CHAPTER 3
METHODS AND MODELS

3.1. Study Area

The Bundelkhand region of central India lies between Indo-Gangetic Plains up north and the Vindhyan range towards the south (Garg et al. 2020). The region is spread across 7.08 million hectares, spans across 7 districts (Jhansi, Jalaun, Lalitpur, Hamirpur, Mahoba, Banda and Chitrakut) in Uttar Pradesh and 6 districts (Datia, Tikamgarh, Chattarpur, Damoh, Sagar and Panna) in Madhya Pradesh and together they constitute some of most backward districts in India (UNDP 2012; Gupta et al. 2014). The region is drained by numerous rivers from the Yamuna River system, including Ken, Betwa, Pahuj, Baghain and Paisuni, followed by their major tributaries Dhasan, Jamni, Birma, Sonar, Katne, Bewas, and Kopra (Gupta et al. 2014). The Betwa River is the major drainage channel in the region and contributes 50% water available in the region (Gupta et al. 2014).

The Betwa River, originates in the Raisen district of Madhya Pradesh and flows 590 kms in North-Easternly direction before joining Yamuna River at Hamirpur district, Uttar Pradesh (Desai et al. 2021). The total drainage area of the Betwa River Basin (BRB) is about 43,946 km^2 and lies between latitude of 22°59′57″ to 26º03′23″ N and longitude 77°05′ 51″ to 80°13′01″ E (Suryavanshi et al. 2017; Desai et al. 2021). Singh and Singh (2022) conducted geo-morphometric and topo-hydrological characterization and observed that the BRB fell under seventh order basin with multitude of headwater streams. The drainage basin was well-dissected, had near elongated shape, relatively gentle east facing slope gradient, rocky and undulated topography, while the drainage patterns were mostly dendritic to sub-dendritic and followed the terrain gradient. The basin’s coarse drainage texture due to the presence of jointed and fractured subsurface granitic lithology resulted in elevated overland flow and lower infiltration rates.

The total population in the basin is around 20.2 million with an average population density of 295.9 people per square kilometre (Chandramouli, 2011). Majority of the population living in the basin are dependent on agriculture/livestock-based activities, they are rural poor, economically deprived, and the region is prone to natural disasters like frequent droughts and floods (Gupta et al. 2014; Singh and Singh 2022). The region has a high rate of poverty, low literacy rates (57%) and vulnerable women and landless people (Padmaja et al. 2020; Garg et al. 2020). Considering the household, industrial, animal, and agricultural sectors, the BRB's yearly water footprint was calculated to be 9186 Mm^3 (or 213.03 mm per km^2) (Mali et al. 2019). The BRB can be distinctly divided into upper and lower BRB based on the elevation ranges. The upper BRB resides at a higher altitude between 358 – 713 meters above sea level while the lower BRB lies between 111 – 400 meters above sea level. This study is focused on the Lower Betwa River Basin (LBRB) which covers approximately 15700 km^2 area and covers three major districts of Jhansi, Lalitpur in Uttar Pradesh, and Tikamgarh in Madhya Pradesh (**Fig 3.1**). Agriculture and barren land occupy over 70% of the basin, while only 4.5% was under built-up area (Tewari et al. 2024). Betwa River and its tributary Dhasan are the two main drainage channels with numerous ephemeral small streams.

Major part of the LBRB is poor and lack access to infrastructure and technology (CGWB, 2017a). Agriculture and livestock rearing is the main occupation in the region and farming was dependent on monsoon rainfall. To combat uncertain and erratic monsoon, multiple dams and canals were constructed. However, during the drought periods these reservoirs were not able to meet the water requirements (CGWB, 2017 a.b,c). As per the 2011 census the total population of the three districts was 46.65 lakhs. With 70% of the

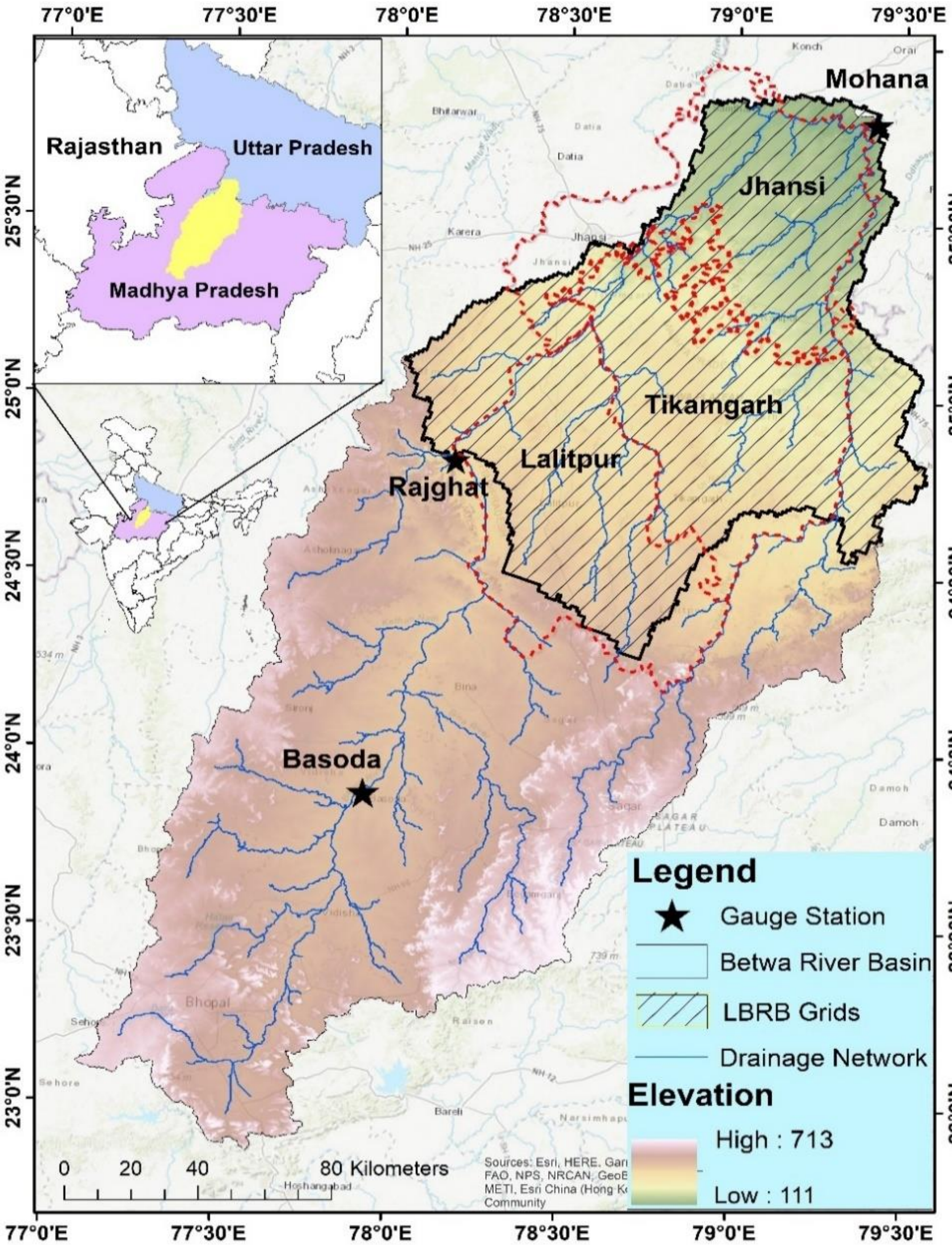


Figure 3.1 Location map of the study area with elevation range and gauge stations

land under agricultural use, farming is the main economy in the LBRB and the cropping intensity stood at 165% (CGWB 2017 a,b,c). According to the latest dynamic groundwater assessment report (CGWB, 2022), the annual groundwater demand in the three major districts within the study area was at 1055 MCM, majority of which was allocated to irrigation (90%) and rest to domestic (9%) and industrial use (1%). The dynamic groundwater recharge was estimated at 1376 MCM and the average stage of groundwater extraction in the three districts worked out to be 77% (CGWB, 2022). In accordance with the stage of groundwater extraction, the LBRB aquifers were under semi-critical condition (CGWB, 2022).

3.1.1. Climate and rainfall

The BRB generally experiences semi- humid to the hot type of climate. The summer season is usually from May to June when the temperature reaches a maximum of 38 to 43ºC and conversely during the winter months of December and January the temperatures dropped to 8 to 12°C (Desai et al. 2021; Gupta et al. 2022). During the monsoon season the temperature fluctuates between 23- 27 °C with relative humidity between 68 – 80% (Gupta et al. 2022). Long term analysis of climate patterns revealed gradual shift from semi-arid moist climate to semi-arid dry and arid climate in the Bundelkhand region (Rao et al. 2013).

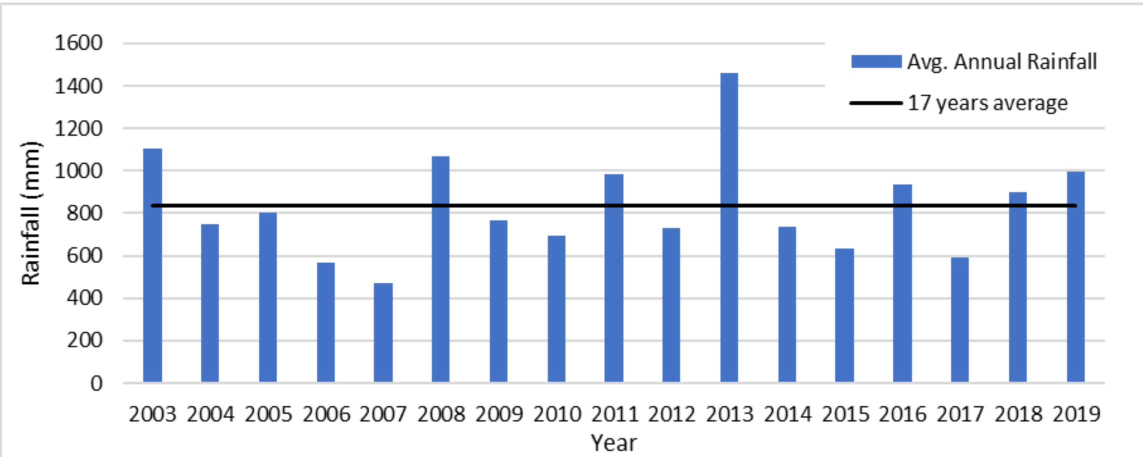


Figure 3.2 Annual average rainfall variations during the study period 2003 – 2019 (Source: https://dsp.imdpune.gov.in/)

The mean average rainfall fluctuated between 700mm - 1200mm during 2000 – 2011 and was concentrated during the monsoon months of June to September (Desai et al. 2021). Rainfall was distributed spatially, with the upper and intermediate basins receiving more rainfall than the lower basin (Singhai et al. 2019). The basin receives 85% of its rainfall during the monsoon season and rest are scattered in the remaining 8 months (Chaurasia and Chandra 2021). Though the region received adequate rainfall but most of it was with high intensity (30-50mm/hour) reaching total rainfall in just few hours or days which resulted in poor infiltration of rainwater into the subsurface (Sinha 2021). Long term analysis of rainfall data revealed a declining trend in the average annual rainfall in the region and a direct correlation between reduction in forest cover and negative deviation from normal rainfall was observed in the region (Gupta et al. 2022; Chaurasia and Chandra 2021).

3.1.2. Geomorphology and Land Use Patterns

Three major geomorphic units exits in the study area (i) the northern highly erodible composite plain province (ii) the middle Bundelkhand pediment pediplain complex and (iii) the southern Vindhyan ranges (CGWB 2017 a,b; Sinha 2021). The northern highly erodible composite plain province is composed of thick repository of Quaternary alluvial deposits, moderately and deeply weathered buried pediplain, residual hills, linear Quartz reefs and old meanders (CGWB 2017a). The middle Bundelkhand pediplain complex corresponds to Archaean granite, gneisses and schists having weathered mantle of colluviums under thin or non-existent alluvial cover (CGWB 2017a). It includes Pediment-Inselberg complex crisscrossed by lineaments and fractures, shallow weathered pediplains, and residual linear Quartz reef. The linear Quartz reefs rise to over 100 meters in height and extends from few hundred meters to tens of kilometres in NE-SW direction (CGWB 2017 a,b). The Bundelkhand Precambrian strata is mostly composed of granite and granite gneisses, Vindhyan sandstone, limestone, and shale, either with or without a thin layer of alluvial cover, underlie the Vindhyan plateau region (CGWB 2017b; Sinha 2021).

The land use analysis of the BRB was done using Landsat 7 satellite images in Google Earth Engine (GEE) and literature. The southern region of the BRB is dominated by urban settlements, industries, hills, and forest while the central and northern regions were occupied by agricultural land, sparse settlements, rocky outcrops, stone mining and

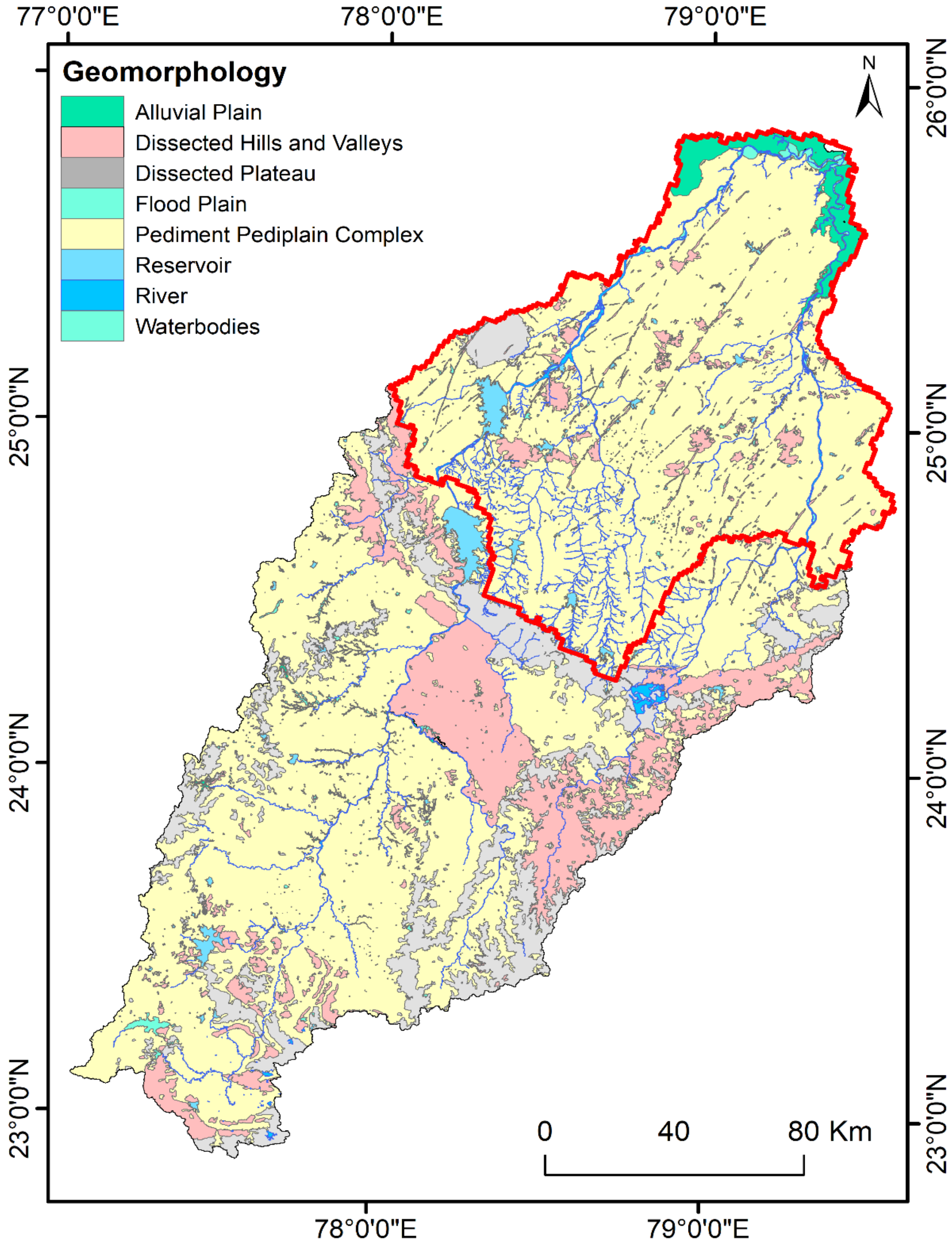


Figure 3.3 Geomorphological map of BRB with observation well locations (extracted from geomorphology 250K, Geological Survey of India, Government of India, Kolkata, India)

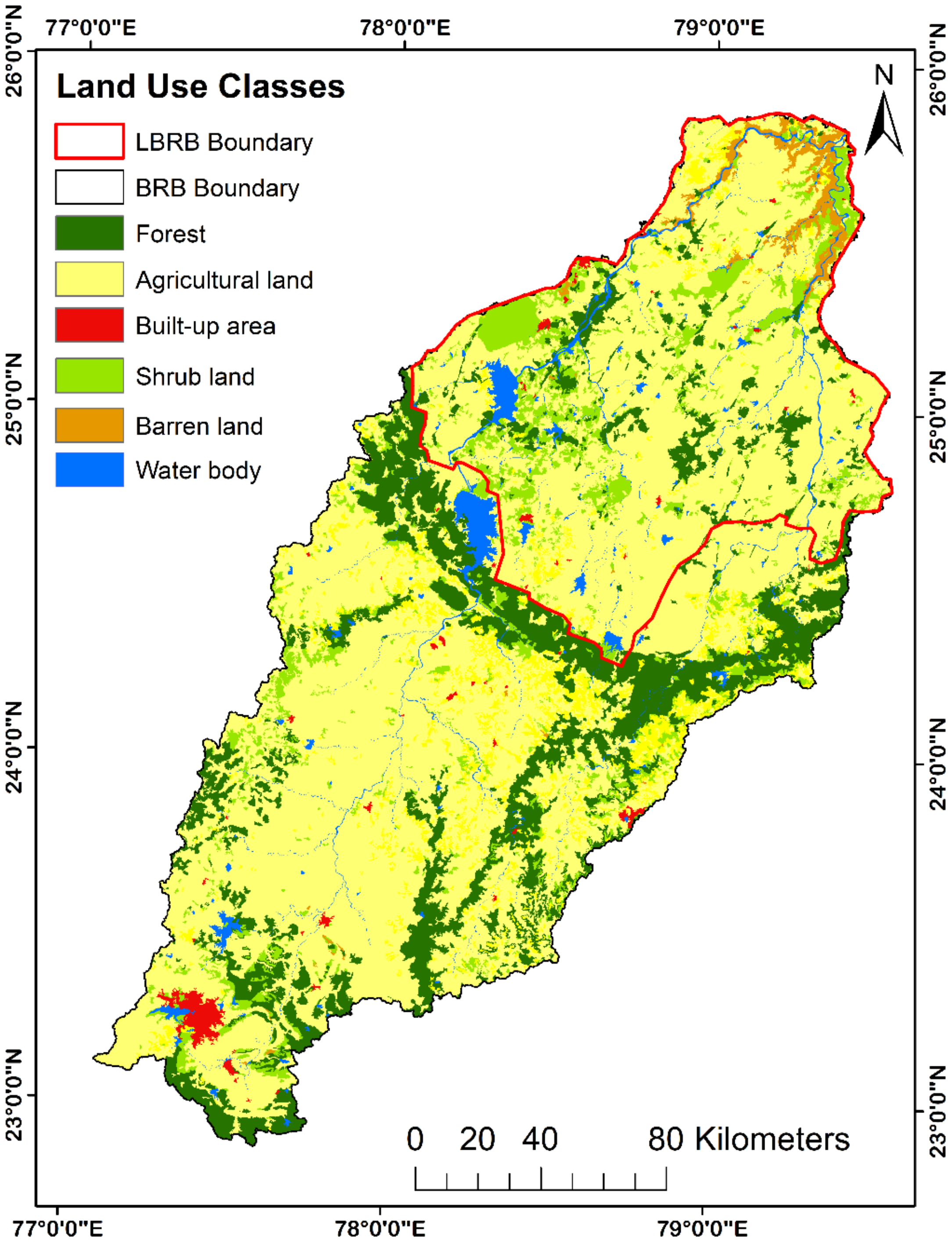


Figure 3.4 Land Use map of the BRB and the LBRB

crushing industries and thermal power plants (Singh et al. 2022). Agricultural land occupied major part of the basin (82%) (Suryavanshi et al. 2017; Desai et al. 2021; Singh et al. 2022) but most of it was rainfed due to inadequate irrigation facilities (Singh et al. 2022). The land use map of the BRB was generated using LANDSAT 7 multi-spectral data of 2005, classified with Random Forest classification. A total of 10 land use classes was defined for the BRB as, agricultural area (70%), forest (deciduous, evergreen, and generic) (2.8%), grassland (8.5%), barren land, built-up area (residential and industrial) (0.8%), and water bodies (2.8%). The main soil types in the BRB were clay, silty clay, clay loam, and sandy loam soil, according to the National Bureau of Soil Survey and Land Use Planning (NBSSLUP), Nagpur, India (Suryavanshi et al. 2017).

3.1.3. Geology

Geologically, the BRB is underlain by litho-assemblages of various age groups, from Archaean to Quaternary period (Singh and Singh 2022). It is based on the geological map of the study area obtained from Bhukosh portal of Geological Survey of India (GSI) (https://bhukosh.gsi.gov.in/Bhukosh/Public). The Deccan trap, Vindhyan Supergroup, the Bijawar group and the Bundelkhand complex are rock groups that collectively underlain the BRB. In the southern or upper regions of the BRB, basaltic rock of Deccan trap extended over 42% of the basin, while 41% of the southern and middle portions was covered by Bundelkhand massif and the Alluvial plains envelope 9% of the northern or lower regions of the BRB (Singh and Singh 2022). The Vindhyan supergroup includes rocks of Bhander group, Kaimur group, Rewa group, and Semri group and is spread across 6% of the basin and the remaining 2% is occupied by Bijawar Group (Singh and Singh 2022) (**Fig. 3.3**).

3.1.4. Hydrogeology

The mode of occurrence of groundwater in any region is determined by the type of hydrogeological unit's existent in it. Detailed hydrogeological description was obtained only for the modelled region of the BRB i.e. the LBRB. The unconsolidated northern alluvium formations consisted mostly of fine to coarse sand, gravel, pebble, silt, clay and kankar. The alluvium along with the underlying weathered zone of granite-gneissic

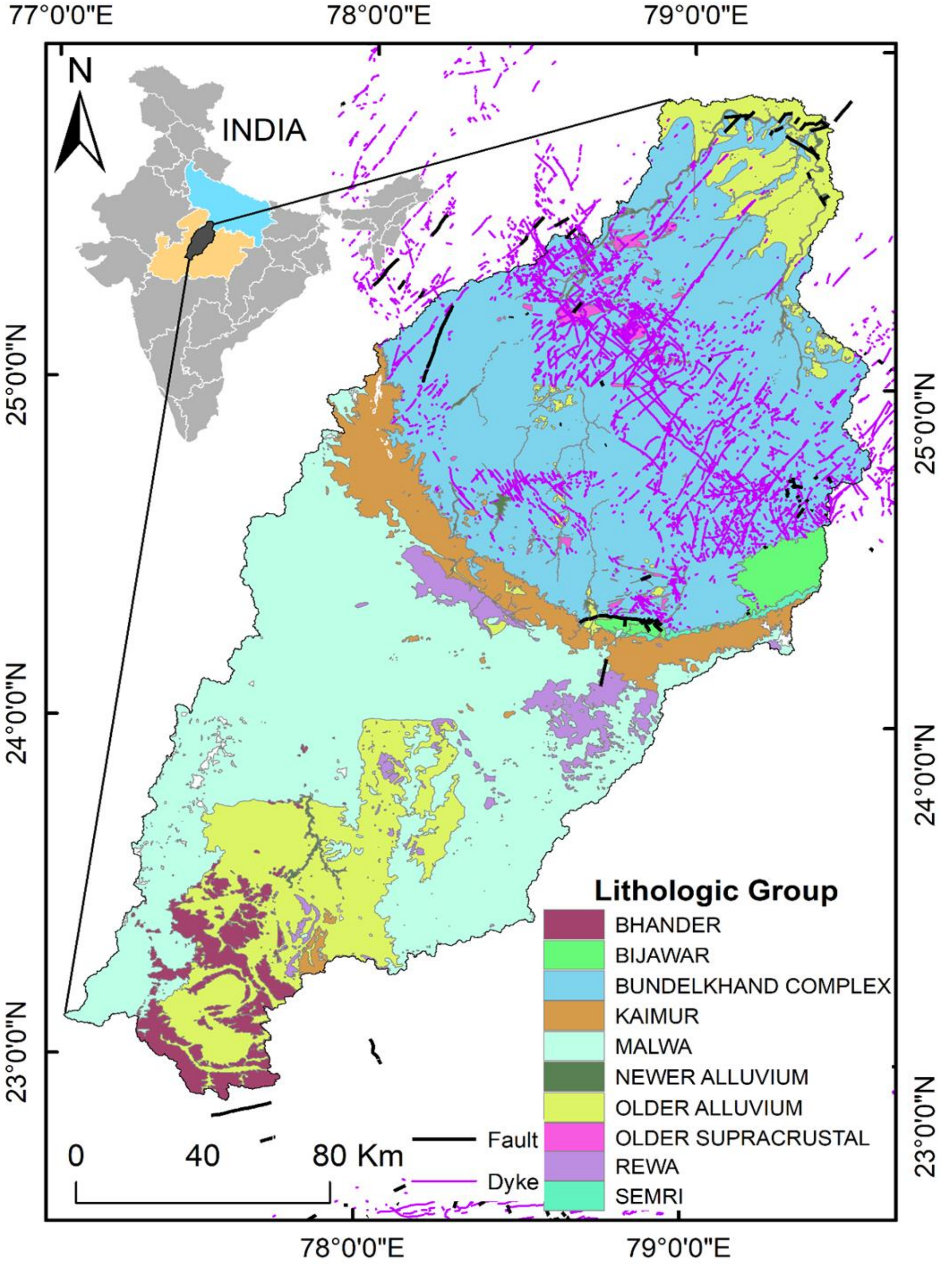


Figure 3.5 Major Lithological Group in the BRB (extracted from Lithology 50K, Geological Survey of India, Government of India, Kolkata, India)

basement formed roughly a homogeneous aquifer system with maximum thickness of 60 meters (CGWB 2017a). Groundwater occurred under water table conditions and moderate yield was available through dug wells and tubewells. Water bearing properties in the consolidated formations like Bundelkhand uplands is administrated by the degree of weathering, presence of fractures, joints, and interconnected pore spaces available (Sinha 2021). The weathered zone of Bundelkhand granite-gneissic complex of Archaean age along with the overlying residual soil principally formed a distinct aquifer system in the central region of the LBRB (CGWB 2017a). Groundwater transpired at favourable sites with good-interconnected fractures which was not existent everywhere in the LBRB area. Additionally, the weathered zone thickness was not uniform averaging 20 to 40 meters and the frequently occurrence of outcrops, hillocks, and linear quartz reef made the aquifer heterogeneous (CGWB 2017a, b). Vindhyan formations composed of sandstone, shale, and limestone, having poor groundwater storage potential, formed the southern boundary of the study area (CGWB 2017b).

3.1.5. Summary

Betwa River Basin is one of the major river basins in the Bundelkhand region of central India. Over 20 million people lives in the basin with majority involved in agriculture and livestock rearing. Over 70% of the basin is agricultural land dependent on surface and groundwater for irrigation. The region is socioeconomically poor and has suffered from frequent drought occurrences in the recent past and the livelihood of the people is at risk due to inadequate water availability. A number of old and new surface water harvesting structures exist in the region but over 50% of its water was lost through evapotranspiration. Majority of the basin was underlain by hard rocks of various rock groups making availability of groundwater scarce and concentrated in regions with good, connected fractures. A densely forested region once is quickly turning into barren terrain due to the declining rainfall patterns and the groundwater levels at multiple locations have witnessed severe decline.

3.2. Methodology

For the proposed framework, the following methodology has been developed based on the study area and most widely adopted spatial and numerical modelling tools. In the first step of the proposed MAR planning framework, SWAT and MODFLOW-NWT model was employed to quantify the surface and subsurface water balance in the LBRB. In the

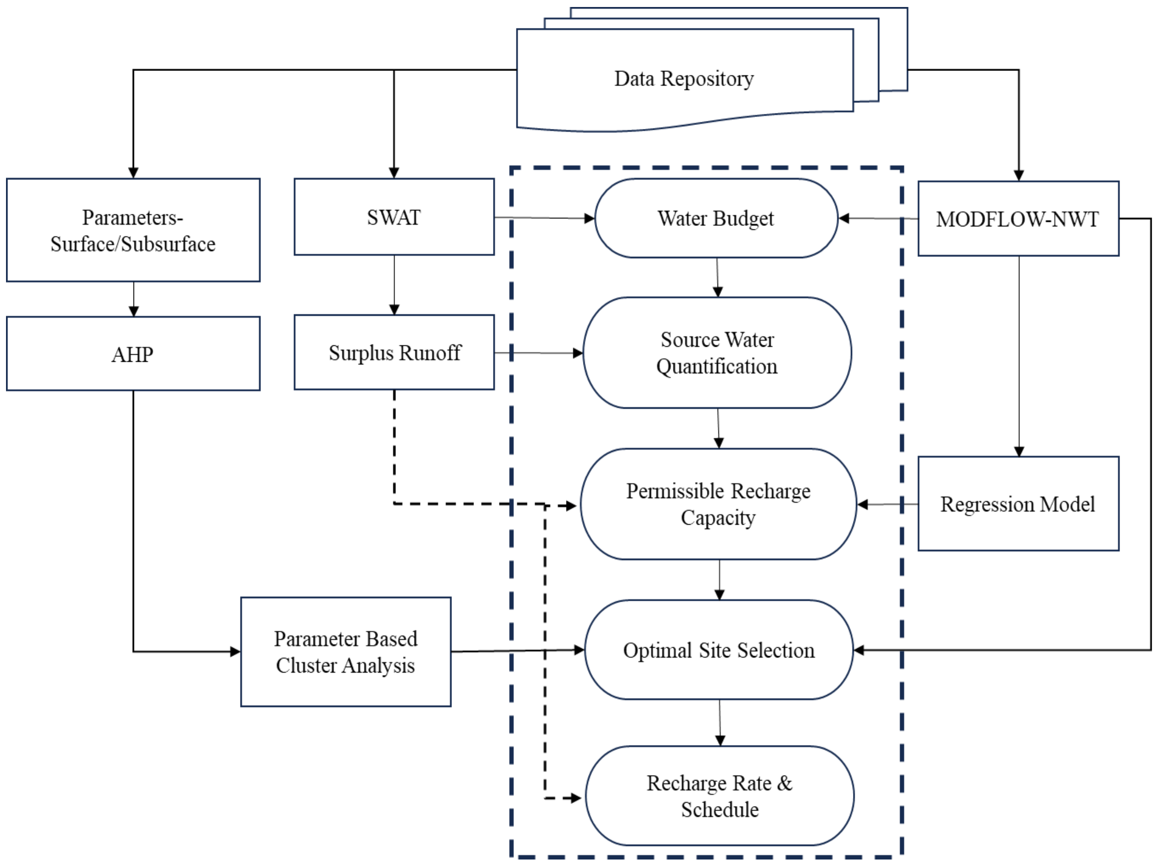


Figure 3.6 Flowchart of the Research Methodology

3.3. Model Development

In order to comprehend and quantify the hydrological process in a catchment or basin, inclusive of groundwater distributions it is important to develop adequate surface water and groundwater models that includes all important processes and represent the real field conditions with fair accuracy. Integrated models using loosely coupled SWAT and MODFLOW models have been widely used in water resources management studies as reviewed in literature. The hydrological process of the BRB has been simulated using the widely used and accepted SWAT model. The output of SWAT model (groundwater percolation and evapotranspiration) is used as input into the groundwater model MODFLOW-NWT and is a widely adopted lose coupling method for integrated studies. The groundwater flow dynamics of the LBRB was simulated using the MODFLOW-NWT model. This chapter entails the entire modelling process from development of SWAT and groundwater model to the calibration and validation process. The chapter also characterizes the aquifer hydraulic properties and the estimated spatial groundwater recharge rates.

3.3.1. Surface water model

Quantification of watershed hydrology is a complicated task often complimented by the use of hydrological models. SWAT model has been employed to simulate the hydrological processes of the BRB based on its versatility, low input data requirements and literature review. Modelling the watershed hydrology in SWAT involves division of watersheds into subbasins based on water network and their consequent fragmentation into hydrological response units (HRUs) (Kumar et al. 2024; Desai et al. 2021; Kausher et al. 2024). HRU are composed of DEM, soil, slope, and land use data to lump areas of similar attributes (Desai et al. 2021; Trivedi et al. 2023). The HRU scale generated surface runoff, groundwater recharge and evapotranspiration data were then regenerated at subbasin scale based on averaging the HRUs that makes up the subbasin (Kausher et al. 2024).

3.3.1.1. Data Requirements

The main datasets required to set up the SWAT model are spatial data (topography, land use, soil,) meteorological and streamflow data. The details of the data input are discussed inflowing paragraphs.

Digital Elevation Model (DEM)

The topography of the BRB was delineated using a 90 × 90 m resolution Shuttle Radar Topographic Mission (SRTM) DEM data. ArcGIS environment was used to process the DEM data and change its projection to UTM (Universal Transverse Mercator) – 43N projection system. The BRB can be divided into two regions based on the elevation, the

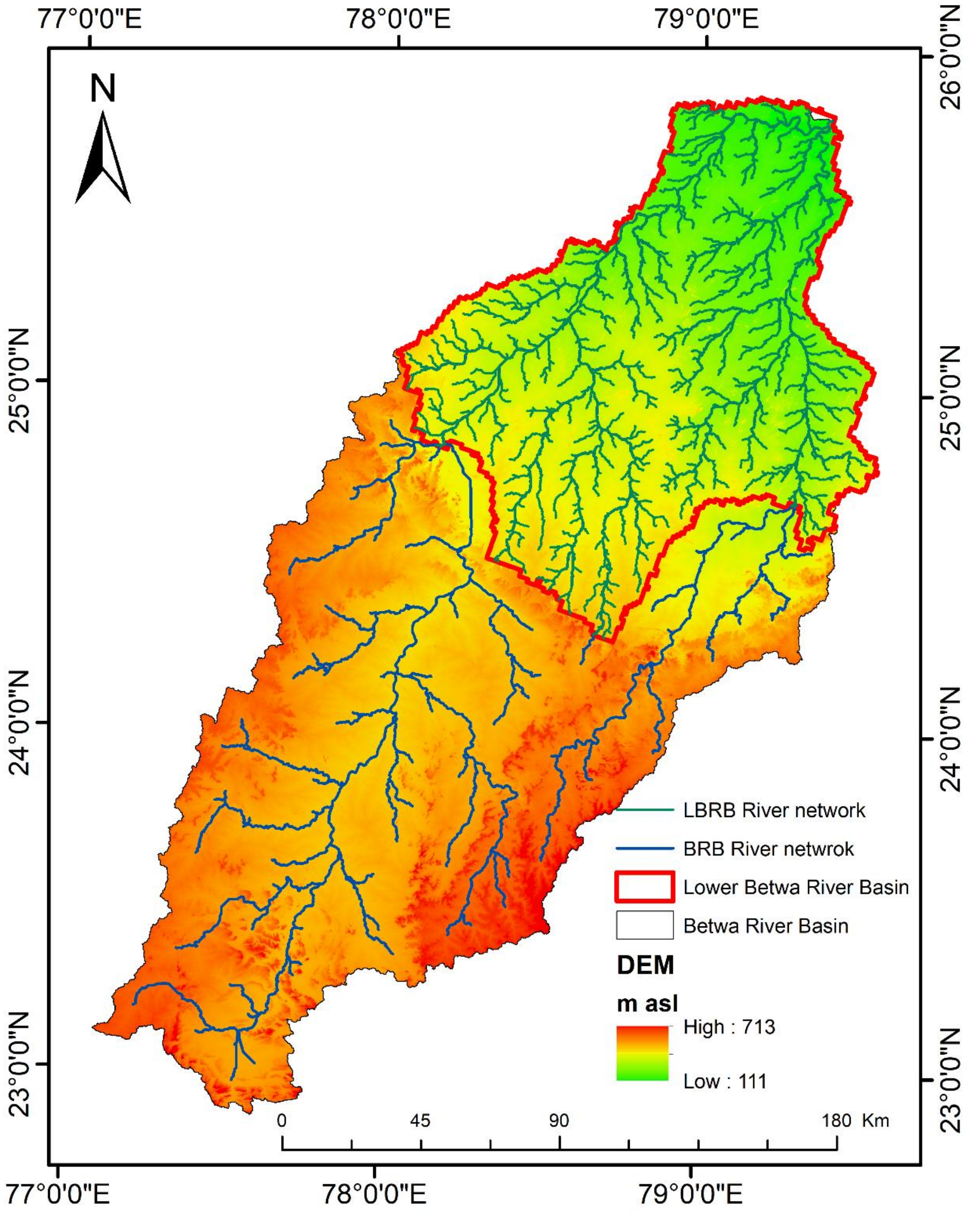


Figure 3.7 DEM and stream network of the BRB and LBRB

LBRB and the Upper Betwa River Basin (UBRB). The LBRB was spread between the elevation range of 110- 400 m asl, while the UBRB had an elevation range of 358-713 m asl. The processed data was used to demarcate the slope, subbasins and analyse the stream network distribution in the basin (**Figure 3.7**).

Land Use Land Cover map

The land use map of the Betwa basin was generated using LANDSAT 7 multi-spectral data of 2005. Supervised classification using Random Forest classifier was employed to generate 6 major land use classes, Agriculture (cropland and fallow land), Built up area, Forest (deciduous and mixed type forest), Shrub land (shrub, grassland and plantation), water bodies and barren land (barren and waste land) (**Figure 3.4**). Majority of the BRB was dominated by agricultural land (70%) followed by forest (16%), shrub land (8%), water bodies (3%), built up area (1%) and barren land (1%).

Soil Map

The soil map of the study area obtained from National Bureau of Soil Survey and Land Use Planning (NBSSLUP), Nagpur, was digitised from Suryavanshi et al. (2017). The BRB is underlain by Vindhyan Sandstone, Deccan Traps and Bundelkhand Granite type rocks (Suryavanshi et al. 2017). The dominant soil types and their area coverage in the basin were classified as Clay (22.3%), Silty Clay (28.1%), Clay Loam (31.4%) and Sandy loam (18.2%) (**Figure 3.8**).

Climate/Weather data

The daily temperature and precipitation data was generated using the Indian Meteorological Department (IMD) 2D gridded data (Temperature- $1^{o}\times1^{o}$, Precipitation- $0.25^{o}\times0.25^{o}$) from 2000 to 2020. Hargreve's method (Hargreaves and Samani, 1985) was employed for PET calculation, based on temperature data. A total of 15 nodes for rainfall and 6 nodes for temperature data time series have been created based on the resolution of

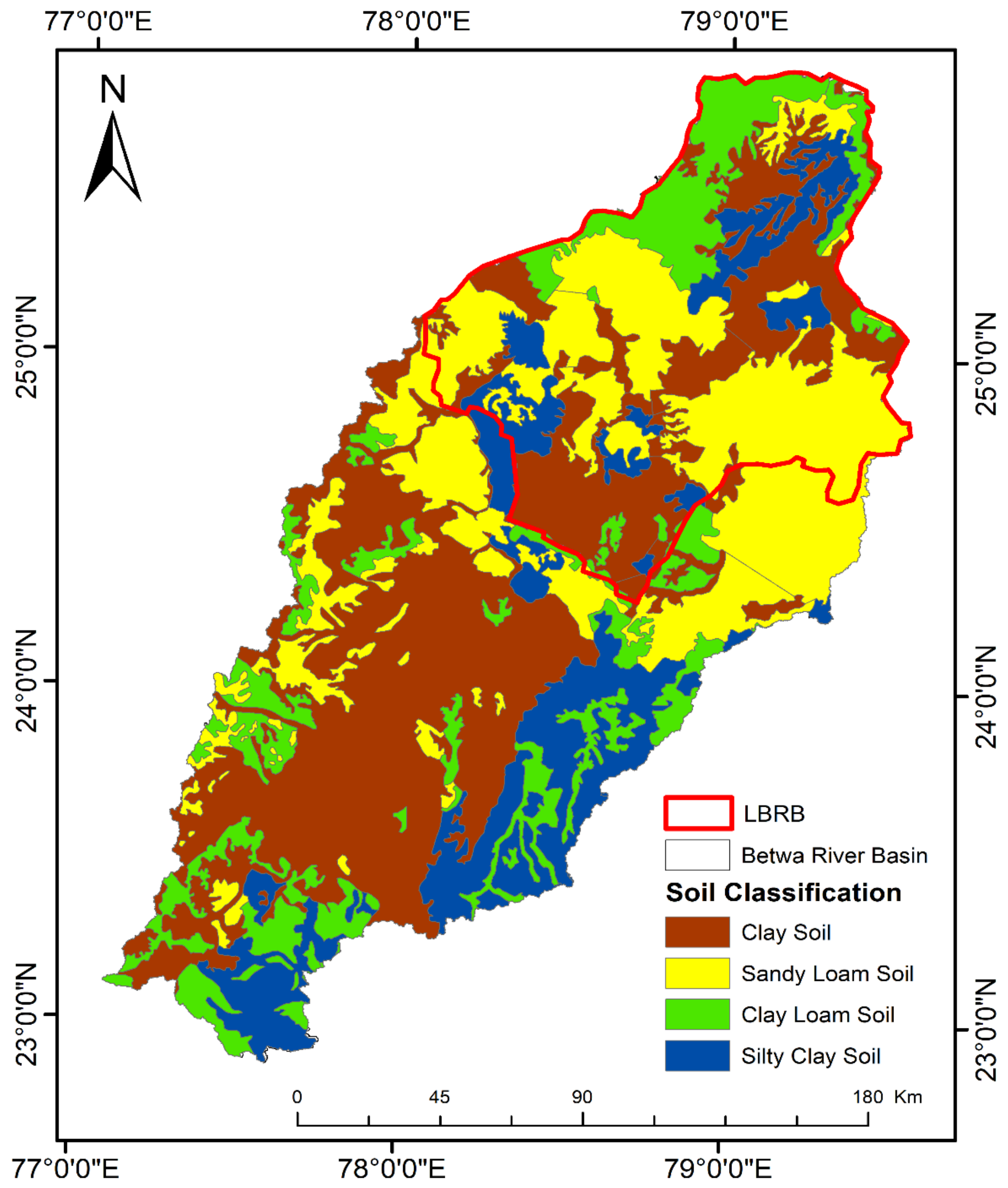


Figure 3.8 Soil Map of the BRB and the LBRB

the available 2D gridded data. Other weather parameters like wind speed, relative humidity, and solar radiation, estimated using long term statistics through weather generator (WXGEN) model, available in the SWAT India database (https://swat.tamu.edu/software/links/india-dataset).

Streamflow data

The monthly average streamflow data for 18 years (2003–2020) were collected from the Yamuna Basin Organization (YBO) of the Central Water Commission (CWC), Government of India. The data was corrected for missing values by linear interpolation. The data from two CWC gauging sites namely Mohana, and Basoda (**Figure 3.1**) and soft knowledge from previous studies were utilized for calibration and validation of the SWAT model.

3.3.1.2. SWAT model setup

The hydrological process in SWAT model represents different components of hydrological cycle like evapotranspiration, interception, surface runoff, soil percolation, lateral flow, and ground water flow. The basin is divided into subbasins based on threshold area and further divided into Hydrologic Response Unit (HRU) based on soil, slope, and land use maps. The hydrological cycle simulated by SWAT is based on the water balance equation:

$$SW_t = SW_o + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}\right) \quad (3.1)$$

Where, SW_t is the final soil water content (mm), SW_0 is the initial soil water content on day i (mm), t is the time (days), R_{day} is the amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm), and Q_{gw} is the amount of return flow on day i (mm) (Neitsch et al. 2002).

The ArcSWAT plugin for ArcMap 10.5 was employed to model the hydrological processes in the BRB. The digitised stream network for the BRB was burned into the DEM for accurate delineation in flat areas. The land use map was categorised according to SWAT land use types and soil look up tables were used to link SWAT code with different soil categories. Slope map was digitised into four classes viz. 0-3%, 3-5%, 5-10%, and >10%. The DEM-based delineation with a threshold of 1000 hectares was used to trace the smaller subbasins. The hydrological response units (HRUs) were generated based on the dominated land use, soil, and slope in the subbasins. A total of 27,654 HRUs in 2,228 subbasins were delineated with the given criteria. The model was simulated for 21 years with initial three-year as warmup period, to stabilize the model for initial conditions.

3.3.1.3. Sensitivity Analysis, Calibration and Validation

Sensitivity analysis was carried out in the BRB to identify the most sensitive parameters affecting the model output. Due to the large numbers of parameters involved in calibration of SWAT model, it was reduced to 10 parameters through thorough review of literature of other SWAT modelling studied in Indian rivers (George and James 2024; Kausher et al. 2024; Sabale et al. 2023; Desai et al. 2021; Suryavanshi et al. 2017). The sensitive parameters based on their ranks and the fitted parameters have been presented in **Table 3.1**. Based on the sensitivity analysis CN2, GW_REVAP, EPCO and SOL_AWC were identified as the most sensitive parameters for the entire BRB. CN2 is associated with the SCS (Soil Conservation Service) Curve Number method, which is used to estimate direct runoff from rainfall and adjusting CN2 can influence the amount of surface runoff generated in the model. It depends on land use, soil type, and antecedent soil moisture. GW_REVAP (Groundwater Revaporation Coefficient) controls the water movement from the shallow aquifer to the root zone, affecting evapotranspiration. EPCO (Plant Uptake Compensation Factor) determines how plants extract water from different soil layers, impacting plant water uptake and evapotranspiration. SOL_AWC (Available Water Capacity of the Soil Layer) refers to the amount of water that can be stored in the soil and affects soil moisture retention, influencing infiltration and plant water availability (Arnold et al. 2012). The minimum and maximum of the parameter values in **Table 3.1** represents the lower and upper bound of the 95 percent prediction uncertainty. The sampling method "Relative" represents the modification of the parameter value by multiplying with 1+r, where r is the fitted value. The "Replace" method represents that the values for all the HRUs have been replaced by the fitted values.

Table 3.1 SWAT Parameters and their calibrated values (mmH_2O represents the equivalent water depths)

Sensitivity Rank	**Parameter**	**SWAT Process**	**Minimum**	**Maximum**	**Fitted**	**Sampling Method**
1	Curve Number, *CN*	Runoff	-0.328	0.298	**0.007**	Relative
2	Groundwater "revap" coefficient, *GW_REVAP*	Ground water	0.134	0.200	**0.198**	Replace
3	Groundwater delay (days), *GW_DELAY*	Ground water	307.951	462.022	**365.214**	Replace
4	Plant uptake compensation factor, *EPCO*	Evaporation	0.648	0.760	**0.702**	Replace
5	Available water capacity of the soil layer, *SOL_AWC*(..)	Evaporation	0.830	1.108	**1.041**	Relative
6	Threshold depth of water in the shallow aquifer for return flow to occur (mmH2O), *GWQMN*	Ground water	1.318	1.796	**1.593**	Replace
7	Baseflow alpha factor (days), *ALPHA_BF*	Ground water	0.392	0.535	**0.432**	Replace
8	Soil evaporation compensation factor, *ESCO*	Evaporation	0.912	1.041	**0.948**	Replace
9	Threshold depth of water in the shallow aquifer for "revap" to occur (mmH2O), *REVAPMN*	Evaporation	0.0	1.856	**1.257**	Replace
10	Effective hydraulic conductivity in main channel, *CH_K2*	Routing	45.286	125.964	**111.039**	Replace

The SWAT-CUP tool with Sequential Uncertainty Fitting (SUFI-2) algorithm was used to calibrate and validate the model. SUFI-2 is a semi-automatic optimization technique that uses the Latin Hypercube sampling scheme which is a highly efficient and widely adopted sampling method for obtaining optimal results in Indian subbasins (Desai et al. 2021). The sensitive parameters were calibrated by maximising the Nash-Sutcliff efficiency (NSE) between observed and simulated discharge values (2003–2012) and the model was validated for the year 2013–2020. The R-squared efficiency (R2) and NSE have been used to evaluate statistics for calibrating and validating the SWAT Model (**Figure 3.9**).

In this study, four iterations with 1000 simulations in each was done. Consecutive values of new parameters were used in next iteration and the SWAT-CUP was run again for 1000 simulations. The step was repeated until the model performance was improved. The model was calibrated for the gauge discharges at two monitoring stations (Mohana and Basoda), provided by Central Water Commission (CWC), India. The supporting literature of Desai et al. (2021) and Suryavanshi et al. (2017) was used as soft data to frame the uncertainty range of the parameters. Given that p_i is the predicted/simulated value corresponding to the actual/observed value o_i , $\bar{o}_i$ is the actual/observed mean and $\bar{p}_i$ is the mean of predicted/simulated values, the R^2 and *NSE* has been calculated as (Krause et al., 2005).

$$R^2 = \left[\frac{\sum_{i=1}^{n}(o_i - \bar{o}_i)(p_i - \bar{p}_i)}{\sqrt{\sum_{i=1}^{n}(o_i - \bar{o}_i)^2}\sqrt{\sum_{i=1}^{n}(p_i - \bar{p})^2}} \right] \tag{3.2}$$

$$NSE = 1 - \frac{\sum_{i}^{n}(o_i - p_i)^2}{\sum_{i}^{n}(o - \bar{o}_i)^2} \tag{3.3}$$

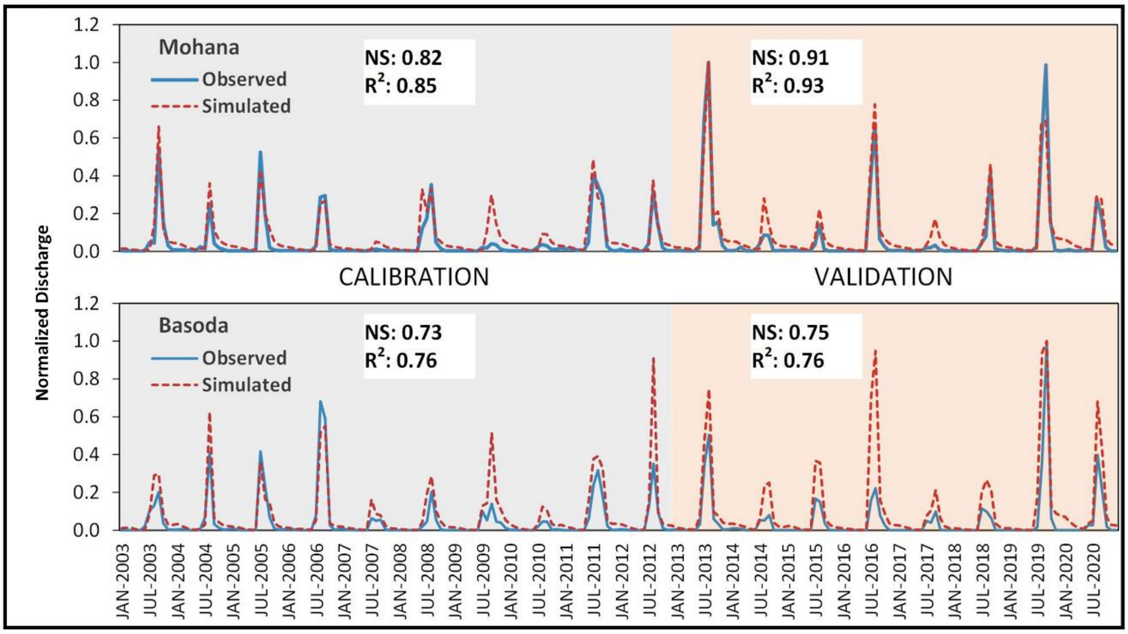


Figure 3.9 Model calibration and validation statistics for the two-gauge stations with normalised discharges.

3.3.2. Groundwater Model

In accordance with the groundwater modelling process described in the literature review section, after the initial determination of the modelling objectives, the conceptual model of the LBRB is developed inclusive of important boundary conditions. The conceptual model is then converted into numerical model using adept governing equations. Then the solving code is selected to solve the established equations. In this study, GMS 10.7 has been used with the MODFLOW-NWT code for modelling the groundwater behaviour and for PEST calibration of the model. The hydro-meteorological, hydrogeological, groundwater level and groundwater demand data obtained from different sources and presented in **Table 3.2.**

3.3.2.1. Conceptual Model

The conceptual model for the LBRB was based on the framework given by Anderson et al. (2015). The topographic and morphological information was retrieved from SRTM DEM data. Aquifer geometry was delineated based on 80 borewell exploration data

Table 3.2 Dataset used to set up the surface and groundwater flow model.

Parameter	Data (Resolution)	Source	Time Period
Topography	Digital elevation model (DEM) (90 m * 90 m)	Shuttle Radar Topography Mission (SRTM) https://earthexplorer.usgs.gov/	-
Land Use	Land use Map (30*30)	Landsat 7 https://earthexplorer.usgs.gov/	8th Oct, 2005
Soils	Digital Soil Map	National Bureau of Soil Survey and Land Use Planning (NBSSLUP)	-
Climate	Rainfall, temperature, relative humidity, wind speed, sunshine hours	IMD gridded data and NASA Power https://dsp.imdpune.gov.in/	Monthly (2003-2020)
Streamflow	Monthly gauge data	CWC, India	2003-2020
Aquifer Geometry	Bore well lithology	CGWB, Lucknow and NAQUIM Report https://shorturl.at/bc469	2017
Hydrogeology	Pumping test	CGWB, Lucknow and NAQUIM Report	2017
Observation Wells	Water level (bgl)	WRIS, India https://indiawris.gov.in/wris/#/groundWater	Quarterly (2003-2019)

and 11 VES survey points to generate a 3D stratigraphy model of four principle hydrogeological units, consisting of alluvium, weathered granite, fractured granite and massive granite (**Figure 3.10**). Hydrogeology was defined based on CGWB (2012) report on Principle Aquifer Systems India (2012) and refined using NAQUIM reports (CGWB 2017 a,b,c). The general groundwater flow is from southwest towards northeast direction with a gradient varying from 0.70 to 2.0 m/km (CGWB, 2017). The boundaries included a no-flow boundary towards the east, west and south based on the general assumption that the topographic highs on surface coincided with the groundwater divide below it (Sophocleous, 2002; Coelho et al. 2017; Jain et al. 2021). Specified Flow Boundary (SFB) was applied towards the south-east, west and north direction, estimated based on

groundwater contour data of wells. Spatiotemporal recharge and ET rates were determined at subbasin scales based on the SWAT model output (Karki et al. 2021). Streamflow data at model boundary was obtained from SWAT simulated outputs. Pumping data was generated using Consumptive Use method from GEC-2015 (CGWB 2017d). The study area was underlain by frequently occurring linear quartz reefs which restricted groundwater flow movement and was conceptualised using the Horizontal Flow Barrier (HFB) Package. The hydrogeological information of aquifers was obtained from National Project on Aquifer Management (NAQUIM) reports, where the transmissivity values ranged from 12.87 to 145 m^2/day and storativity values ranged from 2.8×10^{-4} to 1.57×10^{-3} (CGWB 2017 a,b,c).

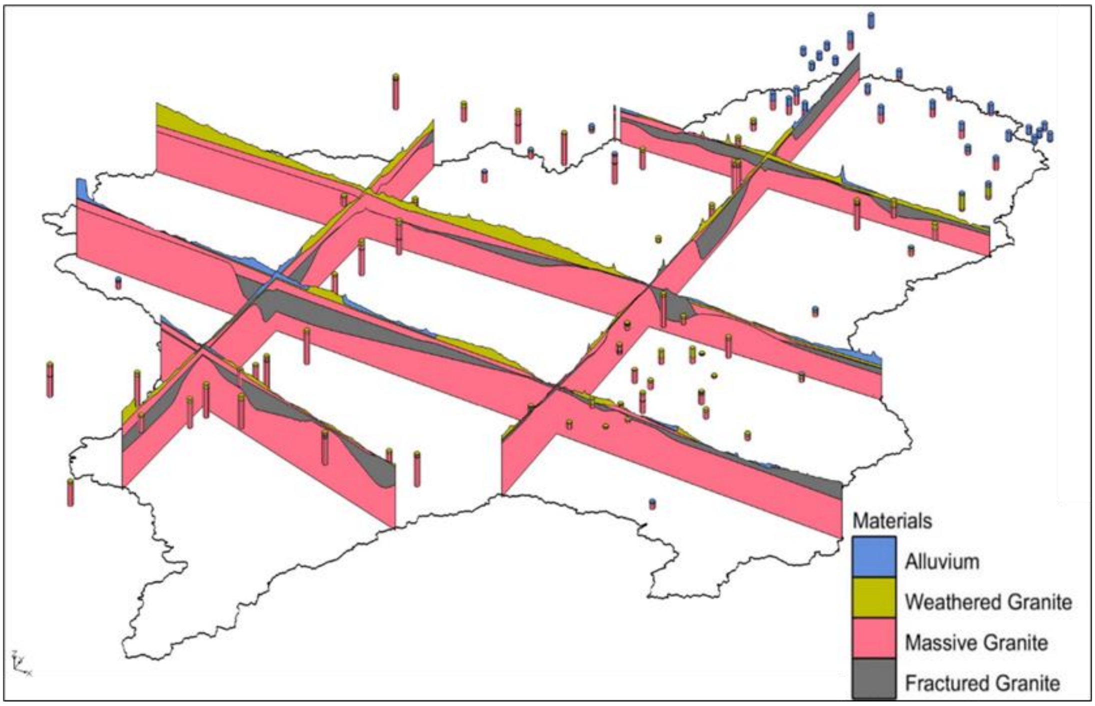


Figure 3.10 Hydrogeological fence diagram of the study area

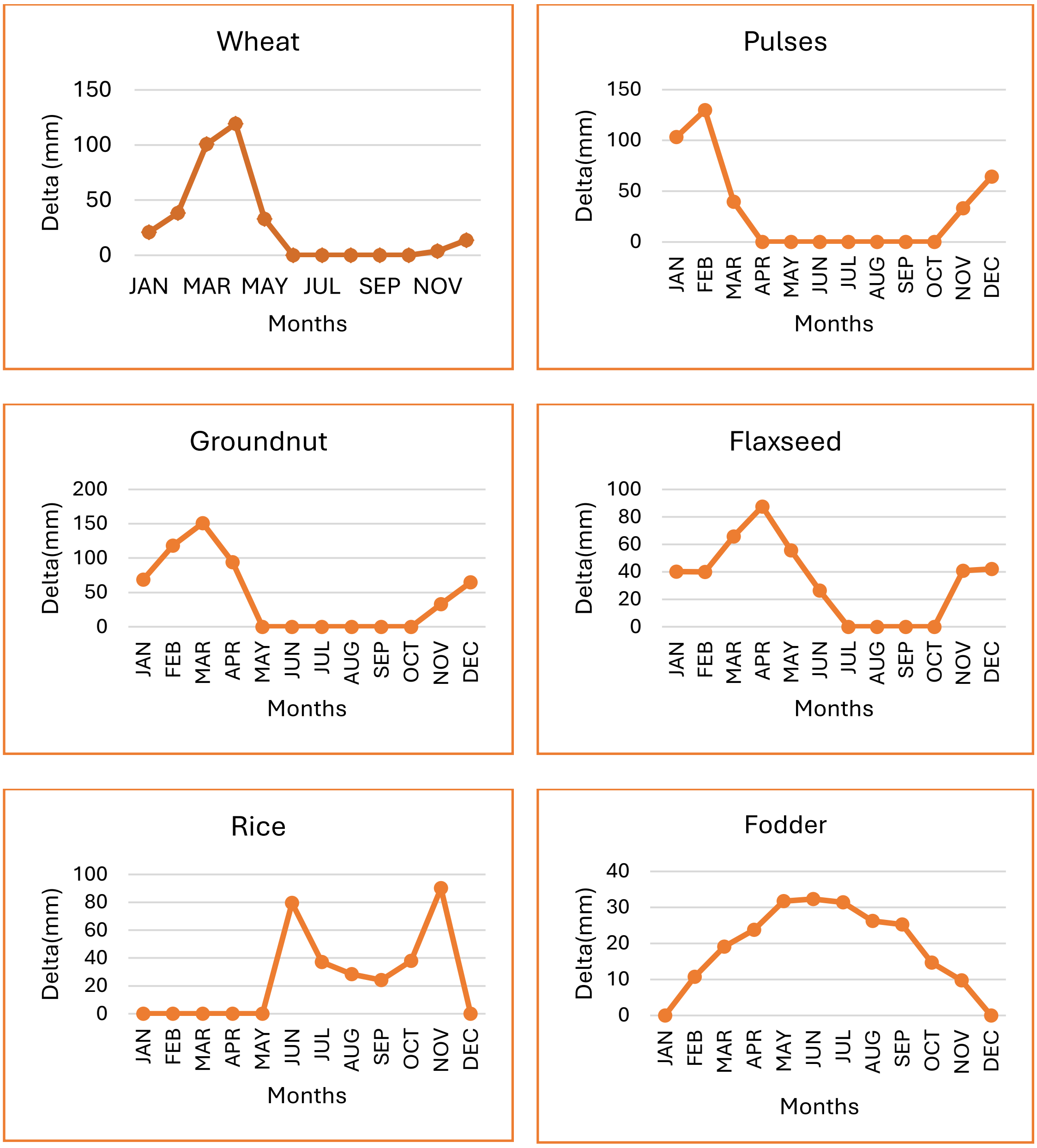
3.3.2.2. *Boundary Conditions*

Groundwater recharge is a very important boundary condition in the model input, as it has the greatest influence in the groundwater budget but is also a difficult parameter to estimate (Healy et al. 2007). Its spatiotemporal variations are influenced by many factors such as land use, vegetation, hydrogeological conditions, climate etc. (Healy et al. 2007; Karki et al. 2021). SWAT model has been successfully implemented in the past, to quantify surface hydrological components of water balance such as surface runoff, evapotranspiration, and groundwater contribution, among others (Chinnasamy et al. 2018; Desai et al. 2021; Karki et al. 2021). The calibrated and validated SWAT model was used to estimate the hydrological variables in the LBRB. The basin was divided into 182 sub-watersheds, 78 out of which were located inside the LBRB. The HRU based recharge estimates was averaged on each sub-watershed and incorporated into the MODFLOW model as specified flux using recharge (RCH) package (Anderson et al. 2015). Similarly, averaged evapotranspiration (ET) rates for each sub-watershed were incorporated into the MODFLOW model using the evapotranspiration (EVT) package with a constant extinction depth of 3 m, similar to Yao et al. (2015).

Groundwater pumpage in the study area was primarily for agriculture and domestic use, with inconsequential amounts for industries (CGWB 2017a, b, c). The domestic demand for water was estimated based on the Consumptive Use Method from GEC-2015 (CGWB 2017d) with per capita demand taken as 70 litres. A geometric increase of the population was considered with 1.2 % increase per year for calculating the water demand from 2003 to 2019. Agricultural demand was calculated based on the cropping pattern method (CGWB 2017d). A total of 10239.7 sq Km area was being cultivated out of which 42.41 % of area was irrigated. The study area had a total 2540 rural and 38 urban settlements with a total population of 46.65 lakhs as per 2011 census report. The draft for each well was estimated using **Eq. 3.4**, based on population and major crops grown in the area (**Figure 3.11**).

$$Q(m^3/d) = -\frac{\sum_{t=1}^{T}\sum_{i=1}^{n}(CF)_i(IR)_i}{30} \times \overline{I} \times CCA - 0.7 \times T_p \quad (3.4)$$

Where, $T_p = T_o\,[1+r/100]^t$, CF_i is the area with crop *i* per unit total cultivated area, *IRi* is the irrigation requirement of crop *i* (consumptive use of crop *i* – effective rainfall), *I* represents the coefficient for irrigation dependency on the groundwater (0.2 for study area), CCA is the cultural command area, *Tp* is the total population at time period *t*, To is the total population at *t=1* and *r* is the rate of population growth.



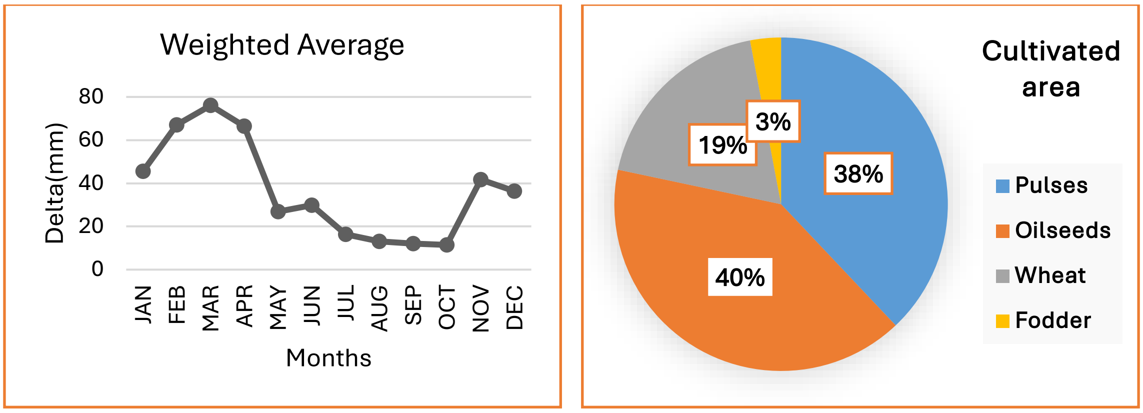


Figure 3.11 Irrigation Requirement of Major Crops

Streamflow in the basin was simulated using two MOFLOW packages: the major rivers (Betwa and Dhasan) were simulated using stream (STR) package and their tributaries using the drain (DRN) package. The river network was divided into segments, which was further divided into reach for each cell flux estimation (Q_R). The flux between river and aquifer was estimated based on riverbed conductance (C_R) and the difference between either river stage (h_R), simulated head (h) or river bottom (B_R), as given by:

$$Q_R = \begin{cases} C_R \,.\, (h_R - h), & if\ h > B_R \\ C_R . (h_R - B_R), & if\ h < B_R \end{cases} \tag{3.5}$$

The riverbed conductance was calculated using equation:

$$C_R = \frac{K \times W \times L}{T} \tag{3.6}$$

Where, K is the riverbed hydraulic conductivity, W is the channel width, L is the segment length and T is the riverbed thickness. Channel width and length data was obtained from CWC office, Jhansi and constant riverbed thickness 0.6 m was adopted. Riverbed conductivity value was adjusted during calibration of the model. For the DRN package bed conductance value was kept at 200 m^2/d/m to ensure sufficient removal of groundwater. The discharge rate Q_d from model cell to drains was calculated by-

$$Q_d = \begin{cases} C_d \,.\, (h - h_d), & if\ h > h_d \\ 0, & if\ h \leq h_d \end{cases} \tag{3.7}$$

3.3.2.3. Numerical Model

All process-based groundwater models are derived from principle of conservation of mass and Darcy's Law (Anderson et al. 2015). A 3D groundwater flow model was prepared based on the conceptual model using MODFLOW-NWT defined by following equation (Harbaugh, 2005):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)=S_s\frac{\partial h}{\partial t}-W \quad (3.8)$$

Where, K_{xx}, K_{yy} and K_{zz} are the hydraulic conductivity (K) of the aquifer in all three directions (x, y and z) (LT^{-1}), W is the volumetric flux (flow) per unit volume (T^{-1}) representing sources and sinks, h is the potentiometric head (L), t is time (T) and S_s is the specific storage of aquifer's porous material (L^{-1}). The code was selected to resolve the problem of drying and rewetting nonlinearities of cells in unconfined aquifers (Sisay et al. 2023).

3.3.2.4. Model Discretization and Simulation

All the relevant data was processed in a GIS environment and MODFLOW-NWT (Niswonger et al. 2011) model was employed to simulate 3D groundwater flow through the system. The LBRB aquifer system was conceptualised as a two-layered system, with the alluvium, weathered zones and outcrops forming the top layer underlain by weathered and fractured rocks. For the fractured second layer, the network of fractures was represented through the concept of equivalent porous medium (EPM) (Anderson et al. 2015).

A uniform grid size of 1000 m × 1000 m was generated with a slight tilt of 45º to match the groundwater flow direction in the study area. The grid size was based on the computational efficiency and maintaining the calibration accuracy of the model. A transient model with quarterly stress period was run for 17-year period (Jan 2003 - Jan 2020). Model sources and sinks were transferred using different MODFLOW packages, consisting of recharge (RCH), ET (EVT), rivers using stream (STR) package and tributaries using drain (DRN) package. Initial values of hydraulic conductivity, specific yield and storage obtained from NAQUIM reports was adjusted during the model calibration.

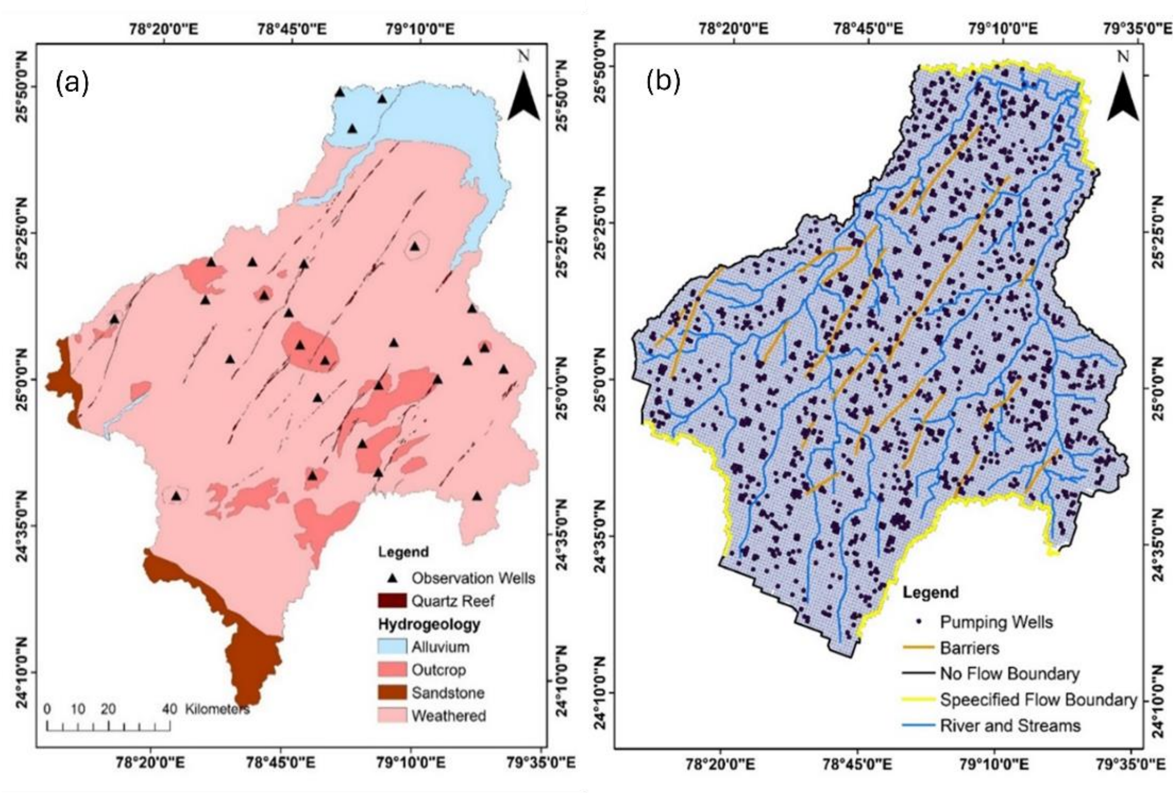


Figure 3.12 a) Hydrogeological map of LBRB. b) Conceptual model of study area

3.3.2.5. Model Calibration

The goodness of fit of model results at any location and time can be quantified by the difference between the observed value and simulated results. From the available data observation wells present in the study area, quarterly groundwater well level data for only 27 wells were available for 2003-2019 period, acquired from the India-WRIS (Water Resources Information System), Dept. of Water Resources, RD & GR, Ministry of Jal Shakti, Govt. of India (GOI). The starting head for the model input was determined based on the groundwater level map prepared for January 2003 well level data (WRIS). Model calibration in this study was done in two phases: an initial calibration using manual trial and error, followed by parameter estimation using inverse modelling code Parameter ESTimation (PEST). With first four stress period being considered for model warm up, 1755 groundwater observations from 27 wells for remaining 65 stress periods were used to calibrate the model using **Eq. 3.9.** Where, Φ (phi) is the minimizing function of the difference between observed (h_{obs}) and simulated (h_{sim}) head.

$$\Phi = \sum_i^n \min (h_{obs} - h_{sim}) \tag{3.9}$$

Initial manual calibration involved the adjustment of K, Ss, and streambed conductance for the STR and DRN package. The simulated recharge and discharge (through pumping wells) rates were corroborated with the NAQUIM reports (CGWB 2017a, b, c). After the initial process, K and Ss parameter was chosen for automated calibration. PEST is a widely supported tool for parameterised model calibration (Doherty and Hunt 2010). Tikhonov regularization was used to provide PEST with sufficient information to obtain an inverse solution. Broad range of K and Ss values obtained from pumping test reports of CGWB, Lucknow and NAQUIM reports was used to constrain the parameter estimation process while avoiding unrealistic parameter distributions. Further, Truncated Singular Value Decomposition (SVD) with parallel PEST was used to reduce the time necessary to complete optimization process.

Mean Error (ME) i.e. mean of residual errors, Mean Absolute Error (MAE), Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE) (**Eq. 3.10** – **3.12**) was employed to evaluate model performance for simulating groundwater heads. Comparison of 1755 groundwater level observations to the corresponding simulated values using scatter plots exhibited a close match (**Figure 3.13**). However, upon closer examination, it was observed that the lower head values (< 190 m) in the northern region of study area, had relatively poor correlation with observed heads (0.772).

$$ME = \frac{\sum_i^n (o_i - p_i)}{n} \tag{3.10}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|(o_i - p_i)| \quad (3.11)$$

$$RMS = \sqrt{\frac{\sum_i^n (o_i - p_i)^2}{n}} \quad (3.12)$$

The poor correlation between simulated and observed values could be due to the location of the well points near the model boundary. The middle (191-300 m) and higher (> 301 m) head ranges had a better R^2 of 0.984 and 0.956 respectively, and the model adequately simulated groundwater head, both spatially and temporally. The values of ME, MAE, RMSE and MAPE obtained was 1.93, 3.54, 4.28 and 1.45% and respectively. Although there are no uniform calibration standards for groundwater models (Anderson et al. 2015), yet RMSE values of less than 5 or 10% of target head range was found to be acceptable (Anderson et al., 2015; Chinnasamy et al. 2018).

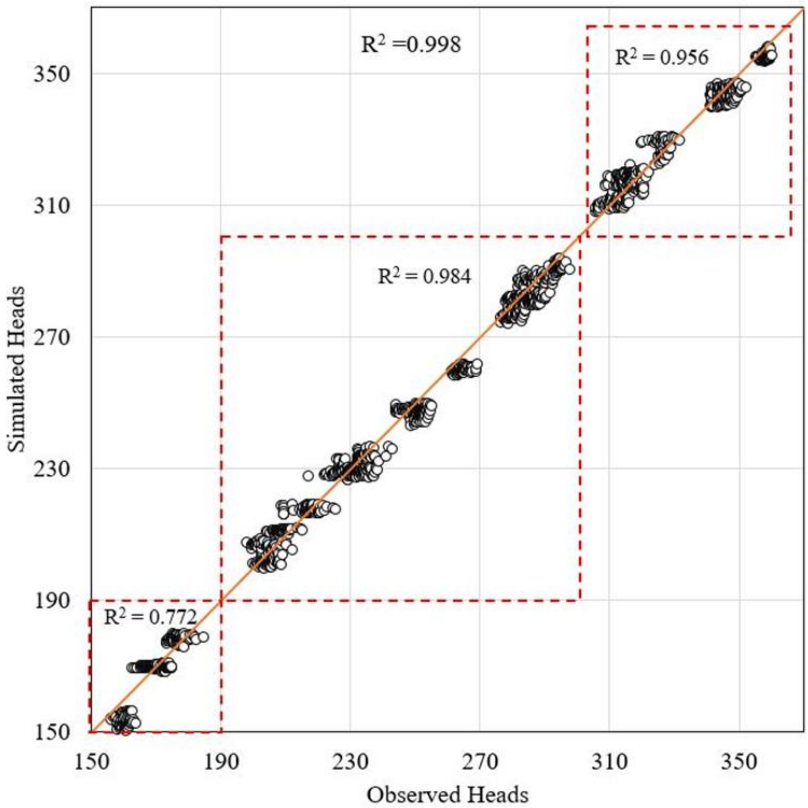


Figure 3.13 Comparison between simulated and observed groundwater levels for total simulation period. (red dotted box indicate the specific R^2 of points occurring inside the box)

Scatter plot analysis of the residual heads revealed that 37% of residuals was under ±2 meters, 47% was between ±2 - ±5 meters and 16% was over ± 5 meters (Fig. 6). Over 84% of the residuals were under ±5 meters, indicating a satisfactory correlation between observed and simulated head for regional models.

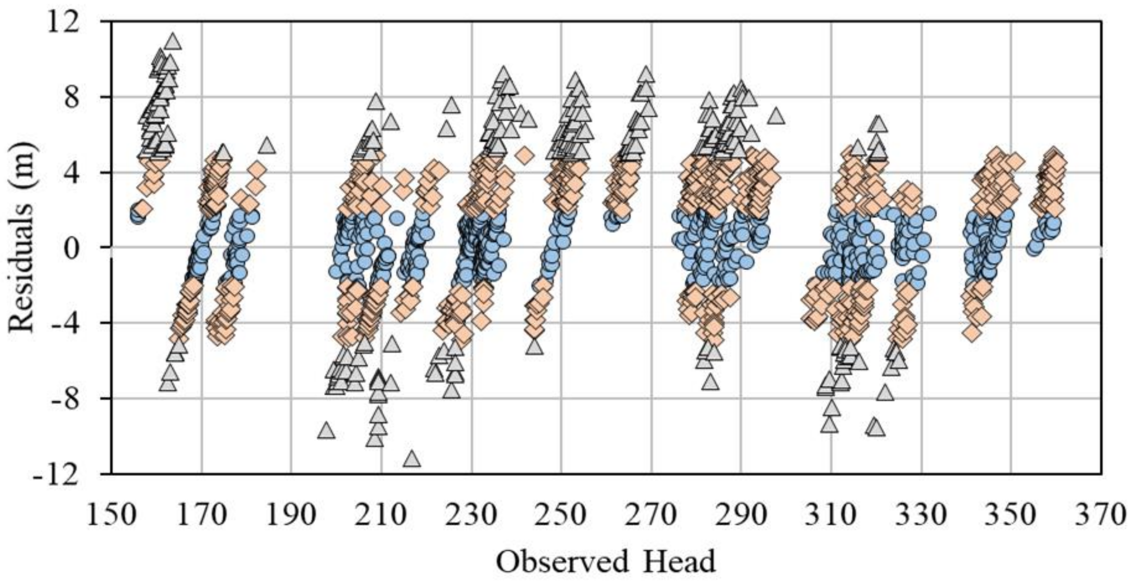


Figure 3.14 Groundwater head residuals of well observations with < ±2 m; ±2 - ±5 and > ±5 m range distribution.

3.3.3. Results

The average curve number of the basin based on different combination of land use and soil was found to be 81.56. The average annual water balance in the BRB is given in **Figure 3.15** in mm/year. The average annual precipitation was estimated at 973 mm and 56% of it was removed through evapotranspiration. Surface runoff was estimated at 221 mm/year and the groundwater percolation including re-evaporation and lateral flow stood at 208 mm/year. In comparison to the previous studies in the basin, the average annual precipitation had both, increased from 878 mm/y during 2000 – 2011 period (Desai et al. 2021) and decreased from 1123 mm/y during 1976 – 2011 period (Suryavanshi et al. 2017). ET had reduced from 61% in 2000 - 2011 to 56% in 2003 - 2020 but was higher than 50%

in 1976-2011 period. The loss of forest cover in the region can be responsible for the decrease in ET rates in the region (Kumar et al. 2023).

Comparison of the observed and simulated values of streamflow at Mohana and Basoda gauging stations indicated the model's ability to capture monthly flows very well. The model performance during the calibration phase was very good for Mohana station with NSE and R^2 values of 0.82 and 0.85 (Parajuli 2010; Desai et al. 2021). Whereas it was good with 0.73 and 0.76 NSE and R^2 values, in the case of Basoda station where the model overestimated some peak streamflow (**Figure 3.9**). In the validation phase, 0.91 NSE and 0.93 R^2 values indicated that the SWAT model captured monthly flows very well at Mohana, however it was lower for Basoda station, as the model simulated low values better than peak values of streamflow (**Figure 3.9**).

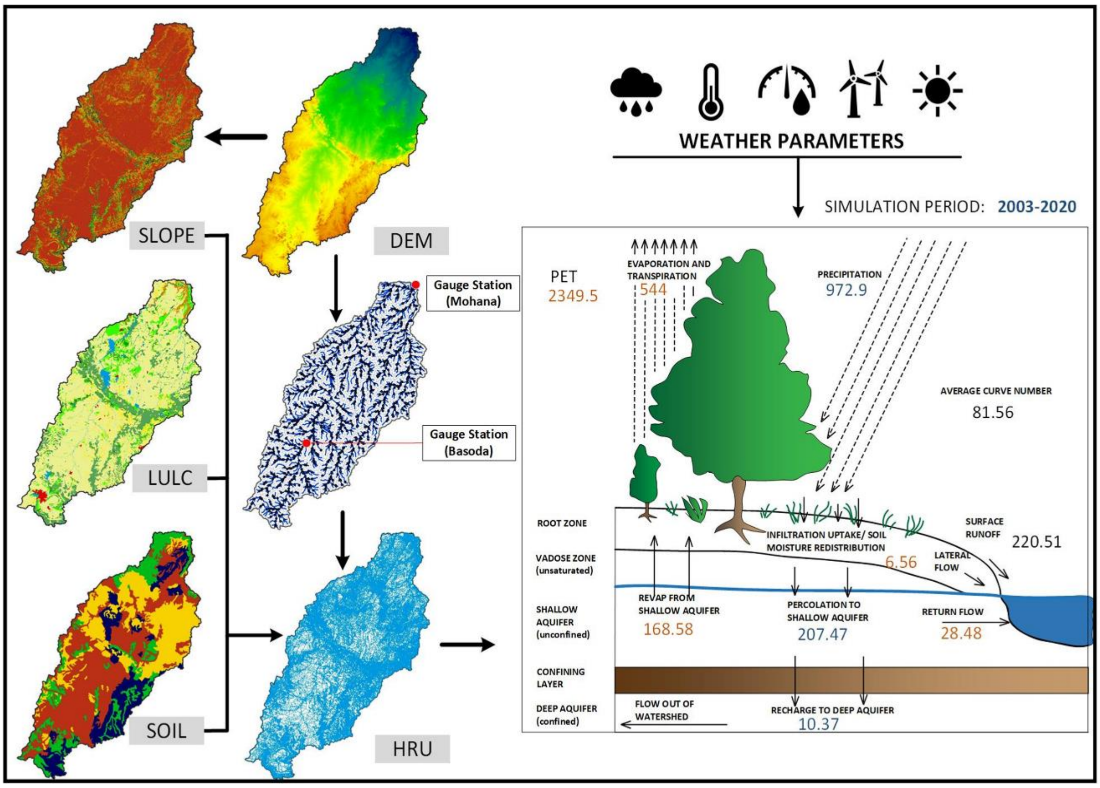


Figure 3.15 SWAT Model setup with annual average results (mm/year) for the period 2003-2020.

The overall thickness of the LBRB aquifers varied from 4 to 101 meters. The first unconfined layer thickness was 4 to 61 m while the second fractured layer thickness varied from zero where it was non-existent to 40 meters. The hydraulic conductivity (K) values varied from as low as 0.015 m/d in hard outcrops to 18 m/d in the alluvium aquifers. Specific yield (Sy) values ranged between 0.8% in fractured media to 12% in alluvial soil and the specific storage (Ss) in the second layer was 1.57×10^{-3}-4.7×10^{-4} /m. Vertical anisotropy or the ratio of horizontal conductivity to vertical conductivity was maintained at three. The fitted aquifer properties after calibration are given in **Table 3.3.**

Table 3.3 Fitted aquifer properties after calibration.

Layer	Thick-ness (m)	Aquifer Type	Hydrogeo logical setting	K (m/d)	Sy (%)	Ss (m^{-1})	Vertical anisotropy (Kh/Kv)
Layer 1	4-61	Un-confined	Alluvium Weathered Outcrop	15-18 1.5-12.5 0.015-11.4	12 1.5-4 1.5-2	-	3
Layer 2	0-40	convertible	Fractured	1.5-4.5	0.8	1.57×10^{-3}- 4.7×10^{-4}	3

3.3.4. Summary

The hydrological properties of the BRB was effectively simulated from 2003 to 2020 using the SWAT model. The popular SUFI 2 algorithm in SWAT CUP was employed for calibration, sensitivity, and uncertainty analysis. The sensitivity analysis revealed that CN2, GW_REVAP, GW_DELAY, EPCO, SOL_AWC, and GWQMN were some of the most sensitive parameters in the BRB. The model performed relatively better during the validation period than the calibration period.

The groundwater dynamics in the LBRB was modelled using MODFLOW–NWT in GMS 10.7. Open online datasets, along with historical observations and literature review were used to conceptualize the complex hydrogeological settings and to describe the groundwater fluxes in unconfined and convertible aquifers of the LBRB region. Two-step calibration process involved the initial manual calibration followed by automated calibration using PEST code. Scatter plot results between observed and simulated head revealed that the model achieved better calibration results in the central and southern region of the LBRB. Overall, the developed model satisfactorily simulated the groundwater behaviour in the LBRB and was ready for flow budget analysis which is discussed in next chapter.