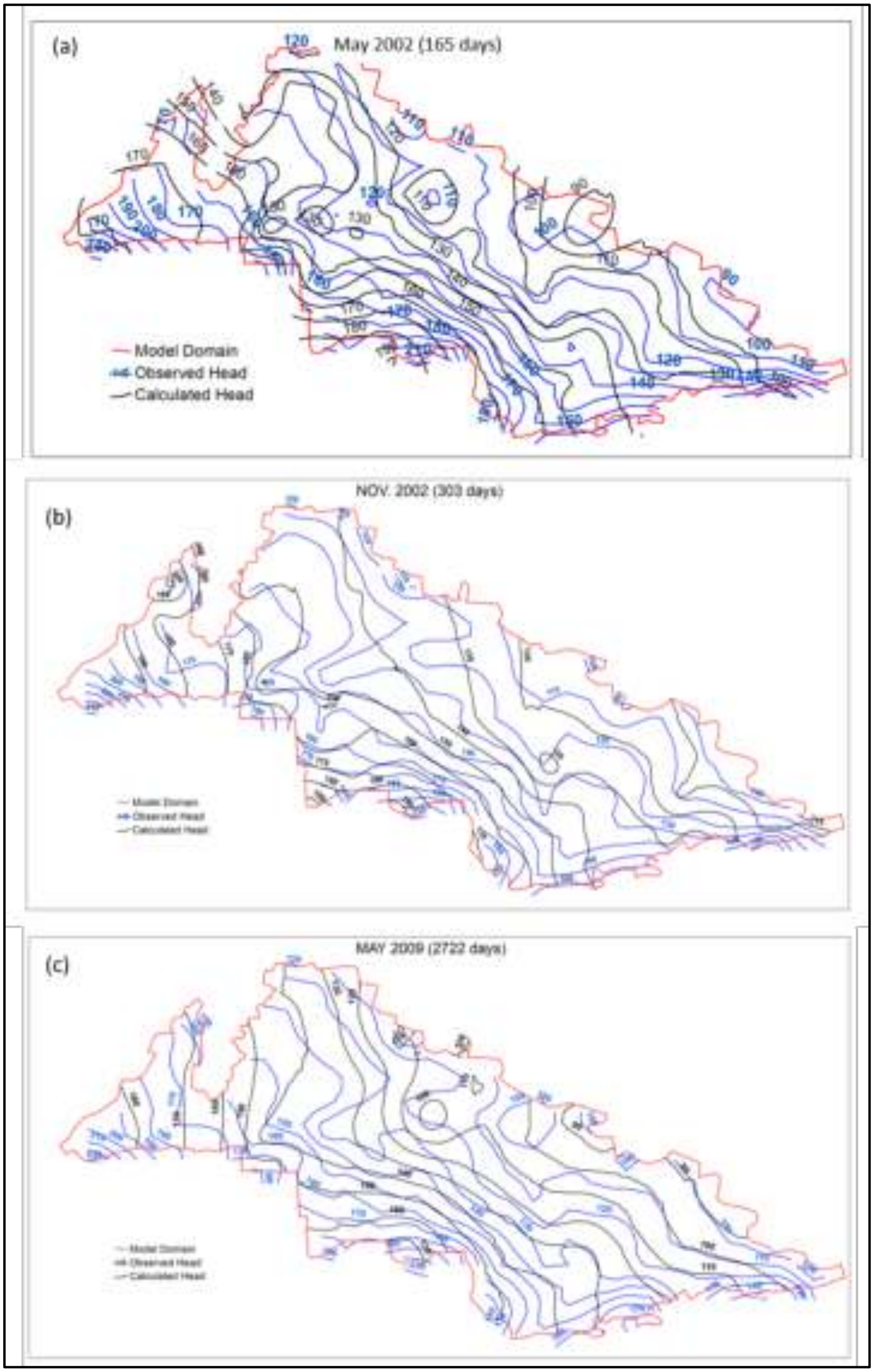


Figure 40: Simulated and observed groundwater head for the different time duration during calibration and validation stage of model run.

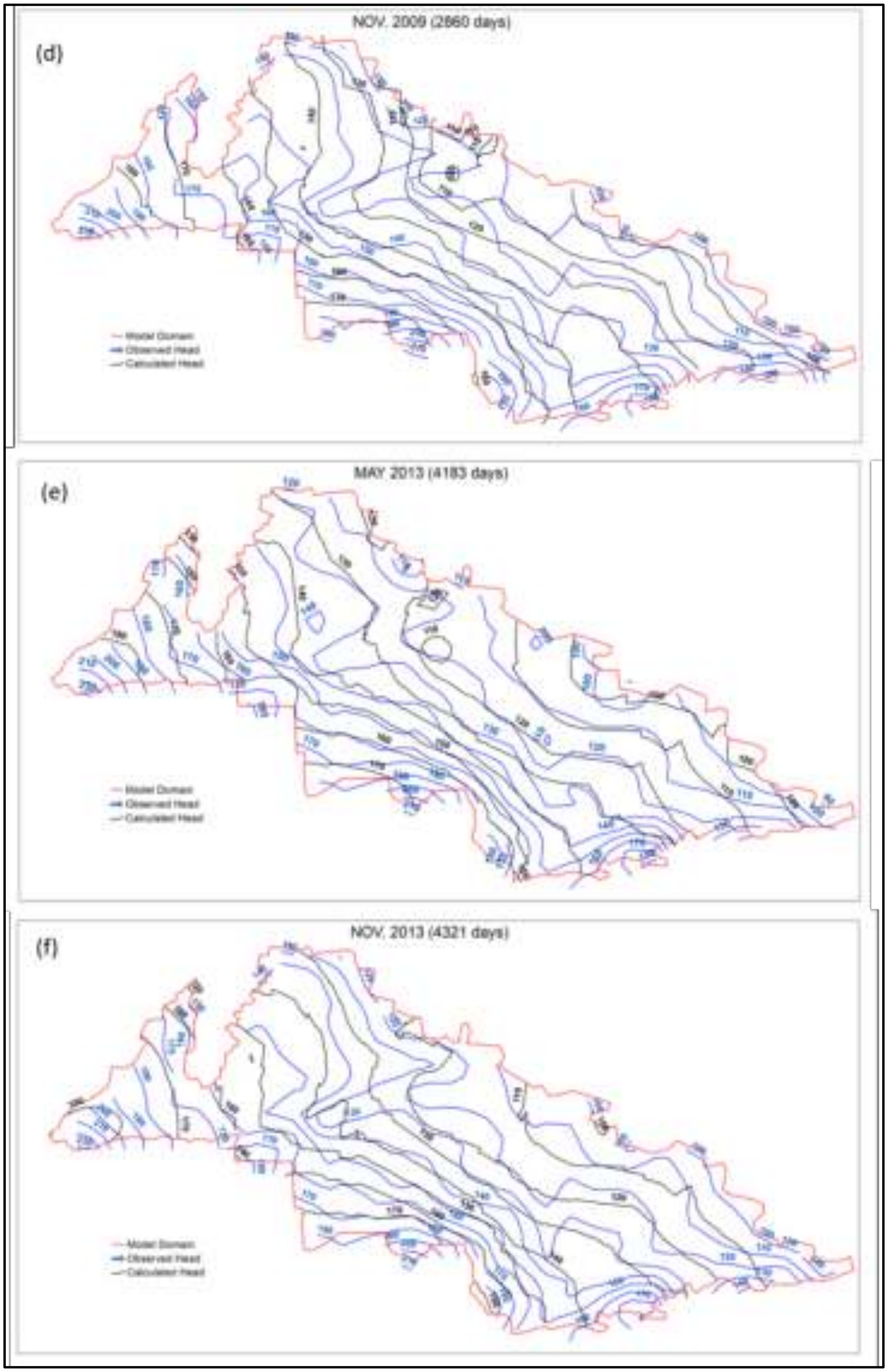


Figure 40 (continued…): Simulated and observed groundwater head for the different time duration during calibration and validation stage of model run.

Figure 40 (continued …): Simulated and observed groundwater head for the different time duration during calibration and validation stage of model run.

The scatter plot of model calculated head and field observed water level data for May and November for the year 2002, 2009, 2013, and 2017 (only for May) in figure 38 show a good correlation. The quantitative analysis for these scatter plots is tabulated in table 18 suggesting correlation coefficient in range of 0.98 – 0.99. Other errors are also in a small range.

Table 18: The summary of calibration errors during different simulation periods.

Time	Error (m)				SEE (m)	RMSE (m)	NRMS (%)	Correlation Coefficient
	Min.	Max.	Mean	Abs. Mean				
May 2002	0.17	-9.5	-3	3.76	0.63	4.5	4.47	0.99
Nov. 2002	-0.17	9.66	1.15	2.16	0.52	3.055	2.93	0.99
May 2009	0.26	12.035	2.26	3.25	0.7	4.35	4.35	0.99
Nov. 2009	-0.098	14.56	4.095	4.22	0.73	5.57	5.28	0.99
May 2013	0.29	14.79	-0.21	2.94	0.7	3.89	3.64	0.98
Nov. 2013	0.44	8.97	1.3	2.37	0.52	3.15	3.089	0.99
May 2019	-0.062	6.8	-0.7	2.79	0.59	3.4	3.87	0.99

8.3.4.2. Hydrograph analysis

After analysing the model output groundwater head spatially at different analysis time, the observed water level data for different location has been compared with the model simulated head for throughout the simulation period. Out of 47 location used for the model calibration analysis; 14 homogenously distributed locations (figure 41) have been selected for presenting the observed vs simulated head in the study area (figure 42).

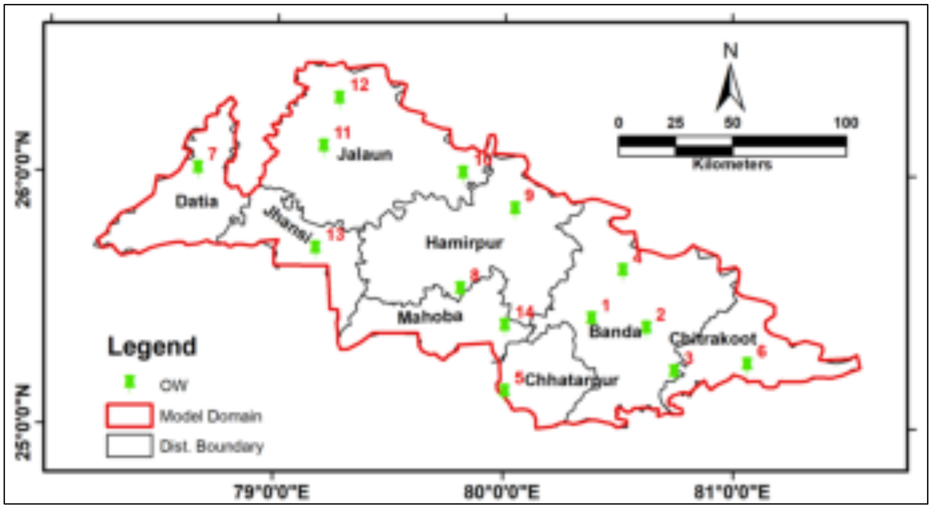


Figure 41: Location map of hygrograph station.

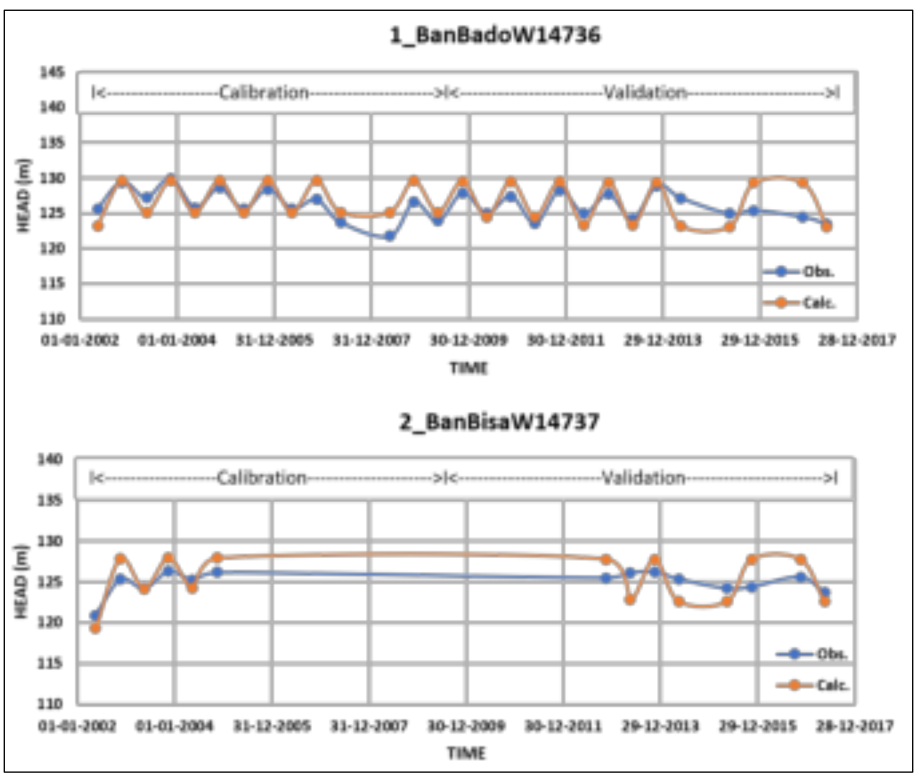


Figure 42: Comparison of observed and simulated hygrograph.

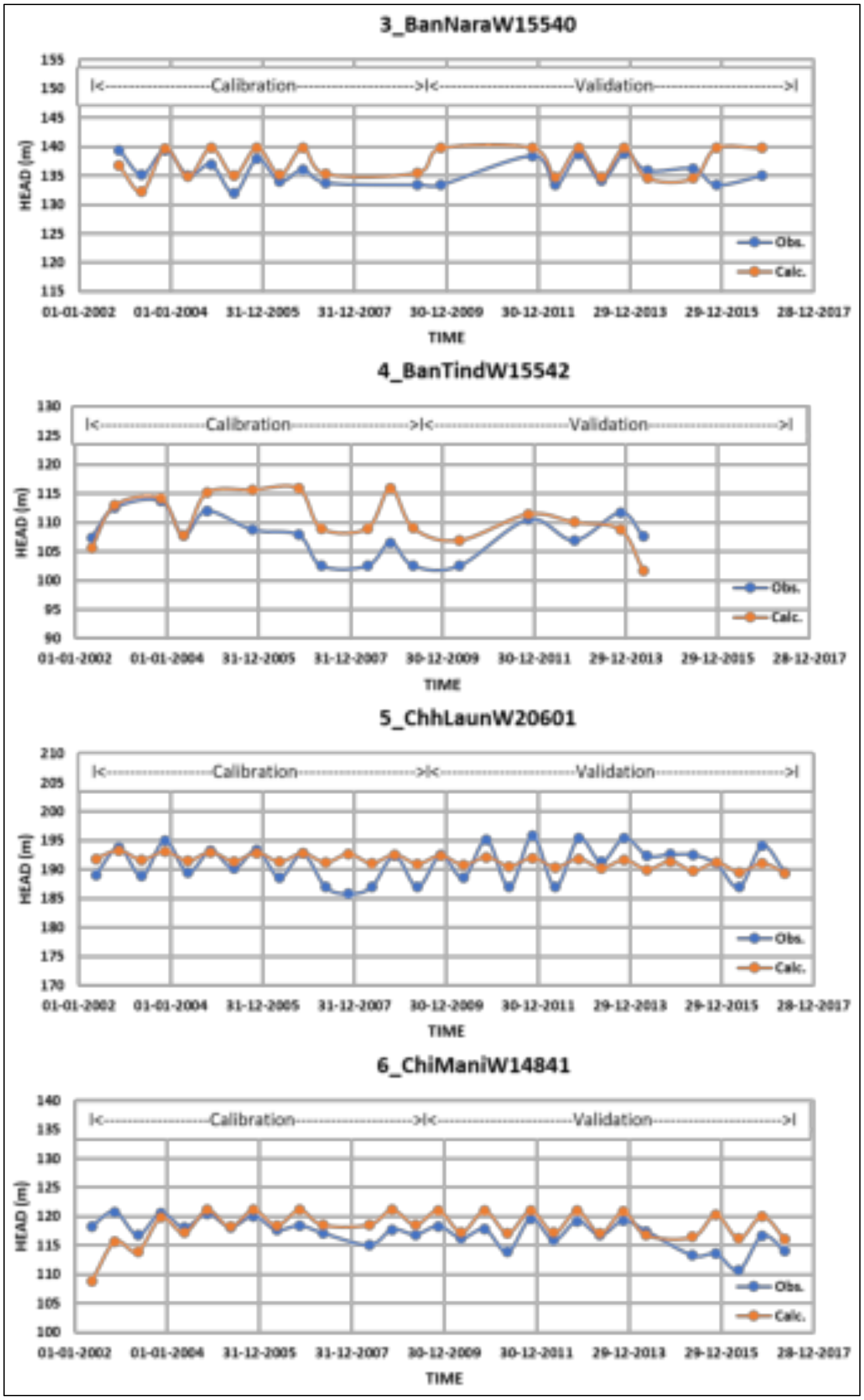


Figure 42 (continued…): Comparison of observed and simulated hygrograph.

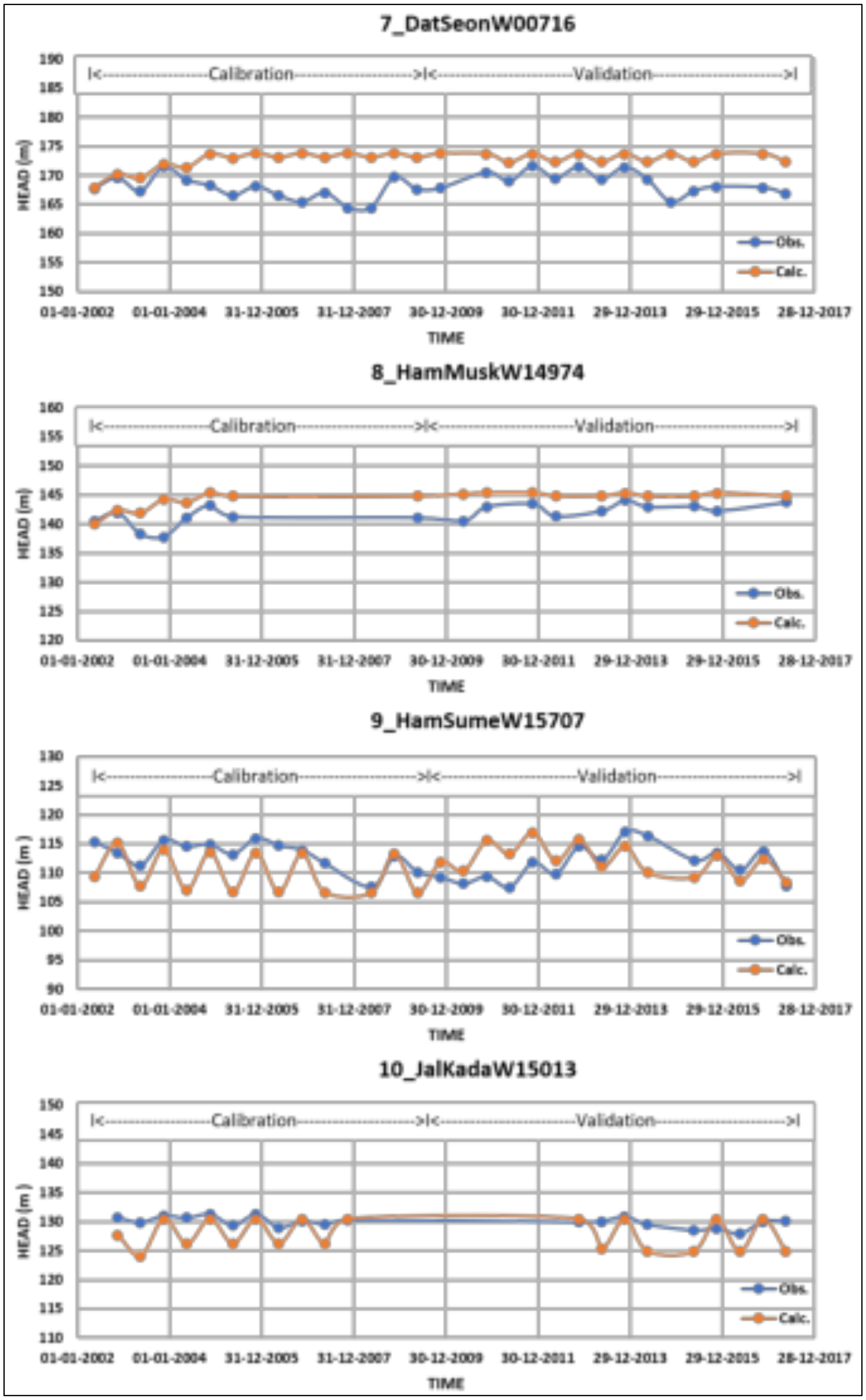


Figure 42 (continued…): Comparison of observed and simulated hygrograph.

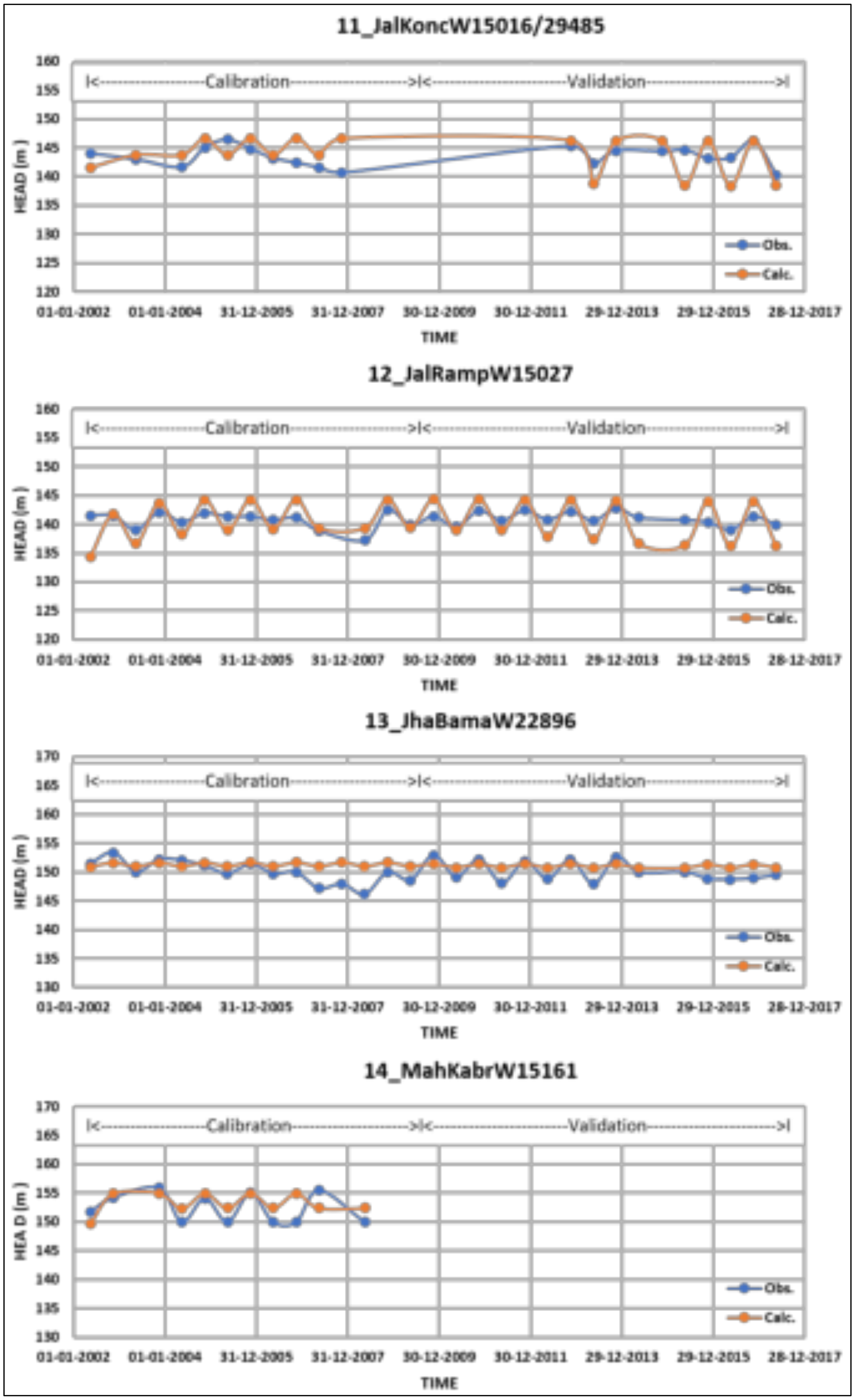


Figure 42 (continued…): Comparison of observed and simulated hygrograph.

8.3.4.3. Mass Balance

The groundwater budget for the study area for the stress period 1, stress period 30 (end of calibration period), and stress period 62 (end of validation period), is obtained from the model run is presented in figure 43, and its comparative study is tabulated in table 19.

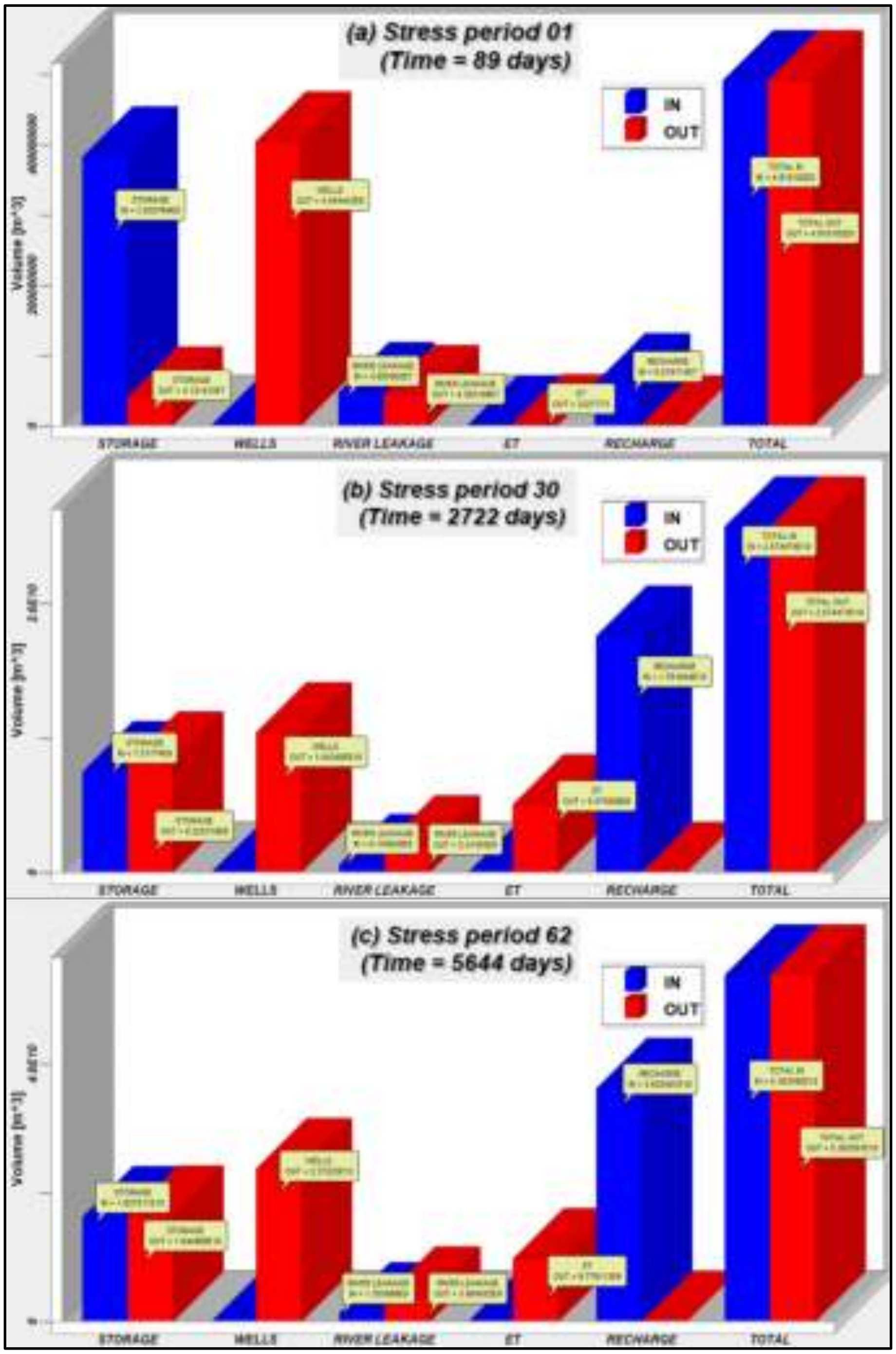


Figure 43: Groundwater balance at 89 days, 2722 days and 5644 days.

The groundwater budget for the stress period-1 shows that the groundwater extracted from the system (404.4 MCM) is totally supplied from the storage (386.8 MCM), and recharges (60.2 MCM). This shows that the model is adjusting with its different inflow-outflow components during the initial periods. During this period, river is not interacting much with the system. Hence, the model results for initial period cannot be considered for any inference.

The groundwater budget at the end of 30th stress period shows that there is about 27879 MCM of water is taking part in this groundwater system through different modes. The pumping well, evapotranspiration and river discharge contribute about 38.8%, 20.2%, and 7.8% as outflow from the system. This outflow is partially compensated by the components of recharge and river by 70.6% and 2.2% respectively contributing into the system. During this entire tenure, there is approximately 1658 MCM of water has been added into the storage.

Table 19: Groundwater budget for the calibration and validation period of the flow model.

	STRESS PERIOD	1	Up to 30	31-62	Cumulative (1- 62)
	DAYS	31-03-2002	15-06-2009	15-06-2017	1/1/02-15/6/17
1		A	B	C	D=(B+C)
2	MODEL INFLOW (MCM & % w.r.t. total IN)				
3	STORAGE	386.8 (78.2)	7569.7 (27.2)	8794.3 (33.8)	16364 (30.4)
4	RIVER	47.9 (9.7)	614.9 (2.2)	705.7 (2.7)	1320.6 (2.5)
5	RECHARGE	60.2 (12.2)	19693.9 (70.6)	16510.9 (63.5)	36204.8 (67.2)
6	TOTAL IN	494.9	27878.5	26010.9	53889.4
7	MODEL OUTFLOW (MCM & % w.r.t. total OUT)				
8	STORAGE	42.7 (8.6)	9228.2 (33.1)	7389.2 (28.4)	16617.3 (30.8)
9	WELLS	404.4 (81.7)	10824.9 (38.8)	12897.4 (49.6)	23722.3 (44)
10	RIVER	45.8 (9.3)	2181 (7.8)	1706.5 (6.6)	3887.4 (7.2)
11	ET	1.9 (0.4)	5644.4 (20.2)	4017.9 (15.4)	9662.3 (17.9)
12	TOTAL OUT	494.9	27878.5	26010.9	53889.4
13	IN-OUT (MCM)				
14	IN-OUT (MCM)	0	0.004	-0.008	-0.004
15	PERCENT DISCREPANCY	0	0	0	0

Similarly, the groundwater budget for the stress period from 31st to 62^{nd,} there is approximately 26011 MCM of water taking part in this groundwater system through different modes. The pumping well, evapotranspiration, and river discharge contributes about 49.6%, 15.4%, and 6.6% as outflow from the system. This outflow is partially compensated by the components of recharge and river by 63.5% and 2.7% respectively contributing into the system. During this entire tenure, there is approximately 1405 MCM of water has been removed from the storage.

8.3.4.4. Zone budget

The study area has been divided into 8 zones (zone 2 to zone 9) following the district boundary (figure 44). The zone 1 is a default zone in the Visual MODFLOW Flex which covers the periphery of the other zone. Since, the scope of the study is kept restricted to these districts, the change in the storage for each zone has been calculated.

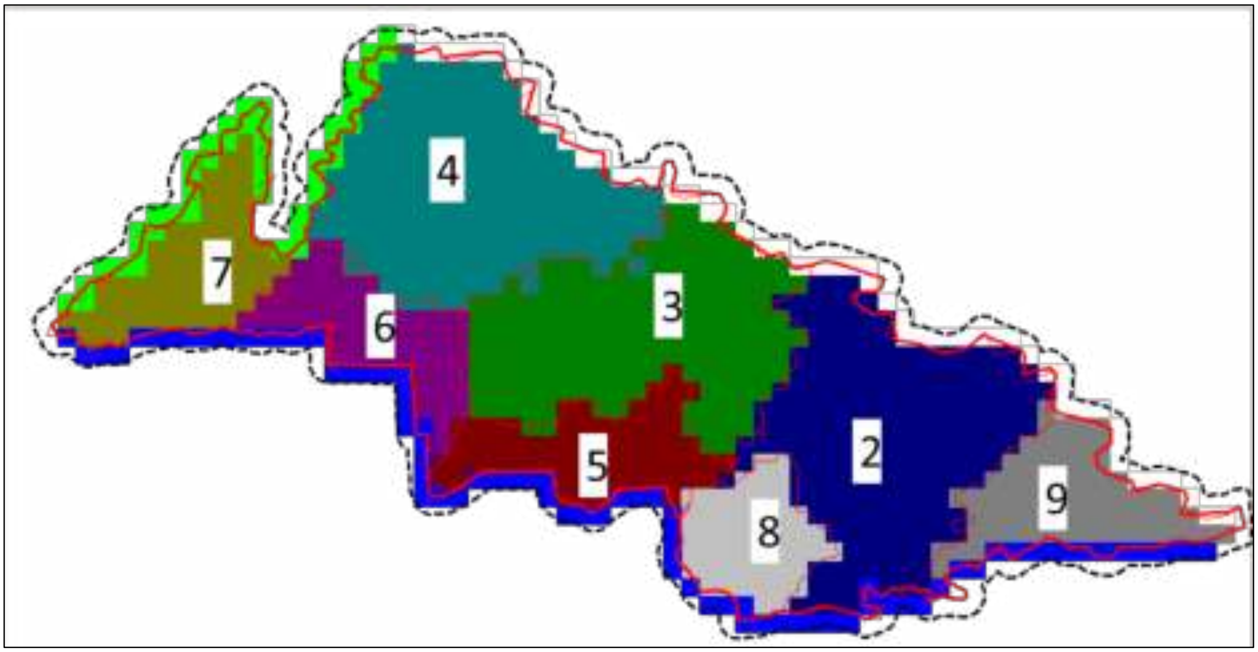


Figure 44: Assigned zones in the groundwater model.

Based on the model simulation, different Inflow and Outflow components compensate each other and deficit, or surplus volume of water is credited as the storage. This results in the change in water level in the aquifer system. Hence, only storage out of different flow components has been analysed for the different zones at the end of the simulation period (62 stress period or 5644 days). The summary has been presented in table 20.

Table 20: Transaction of water from each zone in model area over 62 stress periods (Values are in Million Cubic Meters, MCM).

Zone	2	3	4	5	6	7	8	9
In	3805.4	2891.9	4101.7	1180.2	622.1	1281.3	555.1	1079.6
Out	4004.5	2926.7	4024.4	1136.9	656.4	1509	632.8	1112.3
In-Out	-199.1	-34.8	77.3	43.2	-34.3	-227.8	-77.8	-32.7

The negative values represent the volume of surplus water returned into it which causes the rise in water level. Hence, zone 2, and 7, show more rise in water level in comparison to zone 8, 3, and 9; whereas zone 4, and 5 show a little depletion in storage.

(NOTE: The zones defined for budgeting are different from recharge zone)

8.3.4.4. Findings

Some major observation and findings from table 19:

1) The groundwater budget for the first stress period 1 mimics the groundwater dynamics during the groundwater extraction through a pumping well in an alluvium system. During the initial period, the water flows out from the storage to meet the extraction. The other components start contributing proportionately into the system after some time which could be seen from column B, C, and D.
2) The well vs recharge component analysis (row 9/row 5; in table 19) of the simulation period gives value in a range of 55% - 78%. The overall stage of groundwater development from the different dynamic groundwater reports by CGWB also reported a similar range. This result justifies the decision of considering rainfall recharge for model input rather taking total recharge.
3) The evapotranspiration component is the second most active outflow component. This has an average contribution of 18% to the total inflow which is approximately half of the well. The outflow from the well and evapotranspiration are enough to exhaust the recharge component.
4) Hence, it can be concluded that recharge from the rainfall (or at least equal to it) is actively taking part in the groundwater dynamics of the alluvium floodplain part of the Bundelkhand region. It may also be inferred that any addition recharge may not result in increasing water level but will probably be lost through evapotranspiration or as lateral flow.
5) The overall outflow from the river is always greater than its inflow component (row10-row4; table 19). The ratio of this difference to the recharge component gives values approximately in the range of 6%-8% which matches with the GEC-97 norms for allocating the natural discharge from the recharge.
6) Up to stress period 30, the data suggest the addition of water into the storage, which limits any appreciable long-term decline in water level.
7) Between the stress period 31 and 62, the water budget suggests there is a removal of groundwater from the storage. This removal is calculated to approximately 2% of the total inflow. Since this value is too small to make any further remarkable decline in the water level.

<u>Short comment / recommendation</u>:

1) The recharge from rainfall (or its equivalent amount) is taking part in GW dynamics, so while calculating the stage of groundwater development, recharge from other sources could be ignored.
2) Since the ET is a prevailing phenomenon; it needs to be mentioned while calculating the stage of groundwater development.

9. Scenario testing and management options

The effort behind generating a mathematical model has the ultimate aim to understand the response of the aquifer to the anticipated changes in the stresses keeping the model properties and its boundary unchanged. Although the boundary conditions generally remain the same during prediction, it could be changed if the data with high accuracy is available or has been simulated. A predictive model also requires to incorporate the new field data available with time to do post audit it periodically.

As per the groundwater resource calculation, the stage of groundwater development in most of the blocks in this region is categorised as a safe zone. The water level hydrograph, also, shows that the region has very high seasonal fluctuation in water level rather than any long-term water declining trend. This seasonal fluctuation is very much obvious from the data, and model-generated results that it is due to negligible or no rainfall during the months of October/November to May-June. Also, the agricultural draft rate for the non-monsoon season is higher than that of monsoon period caused a further decline in water level. The rainfall in the following monsoon period fills the aquifer storage.

In light of these hydrogeological conditions, six different scenarios have been created by making different possible changes in draft and recharge which could be possible by efficient irrigation and rainwater recharge techniques by utilising rainwater. These scenarios have been tested for the next 15 years (2017-2032) using the calibrated model. The model output for the various scenarios has been assessed at the regular interval of 5 years on the aspect of:

1) Simulated Head
2) Mass balance and Zone budget
3) Hydrograph, and
4) Drawdown map

9.1. Simulated Head

9.1.1. Scenario-1

In this scenario, the groundwater pumping, and recharge condition (data for the assessment year 2013) at the end of the simulation period were allowed to continue for the next 15 years (16-06-2017 to 15-06-2032). The model generated groundwater head at an interval of five years is shown in figure 45. The result shows the drying of cells (aquifer in the region of Mahoba, and Chitrakoot districts. These regions are in the vicinity of the hard-rock boundary where the aquifer thickness to less to sustain the groundwater draft.

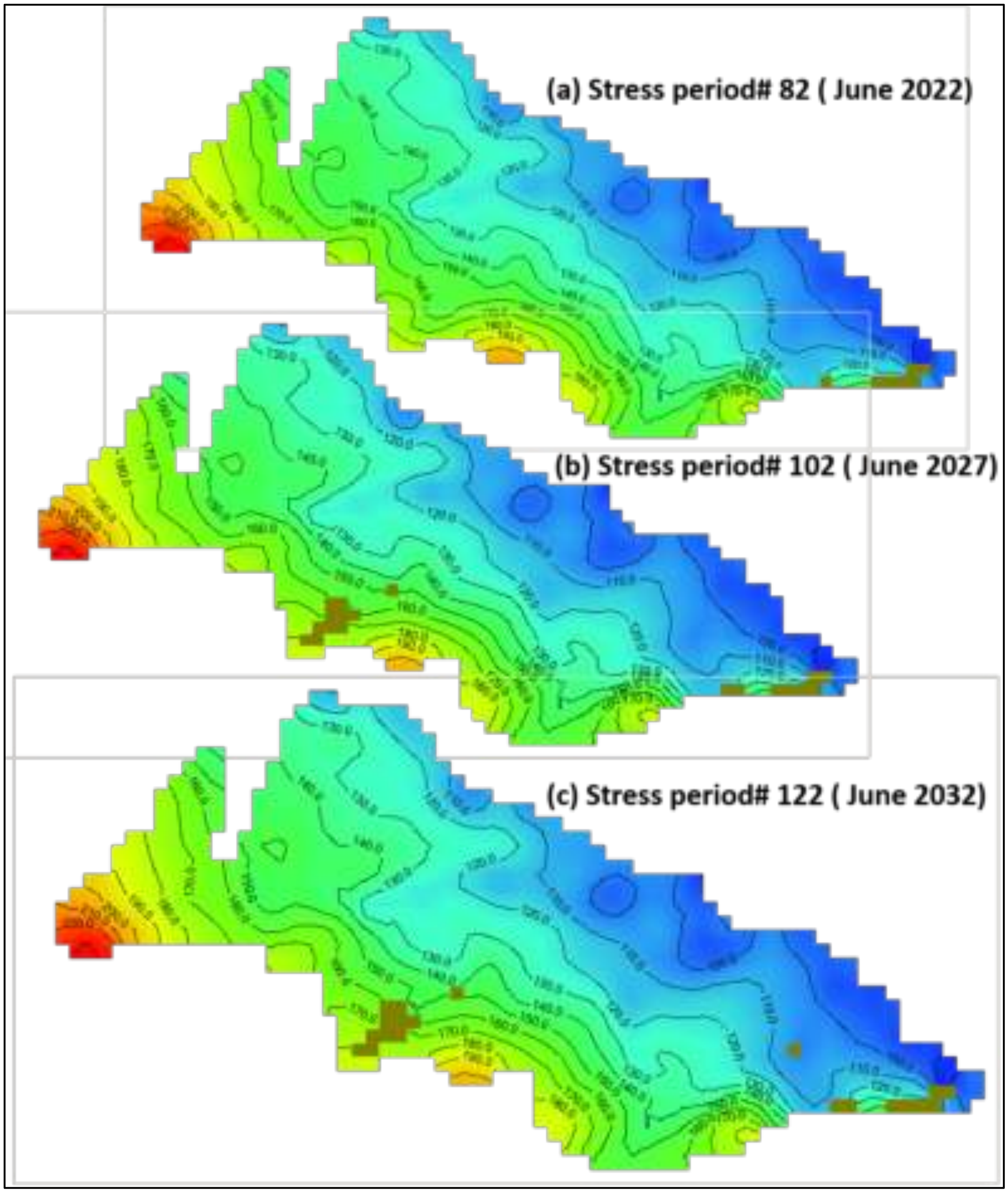


Figure 45: Water Level Map generated in Predictive Model Scenario – 1.

9.1.2. Scenario-2

Later on, new draft and recharge assessed for the year 2017 have been provided. The stage of GW development for this year shows a twofold rise or fall with respect to the year 2013. Therefore, in the second scenario, the draft and recharge used in scenario 1 has been replaced by the latest draft and recharge into the model to understand its effect in near fifteen years (16-06-2017 to 15-06-2032). The model generated groundwater head at an interval of five years is shown in figure 46. The results show the drying of cell mainly in the region of Chitrakoot district within the five years. In later periods, Mahoba district could also face the drying condition which will remain till the last of the model consideration period (June 2032) in the given groundwater inputs. The model predicts the decline in the Banda district also.

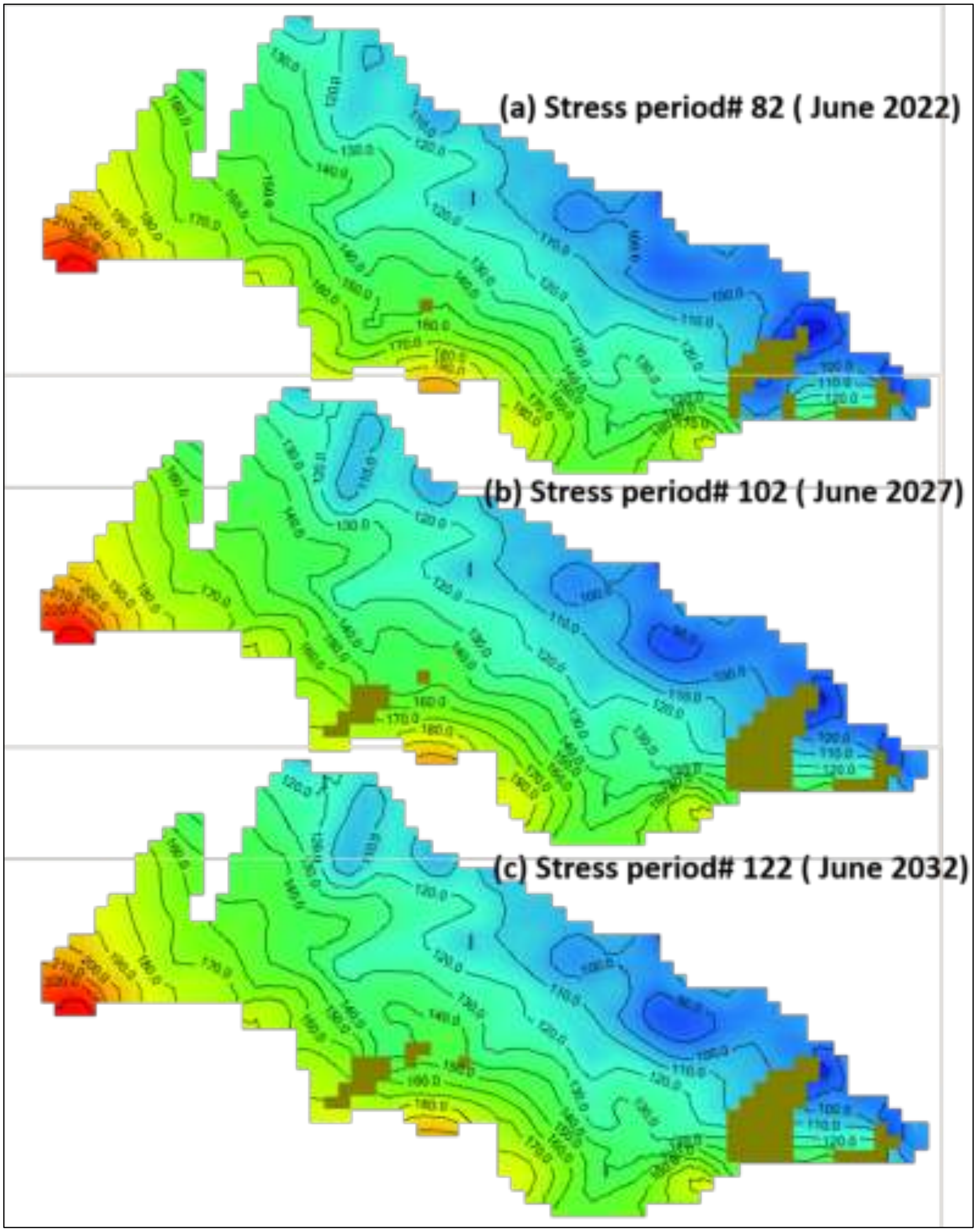


Figure 46: Water Level Map generated in Predictive Model Scenario – 2.

9.1.3. Scenario-3

This scenario has been done as per the approach adopted in different NAQUIM reports of the Bundelkhand region in which the stage of groundwater development is tried to keep within the safe category. Therefore, the total draft has been assumed to be only 60% of the total recharge assessed for the year 2017. Out of the total draft, irrigation draft has been further calculated by subtracting the domestic and industrial draft from the total draft (i.e. 60%). The model input has been calculated as has been discussed in section 6.5.3 and repeated for years 2017 to 2032 (16-06-2017 to 15-06-2032).

The model generated groundwater head at an interval of five years is shown in figure 47. The contours in at the border of Jhansi and Jalaun districts (Moth-Nadigaon-Konch-Dakor blocks) are going to lower in the next five years by approximately 10m (figure 47 (a)). If the same rate continues, the aquifer will be left with no water, as it is shown by the dry cell in figure 47 (b) and (c). These regions were reported having stage of groundwater development around 36% to 46%, and increasing it to 60% has lead to a condition where aquifer may not stand with the assigned recharge.

9.1.4. Scenario-4

This scenario has been done as per the approach adopted in different NAQUIM reports of the Bundelkhand region in which the different artificial recharge (AR) methods is proposed to increase the recharge to the groundwater approximately by 20%-30%.

Since the storage property is less, the aquifer will not be able to accommodate the high recharge within its storage; an increase of 20% in recharge has been considered, the groundwater draft remained same as that of scenario 3.

The model generated groundwater head at an interval of five years is shown in figure 48. The water level condition at the border of Jhansi and Jalaun districts (Moth-Nadigaon-Konch-Dakor blocks) has got improved from scenario 3. The contours in this region show that it will not decline to the extent of cell dry in the next 15 years.

9.1.5. Scenario-5

This scenario has been adopted as per the result from scenario 4 and 5. Since the increase in recharge by 20% is not able to generate the normal contour pattern in Jhansi district, its draft rate has been kept as per its assessment for the year 2017.

The model generated groundwater head at an interval of five years is shown in figure 49. The water level in the condition at the border of Jhansi and Jalaun districts has got restored to the natural pattern of the surrounding for the next 15 years.

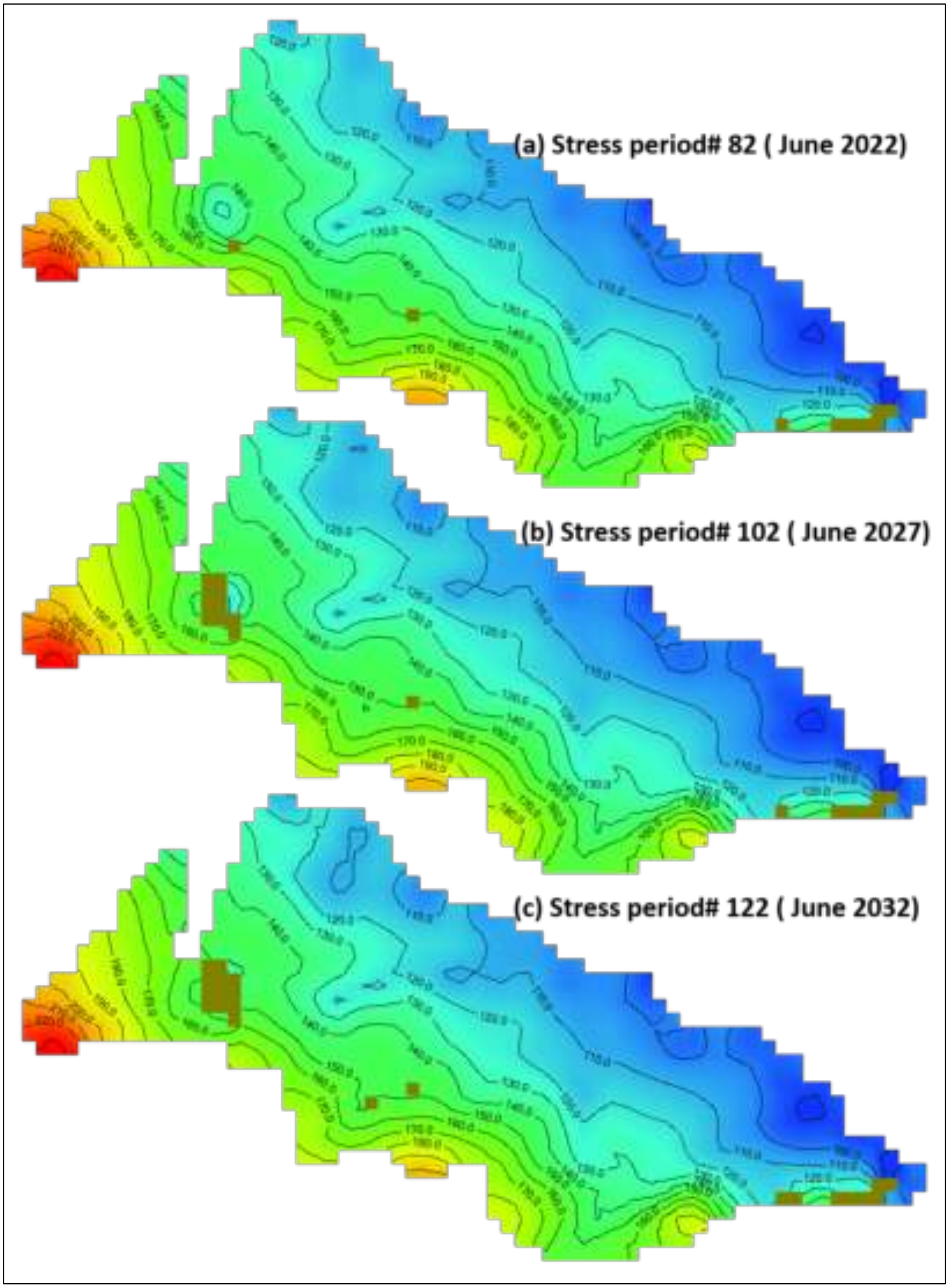


Figure 47: Water Level Map generated in Predictive Model Scenario – 3.

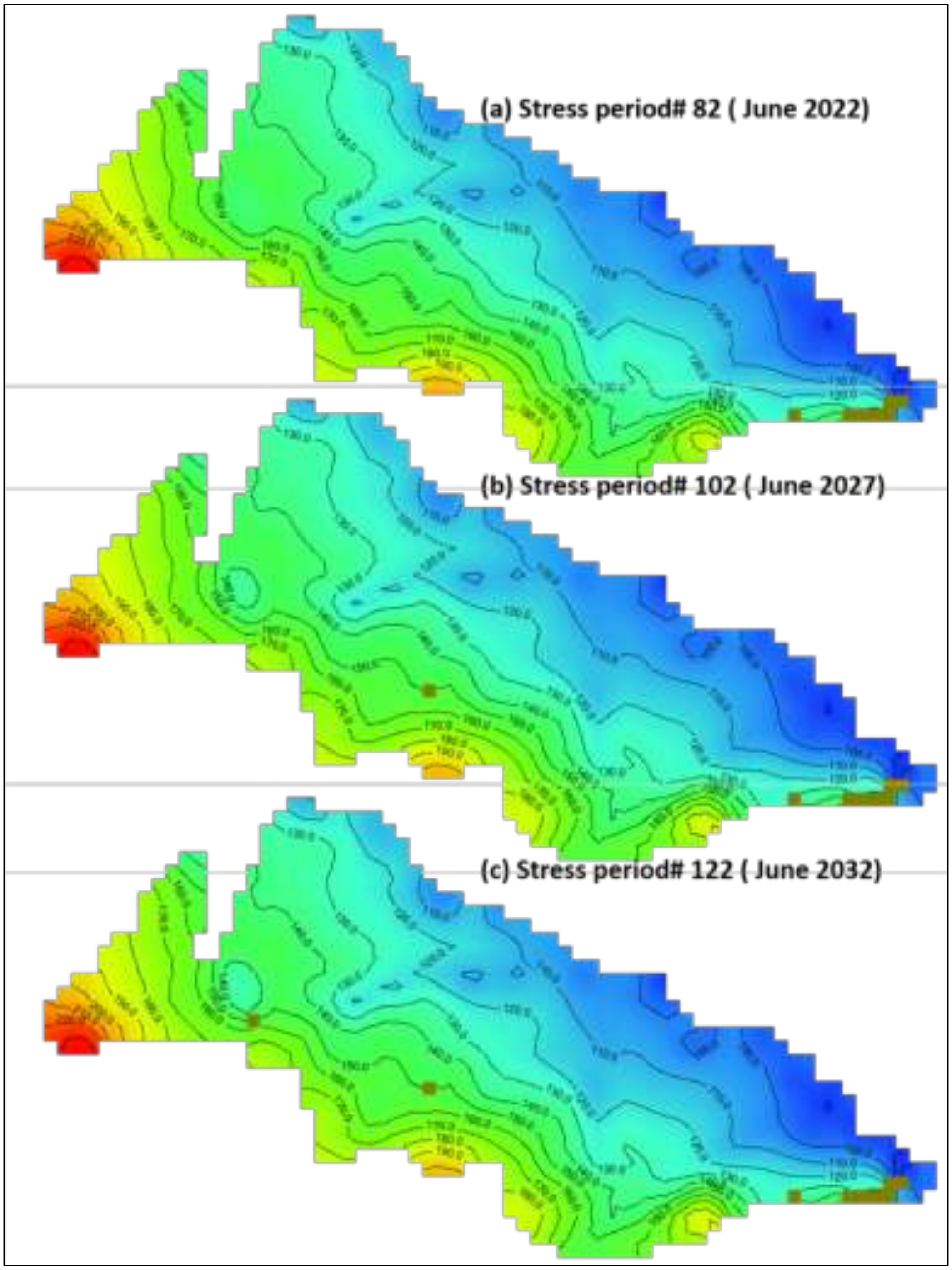


Figure 48: Water Level Map generated in Predictive Model Scenario – 4.

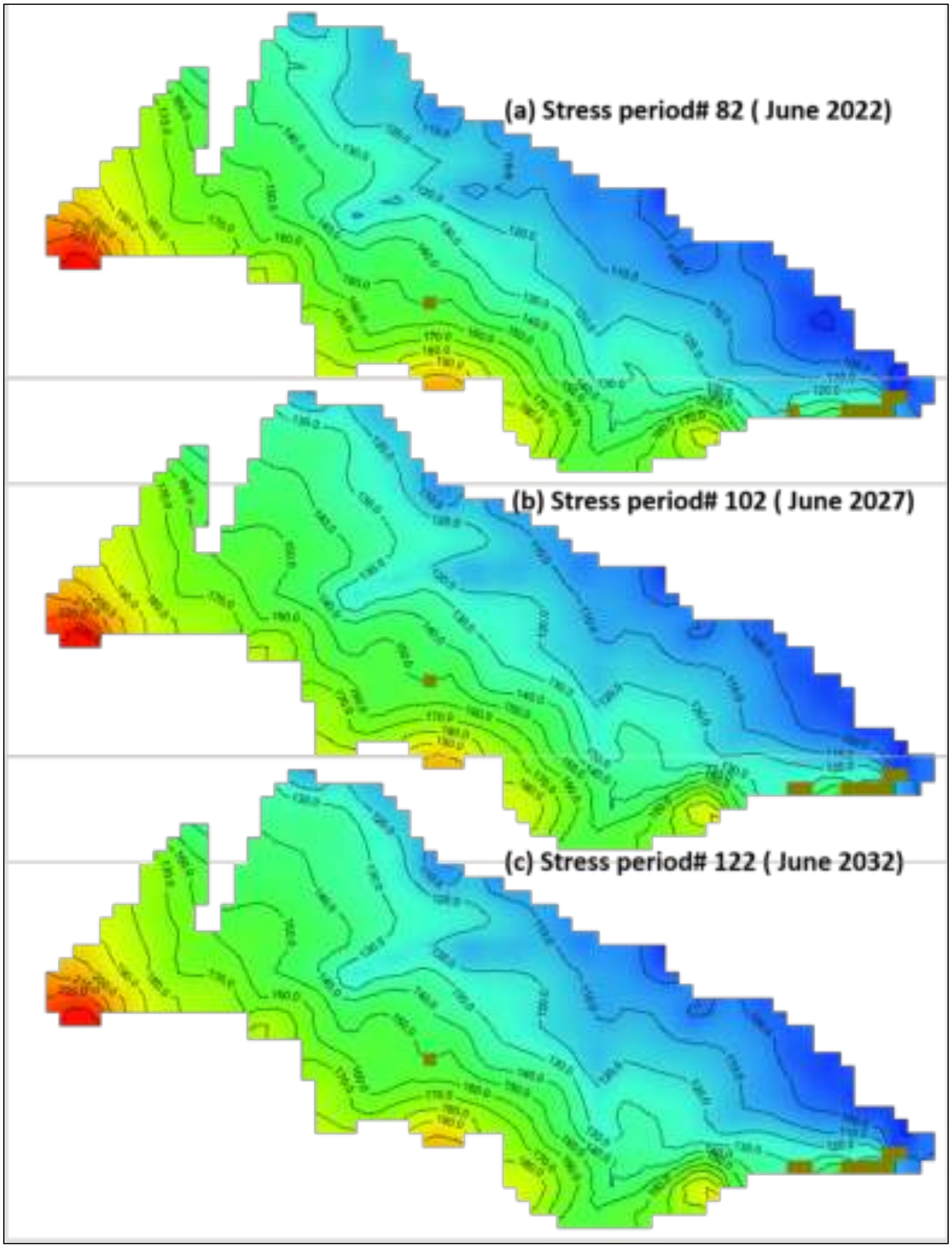


Figure 49: Water Level Map generated in Predictive Model Scenario – 5.

9.1.6. Scenario-6

The unit draft of the well is reported higher in non-monsoon season in the study area. This scenario considers a condition of interchanged rate between the monsoon and non-monsoon rate, associated with increase in rainfall recharge by 20%. This condition could be helpful because the high extraction rate may sustain only during the availability of rainfall recharge.

The model generated groundwater head at an interval of five years is shown in figure 50. The water level in the condition at the border of Jhansi and Jalaun districts has got restored to the natural pattern of the surrounding for the next 15 years.

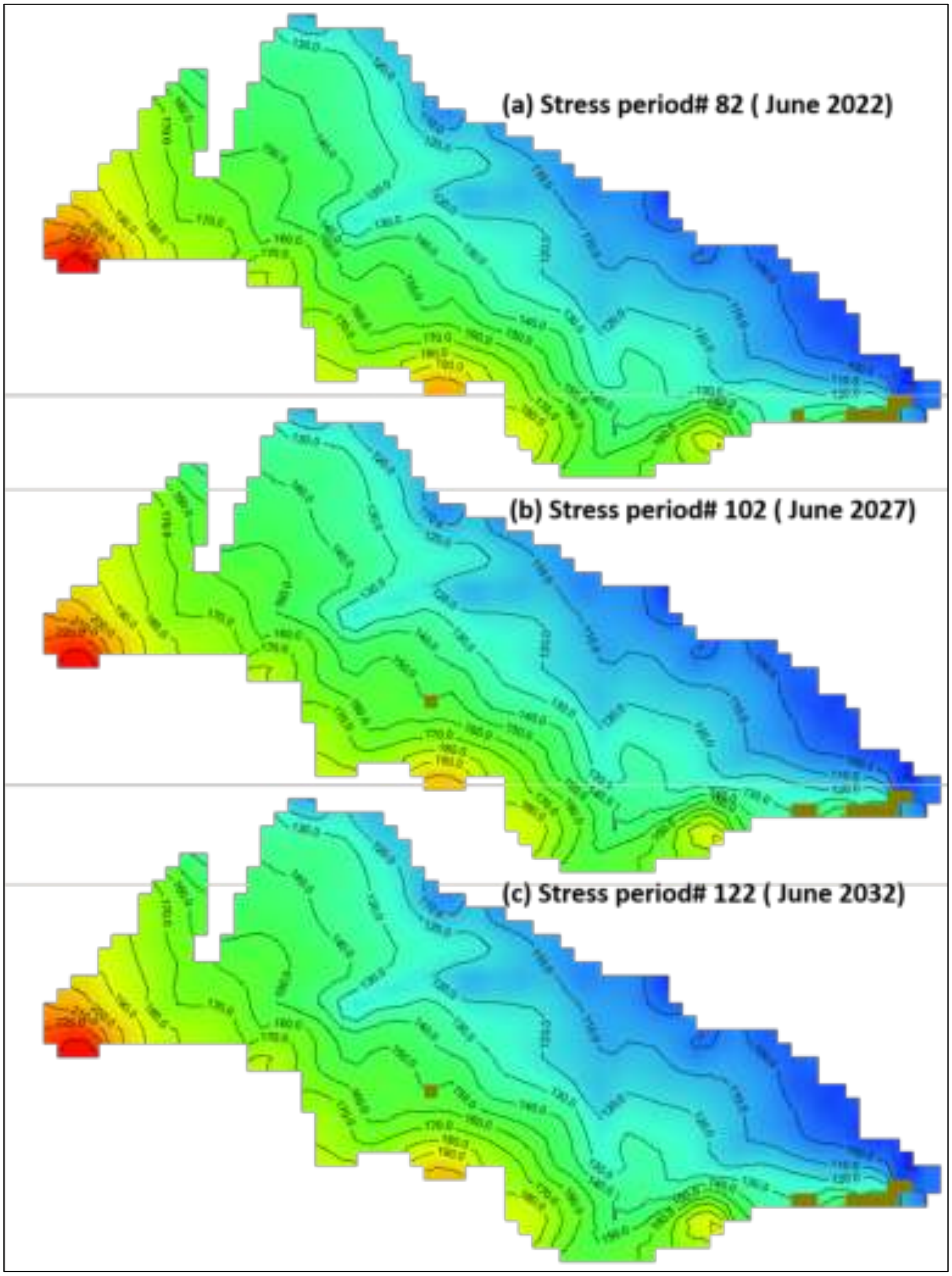


Figure 50: Water Level Map generated in Predictive Model Scenario – 6.

9.2. Mass balance and Zone budget

9.2.1. Mass balance

The groundwater budget under different prediction scenarios has been summarised in table 21 at an interval of 5years (table 21: (a). (b), and (c)), and cumulative sum for the entire prediction period (table 21:(d)). The different inflow and outflow components of the model simulation are compared with their respective results of different scenario by using three colour scale highlight system. The values higher than 50percentile is highlighted with red colour shades and lower than that with green colour shade. The middle range values are highlighted in yellow shades.

The groundwater budget shows that model involves 52.7 billion cubic meters (BCM) to 65.34 BCM of water in scenario 1, and scenario 4 respectively under prediction period. The comparison of Net inflow and outflow from the model for different scenario is presented graphically in figure 51.

Table 21: Mass balance of the model for the different scenarios.

(a) Stress period 63 to 82 (5 years)

Scenarios	1	2	3	4	5	6
	INFLOW (MCM)					
STORAGE	5662.1	6682.8	7183.6	7324	6961.8	4394.7
RIVER	514.3	634.2	661.1	606.5	554.7	362.1
RECHARGE	11510.7	11486.8	11547.8	13861.5	13861.5	13861.5
TOTAL IN	17687.1	18803.7	19392.5	21792	21378	18618.3
	OUTFLOW (MCM)					
STORAGE	5376.6	5977.1	6571	7119.9	6637.8	4928
WELLS	8640.3	9029.6	9805.6	9811.3	10634.5	8112.7
RIVER	1075.5	1115.7	1076.7	1336.8	1251.1	1408
ET	2594.7	2681.3	1939.2	3524	2854.6	4169.6
TOTAL OUT	17687.1	18803.7	19392.5	21792.1	21378	18618.3
IN - OUT	0.004	-0.004	-0.02	-0.061	0.02	-0.02
% DISCREPANCY	0	0	0	0	0	0

(b) Stress period 83 to 102 (5 years)

Scenarios	1	2	3	4	5	6
	INFLOW (MCM)					
STORAGE	5579.9	6243.5	7062.6	7330.1	2781.1	4436.7
RIVER	517.7	662.3	665.1	597.5	244.8	344.9
RECHARGE	11485.1	11185.1	11453.1	13857.6	8314	13861.4
TOTAL IN	17582.7	18090.9	19180.8	21785.2	11339.9	18642.9
	OUTFLOW (MCM)					
STORAGE	5394.1	5912.1	6758.7	7208.4	4004.4	4427.9
WELLS	8555.6	8504.2	9659.5	9801.1	5205.5	8111.4
RIVER	1065.8	1070	1046.7	1344	661.7	1456
ET	2567.2	2604.6	1715.8	3431.5	1468.2	4647.5
TOTAL OUT	17582.7	18090.9	19180.8	21785.2	11339.8	18642.9
IN - OUT	-0.008	0	-0.008	-0.016	0.041	0.016
% DISCREPANCY	0	0	0	0	0	0

(c) Stress period 103 to 122 (5 years)

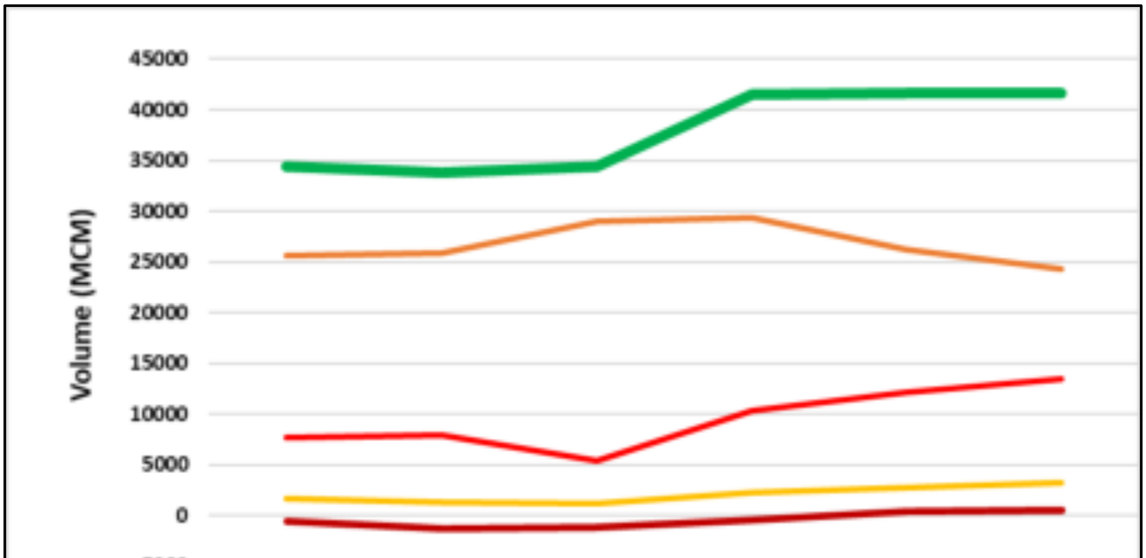
Scenarios	1	2	3	4	5	6
	INFLOW (MCM)					
STORAGE	5512.6	6102.9	6963.8	7319	17561.7	4436.1
RIVER	519.1	673.1	669.1	598.8	1403.2	345.2
RECHARGE	11448.5	11085	11354.7	13839.8	41574.8	13856.7
TOTAL IN	17480.1	17861	18987.6	21757.7	60519.7	18638
	OUTFLOW (MCM)					
STORAGE	5392.6	5873.4	6723.4	7192.2	18000.5	4402
WELLS	8472.5	8333.6	9530.2	9785.5	26259.7	8105.4
RIVER	1061.8	1056.7	1036.3	1343.6	4179.8	1457.2
ET	2553.3	2597.4	1697.6	3436.5	12099.5	4673.2
TOTAL OUT	17480.1	17861.1	18987.5	21757.7	60519.5	18637.9
IN - OUT	0.025	-0.016	0.041	-0.033	0.176	0.074
% DISCREPANCY	0	0	0	0	0	0

(d) Stress period 63 to 122 (15 years)

Scenarios	1	2	3	4	5	6
	INFLOW (MCM)					
STORAGE	16754.6	19029.2	21210	21973.1	17561.7	13267.4
RIVER	1551.1	1969.6	1995.1	1802.9	1403.2	1052.2
RECHARGE	34444.1	33756.9	34355.6	41558.9	41574.8	41579.6
TOTAL IN	52749.9	54755.7	57560.9	65334.9	60539.7	55899.2
	OUTFLOW (MCM)					
STORAGE	16163.2	17762.6	20053.1	21520.6	18000.5	13758
WELLS	25668.3	25867.4	28995.4	29398.1	26259.7	24329.5
RIVER	3203.1	3242.5	3159.7	4024.4	4179.8	4321.2
ET	7715.2	7883.3	5352.7	10391.9	12099.5	13490.4
TOTAL OUT	52749.9	54755.7	57560.9	65335	60539.5	55899.1
IN - OUT	0.02	-0.02	0.012	-0.111	0.176	0.07
% DISCREPANCY	0	0	0	0	0	0

The evapotranspiration and well are the components of the model which allows only removal of water from the system, whereas recharge component adds water. However, river and storage allow moving water into and out of the system. Therefore, the net volume of water for the river and storage may show negatively as well as positive values. In this present case, the river is gaining more water than loosing to the system in all the scenario. On the other hand, storage shows a net loss for the scenarios 1 to 4, net gain in scenarios 5 and 6.

These effective loss/gain from the river and storage is compared with the recharge, well, and evapotranspiration for different scenario. The comparison shows that the depletion of water level could be arrested effectively only after doing artificial recharge and reducing groundwater draft.



	1	2	3	4	5	6
STORAGE	-591.4	-1266.6	-1156.9	-452.5	438.8	490.6
WELLS	25668.3	25867.4	28995.4	29398.1	26259.7	24329.5
RECHARGE	34444.3	33756.9	34355.6	41558.9	41574.8	41579.6
RIVER	1652	1272.9	1164.4	2221.5	2776.6	3269
ET	7715.2	7883.3	5352.7	10391.9	12099.5	13490.4

Figure 51: Different component of inflow and outflow for scenario 1 to 6.

9.2.2. Zone budget

The prediction of water level condition has been studied for each zone for the net storage change over the period of prediction. A zone budget has been calculated for the 5 years segment and added to get the budget for 15 years. The summary of inflow and outflow and net change in the storage is summarised below as table 22 for each scenario.

Table 22: Transaction of water from different zone in model area over during prediction period under different scenario.

Zone No. ->	2	3	4	5	6	7	8	9	2	3	4	5	6	7	8	9
	(a) Scenario1								(b) Scenario2							
Stress period	INFLOW (MCM)								INFLOW (MCM)							
(63-82)	1340.6	807.5	1694.5	358	244.8	441.2	191	354.4	1408.8	999.5	2042.2	378.9	405	384.8	220.1	594.7
(83-102)	1341.8	800.5	1694.8	301.9	241.5	444.1	192	352.4	1392.9	992.4	2021.9	294.2	410.1	386.2	221.3	310.8
(103-122)	1343.5	797.6	1696.4	246.1	240.1	446.1	192.8	350.6	1387.4	977.1	2015.6	253.8	410.3	387	222.5	246.7
Cumulative (63-122)	4025.9	2405.6	5085.7	906	726.4	1331.4	575.8	1057.4	4189.1	2969	6079.7	926.9	1225.4	1158	663.9	1152.2
	OUTFLOW (MCM)								OUTFLOW (MCM)							
(63-82)	1342.4	748.6	1690.8	228.3	226	442.6	189.3	336.5	1333.2	907.6	1893.6	146.4	450.4	402.6	209.6	437
(83-102)	1343.3	762.2	1693.8	219.8	228.8	443	190.9	342.6	1356	934.7	1971.6	142.1	418.7	387.5	218.6	295
(103-122)	1343.7	767.4	1694.7	207.2	230.3	444.6	192	343.5	1362.7	930.8	1989.9	139.5	411.5	386.8	220.6	246.8
Cumulative (63-122)	4029.4	2278.2	5079.3	655.3	685.1	1330.2	572.2	1022.6	4051.9	2773.1	5855.1	428	1280.6	1176.9	648.8	978.8
IN-OUT	-3.5	127.4	6.4	250.7	41.3	1.2	3.6	34.8	137.2	195.9	224.6	498.9	-55.2	-18.9	15.1	173.4
	(c) Scenario 3								(d) Scenario 4							
Stress period	INFLOW (MCM)								INFLOW (MCM)							
(63-82)	1284.3	875.2	2402.7	288.5	659.2	547.2	332.3	505.6	1307.9	914.1	2432.1	292.4	685.2	553.9	342.1	514.1
(83-102)	1291.7	885	2381.8	279.2	564.3	550.4	332.1	505.4	1317.9	929.7	2433.2	285.9	674.9	559.1	342.6	512.9
(103-122)	1295.2	886.2	2373.3	277.4	482.2	552	333.1	505.4	1322	930.9	2436.4	284.9	659	561.9	343.5	512.4
Cumulative (63-122)	3871.2	2646.4	7157.8	845.1	1705.7	1649.6	997.5	1516.4	3947.8	2774.7	7301.7	863.2	2019.1	1674.9	1028.2	1539.4
	OUTFLOW (MCM)								OUTFLOW (MCM)							
(63-82)	1321.3	891.5	2168	172.3	515.5	511.2	293.6	489	1386.5	989.7	2306.7	214.8	606.2	537	311.2	527.3
(83-102)	1305.1	868.9	2326.3	173.2	505	541	326.1	504.8	1337.5	924.5	2432	214.2	644	558.6	340.9	517.7
(103-122)	1300.5	866.2	2344.3	173.3	454.2	545.9	328.4	504.9	1329.4	923.3	2434.1	215	635.9	560.6	342.1	513.4
Cumulative (63-122)	3926.9	2626.6	6838.6	518.8	1474.7	1598.1	948.1	1498.7	4053.4	2837.5	7172.8	644	1886.1	1656.2	994.2	1558.4
IN-OUT	-55.7	19.8	319.2	326.3	231	51.5	49.4	17.7	-105.6	-62.8	128.9	219.2	133	18.7	34	-19
	(e) Scenario 5								(f) Scenario 6							
Stress period	INFLOW (MCM)								INFLOW (MCM)							
(63-82)	1296.7	888.8	2402.7	287.8	428.7	540.4	337.5	508.3	822.8	586.8	1460.5	160.7	311.7	329.8	218	319.4
(83-102)	1118.6	777.5	2012	230.4	429.8	459.3	291.1	432.8	838.3	612.6	1461.5	162.9	316.8	331.2	218.8	319.4
(103-122)	851.6	638.8	1477.6	163	422.9	341.1	225.9	325.2	842.5	613.7	1462.7	160.3	315.9	331.7	219.6	318.3
Cumulative (63-122)	3266.9	2305.1	5892.3	681.2	1281.4	1340.8	854.5	1266.3	2503.6	1813.1	4384.7	483.9	944.4	992.7	656.4	957.1
	OUTFLOW (MCM)								OUTFLOW (MCM)							
(63-82)	1353.5	917.8	2179.5	161	482.9	516.2	301.8	501	999.1	737.9	1536.4	128.4	389.5	360.2	212.4	374
(83-102)	1253.5	869.6	2286.1	174.8	434.4	511.8	316.5	495.5	858.7	616.5	1461.7	123	318.9	333.5	218.5	324.9
(103-122)	867.6	677.5	1507	195.8	423.2	349.7	231.6	335.6	850.7	612.3	1461.5	124.2	316.2	332.2	219.1	319.3
Cumulative (63-122)	3474.6	2464.9	5972.6	531.6	1340.5	1377.7	849.9	1332.1	2708.5	1966.7	4459.6	375.6	1024.6	1025.9	650	1018.2
IN-OUT	-207.7	-159.8	-80.3	149.6	-59.1	-36.9	4.6	-65.8	-204.9	-153.6	-74.9	108.3	-80.2	-33.2	6.4	-61.1

9.3. Hydrograph

Hydrograph could be a great tool to track the temporal change in water level. Therefore, it has been produced from the prediction period for the pre-monsoon (15th May) and post-monsoon (15th Nov.) season. The location point for the prediction hydrograph is same location used during the calibration-validation period. The hydrographs were generated for each scenario and compiled into one graph (figure 52) for one location to understand the effect and compare the suitability or need of the method. From each zone, two locations are selected to represent the highest SoD (left image) and lowest SoD (right image) of that particular zone.

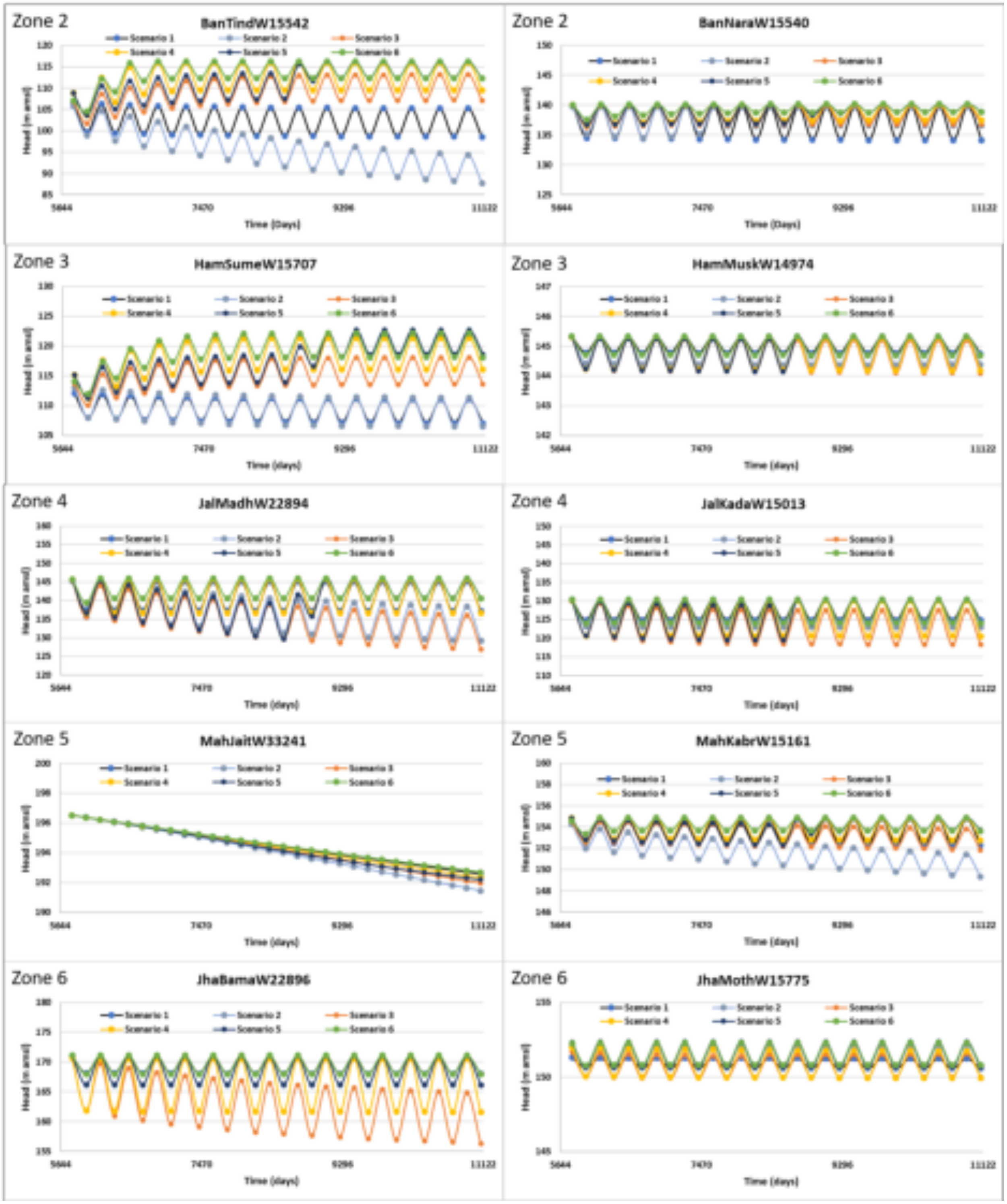


Figure 52. Representative Hydrographs generated in Predictive Model Scenario – 1 to 6. (Hydrographs in left-hand side- are selected from the highest SoD whereas hydrographs in the right-hand side are selected from lowest SoD of that particular zone).

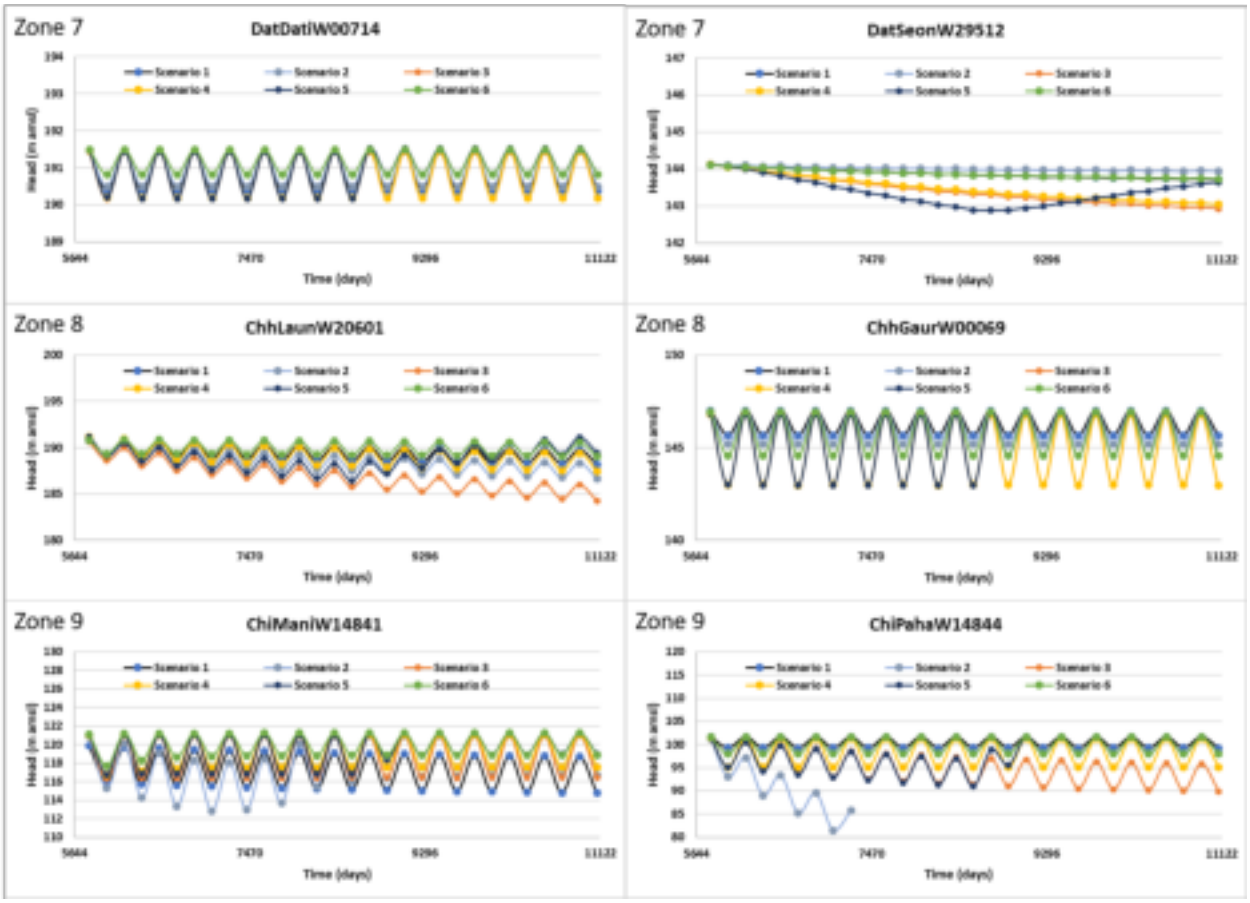


Figure 52 (cont…). Representative Hydrographs generated in Predictive Model Scenario – 1 to 6. (Hydrographs in left-hand side- are selected from the highest SoD whereas hydrographs in the right-hand side are selected from lowest SoD of that particular zone).

9.4. Drawdown map

The drawdown map for the stress period 62, 82, 102, and 122 has been mosaiced together to understand the effect of different scenario resulting in declining or rising of water level. The zone of decline and dry cells has been highlighted with the red broken line in figures (figure 53 – figure 58) showing the change in water level at an interval of 5 years during the prediction period. The following sub-section summarises the hydrogeological condition in the study are predicted under different scenarios.

9.4.1. Scenario-1

After continuing the recharge and draft assessed for the year 2013, model predicts some prominent depression (figure 53) in the districts of Jalaun (Madhogajn, Jalaun, Nadigaon blocks), Jhansi (Moth block), Hamirpur (Sumerpur, Kurara, and Gohand blocks), Mahoba (Panwari, and Charkhari blocks), Banda (Tindwari, Jaspura, and Badokhar-Khurd block) and Chitrakoot district (Karvi, Mau, and Ramnagar blocks). These depressions will keep on expanding and lead to a situation of total depletion in parts of Chitrakoot and Mahoba districts.

The blocks in the Chitrakoots districts shows the dry cells from the validation period of modelling. It is mainly due to the thickness of the aquifer is not much near the model boundary and unable to accommodate water for the demand and ultimately leads to dry-cell. A similar kind of hydrogeological condition is present in a few parts of Datia district where model simulates deep water level.

9.4.2. Scenario-2

After continuing the recharge and draft assessed for the year 2017, the model predicts high rate of water decline (figure 54) in the districts of Jalaun, and Banda. In the district of Jalaun, the model calculates a decline in groundwater greater than 25 meters in its Jalaun block influencing the groundwater level in its surrounding blocks of Madhoganj and Kuthund adversely.Similarly, in Bands district, model predicts a decline of more than 20meters in Tindwara and Baberu blocks.

In Chitrakoot district, the groundwater condition in Karvi and Pahari blocks is predicted to start drying in the year 2021-22. Similar prediction is done for Panwari block of Mahoba district, which will also adversely affect its adjacent block namely Rath of Hamirpur district. In its most part water level will decline by more than 15 meters and eventually it will start drying within 15 years. Sumerpur block of this district also shows a decline in water level which should not be avoided.

9.4.3. Scenario-3

In this scenario, either high or low extraction of groundwater has been put to the 60% SoD with respect to the net available recharge assessed for the year 2017. Figure 55 shows the simulated effect in the future. The result shows three hotspot zone in the model area: Jalaun, Jhansi and Mahoba.

In Jalaun, the water level condition will face a decline in water level in the range of 20-25 m bgl which is a little improved condition with respect to scenario 2. The hydrogeological condition of the Month block in Jhansi is predicted to start drying after at the end of year 2023. Some small region in Muskara block (Hamirpur district) and Panwari block (Mahoba) may face drying condition by 2032.

On the other hand, the model predicts an improvement in the groundwater level in Tindwara and its surrounding block (Banda district), and other regions.

9.4.4. Scenario-4

In this scenario, draft values are kept same to that of scenario-3, and a 20% increased recharge has been considered for understanding the improvement over the scenario-3. The output of the model prediction is presented in figure 56 which clearly shows that the decline could be controlled and water level may start rising under this scenario except for Moth block in Jhansi district.

9.4.5. Scenario-5

This is a replica of scenario 4, in which groundwater draft for the Jhansi district has been changed back to originally calculated for the assessment year 2017. The output of the model prediction is presented in figure 57 which clearly shows improvement in groundwater condition of Jhansi.

that the decline could be controlled and the water level may start rising under this scenario except Moth block in Jhansi district. The occurrence of deep water level condition in Mahoba region is due to abrupt model boundary whose thickness is inconsistent.

9.4.6. Scenario-6

The groundwater resources suggested the high extraction rate in low or no recharge period and vice versa. This scenario is created for understanding the effect of interchanging the groundwater extraction pattern for monsoon season. In this scenario, the recharge rate is also assumed to be 20% higher by means of AR and efficient - irrigation methodology. Model prediction results under the scenario-6 are presented in figure 58. The model output suggests that the water level in the aquifer will rise with drawdown not more than 5 meters. Also, in many region groundwater will start rising in the range of 5 meters within the five years of its implementation. But the rise in water level may not go much above due to natural discharges and evapotranspiration factors.

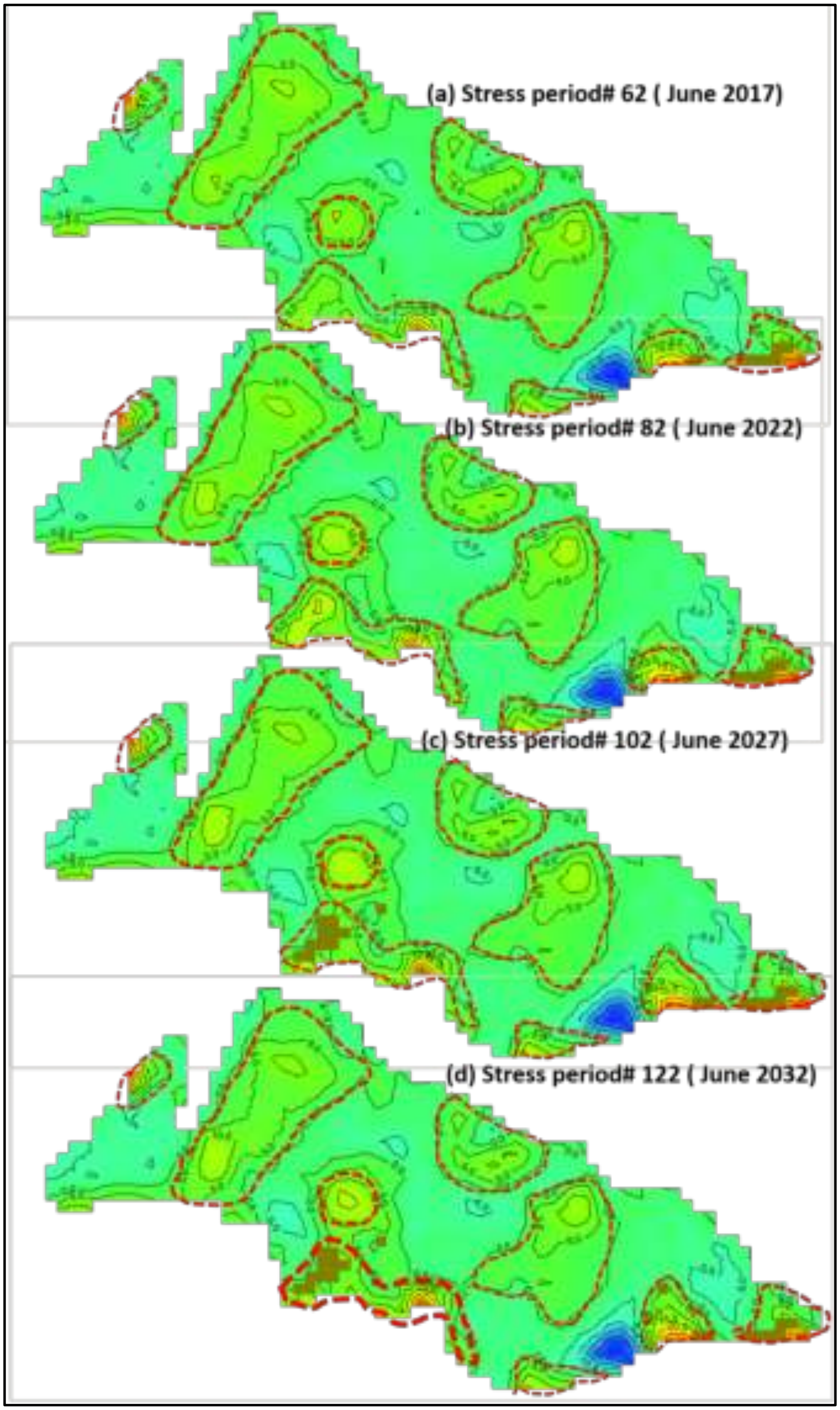


Figure 53: Depth to water level map generated in Predictive Model Scenario – 1.

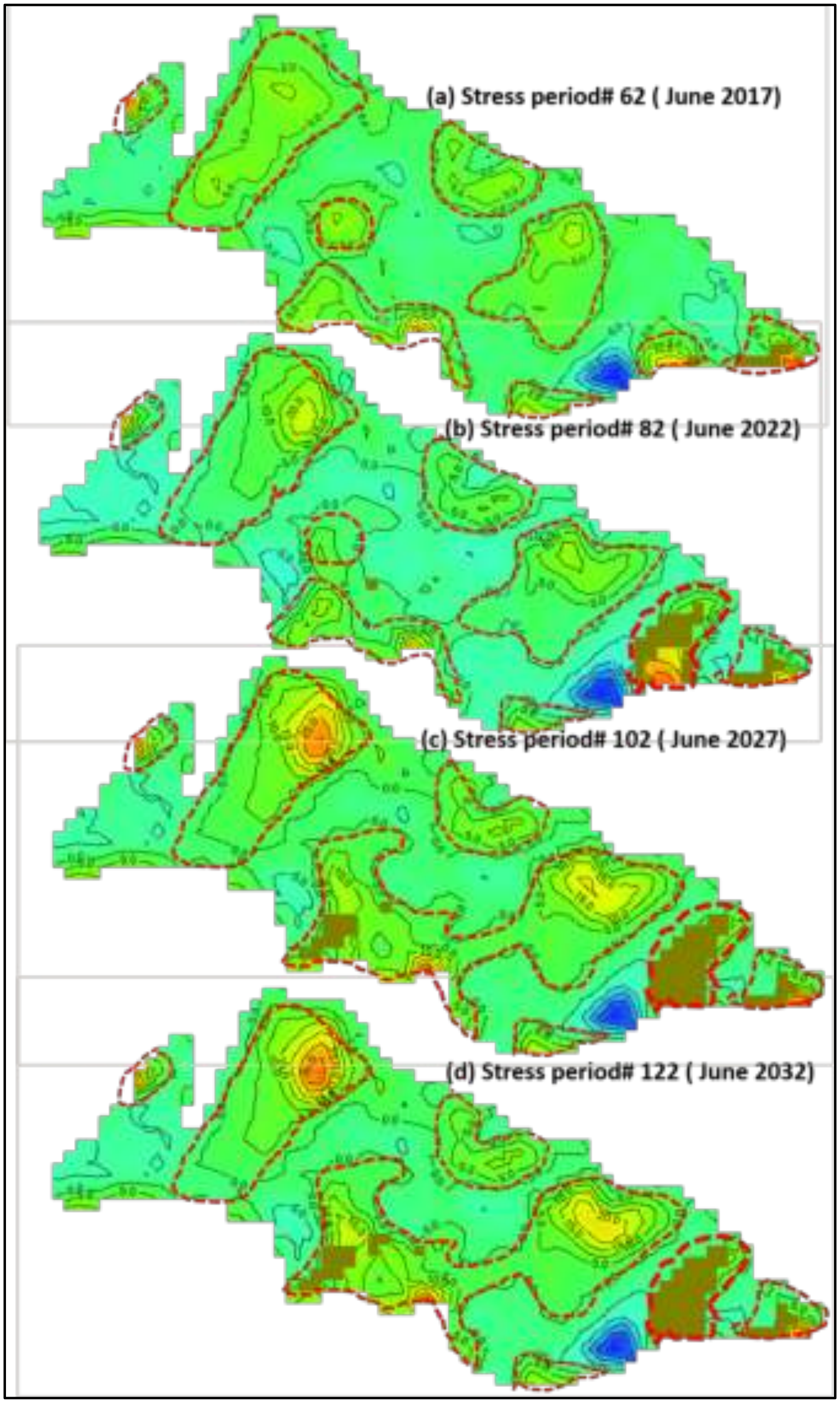


Figure 54: Depth to water level map generated in Predictive Model Scenario – 2.

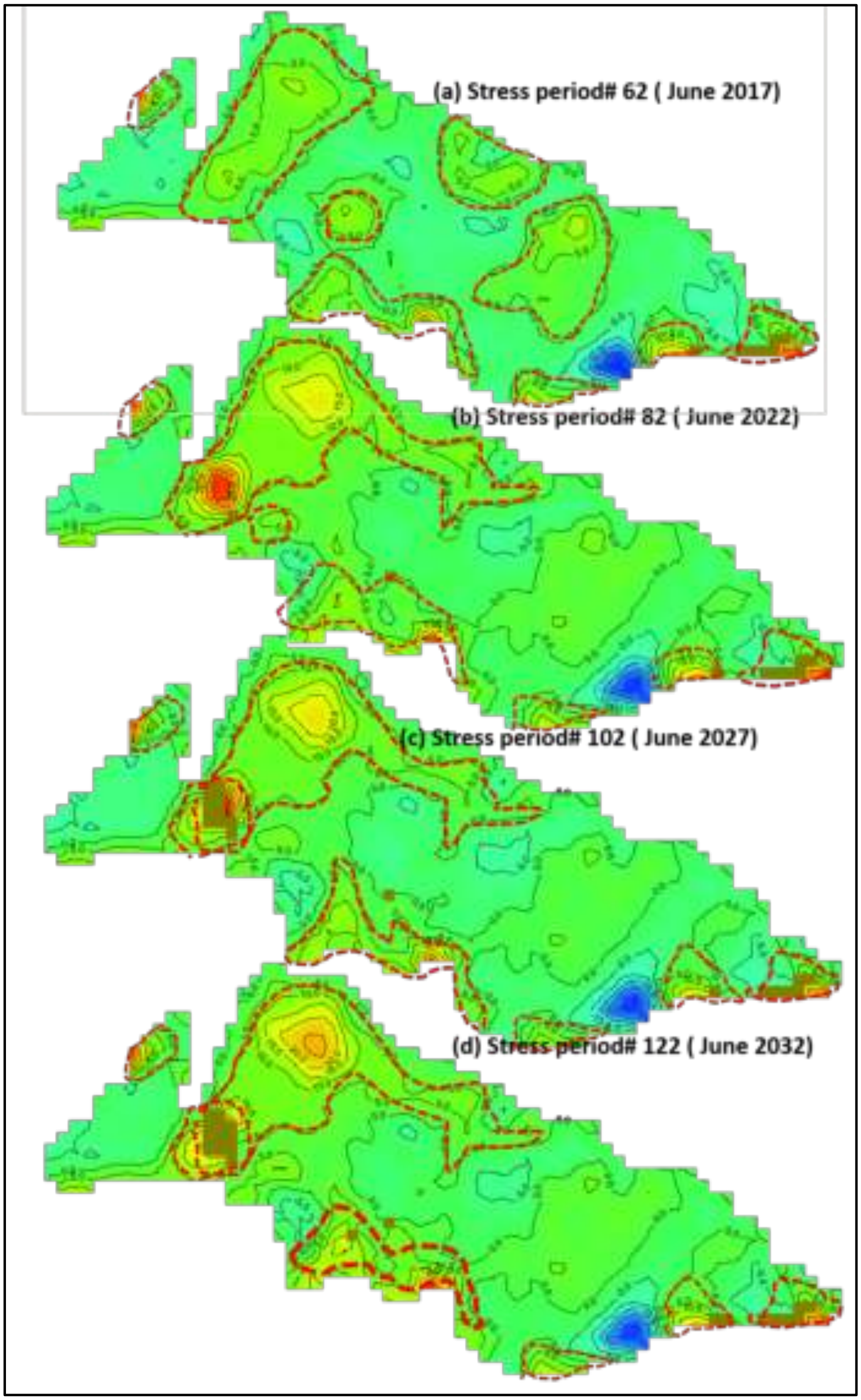


Figure 55: Depth to water level map generated in Predictive Model Scenario – 3.

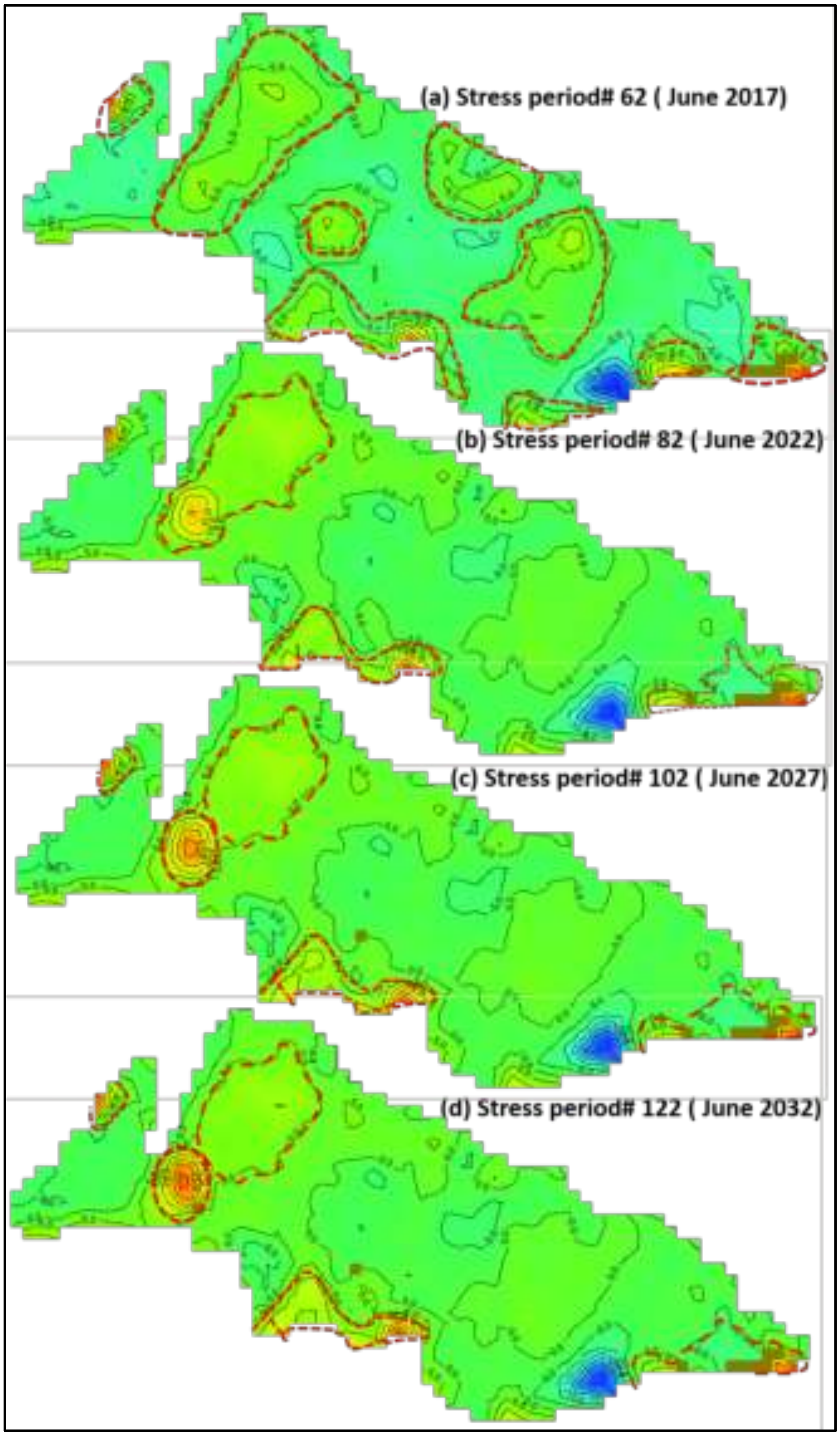


Figure 56: Depth to water level map generated in Predictive Model Scenario – 4.

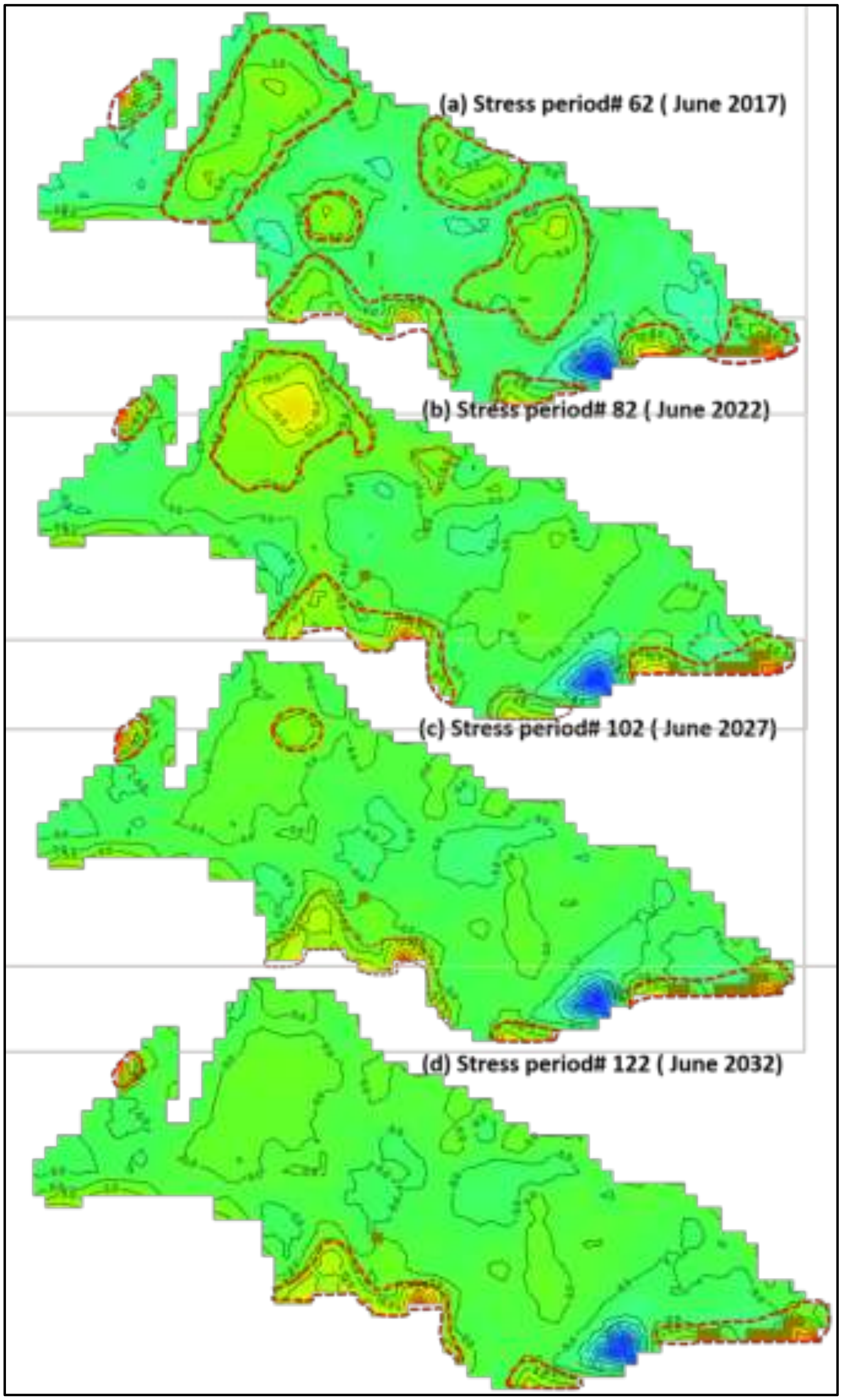


Figure 57: Depth to water level map generated in Predictive Model Scenario – 5.

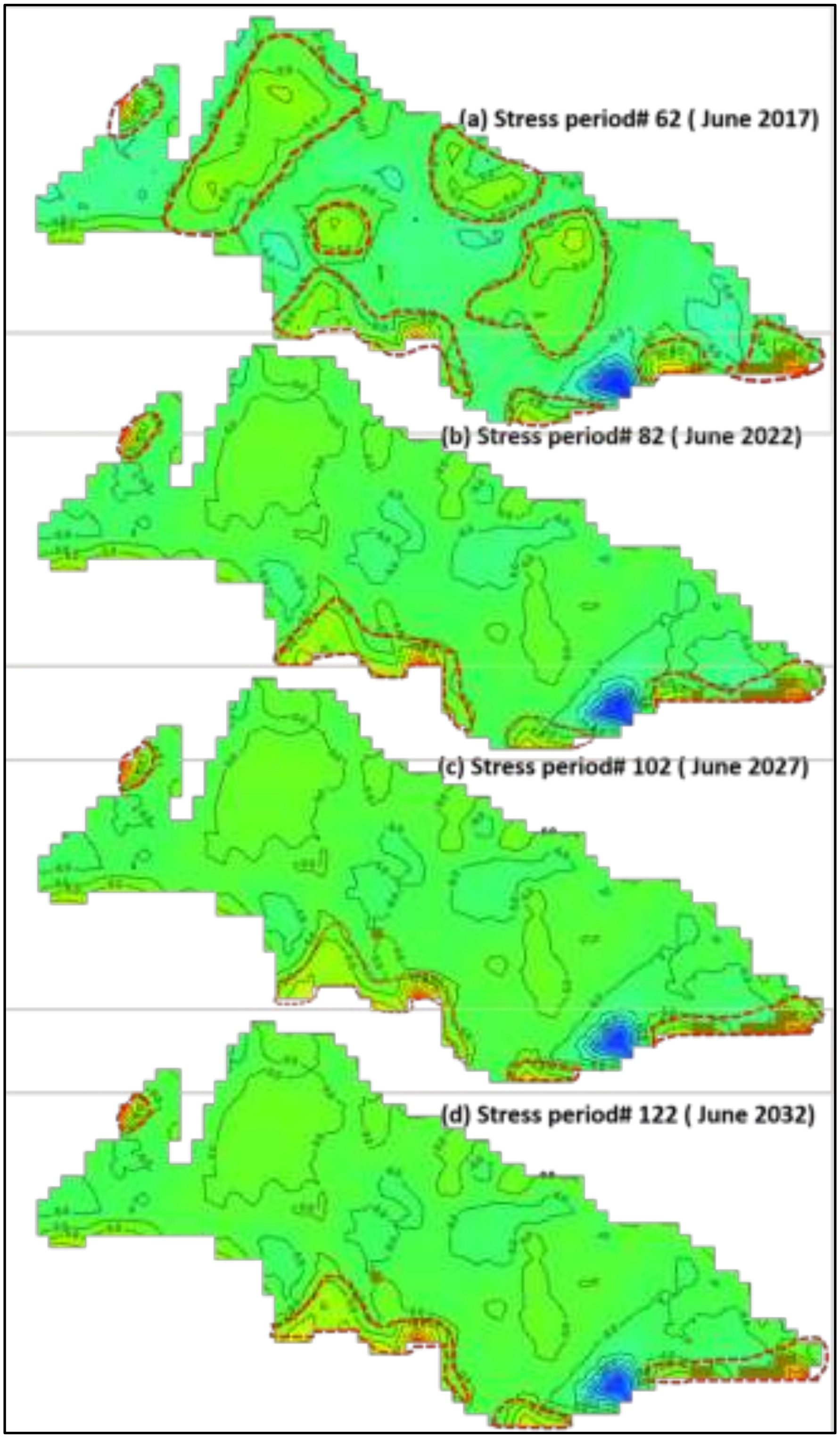


Figure 58: Depth to water level map generated in Predictive Model Scenario – 6.

10. Groundwater Management Strategy

There are six approaches tested to investigate the response on the groundwater system if the considered withdrawal and recharge continues for the next 15 years. The model output has been analysed through model generated (1) Spatio-temporal variation in model generated head, (2) Mass balance and zone budget, (3) Composite hydrographs, and (4) Spatio-temporal variation in drawdown.

10.1. Model prediction summary

A quick summary of the model output could be presented by drawdown map (figure 59) and tabulating the net storage change (table 23) and at the end of prediction period.

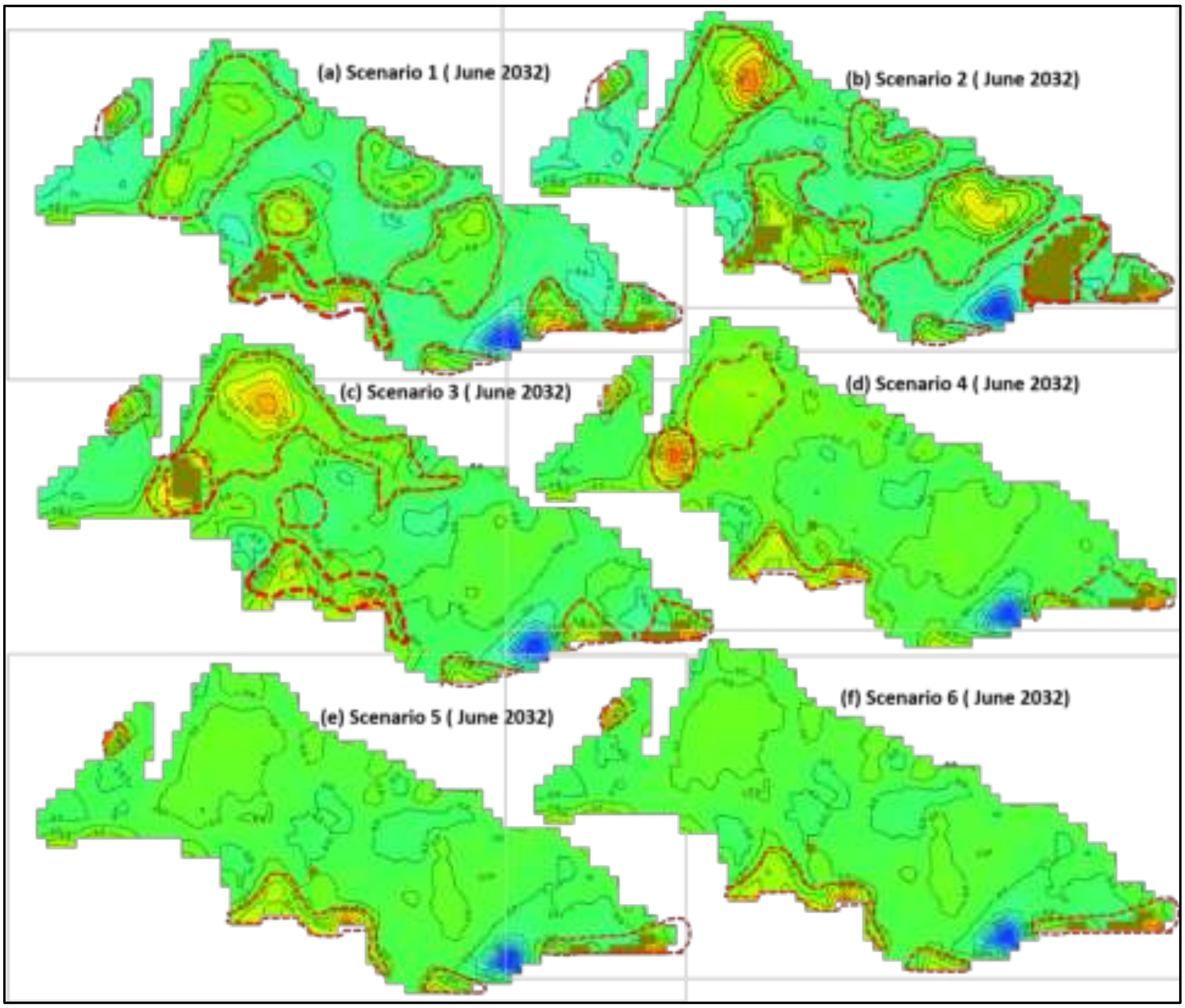


Figure 59: Summary of the probable hydrogeological condition after 15 years under different scenarios. The red broken line suggests the region to focus for implementing the AR and/or efficient irrigation under different scenarios.

Table 23: Summary of storage change under different scenarios.(values are in MCM)

Zones	2	3	4	5	6	7	8	9
Scenario 1	-3.5	127.4	6.4	250.7	41.3	1.2	3.6	34.8
Scenario 2	137.2	195.9	224.6	498.9	-55.2	-18.9	15.1	173.4
Scenario 3	-55.7	19.8	319.2	326.3	231	51.5	49.4	17.7
Scenario 4	-105.6	-62.8	128.9	219.2	133	18.7	34	-19
Scenario 5	-207.7	-159.8	-80.3	149.6	-59.1	-36.9	4.6	-65.8
Scenario 6	-204.9	-153.6	-74.9	108.3	-80.2	-33.2	6.4	-61.1

10.2. Aquifer management plan

To manage an aquifer, increasing rainfall recharge and controlled water extraction are key parameters. The hydrogeological condition and extent of demand should be taken care while proposing management plans. It is very much important to come out with a plan which should be cost-effective and feasible. Hence, any plan suits better if it involves change in recharge and draft than putting pressure on anyone. The recharge in the Bundelkhand region is mainly from the rainfall during monsoon season in which artificial recharge could store more water to the subsurface. However, any recharge structure cannot store all water into the aquifer. Also, NAQUIM reports for other districts, suggest an average of 20% of improvement in recharge by different artificial recharge methods. On the other hand, crops with a low water requirement could be a solution to reduce groundwater draft during non-monsoon period. Combining all the possibilities, six scenarios have been created on the basis of which suitable management strategy for the different zone is summarised below and tabulated as table 24.

Zone 2: Banda

- In Banda district, Tindwari, Jaspura, and Badokhar-Khurd blocks were the main spots of high decline. These decline in water level may be arrested effectively by combined effect of interchanging the groundwater extraction pattern and increasing the rainfall recharge by 20%.
- Alternatively, condition may also improve equally by setting the stage of groundwater development to 60% and increasing the rainfall recharge by 20%.
- Besides this, restricted SoD of 60% and rainfall recharge assessed for the year 2017 may also show a slow but positive result.

Zone 3: Hamirpur

- Sumerpur, Kurara, and Gohand blocks of Hamirpur zone face a decline of 10 -15 meters in the present scenario. These decline in water level may be arrested effectively by implementing the interchanged groundwater extraction rate and increasing the rainfall recharge by 20%.

- A similar result could be produced if the SoD were to fixed to 60% instead of interchanging the draft rate.
- A slow but promising result can be expected in the direction of improving the groundwater condition by restricting the SoD to 60%, and let the rainfall recharge assessed for the year 2017 continue.

Zone 4: Jalaun

- Madhogajn, Jalaun, Nadigaon blocks of this district show a decline of above 15 meters in the present scenario. More than 30 meters of decline is predicted if the groundwater draft and recharge continues as per the data for the assessment year 2017. A comparatively lesser rate of decline is precited if recharge and draft data would have continued as per the assessment year 2013.
- These decline in water level may be arrested effectively by implementing the interchanged groundwater extraction rate, and 20% increase in rainfall recharge.
- A similar result could be produced if the SoD were to fixed to 60% instead of interchanging the draft rate.

Zone 5: Mahoba

- The Panwari, Kabrai, and Charkhari blocks under the model area are highly exploited. The SoD for the Patwari block has been reported more than 120% in groundwater resource reports for year 2009, 2011, 2013 and 2017. Whereas other two blocks are reported having SoD in range of 70% -80% for years 2009 and 2017, which were reported more than 94% in year 2013, and 2017.
- In region with such high exploitation practice, strong restrictions need to be implemented on draft. The recharge, beyond a limit, can not improve the condition because of thin aquifer geometry and the boundary with the hard rock terrain.
- Therefore, it is very hard to say that any of the considered scenarios will improve the condition considerably. But, restricting the SoD to 60% and the interchanging in draft rate, along with the different suitable artificial recharge may slowly improve the condition.

Zone 6: Jhansi

- Aquifer system of the Moth block in Jhansi district shows a decline in water level faster than the surrounding blocks. If the draft assessed for the year 2017 continues for next 15-year, Moth block in the model area will face a decline in water level more than 30 meters which will lead to a dry aquifer condition.
- To avoid this condition, a recharge from rainfall must be increased by 20% and high groundwater draft must be lowered to monsoon season draft.

(Note: The recharge for the Moth and Bamaur blocks for the assessment year 2017 have been reported to be two times higher than that reported in the year 2013, due to which the calculation shows 30% as SoD. Therefore, the concept of restricting draft at SoD of 60% becomes very much high and causes dry cells in the model.)

Zone 7: Datia

- The alluvial aquifer system in Datia has shallow water levels in the range of 5-10 mbgl. Hydrographs also suggest small fluctuations with no long term decline. Hence, management plans are not much necessary to evolve. However, as a long term strategy, it will be useful if the high non-monsoon draft could be reduced or interchange with monsoon draft and rainfall recharge could be increased.

Zone 8: Chattarpur

- Laundi and Gurihar blocks come under the model area whose SoD has been estimated as 59% and 20% respectively in the assessment year 2013. The total draft in the Laundi block kept on increasing from year 2004 to 2017. The region is having a shallow water level (2-10 mbgl) condition in the model domain. Hydrographs suggest a fluctuation of 5-8 m between pre and post-monsoon condition.
- Therefore, to manage the aquifer system, the best way is to decrease the difference between the draft during monsoon and non-monsoon periods. Since, the region is having a higher recharge than the draft, 20% increase in recharge will provide enough to make aquifer system sustainable.

Zone 9: Chitrakoot

- Karvi, Mau, and Pahari blocks of Chitrakoot district have SoD in range of 70%-94% in the assessment year 2017. But, in absolute sense, the draft for the year 2017 has increased by 2-3-fold with respect to year 2013. Hence, model shows a dry condition after using 2017 draft in prediction model.
- So, to stop aquifer drying in this zone, the draft should be restricted to 60% of the available resource for the year 2017. Improved rainfall recharge through various artificial methods will help in improving the water level condition.

The above-discussed management strategies have been compiled in table 24. The applicability has been shown using different symbol (✓, **!**, and X). The symbol (✓) indicates the suitability, (**!**) indicates that the said scenario may arrest the further decline in water level, but it will not improve very much, and (X) shows that the particular scenarios will impact the aquifer negatively. The degree of suitability or unsuitability is denoted by its repetitiveness.

Table 24: Summary of suitability of different scenarios for different zones.

Zone	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Banda	!	X	✓	✓✓	✓✓✓	✓✓✓
Hamirpur	XX	XXX	✓	✓✓	✓✓✓	✓✓✓
Jalaun	X	XXX	XXX	XX	✓✓	✓✓
Mahoba	XX	XXX	XXX	!	!	✓
Jhansi	X	✓	XXX	XX	✓	✓✓
Datia	!	✓	X	X	✓✓	✓✓
Chhatarpur	!	X	X	X	!	!
Chitrakoot	X	XXX	X	!	✓	✓

11. Model limitations:

- This model is a numerical representation of the alluvium terrain of the Bundelkhand region.
- It is a numerical simulation of the flow condition, not verified solute transport model. But it may be used for simulation of particle tracking with assumptions.
- This model is a Coarse grid model in which each grid gives an average hydrogeological representation of 5km* 5km area.
- Model is conceptualised by making minor changes in the litholog to remove a sudden drop or rise in the aquifer layers. Hence, the geometry of the interpolated aquifer will not match with the individual litholog record.
- The upper clay body with variable thickness is present throughout the model area underlain by silty/clayey sand. Both horizons clubbed together. Hence, the numerical model has to be dealt with different aquifer parameter to produce the result.
- MODFLOW has its limitation near the boundary where lithology or layer terminates. Hence, it will produce a rough approximation of flow condition near the

Hard rock terrain boundary. Some anomalous result such as dry cells, or more decline in water level than adjacent cells is obvious near the boundary.

- Inverse modeling was done using PEST code for determining the hydraulic conductivity, which produced the distributed values in the model domain. The output result was not much different than the manual zonation. Hence, PEST output was discarded to avoid complexity.

- Model is very sensitive to specific yield and evapotranspiration. A drastic change in it will lead to non-convergence or shooting of head above ground surface.

- The model is fed data in repeatedly using the assessment year data. So, it will not explain any anomalous behaviour in water level of any particular OW of any particular time.

- The present model may be updated as per the data availability for solving any site-specific problems.

- The zone budgeting is calculated manually from the flow rate data, so the total zone budget will be higher than the sum of individual zone budget.

12. Regional Modelling for Hard rock terrain of Bundelkhand region

For developing the model of a hard-rock terrain, it is very necessary to understand the variation in the geology and its hydrogeological properties. Hence, it is very much necessary to study the lithologs, and other supporting investigations very detail before carrying out a modelling work of the highly variable geological setting.

12.1. Litholog/Aquifer grouping

The lithology of the study area is very much variable. In general, the top layer consists of overburden mass (weathered/fractured granite, sandstone, shale etc.), and alluvium and clayey soil in some regions. This layer thickness varies between 1m to 93m. This layer gets discontinued due to the presence of the massive rocks as hills. The aquifer mapping done under the NAQUIM project, previous lithological records (from BDR) and different geophysical investigations infer about its heterogeneous geology. The lithologs of these regions show the presence of 0 to more than 4 fractures/water-bearing horizons. These horizons are of very small thickness and can sustain a low capacity of borewells for 4-6 hours of pumping in general.

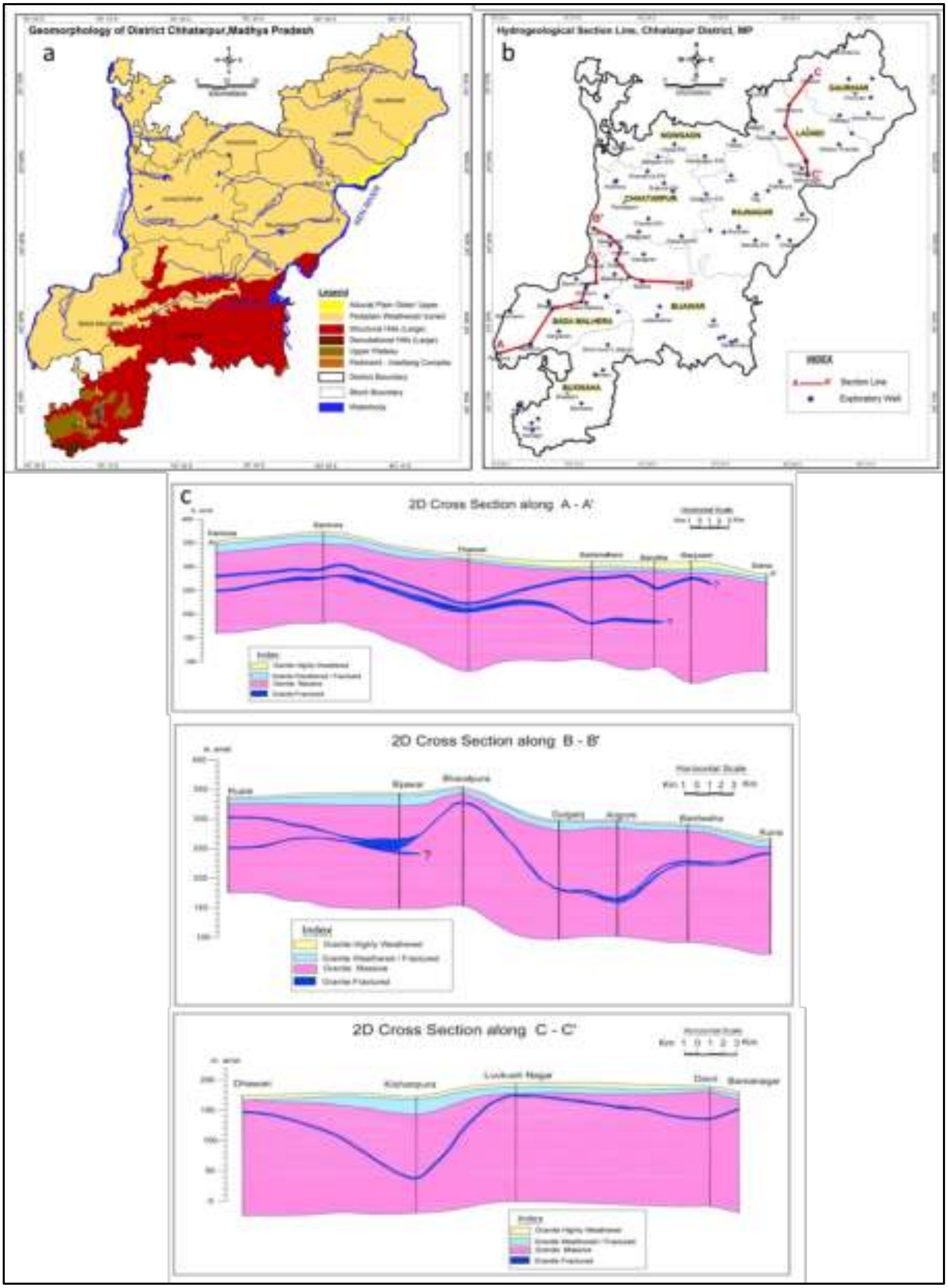
The presence of fractures/water-bearing horizons are discontinuous. It cannot be used to delineate as a continuous layer of an aquifer. Hence, based on the cross-section of different districts, litholog-data has been grouped into the different aquifer (fractures) and aquiclude (massive rocks) horizons. The process of grouping these data has been briefly mentioned as follows:

1) Chattarpur:

Chattarpur district can be divided into mainly three lithostratigraphic units (Fig. 60a).

1. The Panna range,
2. The Central Plateau, and
3. The Northern Plains.

The detailed study has been done by CGWB using the borehole logs to understand the subsurface lithological variation. Three cross-sections along A-A’, B-B’, and C-C’ (Fig. 60b and c) in this district has been prepared to delineate the water-bearing horizons. The cross-sections suggest the presence of weathered and fractured granite of various intensity is underlain by the massive granitic basement. The basement rock has the presence of fractures of minimal thickness whose lateral continuity is doubtful.



Geomorphology of District Chhatarpur,Madhya Pradesh
a
Legend
Hydrogeological Section Line, Chhatarpur District, MP
b
INDEX
Section Line
Exploratory Well
c
2D Cross Section along A - A'
2D Cross Section along B - B'
2D Cross Section along C - C'
Index

Figure 60: (a) Geomorphological setting, (b) location of lithological cross-sections and (c) 2D cross-sectional profile in the Chattarpur district. (Source: NAQUIM report, CGWB)

Based on the available cross-sections, the lithological data has been broadly classified into four units (table 25) as follows:

Table 25: Categorization of lithological units into various hydrological units of Chattarpur district.

Layer	Lithology	Assigned hydrogeological unit	Remarks
1	Weathered and/or fractured zone	Aquifer 1 (AQ1)	Top layer
2	Massive granite	Aquiclude 1 (AC1)	First encountered
3	Fracture	Aquifer 2 (AQ2)	First encountered fracture (or set of fractures)
4	Massive granite	Aquiclude 2 (AC2)	Fractures discarded

2) Damoh:

Damoh district has mainly three lithostratigraphic units (Fig. 61a).

1. Sandstone,
2. Shale, and
3. Limestone.

The detailed study has been done by CGWB using the borehole logs to understand the subsurface lithological variation. A cross-section along A-A’ (Fig. 61b and c) in this district has been prepared to delineate the water-bearing horizons. The cross-sections suggest the presence of weathered and fractured sandstone and shale, and fractured limestone, massive sandstone and shale.

Based on the available cross-sections, the lithological data has been broadly classified into four units (table 26) as follows:

Table 26: Categorization of lithological units into various hydrological units of Damoh district.

Layer	Lithology	Assigned hydrogeological unit	Remarks
1	Weathered and/or fractured zone	Aquifer 1 (AQ1)	The top layer (Shale and Sandstone)

2	Hard and compact Sandstone and Shale	Aquiclude 1 (AC1)	First encountered
3	Fractured Limestone	Aquifer 2 (AQ2)	First encountered fracture (or set of fractures)
4	Hard and compact Shale	Aquiclude 2 (AC2)	Fractures discarded

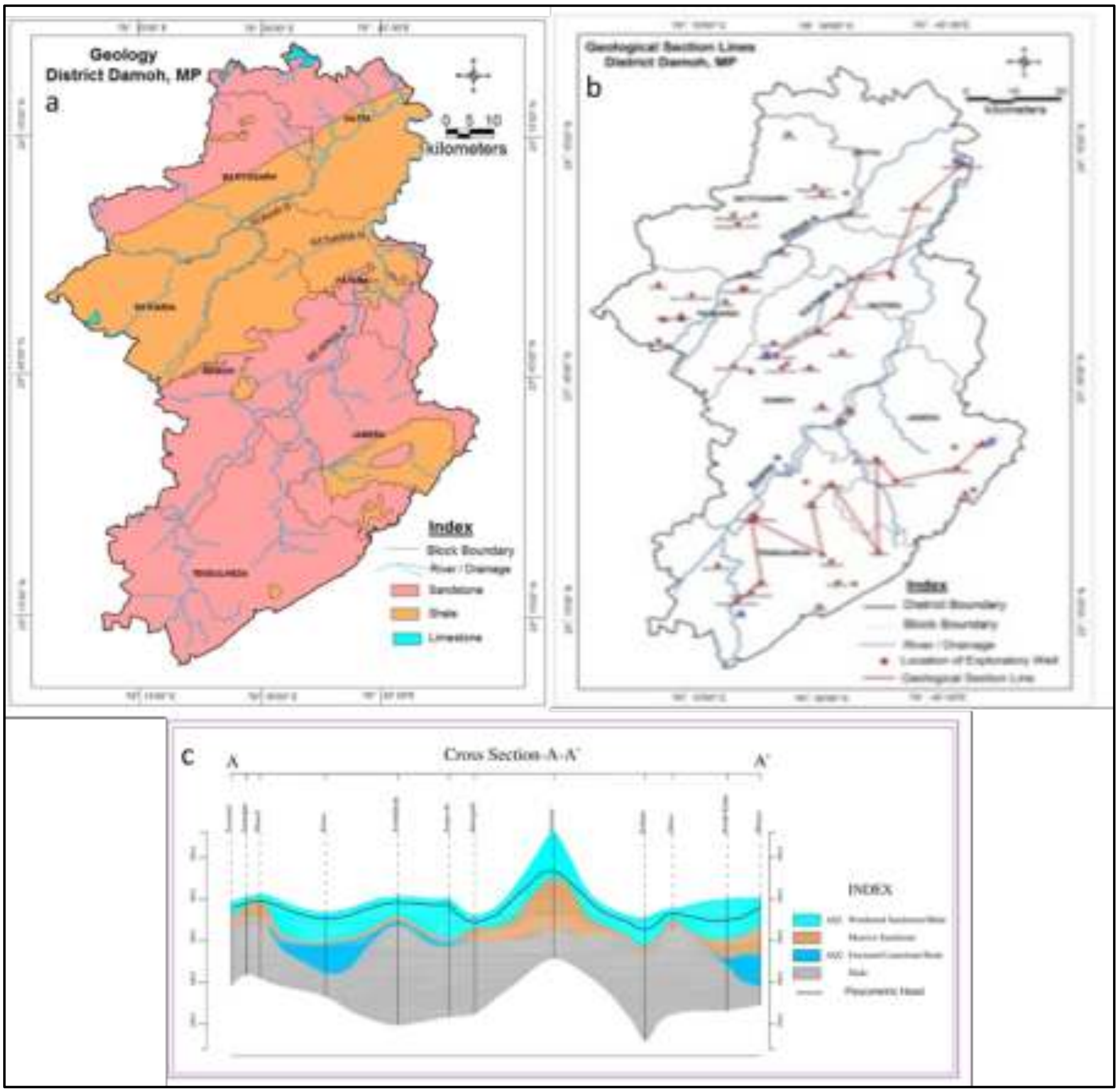


Figure 61: (a) Geological map, (b) location of lithological cross-section and (c) 2D cross-sectional profile along A-A' in the Damoh district. (Source: NAQUIM report, CGWB)

3) Datia:

Datia district comprises predominantly alluvium and granitic terrain (Fig. 62a). Detailed stratigraphy of the districts is presented as a 3D model (Fig. 62b) using rockwork for demarcating the aquifers. The lithologs of granitic terrain and some lithologs from nearby alluvium terrain are used for aquifer delineation for modelling purpose.

Based on the available 3D cross-section, the lithological data has been broadly classified into four units (table 27) as follows:

Table 27: Categorization of lithological units into various hydrological units of Datia district.

Layer	Lithology	Assigned hydrogeological unit	Remarks
1	Weathered and/or fractured zone	Aquifer 1 (AQ1)	All alluvium layers were grouped into AQ1
2	Massive granite	Aquiclude 1 (AC1)	First encountered
3	Fractured granite	Aquifer 2 (AQ2)	First encountered fracture (or set of fractures)
4	Massive granite	Aquiclude 2 (AC2)	Fractures discarded

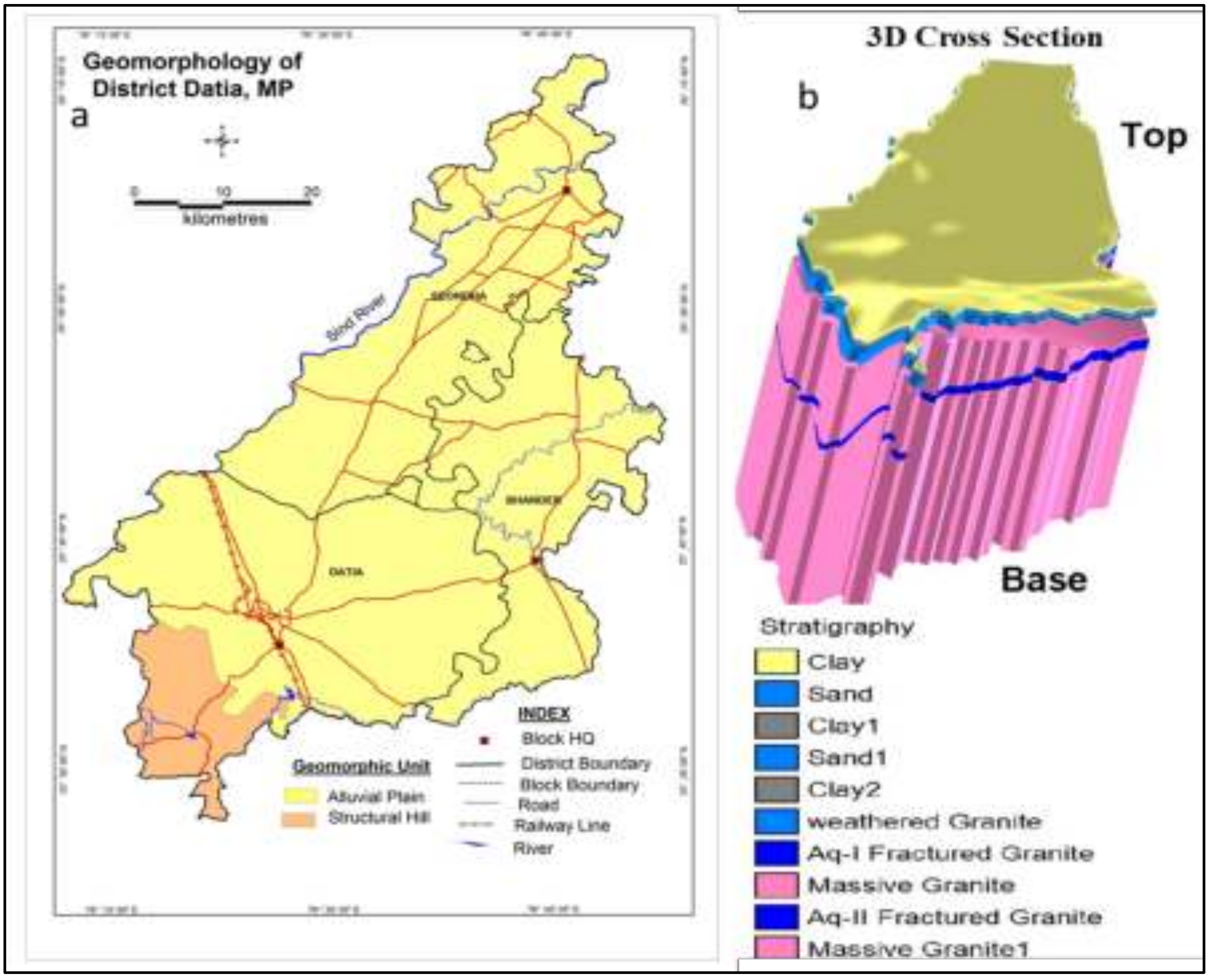


Figure 62: (a) Geolomorphological map, (b) 3D rockwork Model of Datia district.(Source: NAQUIM report, CGWB)

4) Panna:

In Panna district, the following lithostratigraphic units are found:

1. Granite
2. Sandstone
3. Shale
4. Limestone
5. Localised patches of Alluvium

The detailed study has been done by CGWB using the borehole logs to understand the subsurface lithological vaiation. A cross-sections along X-X' (Fig. 63b and c) in this district has been prepared to deleniate the water bearing horizons. The cross-sections suggests the presence of weathered and fractured sandstone and shale, and fractured limestone, massive sandstone and shale.

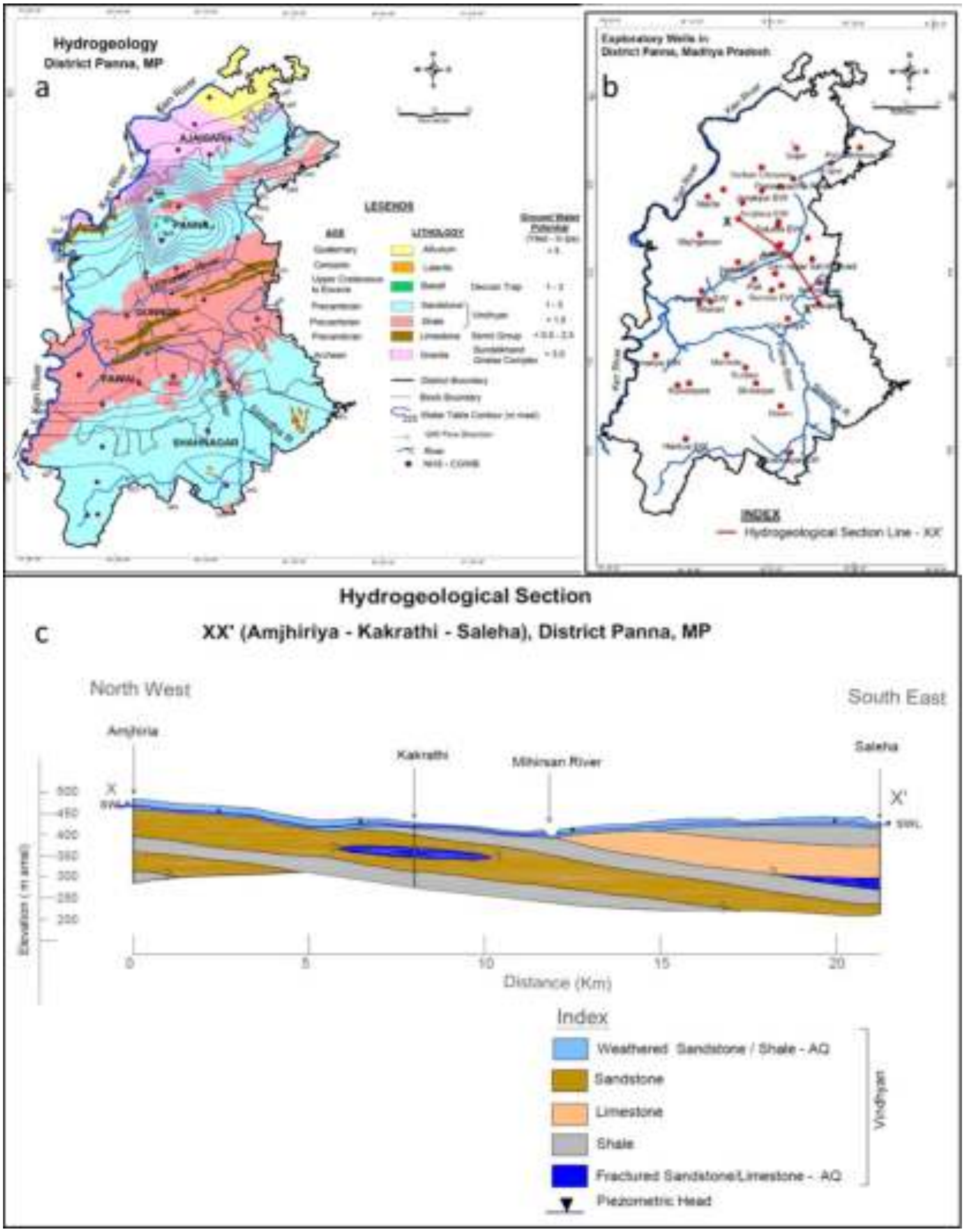


Figure 63: (a) Hydrogeological map, (b) location of lithological cross-section and (c) 2D cross-sectional profile along X-X’ in the Panna district.(Source: NAQUIM report, CGWB)

Based on the available cross-sections, the lithological data has been broadly classified into four units (table 28) as follows:

Table 28: Categorization of lithological units into various hydrological units of Panna district.

Layer	Lithology	Assigned hydrogeological unit	Remarks
1	Weathered and/or fractured/jointed zone	Aquifer 1 (AQ1)	The top layer (alluvium sediments are also grouped as AQ1)
2	Massive Sandstone and Shale	Aquiclude 1 (AC1)	First encountered
3	Jointed sandstone	Aquifer 2 (AQ2)	First encountered
4	Massive Sandstone and Shale	Aquiclude 2 (AC2)	Soft Shale discarded

In a few lithologs, the basement rock has the presence of fractures/joint has been observed. So it is very difficult to trace the continuity and interconnectedness of the second aquifer.

5) Sagar:

The geology of Saga district is very complex due to the presence of basaltic lava flow and linear ridges. The major type of lithostratigraphic units are as follows:

1. Deccan trap
2. Granite
3. Sandstone
4. Shale
5. Limestone

The detailed hydrogeological investigation using the exploratory wells has been carried out by CGWB (Fig. 64a). Based on the litholog data, cross-sections along A-A', B-B', and C-C' have been constructed to understand the variation in the hydrogeological units (Fig. 64b and c). in this district has been prepared to delineate the water-bearing horizons. The cross-sections suggest the basalt having features such as weathering, vesicular and fractured, and fractured sandstones are major water-bearing horizons.

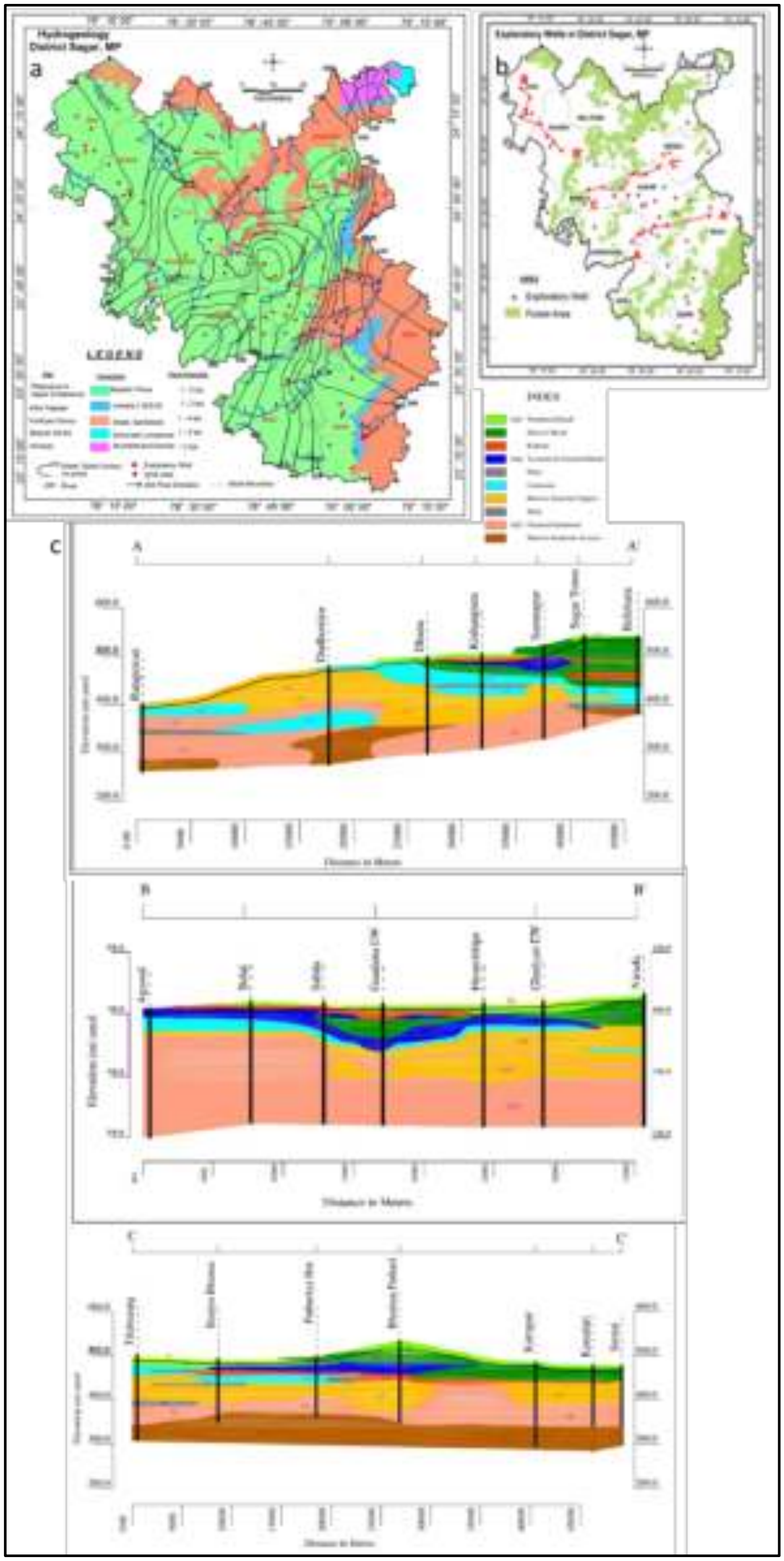

a
b
c

Figure 64: (a) Hydrogeological map, (b) location of lithological cross-section and (c) 2D cross-sectional profile along A-A’, B-B’, and C-C’ in the Sagar district. (Source: NAQUIM report, CGWB)

Based on the available cross-sections, the lithological data has been broadly classified into six units (table 29) as follows:

Table 29: Categorization of lithological units into various hydrological units of Sagar district.

Layer	Lithology	Assigned hydrogeological unit	Remarks
1	Weathered basalt	Aquifer 1 (AQ1)	Topsoil, clay etc.
2	Massive Basalt	Aquiclude 1 (AC1)	First encountered
3	Vesicular basalt	Aquifer 2 (AQ2)	First encountered
4	Massive basalt, sandstone and Shale	Aquiclude 2 (AC2)	Thick clay layers were also included.
5	Fractured sandstone	Aquifer 3 (AQ3)	
6	Massive sandstone/quartzite	Aquiclude 3 (AC3)	Upto borewell depth.

In a small number of lithologs (~10 lithologs), layer 5 and 6 has been classified. The layers are not spread in the entire region.

6) Tikamgarh:

The geological setting of Tikamgarh district comprises of granitic rocks dissected by a series of linear NE-SW trending giant Quartzitic reef (Fig. 65a). The granitic terrain forms the basement, and it is exposed as hills and inselbergs in the district. The moderately buried pediplain covers the basement rock.

The detailed hydrogeological investigation using the exploratory wells, piezometers etc. has been carried out by CGWB to understand the variation in the hydrogeological units. Based on the litholog data, cross-sections along A-B, and X-Y, have been constructed Fig. 65b) in this district has been prepared to delineate the water-bearing horizons. The cross-sections suggest the weathered granite is the major aquifer. The massive granitic body has some fractures but data is not able to suggest the connectivity between the fractures recorded in well-logs.

The lithological data available with us is taken from the NAQUIM report. It provides the depth at which well tapped the groundwater. The position of aquifer zone (table 30) was defined relative to the presence of the thick granitic body as follows:

Table 30: Categorization of lithological units into various hydrological units of Tikamgarh district.

Layer	Lithology	Assigned hydrogeological unit	Remarks
1	Weathered & Fractured Granite, Sand Boulder Cobble	Aquifer 1 (AQ1)	Up to well tapped above AC1
2	Massive Granite	Aquiclude 1 (AC1)	First encountered
3	Deeper zones of Well tapped	Aquifer 2 (AQ2)	Layers between AC1 & AC2
4	Massive Granite	Aquiclude 2 (AC2)	Thick clay layers were also included.

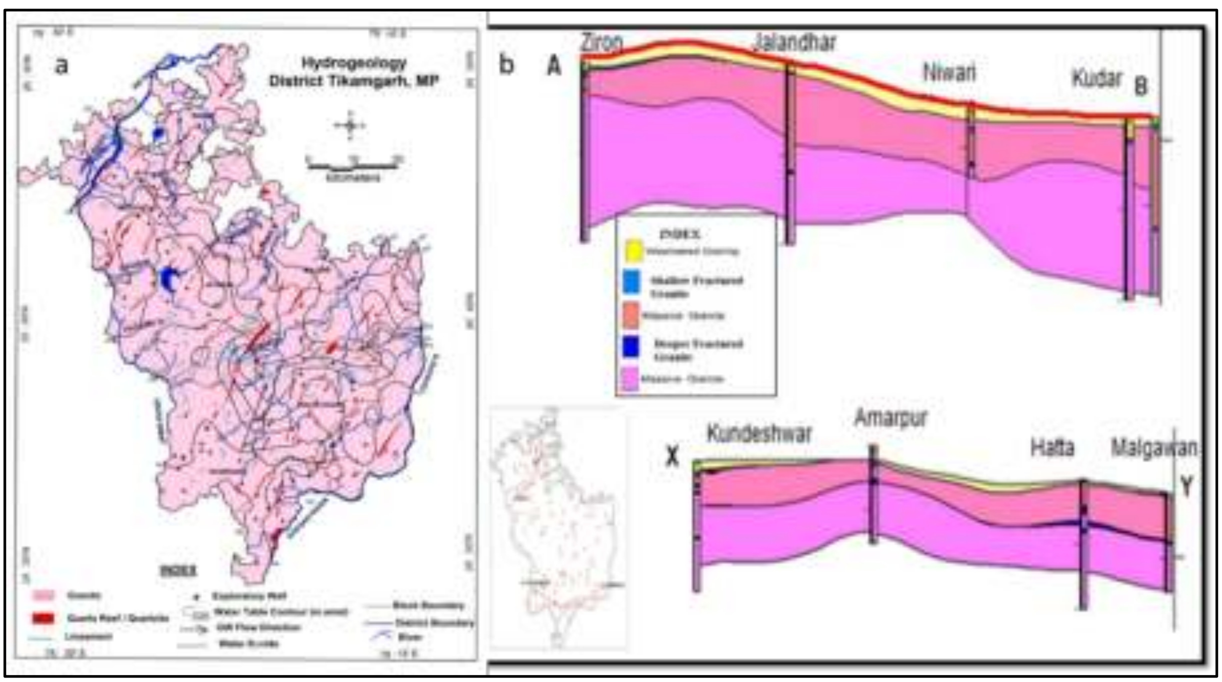


Figure 65: (a) Hydrogeological map, (b) 2D cross-sectional profile along A-B, X-Y in Tikamgarh district. (Source: NAQUIM report, CGWB)

7) Jhansi and Lalitpur:

Jhansi and Lalitpur districts comprise of granite gneisses, schists, Quartz reefs, mafic rocks, sandstones, shales, laterites and alluvium (Fig. 66a and 67a). The presence of hillocks, linear quartz reef, etc. make the system heterogeneous. The top weathered zone and alluvium/valley fill, and fractures are the primary sources of groundwater in this region.

The detailed hydrogeological investigation using the exploratory wells, piezometers etc. has been carried out by CGWB to understand the variation in the subsurface configuration ((Fig. 66b and 67b and c). Based on the available cross-sections, the lithological data has been broadly classified into two units (table 31) as follows:

Table 31: Categorization of lithological units into various hydrological units of Tikamgarh district.

Layer	Lithology	Assigned hydrogeological unit	Remarks
1	Weathered & Fractured Granite, alluvium	Aquifer 1 (AQ1)	Up to well tapped above AC1
2	Consolidated rock formations	Aquiclude 1 (AC1)	First encountered to depth of borehole

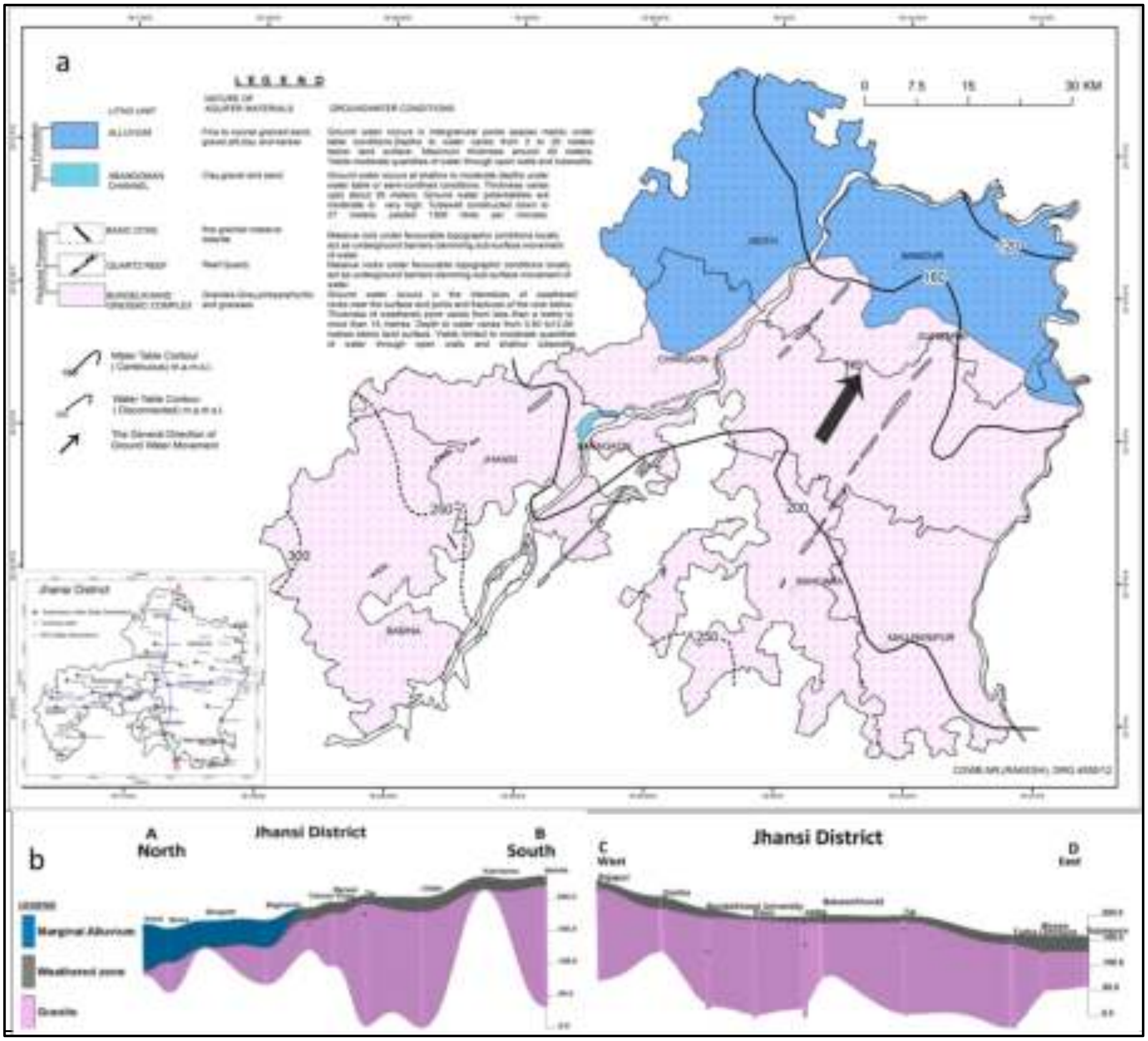


Figure 66: (a) Hydrogeological map, (b) 2D cross-sectional profile along A-B, X-Y in Tikamgarh district. (Source: NAQUIM report, CGWB)

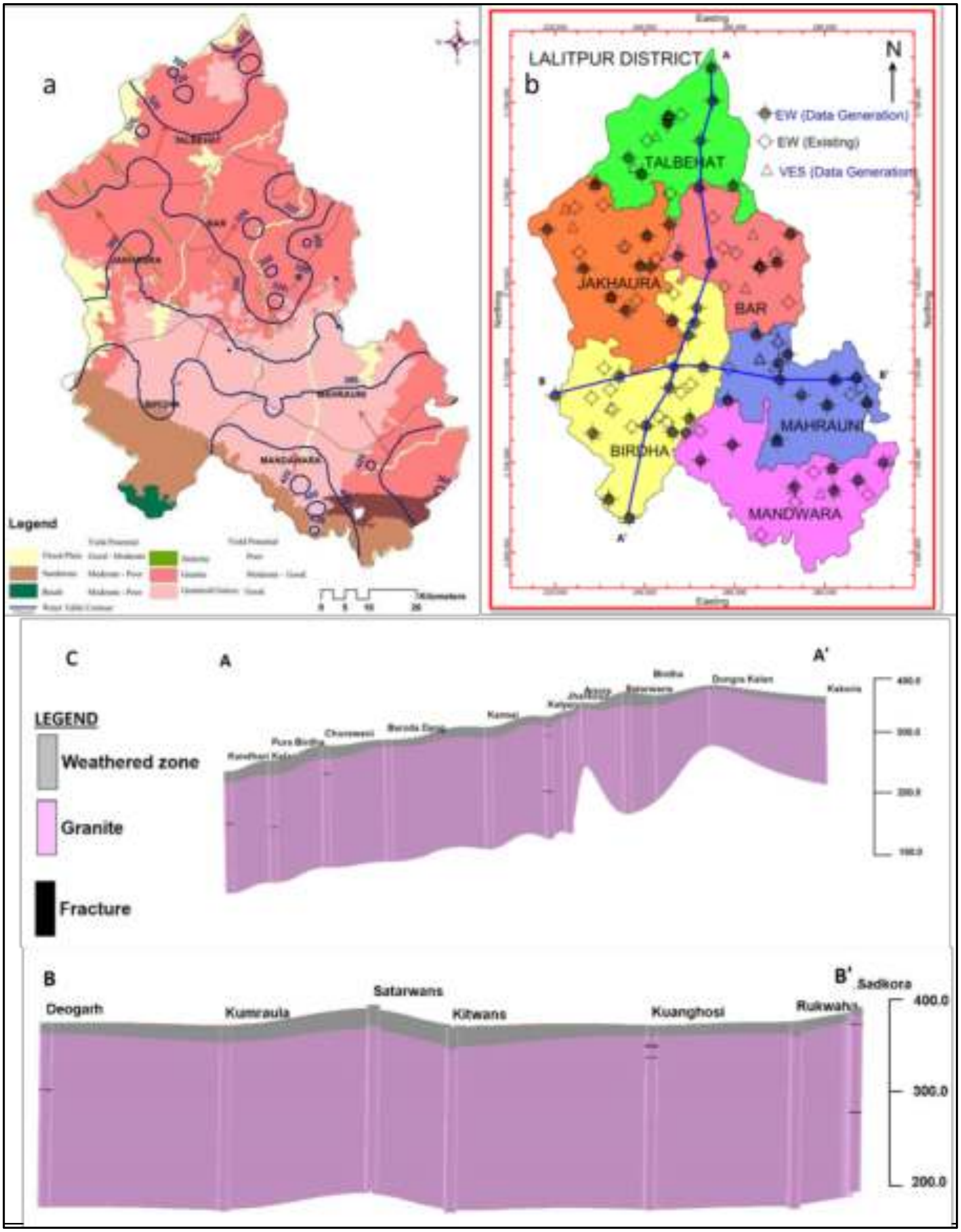


Figure 67: (a) Hydrogeological map, (b) 2D cross-sectional profile along A-B, X-Y in Tikamgarh district. (Source: NAQUIM report, CGWB)

8) Chitrakoot:

The lithologs of Chitrakoot district suggest the presence of alluvium, and consolidated rocks such as sandstone, shale, limestone, and granite in the northern and southern part of the district respectively. Categorization of lithological units into various hydrological units of Chitrakoot district has been done similar to as mentioned in table 31.

12.2. 3D Conceptual Model development

12.2.1. Regional Conceptual Model

The lithologs have been studied for defining the sub-surface configuration, about 310 litholog were finalized to use for creating layers for developing the conceptual model of the whole hard rock region. The political boundary the Chitrakoot district is detached with the other part of the hard rock terrain of the Bundelkhand region. So. The Scientists from CGWB-Lucknow and Bhopal suggested interpolating the available litholog data in the gap regions to develop a continuous layer. The litholog of the well from hard rock and its nearby alluvium region (Fig. 67) has been used to generate the layer.

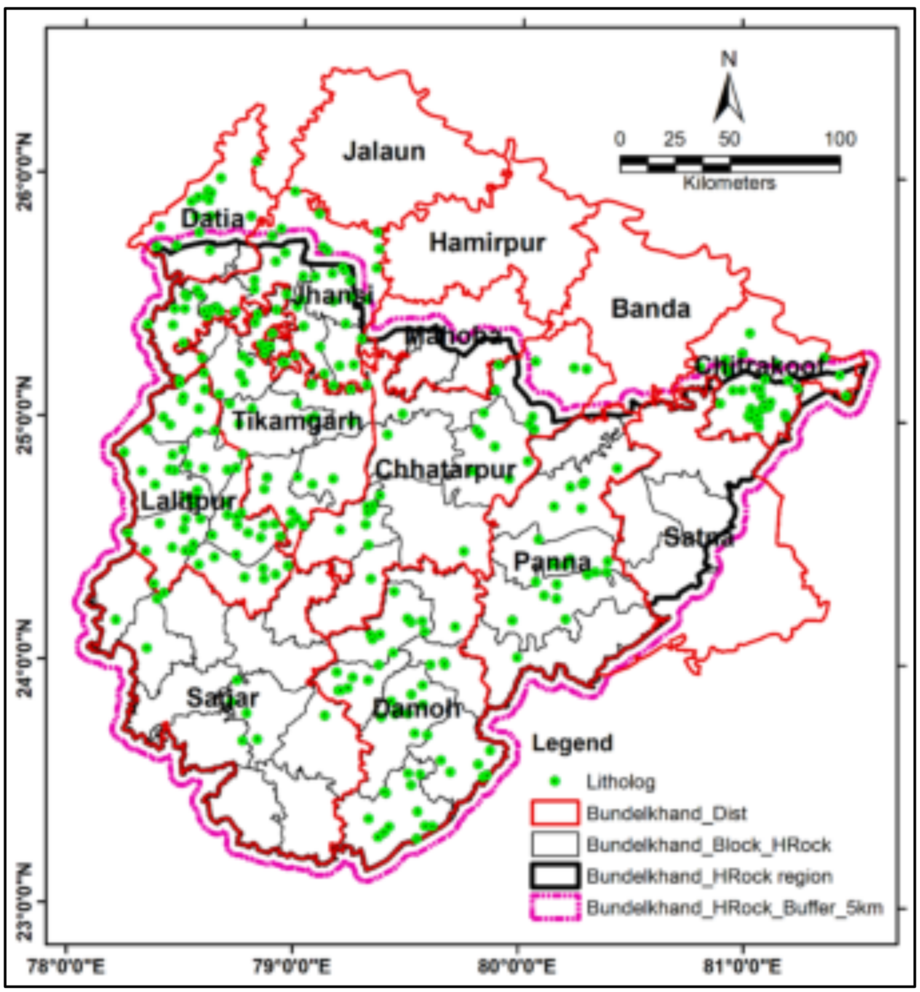


Figure 67: Demarcating the extent of the conceptual model of the Hard rock terrain of the Bundelkhand region and location of the lithologs to define it.

12.1.1.1. Layer Setup

The aquifer layers have been defined on the basis of 311 litholog data. The lithologs information of the alluvium terrain has been included to increase the resolution in the variation of the layer. However, the number of data decreased with depth, leading to low subsurface resolution. Therefore, the model has been restricted to four zones. The top layer is taken from the SRTM redefining the resolution of 5km (as per the grid size of the numerical model). The available data has been interpolated in the MODFLOW Flex to define layers (Fig. 68).

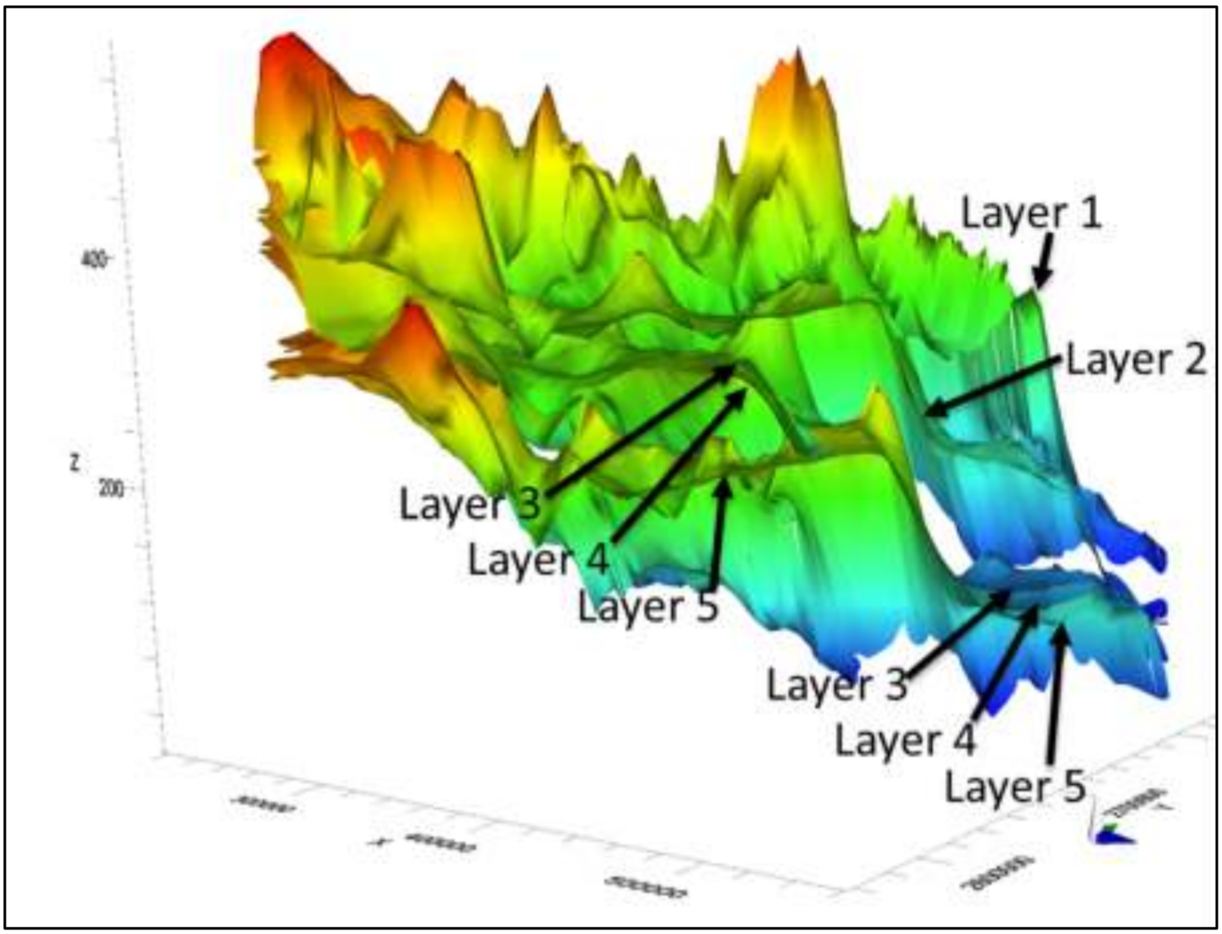


Figure 68: Different layers based on the CGWB lithologs. (Vertical exaggeration =500).

12.1.1.2. Vertical and Horizontal Extent

The model has been conceptualised with the four hydrogeological layers. The layer defined in figure 68 has been converted into the four zones in the Visual MODFLOW Flex (Fig. 69a). Each horizon represents different types of aquifer/non-aquifer lithology.

Horizon 1 represents the weathered/fractured layer; horizon 2 represents the massive rock units; horizon 3 represents the fractured aquifer system, and horizon 4 represents the massive hard-rock acting as the basement. Figure 69 a, b, c, and d show that different horizons are discontinuous and intruded by the underlying hard-rock horizons.

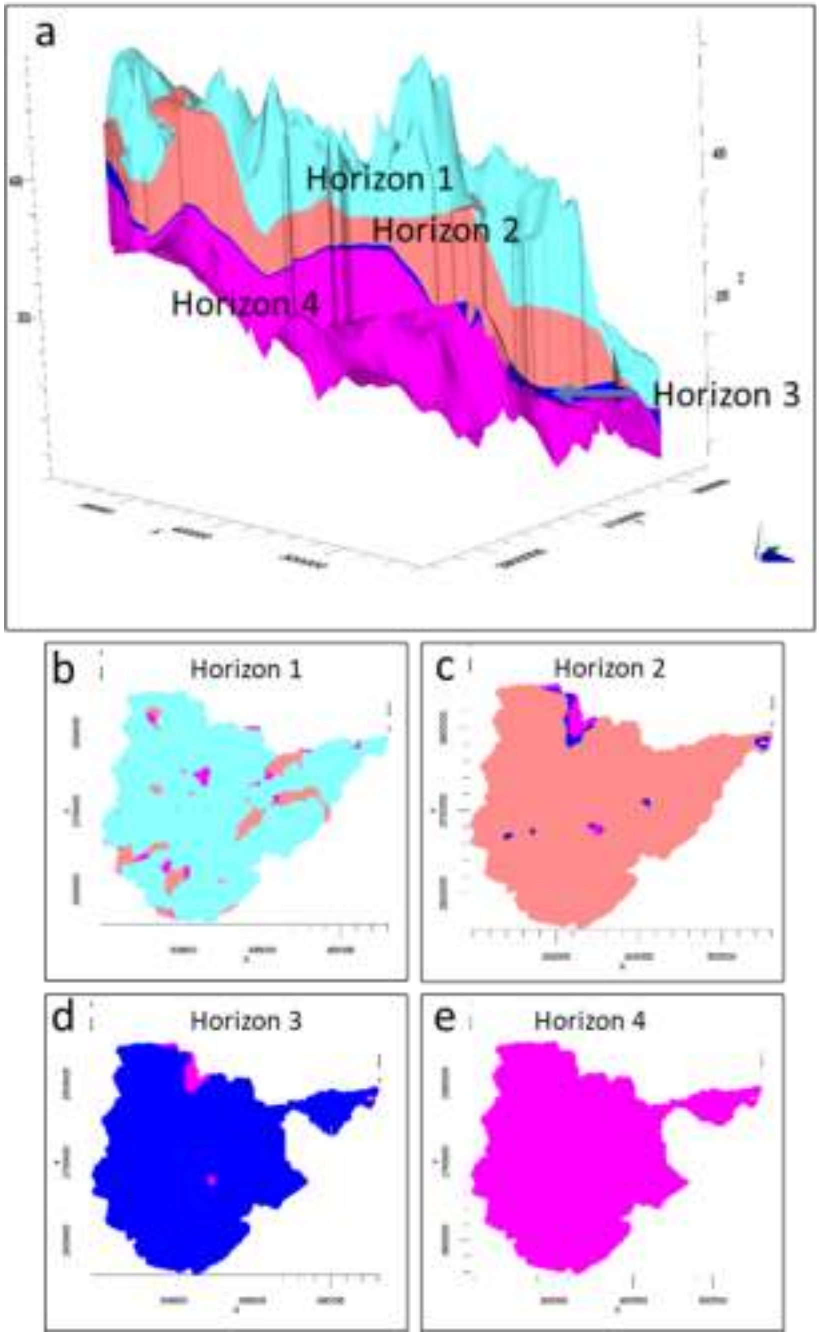


Figure 69: (a) Defining the horizons of the Bundelkhand Conceptual model for the hard rock terrain. (b) Horizon 1 intruded by horizon 2, (c) horizon 2 intruded by horizon 3 and 4, (d) horizon 3 intruded by horizon 4 (e) Horizon 4

12.2.2. Defining Finite Difference Grid

The conceptual model has been discretised horizontally into the finite-difference grid with 60 rows and 74 columns with an approximate distance of 5000m without any rotation. The grids outside the model area are assigned as inactive cells and inside cells are assigned as active cells(figure 70a). The vertical connectivity of the cells along row-24 and column-20 is shown in figure 70b. The three dimensional variation in the grid cell for all layers are mosaiced in figure 70c.

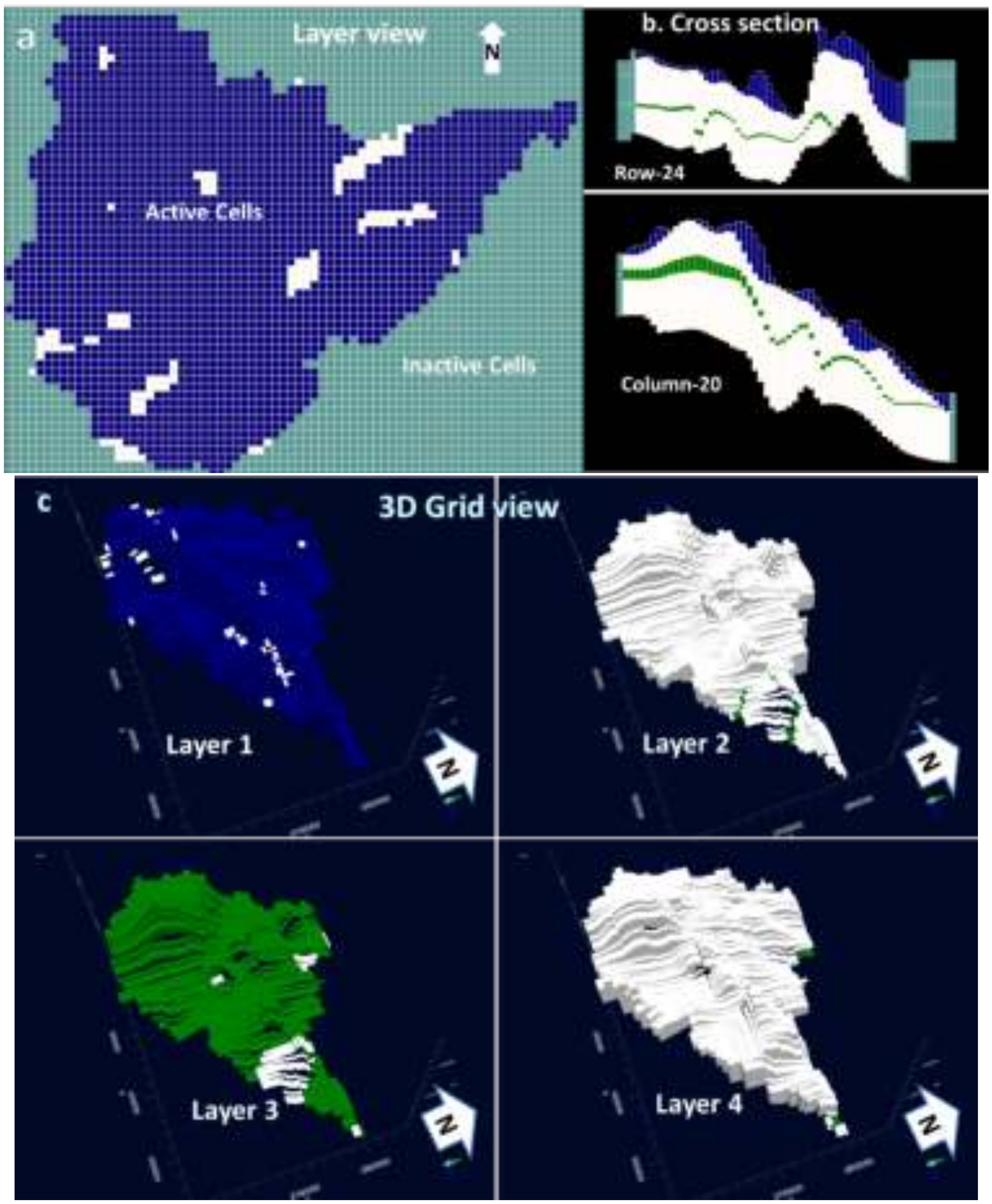


Figure 70: Showing the numerical grid in (a) Layer View, (b) cross-sectional view along row 24 and column 20, and (c) three-dimensional view of each layer.

Figure 70 clearly shows that the grid cells which represent the aquifer layers (layer 1 and 3) for numerical translation are laterally not connected. The detachment of the grid cells "causes an inability to model flow between cells in the same layer" (https://www.waterloohydrogeologic.com/) which leads to convergence failure during the numerical simulation. Hence, as suggested by Scientist from CGWB Lucknow and Bhopal, The modelling exercise was tested on one district of the Bundelkhand region. Understanding the limited suitability of the approach for solving the highly heterogeneous aquifer system and disconnected grid cell, it has been suggested to suggested do the groundwater modelling exercise on any district to demonstrate the utilization and effect of the proposed intervention in NAQUIM reports. The following section describes the numerical groundwater modelling exercise in Damoh District.

13. Groundwater Model development of Damoh district (Bundelkhand region)

13.1. Preparation of datasets in the GIS framework

13.1.1. Litholog/Aquifer grouping

The lithologs data provided in the NAQUIM Report of Damoh District has been used for preparing the 3D aquifer disposition maps. Figure 71 shows the location of 57 litholog data finalised after correcting their lat/long.

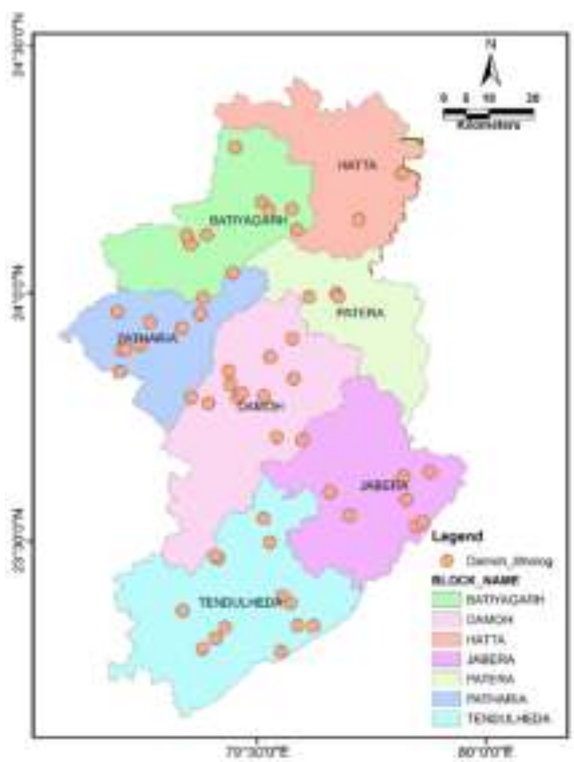


Figure 71: Spatial distribution of the litholog of Damoh District.

13.1.2. Observation Wells (OW) / Water level data

There are about 30 water level data has been used for assessing the model simulated water level head. The geographical location of those observation wells is plotted in figure 72. These OW have been classified as dug well and borewell assuming they reflect the observation from the weathered zone and fracture zone respectively. Therefore their name has been started with digit 1 and 2 for denoting aquifer-1 and aquifer-2 respectively. The observation wells have data for the months of May and November from the year 2002 to 2016. The latest water level data used is of Nov. 2016.

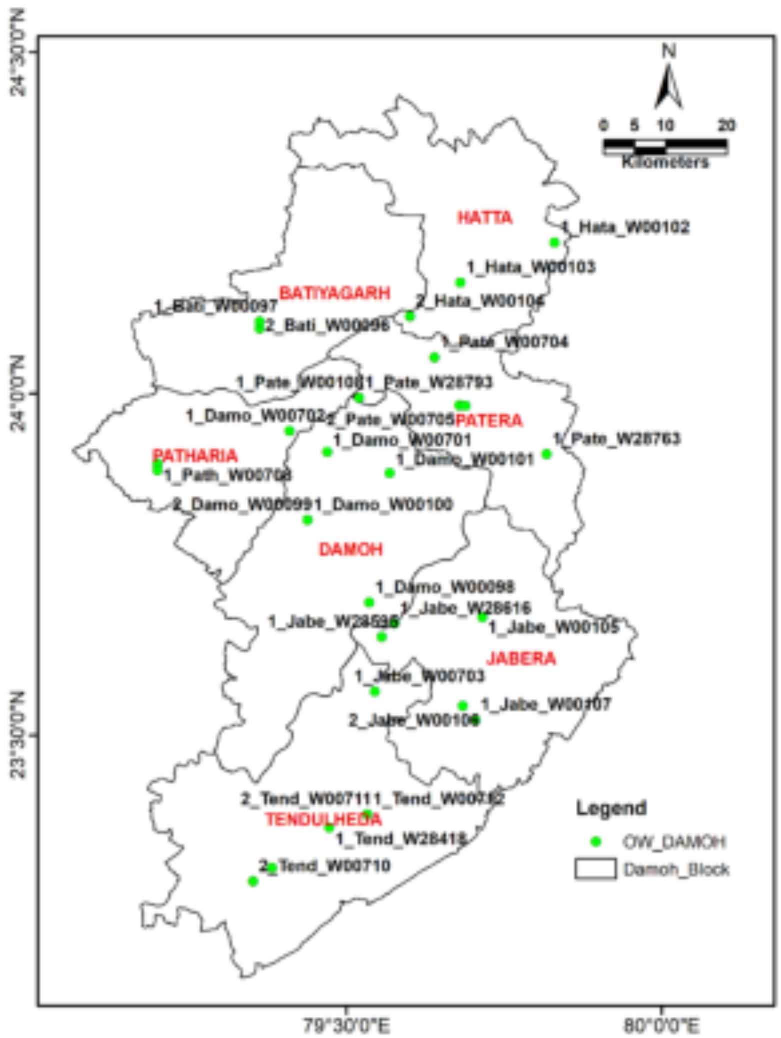


Figure 72: The spatial distribution of observation wells in the study area used for the model calibration.

13.1.3. Groundwater draft

The layers of the model are not thick enough to define the input parameter of Pumping-well (such as well-top/bottom, and screen elevation/bottom) as per the requirement in Visual MODFLOW Flex. Hence, to input the groundwater draft data in the model, specified flux boundary has been used. The specified flux data have been calculated at the block level.

The groundwater draft (and recharge) data for the year 2004, 2009, 2011, 2013, 2015, and 2017 has been provided in a different format. The data for the year 2009 and 2013 has detailed calculations such as no of operating pumping wells in command and non-command regions, their unit abstraction rate in different seasons, etc. For the rest of the data, the total draft for agriculture, and domestic and industrial uses has been provided. To input the draft values into the model, groundwater abstraction data has been converted into m/day after analysing the data for years 2009 and 2013 as follows:

Step 1:

1A) Calculation of the irrigation draft from dug well (aquifer-1) and borewell (aquifer-2) for monsoon and non-monsoon seasons:

Calculation of Seasonal Draft from command and non-command area (separately)=
∑(Season Wise unit Draft of different pumping structure)X
(No. of different pumping Structure) Eq. 4 (previously mentioned)

1B) Calculation of total irrigation draft from dug wells and borewell:

Total Irr. Draft from dugwell= Irr. draft from command area+ Non-command area

Total Irr. Draft from borewell= Irr. draft from command area+ Non-command area

1C) Calculation of fraction of irrigation draft from dug wells (or borewell):

Fraction =Total Irr. Draft from dug well (or borewells)*100 / (Total Irr. Draft from dug well + Total Irr. Draft from borewell)

Step 2: Calculation of Seasonal draft fraction for both aquifers.

Result: The final values of draft fraction for aquifers and their seasonal abstraction used for the calculation of the specified flux is given in table 32. The variation in the range of 0.01-0.03 has not been considered for calculation.

Table 32: Estimation of draft fraction for aquifer-1 and 2, and non-monsoon season.

	Batiagarh	Damoh	Hatta	Jabera	Patera	Patharia	Tendukheda
Year 2009 (Aquifer 1)	0.39	0.91	0.47	0.68	0.8	0.49	0.73
Year 2013 (Aquifer 1)	0.39	0.79	0.49	0.63	0.65	0.32	0.7
Non-Monsoon (Aq1)	0.77	0.77	0.77	0.77	0.77	0.77	0.77
Non-Monsoon (Aq2)	0.86	0.86	0.86	0.86	0.86	0.86	0.81

(Note: The values for aquifer-2 and monsoon seasons can be calculated by subtracting values form aquifer-1 and non-monsoon periods respectively)

The values obtained from the year 2009 has been used for calculation for years 2004, 2009 and 2011 and valued obtained from the year 2013 has been used for calculation for the years 2013, 2015 and 2017.

Step 3: The final values for the different aquifers and for the different seasons have been used for calculating the specified flux using equation 9:

$$Sp.Flux\ (\frac{m}{day}) = \frac{Draft\ (HaM)*10\text{^}4*Aquifer\ fraction*Seasonal\ fraction}{(139\ or\ 226\ or\ 365)day*\ area\ (km^2)*10\text{^}6} \qquad \text{Eq. (9)}$$

The values of days 139, 226, 365 represent the no of days for monsoon period, non-monsoon period and year. The Domestic and industrial draft has been considered to be extracted from aquifer-1 and equally for the whole year.

To input the groundwater draft data, a time schedule and corresponding sp. Flux for the different blocks has been imported in the model. The format of the time schedule for the groundwater draft is mentioned in table 14. The time schedule for the sp. Flux has been mapped with the corresponding polygon.

13.1.4. Recharge

The recharge values for the years 2009 and 2013 have detailed data for the monsoon and non-monsoon seasons. For the rest of the data, only the net recharge value was available. Therefore on the basis of recharge data for years 2009 and 2013, the recharge fraction for different seasons has been estimated. The fraction values obtained from the year 2009 has been used for calculation of seasonal recharge for years 2004 and 2011, and fraction values obtained from the year 2013 has been used for calculation of seasonal recharge for the years 2015 and 2017.

The final calculation of recharge to input in the model has been done using eq.-9. The recharge value has been assigned to layer one by following steps similar to that of groundwater draft.

13.1.5. Evapotranspiration

For simulating the groundwater model, the reference crop evapotranspiration has been used. It is one of the important factors which controls the availability of water. The water loss due to evapotranspiration could be as good as a small tubewell depending upon the climatic conditions.

The ET data is not available for the modelling period which leads us to use the monthly average values of the last three years (2000, 2001, & 2002) data for the study area. The variation in the evapotranspiration data is not very high (figure 73) in the model area. This finding gives the liberty to assign one value in the entire model domain within the defined stress period.

Figure 73 shows the plot for the three year average monthly data plotted for the Damoh districts of the model area. For simulation, the ET values of 0.00696 m/day (6.96mm/day) and 0.00413m/day (4.13mm/day) has been used for period 1st April to 30th June, and 1st July to 31st March, respectively. The evapotranspiration data has been assigned manually during the development of the conceptual model in the top layer. During the translation of the conceptual model into a numerical model assigns the values in the grid cells.

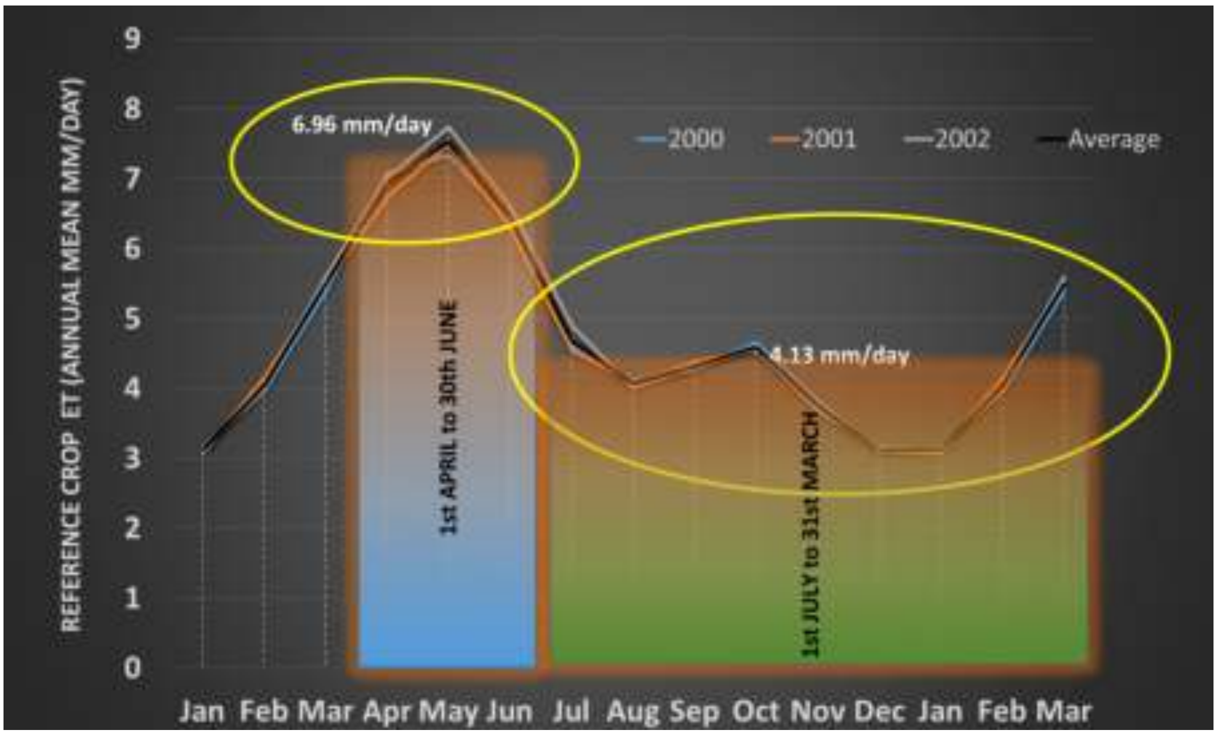


Figure 73: Variation in evapotranspiration in the Damoh district. The different zones are demarcating the two broader prevailing ET rates.

13.2. Developing a conceptual groundwater model.

13.2.1. Defining layers

On the basis of lithologs of the Damoh district, four layers can be defined (figure 74) i.e. layer1- weathered zone, layer2- massive sandstone/shale, layer3- fractured zone, layer4- massive sandstone/shale. Since the knowledge about the occurrence, orientation, and density of fractures, joints, dykes etc. in the subsurface is not good, three models have been conceptualised as follows:

1) Three-layer model: Defining layer1: aquifer-1 (Aq1), layer2: aquiclude-1 (Ac1), and layer3: aquifer-2 (Aq2). Layer 4 is incorporated as inactive during the simulation.

2) Two-layer model: Defining layer1: aquifer-1 (Aq1), and layer2: Merging aquiclude-1 (Ac1), and aquifer-2 (Aq2).

3) Single-layer model: Merging layer of aquifer-1 (Aq1), aquiclude-1 (Ac1), and aquifer-2 (Aq2).

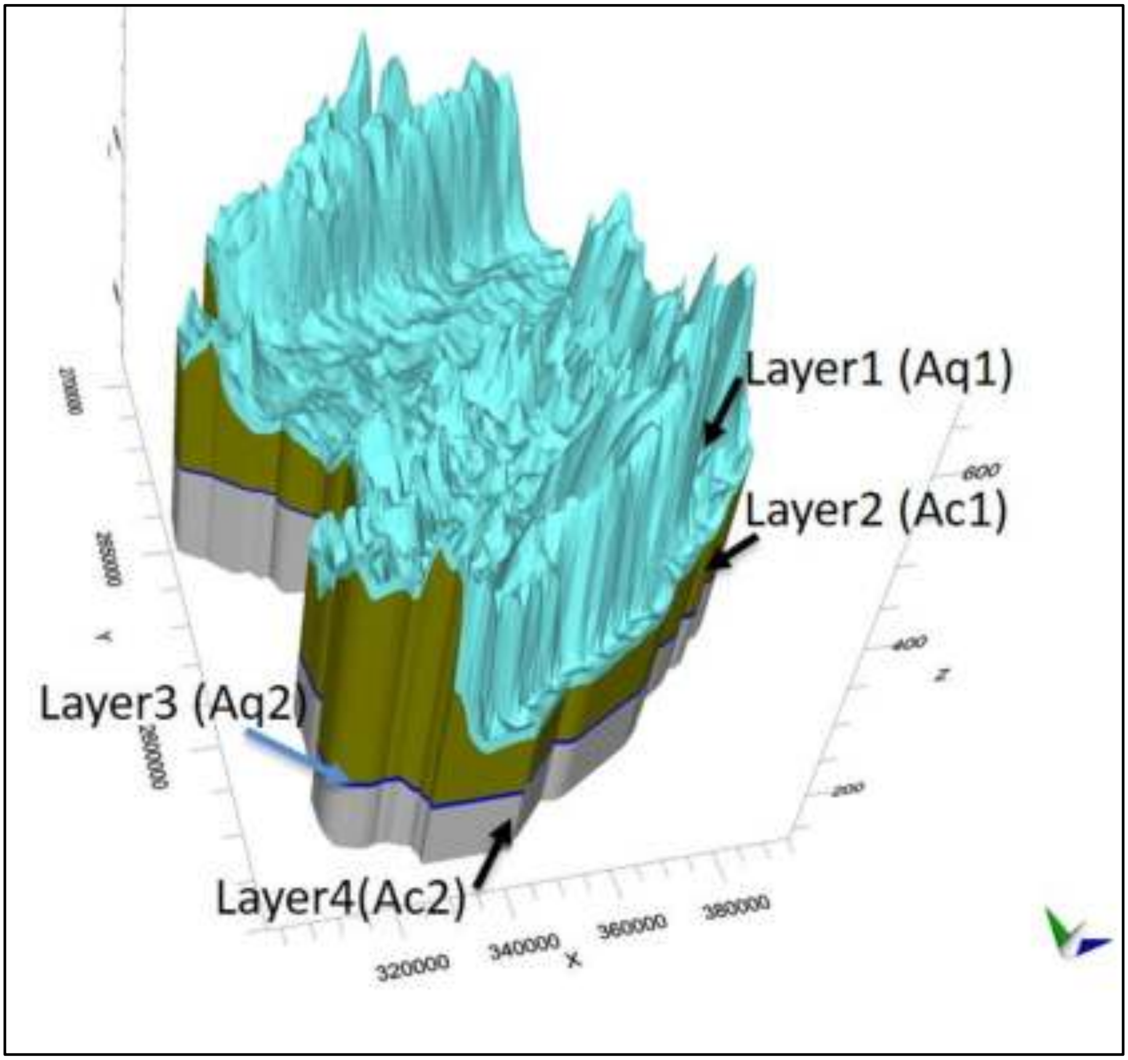


Figure 74: Conceptualization of different model layer using litholog data. (Vertical exaggeration =500).

13.2.2. Defining Finite Difference Grid

The conceptual model has been discretised horizontally into the finite-difference grid with 74 rows and 49 columns with an approximate distance of 2000m without any rotation (figure 75a). The grids outside the model area are assigned as inactive cells and inside cells are assigned as active cells. The properties and input parameters of the active cells of the modelling domain are used for the numerical calculation purposes whereas the inactive cell is by default assigned as no property zones by the modelling software.

In figure 75 (a,c, and c), the vertical thickness of the aquifer and non-aquifer layers have been discretized by defining the vertical grid as “DEFORMED”. In the deformed grid, the top and bottom of the grid follow the defined elevation of the layer surface. (https://www.waterloohydrogeologic.com/help/)

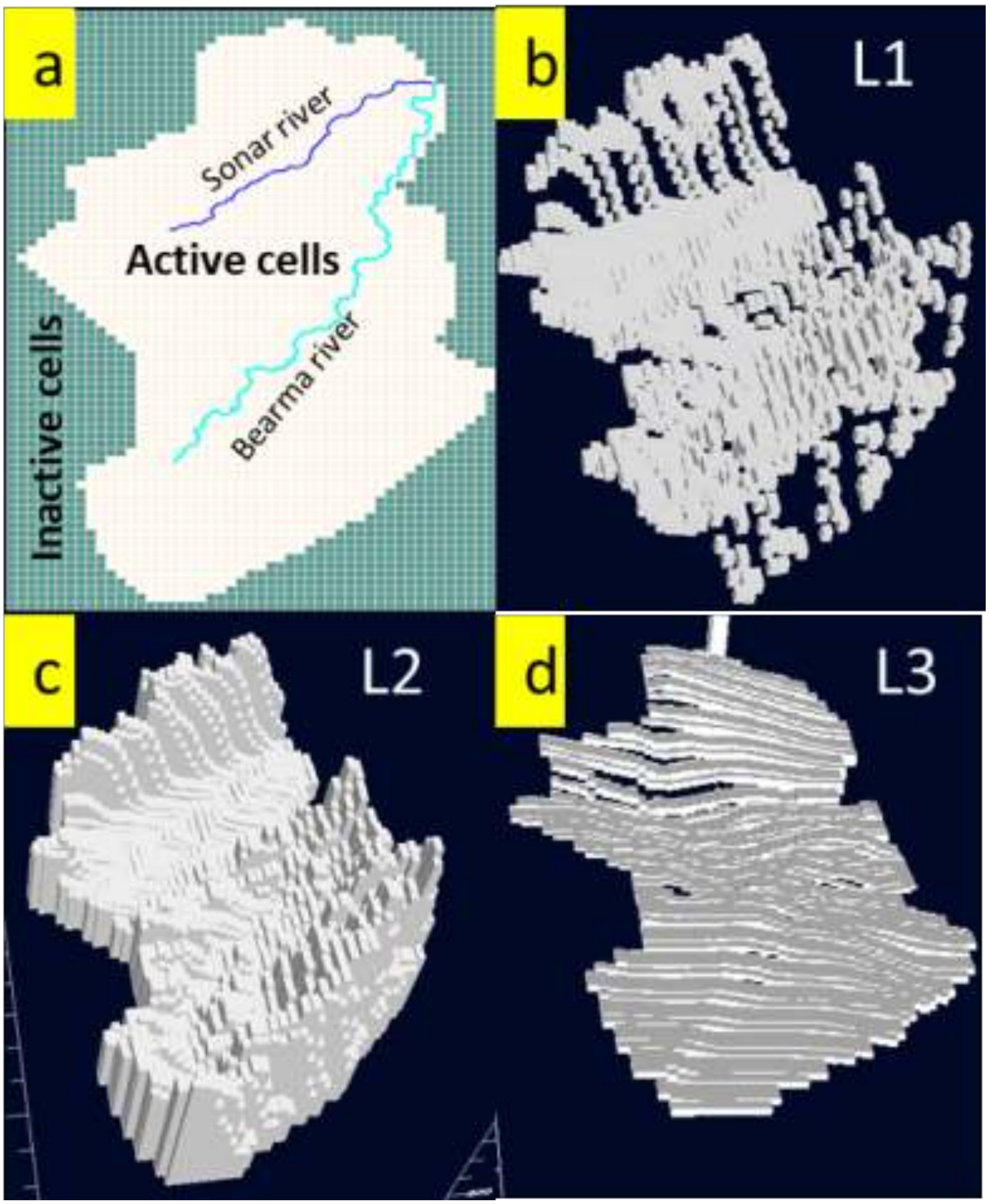


Figure 75: Defining the grids (a) layer view and (b, c, and d) 3D grid setting for layers 1, 2, and 3 after converting conceptual model (3-layer model) to a numerical model.

The finite difference grid has been generated in same way for the two and one layer model from the conceptual model (section 13.2.1)

13.2.4. Temporal discretisation of data

The simulation period starts from 1st January 2002 and ends 14th June 2017. As per the data input scheme for groundwater draft, recharge and evapotranspiration, the entire simulation period have been divided into 86 stress periods in the visual MODFLOW Flex as following:

a) Calibration period: 01-01-2002 to 14-06-2009 (0-2722 days) => 40 stress period

b) Validation period: 15-06-2009 to 14-06-2017 (2723-5644 days) => 86 stress period

13.3. Development and calibration of the numerical groundwater flow model

The conceptual models have been translated into a numerical model. In numerical modelling, simulation is done on the basis value assigned to the particular boundary condition, or stress period or property. The study area is divided into 74 rows and 49 columns with an approximate distance of 2000m. The input parameters are described below:

13.3.1. Properties

The input parameters are taken from the NAQUIM reports and textbooks. The zonation of these properties for different calibrated numerical models are presented below:

13.3.1.1. Conductivity and Storage

(a) Model 1: 3-layer model.
Based on the geological settings (figure 61a), the hydraulic conductivity and storage are digitized in different zones described below in figure 76 and table 33.

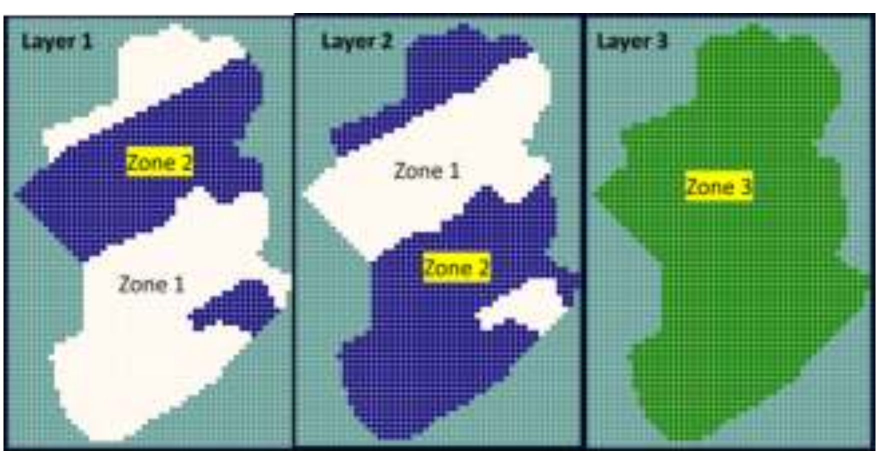


Figure 76: Conductivity values assigned in the model (calibrated model) active grid cells.

Table 33: Properties value assigned in the model (calibrated model).

	Kx	Ky	Kz	Sy	Ss
Zone 1	1	1	0.1	0.05	0.015
Zone 2	9E-5	9E-5	9E-6	0.01	0.001
Zone 3	0.09	0.09	0.009	0.04	0.015

(b) Model 2: Two-layer model.

This model has been assigned hydraulic properties for the layer 1 and 2 as described in figure 76 and table 33.

(c) Model 3: Single-layer model.

The layers 1, 2, and 3 were merged into one single layer as an 'equivalent porous medium' of the Damoh aquifer system. The layer has been assigned the hydraulic properties as shown in figure76 and table 33. But later on during calibration, the values have been changed as given in table 34.

Table 34: Properties value assigned in the single-layer model (calibrated model).

	Kx	Ky	Kz	Sy	Ss
Zone 1	6.1	6.1	0.1	0.02	0.01785368
Zone 2	6.95E-5	6.95E-5	9E-5	0.03	0.008370647

13.3.1.2. Initial head (IH)

The depth to water level from the observation wells have been interpolated in the ArcGIS platform with a resolution of 5km by 5km scale to match the model grid. This raster layer has been subtracted from the DEM resampled at 5km by 5km scale. Figure 33 shows the resultant initial water level condition assigned to the model

(a) Model 1 and 2: 3-layer model. And the 2-layer model

The depth to water level form the observation wells for January 2002 have been interpolated in the ArcGIS platform with a resolution similar to that of Surface elevation/ grid size of the model. This raster layer has been subtracted from the DEM (resampled at 2km by 2km scale) to avoid the layer cutting the top/bottom of the top aquifer layer which is very thin at many regions. Figure 77(a) shows the resultant initial water level condition assigned to both models.

(b) Model 3: Single layer model

The model has been assigned the interpolated Water table data fo the district recorded during Jan-2002. Figure 77(b) shows the distribution of initial head assigned in the study area.

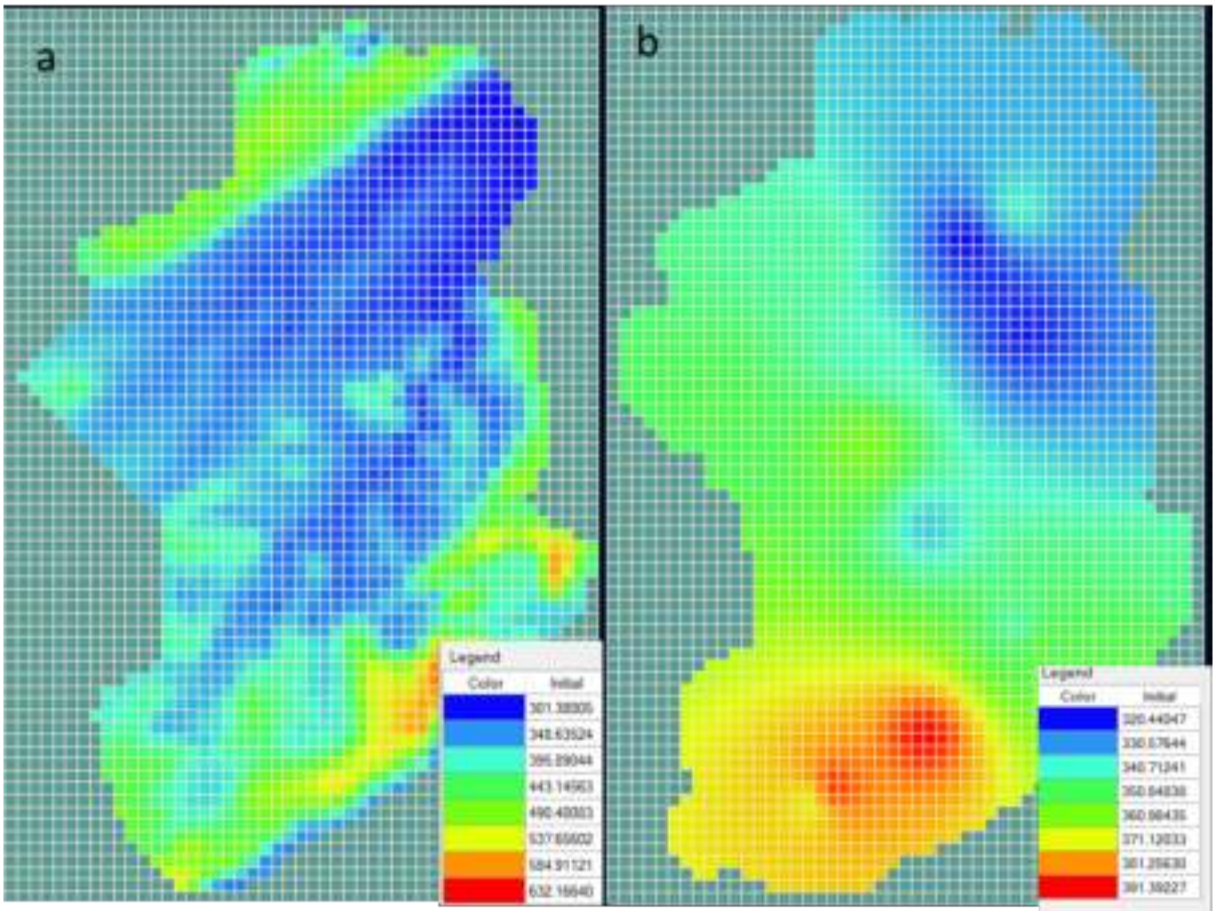


Figure 77: Distribution of initial head (IH) in (a) two-layer and three-layer model, and (b) single-layer model.

13.3.2. Boundary condition

The study area has two major rivers namely Sonar and Bearma flowing along the slope of the district. Both river confluence at the north-eastern boundary of the district (figure 75a). The parameters defined at starting and ending vertex of rivers in the numerical model is given in table 35. The intermediate values of the river stretch have been automatically interpolated through the model inbuilt- functions.

Table 35: The summary of data input for the river in the model domain.

	River stage start (m)	River stage end (m)	Riverbed bottom start (m)	Riverbed bottom end (m)	River width (m)	riverbed conductivity (m/day) (Wojnar, A. J., 2008)	Conductance (m^2/day)
Sonar	348	299	346	297	140	0.1	Calculated using model functions
Bearma	348	299	346	297	100	0.1	

Other boundary conditions such as groundwater draft, recharge, and evapotranspiration are assigned as discussed in section 13.1.

13.3.3. Code Selection

The two-layer and three-layer model were run using 'MODFLOW NWT' flow engine for the transient condition. In the next step, UPW as property package along with Newton Formulation Solver (NWT) solver has been selected to simulate the model. The single-layer model was run using "USGS MODFLOW 2005 from WH" flow engine. In the next step, LPF as property package and Conjugate Gradient Solver (PCG) as solver has been selected. PCG solver was run with maximum outer and inner iteration as 5000 and 2500 respectively. In the transient condition, MODFLOW Flex prepares the data set for a transient flow simulation during which it automatically merges all data sets and creates a time-dependent flow solution.

13.3.4. Calibration process and Results

The transient calibration of the system is to simulate the condition in which head changes with time. The water level data shows a high seasonal fluctuation in the model area. So, it is very rare to attain a steady-state condition (Maheswaran et al., 2016). Hence, it has been chosen to run the model under the transient state.

13.3.4.1. Calibration

The model was calibrated to the transient state from January 2002 to June 2009 by diving a year in different stress period based on the draft/recharge and evapotranspiration data. During calibration, the rainfall recharge and draft from irrigation, domestic and industrial uses have been adopted to achieve the result. The numerical simulation has been further extended to June 2017. The observed water level data for May and November has been compared with the corresponding computed head. The calibration statistics for the model run for three-layer, two-layer and single-layer models is plotted and a linear trend line is fitted in figure 78. The correlation coefficient and (R^2) of the model output are 0.86 and 0.74; 0.85 and 0.72; and 0.92 and 0.84, for the 3-layer, 2-layer and single layer models respectively. The figure shows that the calibration of multiple-layer models are not good. The calibration-statistics of the single-layer model is better than the other two models. Hence, the outcome form this single-layer model has been presented in the following sections.

The distribution of model generated head at the end of the 86^{th} stress period (5644 days) is presented in figure 79a. Its cross-sectional views along the row no. 40 and column no. 25 is presented in figure 79b and 79c respectively. The head in the study area varies in the range of 386 m to 307m above mean sea level.

The comparison of observed and calculated head for the month of May and November for years 2002, 2009, and 2016 is shown in figure 80. The scatter plot of model calculated head and field observed water level data in figure 80 show a good correlation. The quantitative analysis for these scatter plots is tabulated in table 36 suggesting correlation coefficient in range of 0.98 – 0.88. Other errors are also listed in detail in table 36.

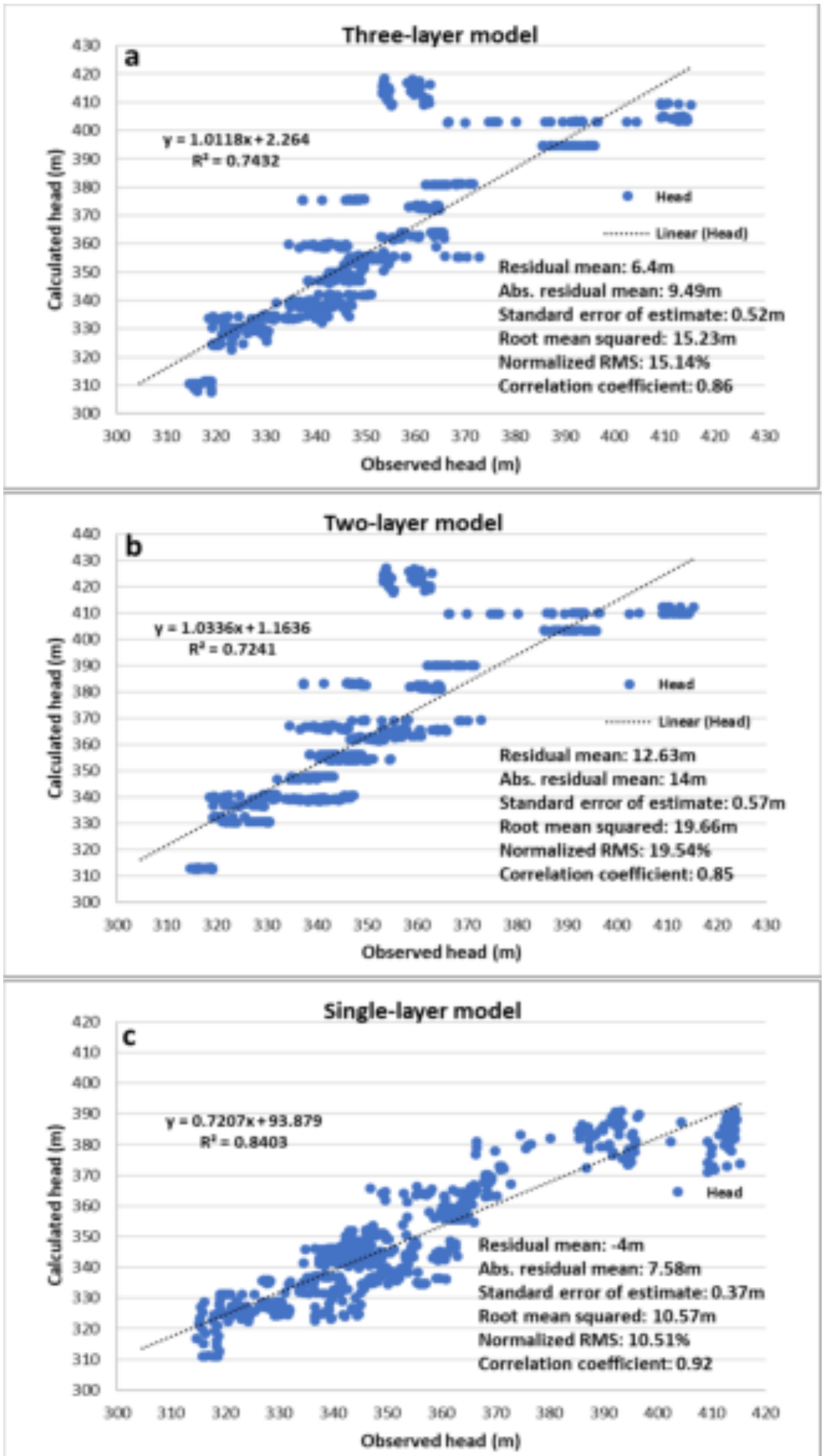


Figure 78: The scatter graph of calculated and observed heads for the alluvium part of the Bundelkhand region for the entire calibration and validation period (01/01/2002 to 15/06/2017).

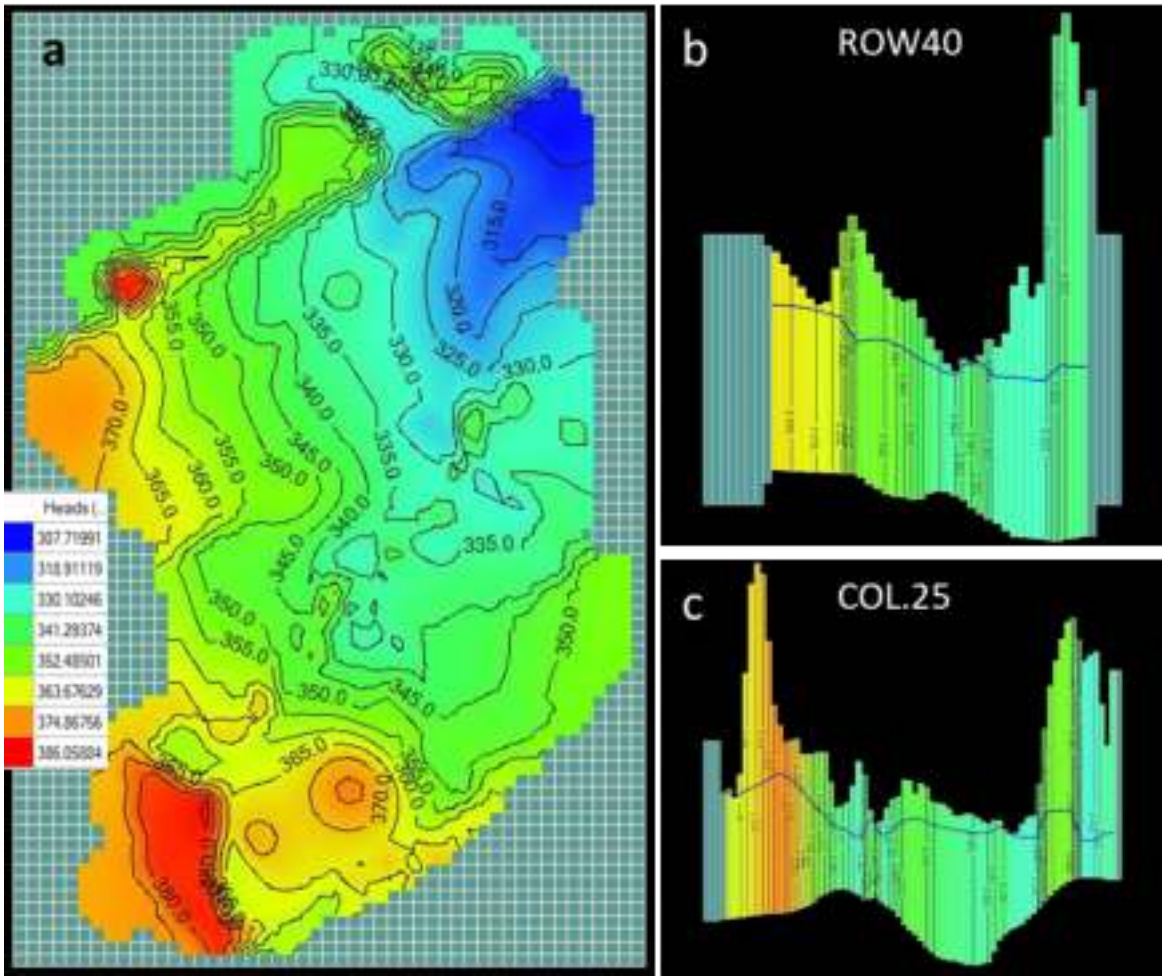


Figure 79: Model calculated head in the study area in (a) 3-D view, (b) along row# 40, and (c) along column#25 at the end of 86th stress period (5644 days). Vertical black lines indicate the head and solid blue represents the variation of water table along the respective row/column.

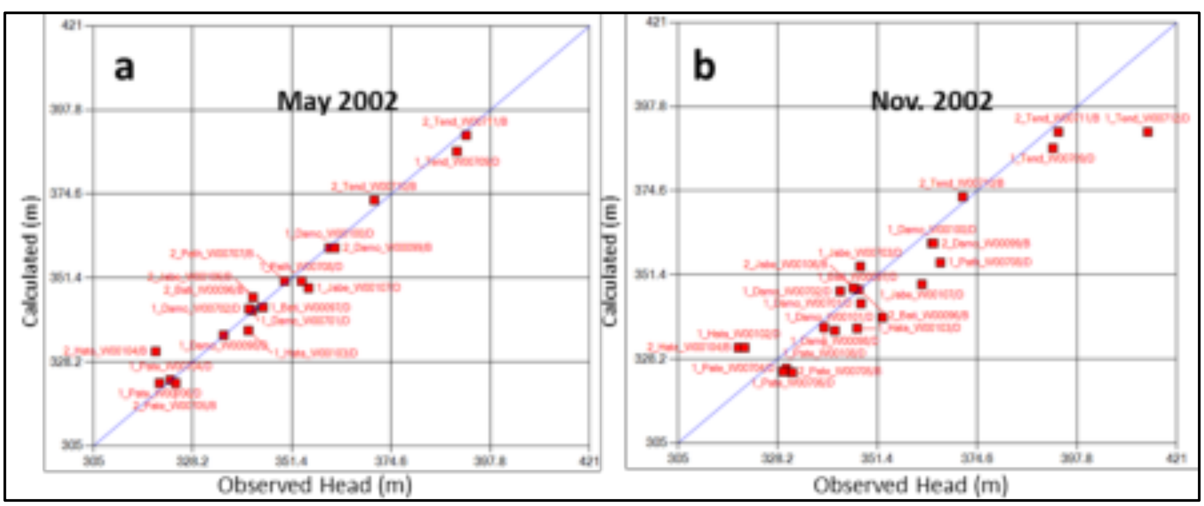


Figure 80: Calibration statistics for the different time during Calibration and validation stage in the model run.

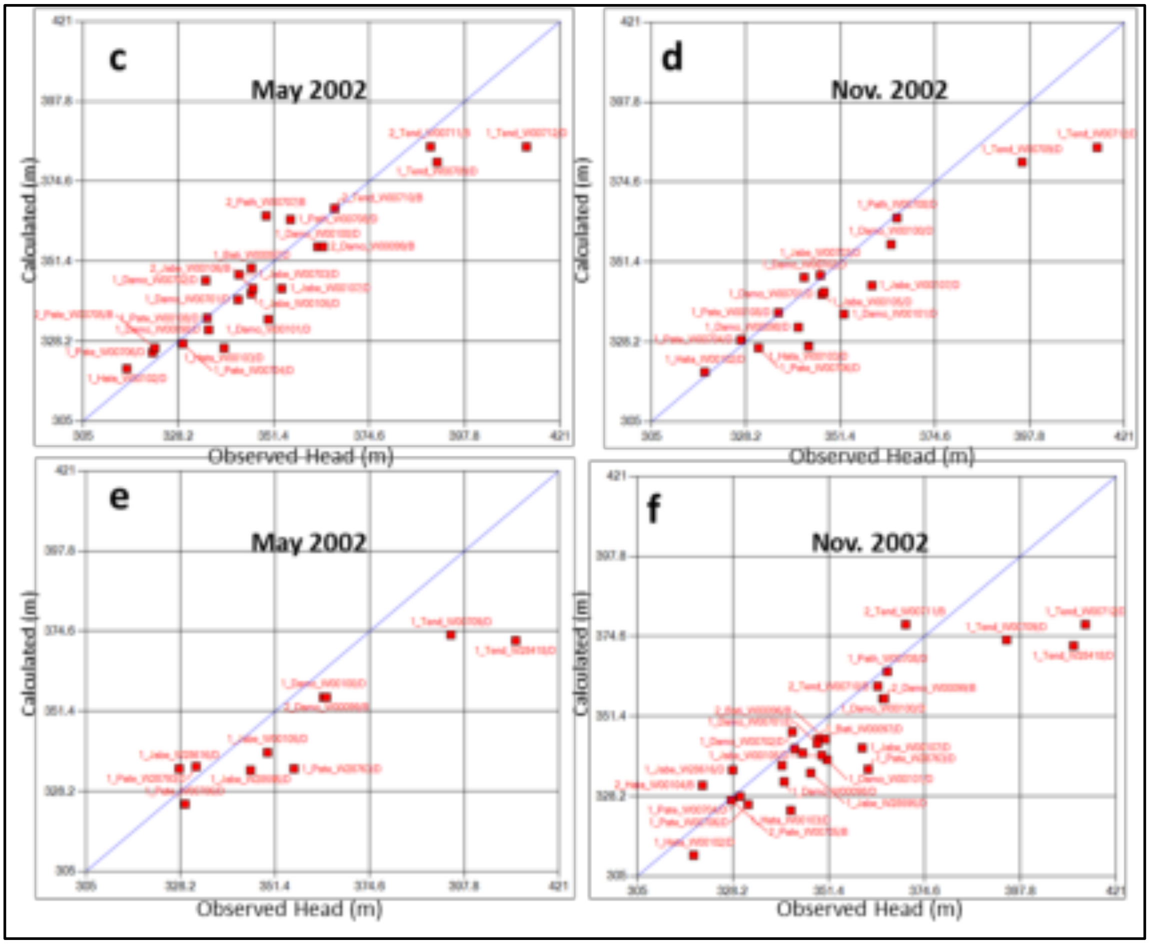


Figure 80 (continued …): Calibration statistics for the different time during Calibration and validation stage in the model run.

Table 36: The summary of calibration errors during different simulation periods.

Time	**Error (m)**				**SEE (m)**	**RMSE (m)**	**NRMS (%)**	**Correlation Coefficient**
	Min.	Max.	Mean	Abs. Mean				
May 2002	0.13	11.51	-0.22	2.52	0.86	3.67	5.05	0.98
Nov. 2002	0.29	-23.4	-3.4	6.66	1.66	8.49	8.92	0.95
May 2009	-0.37	-28.1	-2.5	7.22	1.96	9.52	9.8	0.92
Nov. 2009	0.43	-29.6	-7.2	8.28	2.29	11.41	11.88	0.94
May 2013	3.21	-38.4	-11.3	13.31	4.14	16.77	20.32	0.93
Nov. 2013	-0.71	-38.8	-8.2	10.32	2.2	14.03	14.78	0.88

13.3.4.2. Hydrograph analysis

After analysing the scatter plots at different calibration time, the observed water level data for different location has been compared with the model simulated head for throughout the simulation period. Some of the hydrograph has been presented in figure 81 for comparing the groundwater head variation. The name ending with 'B' and 'D' represents the bore well and dug well respectively.

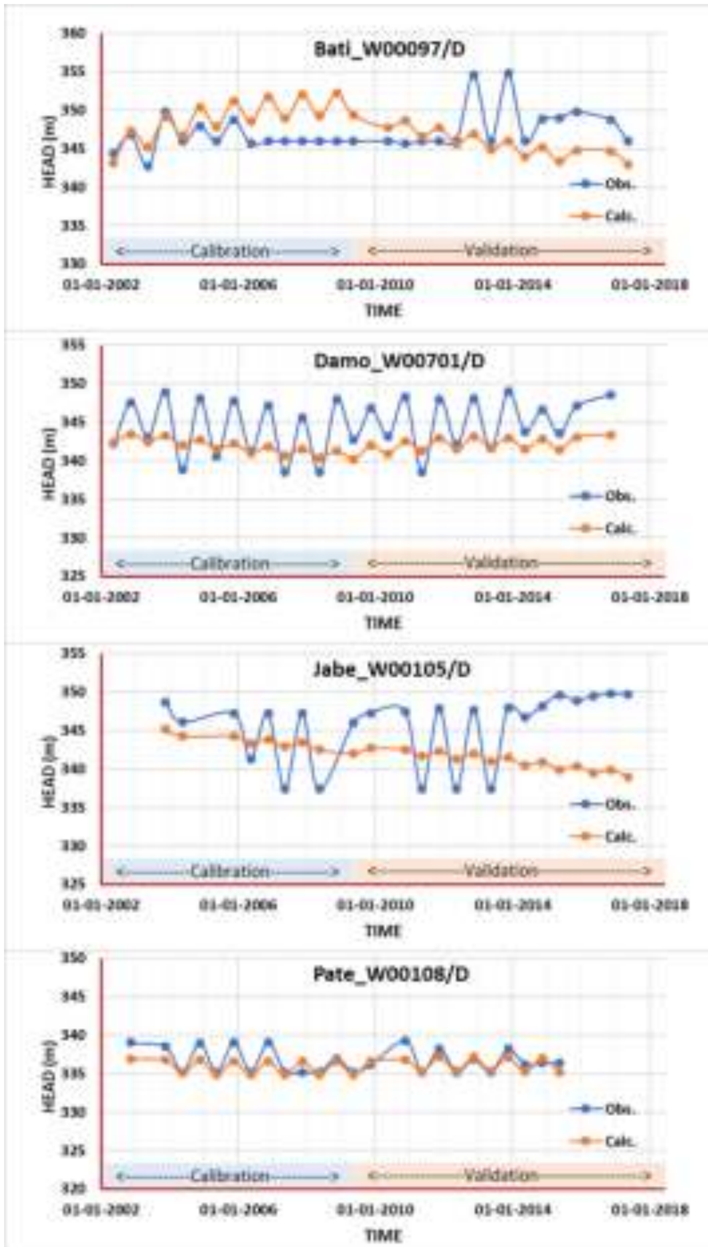


Figure 81: Comparison of observed and simulated hygrograph.

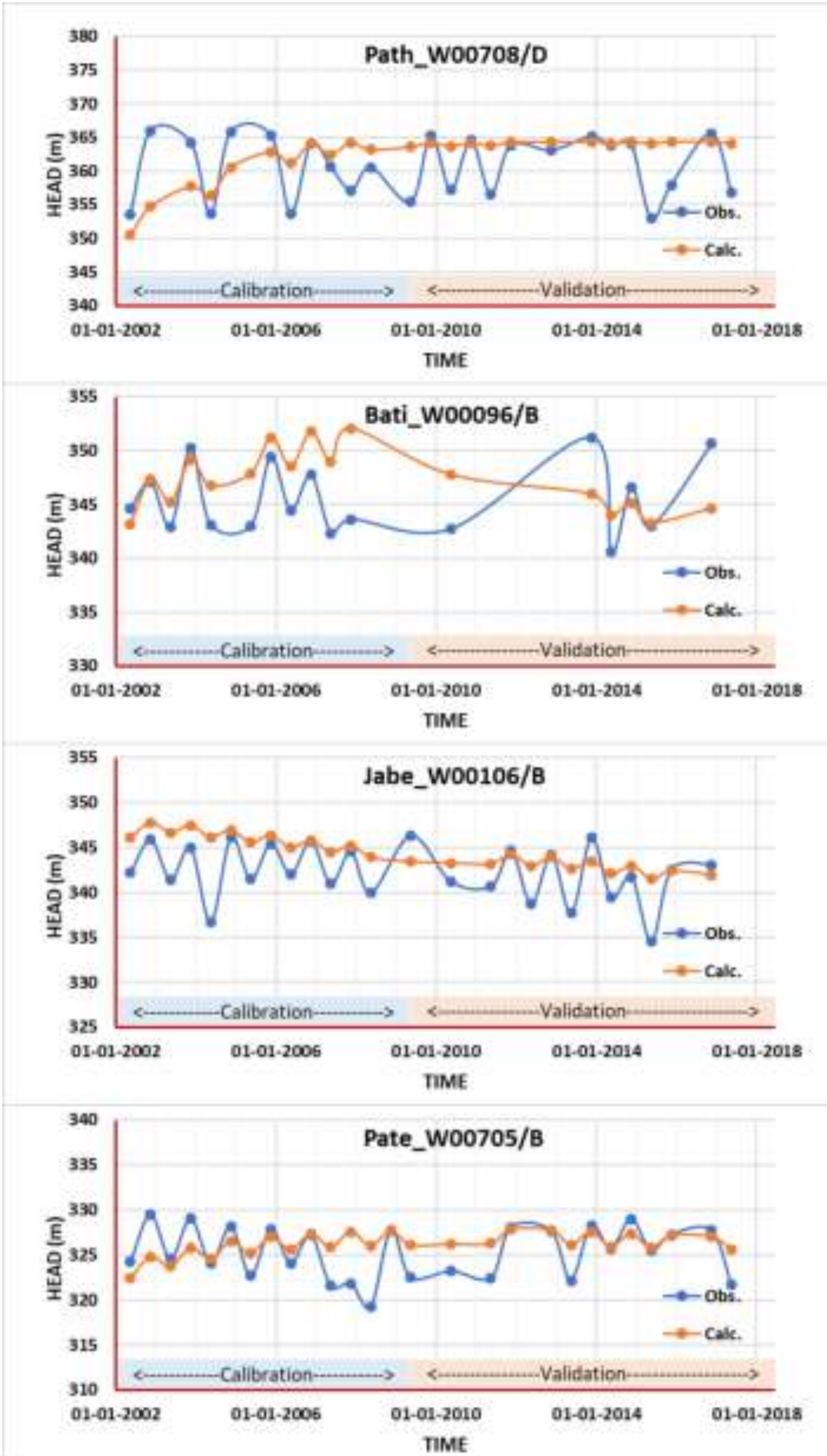


Figure 81 (continued…): Comparison of observed and simulated hygrograph.

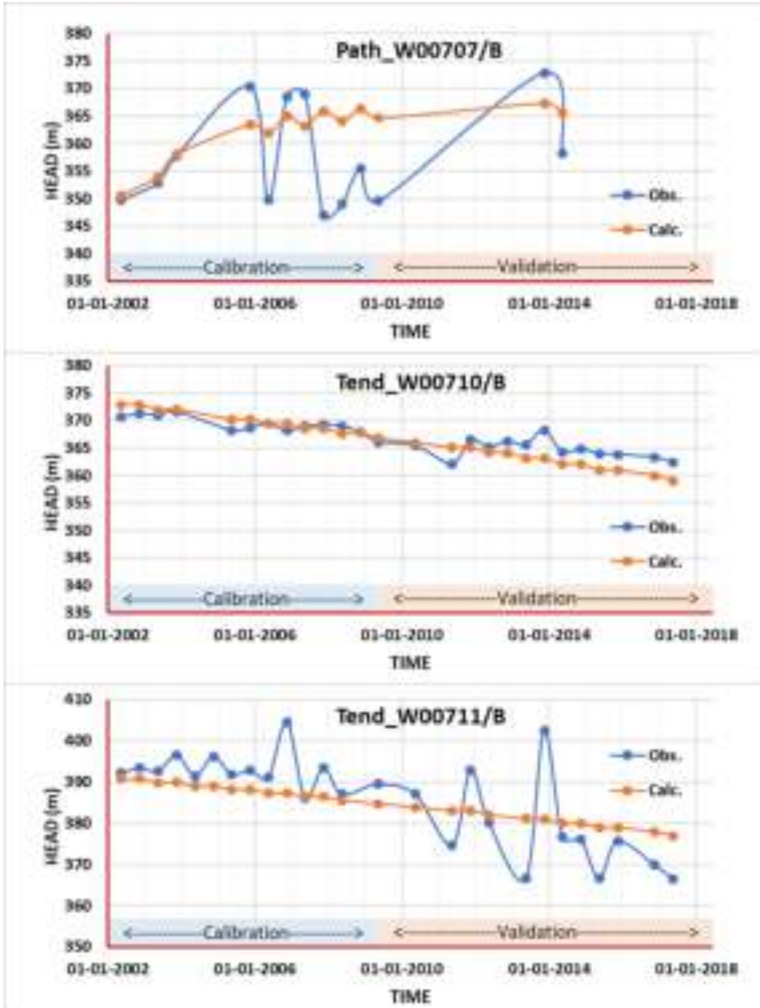


Figure 81 (continued…): Comparison of observed and simulated hygrograph.

13.3.4.3. Mass Balance

The groundwater budget for the study area for the stress period 1, stress period 40 (end of calibration period), and stress period 86 (end of validation period), obtained from the model run is presented in figure 82, and its comparative study is tabulated in table 37.

The groundwater budget for the stress period-1 shows that the groundwater is extracted mainly through the evapotranspiration mode and river leakage. It has been compensated through the storage loss. At the end of simulation period, the groundwater abstraction is about 18% of the total abstraction during the entire simulation, which is directly compensated through the recharge (20%) component. More than the pumping well, the high evapotranspiration (64%) is major factor behind the storage loss.

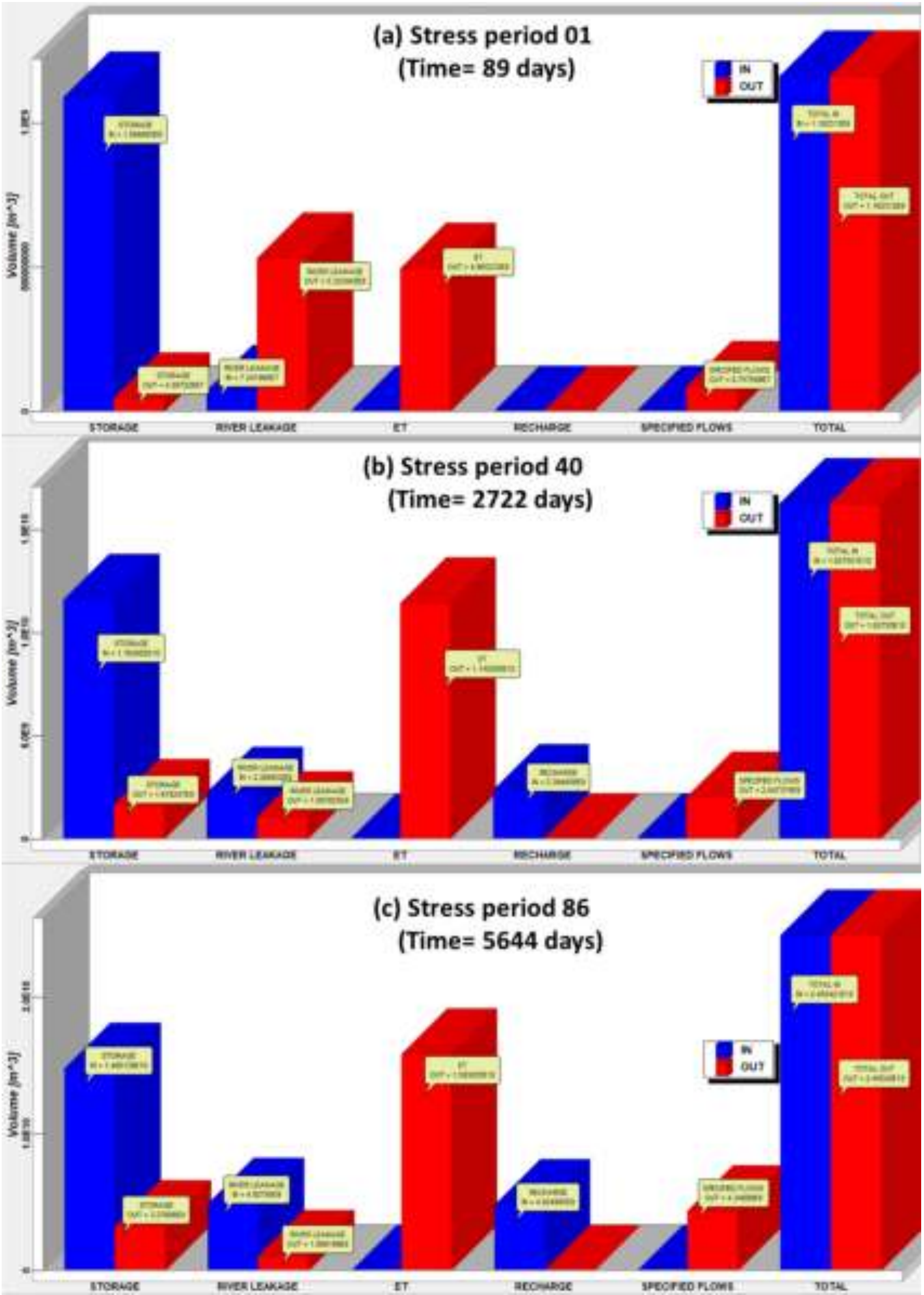


Figure 82: Groundwater balance at 89 days, 2722 days and 5644 days.

Table 37: Groundwater budget for the calibration and validation period of the flow model.

	STRESS PERIOD	1	Up to 40	41-86	Cumulative (1- 62)
	DAYS	31-03-2002	15-06-2009	15-06-2017	1/1/02-15/6/17
1		A	B	C	D=(B+C)
2	MODEL INFLOW (MCM & % w.r.t. total IN)				
3	STORAGE	51.3 (80)	11620.8 (71)	3180.6 (39)	14801.4 (60)
4	RIVER	12.8 (20)	2260.6 (14)	2667.2 (32)	4927.9 (20)
5	RECHARGE	0	2394.1 (15)	2430.9 (29)	4825 (20)
6	TOTAL IN	64.1	16275.5	8278.7	24554.2
7	MODEL OUTFLOW (MCM & % w.r.t. total OUT)				
8	STORAGE	12.6 (20)	1678.2 (10)	1598.6 (19)	3276.9 (13)
9	RIVER	28.9 (45)	1097.8 (7)	0.4 (0)	1098.2 (5)
10	ET	19.2 (30)	11452.1 (70)	4378.2 (53)	15830.3 (64)
11	SPECIFIED FLOWS	3.4 (5)	2047.4 (13)	2301.5 (28)	4348.9 (18)
12	TOTAL	64.1	16275.5	8278.7	24554.2
13	IN-OUT (MCM)				
14	IN-OUT (MCM)	0	0	0	0
15	PERCENT DISCREPANCY	0	0	0	0

13.3.4.4. Findings and recommendations

1) The groundwater budget during the calibration period (2002 to 2009) shows a high aquifer loss (B3-B8) which has reduced drastically (C3-C8). This shows the improved condition in recent years. On the other hand, it may also indicate about the exhausted aquifer storage, which is not able to interact actively with the groundwater dynamics of the system.
2) The role of the river in the present model output is not very much evident. The data shows that water level has gone below the riverbed due to which groundwater is not able to contribute into the river. However, the river is adding the water through the leakage. To make any concreate statement, it is very necessary to have river stage data on small time scale such as weekly or monthly at different gauging stations.
3) The ET loss indicates the removal of water from the soil through direct radiation and crop cultivation. A field-based measurement of ET could add the reliability of the model output.

4) The aquifer structure in the hard rock terrain is very much difficult to be understood. Due to the presence of faults and dykes intersecting each other, the output of the model could be less reliable.
5) The present modelling exercise has been attempted to understand the groundwater dynamics in the Damoh district, which has been fed with detailed recharge, draft and ET only.
6) The present modeling is attempted considering the spatial as well as vertical variation in the lithology of Damoh distrct. Due to, lack of knowledge about essential inputs, the multilayer model showed an inferior/ less reliable results in comparison to single layer model. Hence defining the modelling exercise based on the political boundaries are not able to serve the purpose.
7) The modelling of hard rock requires a massive amount of data regarding the faults, lineaments, change in geological boundaries and their hydrogeological properties, water level monitoring with dedicated depth consideration, etc. are to refine the model further.
8) Hard rock modelling requires an integrated modelling (Ebrahim et al. 2019) approach where feedback from the different processes such as ET, surface and groundwater interaction, flow from unsaturated zones (Markstrom et al. 2008) is considered.
9) Xu et al. (2012) recommend using modules for estimating and linking different fluxes with the groundwater internally instead of external estimations.

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