CHAPTER 5
QUANTIFICATION OF MAR SOURCE WATER AND SAFE RECHARGE CAPACITY

5.1. MAR Source Water Quantification

Identification and quantification of the source of surplus water for recharge is the second step of the proposed MAR framework. The most common types of source water for MAR were surface water (river and lakes), stormwater, wastewater, and groundwater (Alam et al. 2020). After river and lakes, stormwater was the second most common source of recharge water for MAR (Alam et al. 2020). In regions with satisfactory rainfall, the excess floodwaters can be a diverted into aquifers for storage (Chinnasamy et al. 2018; Okofo and Martienssen, 2022). In arid and hyper arid regions desalinated or highly treated wastewater can become the alternate source of artificial recharge to restore groundwater levels (Hassan et al. 2021; Khalil et al. 2022) or to mitigate salinity in coastal aquifers (El-Rawy et al. 2019). In case of the LBRB, the region experienced declining annual average rainfall trend with short periods of intense rainfall. High intensity rainfall caused erosion of topsoil and movement of water out of the basin. This excess surface runoff can be captured and recharged into aquifers for later use and is the identified source of water for MAR in the LBRB. It is presumed that the runoff generated is clean and can be safely injected into the ground. Surplus water can be defined as the excess available water after deducting the committed supply for each state (CGWB, 2021). In this thesis, surface runoff estimated using SWAT model was employed to determine the available surplus water at subbasin scale in the LBRB.

5.1.1. Methodology

Available Surplus Runoff

Surplus water for recharge is defined as the excess available water after deducting the committed supply for each state (CGWB, 2021). In this study, the availability of surplus runoff for artificial recharge has been considered at a monthly resolution of 75% dependability for each subbasin. The flow rates greater than 75% dependable flow have the probability to exceed only 25% times during the analysis period (Reddy, 2005). The higher value of dependable flow was purposefully chosen to avoid conflict in water demand and to restrict exceedance probability to only the monsoon season of July to September. The monthly simulated runoff (SURQ_CNTmm) of the SWAT model (2003-2020) has been utilised to generate the surplus runoff of each subbasin.

The flow-duration curve is a cumulative frequency curve that indicates the percent of time specified discharges were equalled or exceeded during a given period (Searcy, 1959). The monthly surface runoff in each subbasin from 2003 to 2020 was arranged in chronological order from largest to the smallest value. The ranks have been assigned to each runoff value such that the highest rate gets first, and the lowest rate gets the last rank. The probability of exceedance (P) is then calculated as.

$$P_i = 100 \times \left[\frac{M_i}{n + 1}\right] \tag{5.1}$$

Where M_i is the rank of i^{th} runoff rate and n is the total number of runoff rates. The runoff rates corresponding to the 25% percentile exceedance probability has been taken as the 75% dependable flow. The flow duration curve for all the subbasins has been plotted in **Figure 5.1A**. The flow duration curve at 25% exceedance limit has been taken as the threshold discharge rate of each subbasin. The distribution of subbasins w.r.t the 75% dependable flow is represented in **Figure 5.1B** and its spatial distribution in the basin is given in **Figure 5.1C**. It is presumed that the runoff generated is clean and can be safely injected into the ground and the head in the well and in the MODFLOW grid is same (i.e. no head loss due to skin or wellbore storage).

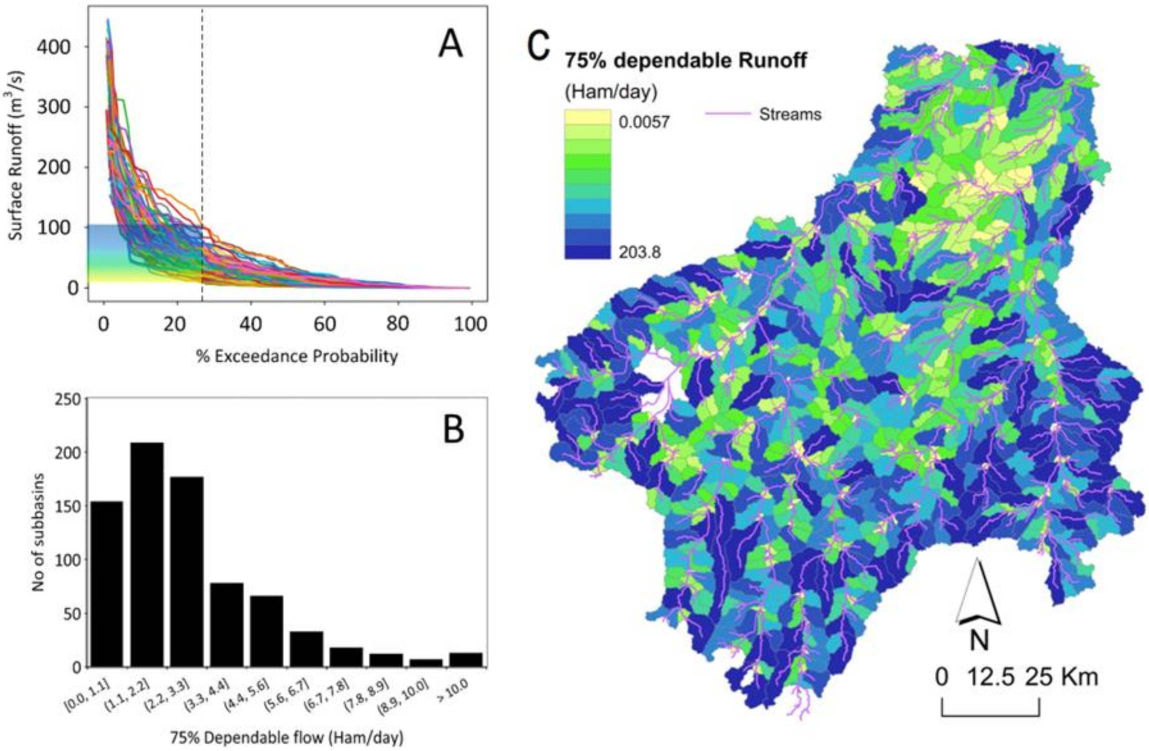

Figure 5.1 A. The flow duration curve of all subbasins with 25% exceedance probability represented by the dotted line. **B.** The histogram representing the number of subbasins corresponding to 75% dependable flow. **C.** Subbasin-wise threshold values of runoff at 75% dependable flow.

5.1.2. Results and Discussion

Surface water hydrology and available surplus runoff

Rainfall as precipitation and the evapotranspiration variations are the main hydrological flux that drive the water budget in arid and semi-arid regions (Gaur et al. 2023; Gazal and Eslamian 2022; Neves et al. 2020). Rainfall in the BRB was unevenly distributed and erratic (Desai et al., 2021). The average annual rainfall in the LBRB for the 17-year study period was 973 mm and showed an increasing trend of 12.3 mm/year. While the frequency of high rainfall years was decreasing, the rainfall intensity showed an average increase of 1.1 mm/year (Kumar et al. 2024). The overland flow in the LBRB decreases towards the downstream of the Betwa River as the basin shows mature denudation stage (Singh and Singh, 2022) resulting in high runoff and lower percolation of rainwater. The LBRB received 90% of its annual rainfall during the monsoon period which resulted in 97% of its total runoff (Suryavanshi et al. 2017). Most of the precipitation was lost as evapotranspiration (56%) and the rest as surface runoff (23%) and groundwater percolation (21%). The percolated groundwater contributed to shallow aquifer recharge, baseflow and plant transpiration and 5% of it recharged deep aquifers.

The annual water footprint of the whole Betwa River Basin, considering the agricultural, livestock, domestic and industrial sectors was estimated at 9186 Mm^3 (or 213.03 mm per km^2) (Mali et al. 2019). The annual water demand in the LBRB, based on three major districts of Jhansi, Lalitpur and Tikamgarh in 2020 was around 1.165 Mm^3 (CGWB, 2021) or 76.8 mm/km^2. It was observed that the northeast region and few areas in the west of the LBRB had a lower groundwater recharge rates than 76.8 mm, indicating a dearth in the available amount of recharge water in the area (**Figure 5.2**). The east and the west zones had large values of surface runoff and the average groundwater recharge rates was about 85-351 ($mm/year/km^2$). These subbasins were currently self-sufficient for the requisite groundwater demand. However, the region represented with yellow and light green colour (Upper and some of the middle part) has found to have less groundwater recharge than the required groundwater demand. The generated surface runoff was insufficient for the groundwater requirement in these regions, even if all the surplus runoff was recharged into the aquifers. In these areas, inter-subbasin transfer from the upstream subbasins, with high runoff potential could redeem the groundwater requirements.

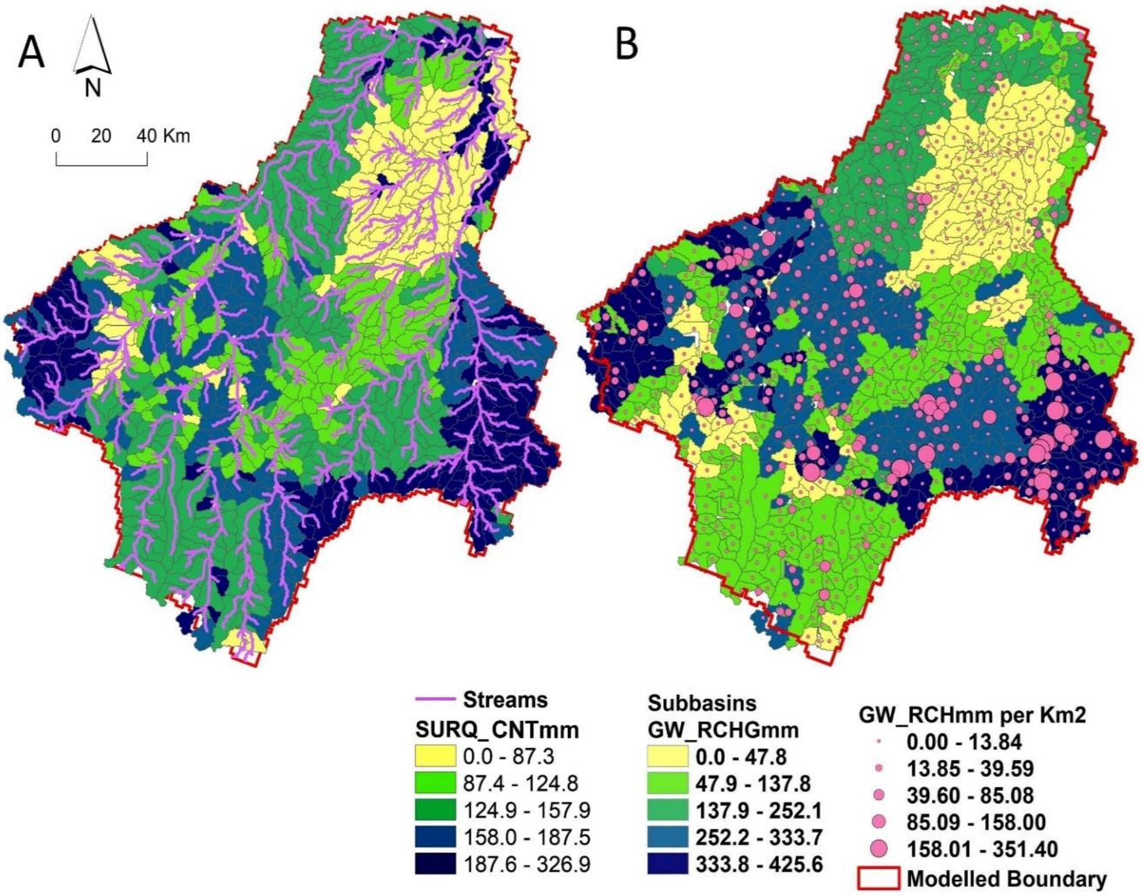

Figure 5.2 A. Spatial Distribution of average surface runoff (SURQ_CNT) and **B.** total groundwater recharge (GW_RCH) in mm/year during the 17 years (2003-2020). The groundwater recharge per unit area of the subbasin has been denoted with bubble plots.

Spatial distribution of the available surplus water for each subbasin (**Figure 5.1C**) showed variability in runoff generated over the LBRB, with over 85% of the subbasins having surplus runoff over 182.5 Ham/year (**Figure 5.1B**). The lower infiltration rate in the BRB due to local geological factors such as rugged terrain, dissected topography, and underlain rock formations, resulted in higher runoff to streams (Singh and Singh, 2022). Surplus runoff in the north-eastern part was comparatively lower than the rest of LBRB and attributed to poor average rainfall received in the area. The resultant groundwater recharge was also low (**Figure 5.4**) and influenced by hydrogeomorphology of the region where short length of overland flows resulted in high runoff velocities (Singh and Singh, 2022). High intensity rainfall events cause floods in the downstream of the Betwa river, and water is lost from the basin, which necessitates the dire need for the conservation of the surface runoff for later use during non-monsoon season (Suryavanshi et al. 2017).

5.2. Safe Aquifer Recharge Capacity

The third step of the proposed framework is quantification of the safe storage capacities of the LBRB aquifer. In case of unconfined aquifers, it is important to determine safe recharge capacities in aquifers to prevent soil salinity or water logging (Dillon et al. 2014; CGWB 2021). In India, the "Master Plan for Artificial Recharge to Groundwater India 2020" states that the space available up to 3 m to 5 m below ground level, depending upon criteria adopted in different states, can be used as the available space for groundwater storage. Only few reported studies have investigated injection capacities in case of unconfined aquifers (Shandilya et al., 2022a). Field studies have been conducted to determine recharging capacity in unconfined aquifers (Dwivedi et al. 2015) or pilot studies to study performance of recharge wells (Alam et al. 2020) or to identify the impact of injection well intervals on injection rates (Choi and Kim, 2023). Mathias and Moutsopoulos (2016) presented approximated solutions for water injection in unconfined aquifers with unsteady flow using Forchheimer's equation. Gibson et al. (2018) applied Theis (1935) and Copper-Jacob (1946) approximation to ASR wells to find suitability or aquifer response to recharge, but the type of aquifer was not mentioned. Shandilya et al. (2022a) worked out aquifer-scale injection capacity map in confined and unconfined aquifers by applying Theis (1935) solution for infinite confined homogenous aquifer with constant rate of injection. Dupuit (1857) presented the steady state solution for pumping well in confined aquifers and the first transient solution for well in confined aquifer was derived by Theis (1935). The first analytical solution of a pumping well in unconfined aquifer is presented by (Neuman, 1972), which was further improved to include the wellbore storage and skin effect (Moench, 1997).

In this thesis, a novel methodology to derive the Permissible Aquifer Recharge Capacity (PARC) in unconfined aquifers was developed and evaluated for the LBRB aquifers. Neuman's (1972) analytical solutions for recharge capacity in unconfined aquifers have been used to develop a linear regression model between the recharge rate and the corresponding change in groundwater head levels. The main objective of this step is to determine the PARC values of the LBRB at subbasin scale, based on linear regression model derived from numerical groundwater flow model. Studies at such subbasin scale can be effective in providing satisfactory information in case of heterogeneous weathered aquifers and can augment the field problem of determining recharge capacity in aquifers aiding as a decision-making tool in artificial recharge projects.

5.2.1. Methodology

5.2.1.1. Linear Regression Model

In this study, PARC was estimated using a linear regression model developed between the injection rate and the groundwater head (**Figure 5.3A**). Regression models are widely used in research to reduce the computational burden of 3D groundwater flow models with reasonable accuracy (Vermeulen et al. 2004; Winton et al. 2011). The analytical solution for pumping wells in unconfined aquifers (Neuman, 1972) was used as a base to derive a linear relationship in determination of the head generated in the MODFLOW grid in response to a given recharge rate. As per Neuman (1972), the head (*h*) for a fully penetrated well in an unconfined aquifer situated at radial distance r from the pumping well at time t for a given pumping rate (*Q*) is given as.

$$h = h_0 - \frac{Q}{4\pi K_r h_0} . W(u_a, u_y, \beta) \tag{5.2}$$

such that,

$$u_a = \frac{r^2 S}{4K_r h_0 t}, \; u_y = \frac{r^2 S_y}{4K_r h_0 t} \text{ and } \beta = \frac{r^2 K_z}{h_0^2 K_r}$$

Where, h_0 is the initial groundwater head, r is the radial distance of observation from the well, S is the storage coefficient (considering aquifer as confined), Sy is the specific yield, β is a non-dimensional parameter for delayed yield, K_z and K_r are the vertical and radial hydraulic conductivities.

The well function (W) becomes constant for a given r = radius of well and time. For a constant well function head developed in the modelled grid correlates linearly to the recharge/discharge rate (Holländer et al., 2009). The correlation between the head developed in the MODFLOW grid and the injection rate has been established with linear regression as follows.

$$h_{i,t} = Q_i \alpha_i + \epsilon_i \qquad (5.3)$$

Where, h is the vector of simulated heads for injection duration of t, Q is the vector of injection rates, α is the vector of regression coefficients (slope and intercept) and ϵ is the error term. The subscript i represents the cell id. The transient head array for the selected cell and known injection rates (500, 1000, 2000, 4000, 8000, and 16000 m^3/day) was generated. **Eq. 5.3** was then trained with the simulated data for the grid cell and injection duration to get a model that determines the aquifer response to the injection. The trained model has been tested for the accuracy using co-efficient of determination (R^2) before the calculation of PARC values.

PARC was estimated using the **Eq. 5.3**. The value of recharge rate for a given duration of injection is equal to PARC if the maximum of the transient head vector during the injection becomes equal to the permissible head. For a given cell in the subbasin, the heads are simulated for different values of injection. Using this simulated data, the regression model is trained for the given duration of injection to map the aquifer response to the injection at each cell within the subbasin. The PARC for the given duration (*t=T*) is calculated with the trained model of the same duration, determining the injection rate corresponding to permissible head (H_{per}) at cell i (**Eq. 5.4**).

$$PARC_{t=T} = \frac{(h_{per_i} - \epsilon_i)}{\alpha_i} \quad (5.4)$$

This helps reduce the computational burden of repeated simulations of groundwater flow model to calculate the transient recharge rate corresponding to the permissible head, which could be time consuming if calculated with any optimisation method.

5.2.1.2. Permissible Aquifer Recharge Capacity (PARC)

The capacity of an aquifer to store injected water broadly depends on the aquifer parameters such as storage co-efficient and transmissivity (Rushton and Srivastava, 1988; Händel et al., 2014; Khadri and Moharir, 2016). The spatial heterogeneity of these parameters' manifest variability in the storage capacity of aquifer formations (Hugman et al., 2012). According to Shandilya et al. (2022a), the maximum volume of water that can be injected or extracted within the permitted head change limit is the aquifer's pumping capacity for a given set of operational parameters (duration and well characteristic) (Schiff, 1964). The analytical solution presented by Shandilya et al. (2022a) had limited application as it only described the solution for the conditions without any external sources and sinks. In the real world, the height of the groundwater head generated due to an injection well is influenced by adjacent pumping wells or other recharge sources, which makes the calculation of maximum recharge rate challenging.

In unconfined aquifers, the major risk associated with injection was water logging or flooding near the well (CGWB, 2021; Shandilya et al. 2022a). The PARC of any region is defined as the steady rate of recharge with which if an aquifer is injected continuously, will yield a rise in the groundwater level equal to the permissible groundwater table (GWT) below the land surface for a given injection duration (**Figure 5.3B**). The duration is an important parameter since an aquifer can accommodate infinite amount of water when injected for infinite time at a suitable recharge rate (Shandilya et al. 2022c). The permissible head depth can be determined based on land use and land cover patterns of the injection well location (Shandilya et al. 2022a). In India, the recommended head is 3 to 5 m below ground level depending on criteria adopted in different states (CGWB, 2021). The permissible head (H_{per}) was taken as 3m below ground level in this study.

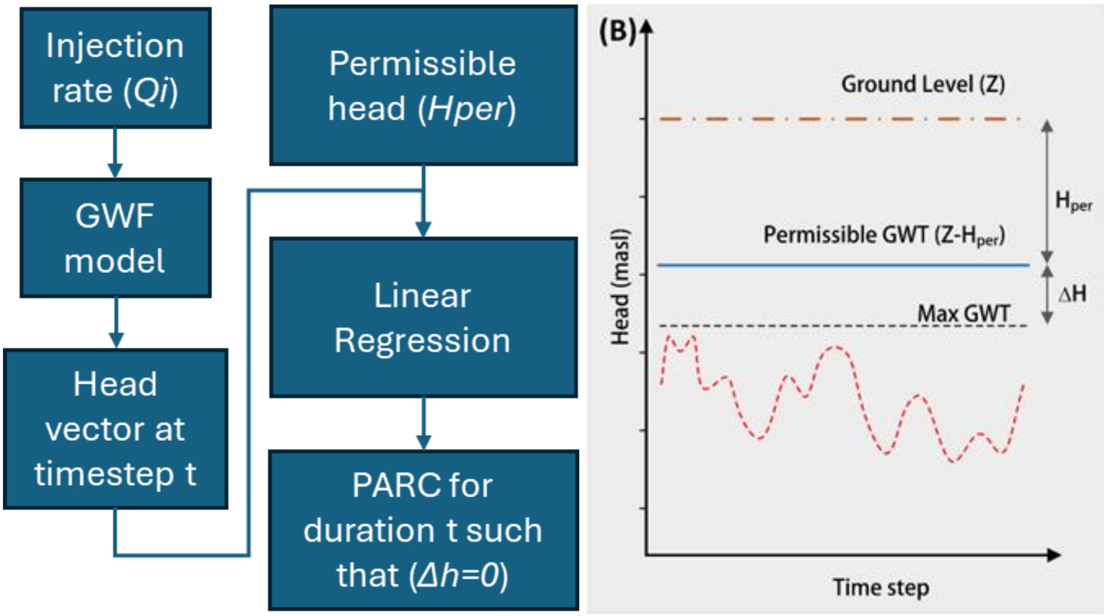

Figure 5.3 A. Methodology Flowchart **B.** Diagrammatic illustration of PARC (Q_i is the injection rate through MAR; H_{per} is permissible head)

5.2.2. Results and Discussion

5.2.2.1. Linear Regression Model

To reduce the computational burden of simulation model for the iterative process to find PARC, the aquifer response to MAR was mapped by the developed linear regression model. The model for the given duration of injection was trained for each grid cell in the groundwater model to ensures the spatiotemporal variability of the aquifer response (Wu et al., 2023). The reduction of the groundwater model to a low dimension has been derived from the concept of Reduced Order Model (Vermeulen et al. 2004; Winton et al. 2011). The traditional approach involved use of sophisticated surrogate modelling approaches such as Proper Orthogonal Decomposition (McPhee and Yeh, 2008), Support Vector Machines or Artificial Neural Networks (Gosses and Wöhling, 2019) to reduce the groundwater model dimensionality. The model for each gird cell has been reduced to two-dimension (injection rate (Q) and head (h)) based on the linear relationship manifested by the injection rate and corresponding change in head.

The model effectively mapped the aquifer response to injection with high accuracy (**Figure 5.4**). The co-efficient "αslope" represented the slope of the fitted linear relationship between the recharge rate and the corresponding head buildup. The values varied from 2.59 to 209,355 ($L^{-2}T$) with a mean of 1121.3 $L^{-2}T$, with majority of the sub-basins having a variation of 300–1000 $L^{-2}T$ (**Figure 5.4**). The higher values of slope represent that the

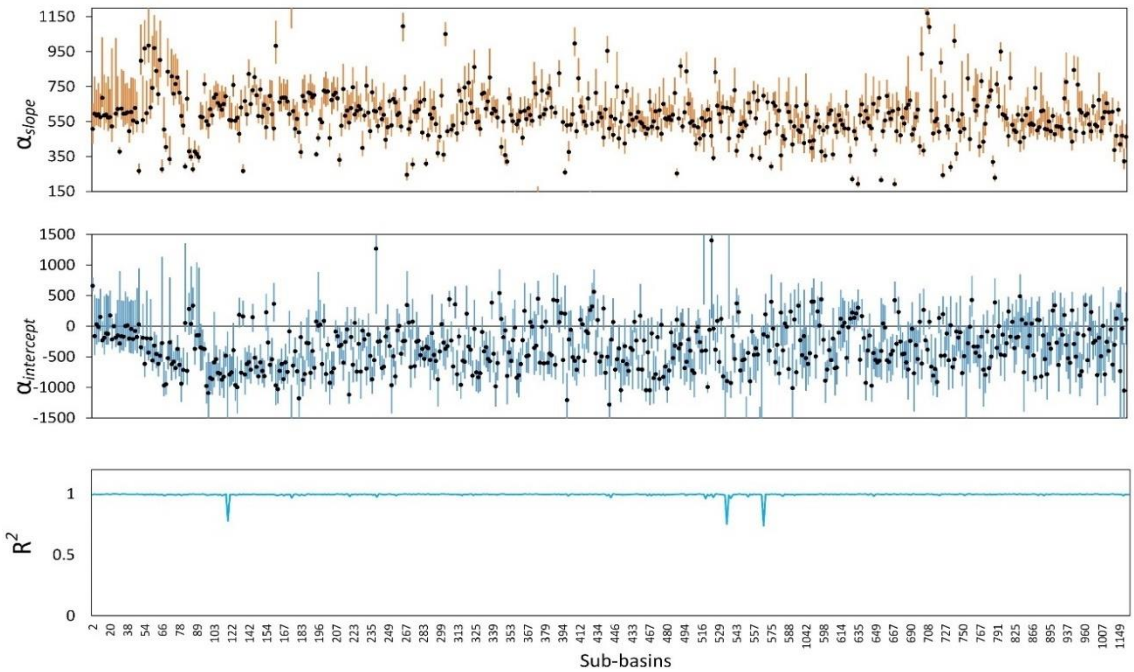

Figure 5.4 Regression coefficients (slope and intercept) representing the mean (black dot), maximum and minimum values with the corresponding average goodness of fit for each subbasin (R^2). The range of the coefficients represents the temporal behaviour of the groundwater heads as different models has been trained for each injection duration

aquifer response is highly sensitive to the given recharge rate (i. e. large head variations for small recharge rates) and vice versa. The co- efficient "αintercept" represented the intercept and varied from −1323.79 to 2626.86 (L), with majority of the sub-basin having a variation between −1000 and 550 (L) (**Figure 5.4**). The goodness of fit between the simulated and fitted values was evaluated with R^2. The overall mean of 0.99 for the R^2 was achieved with minimum of 0.74 for all subbasins.

5.2.2.2. Transient aquifer recharge capacity and PARC

The PARC estimation was developed to determine the maximum rate with which an aquifer can be safely recharged, such that the groundwater table rise is within the permissible limit of 3m bgl to avoid water logging or soil salinity in the unconfined aquifers (CGWB, 2021). This augments the practical problem of determining recharge rates in the field during water injection to the unconfined aquifers. The solutions provided by (Rushton and Srivastava, 1988; Shandilya et al. 2022b) had limited application since it did not consider the external source and sink influences on the drawdown/head buildup during injection to a well (Chahar, 2015). Numerical models were well suited to map the effects of all the source and sink on the injection/production wells (Bair, 2015), but the computational requirement would be high due to forward modelling approach. The Neuman (1972) analytical solutions was used to derive the linear relation between injection rate and the head buildup. The model is then used to calculate the recharge rate corresponding to the permissible head reducing the computational burden.

As the PARC is dependent on the injection duration (Shandilya et al. 2022a), it is calculated for each month to generate a monthly PARC value. The dataset is then utilized to determine the suitable monthly recharge rates for each subbasin. The PARC values for the continuous injection in multiple months has been taken as the lowest value as to avoid reaching the constraint permissible head. The variation of PARC with injection duration has been presented in **Figure 5.5.**

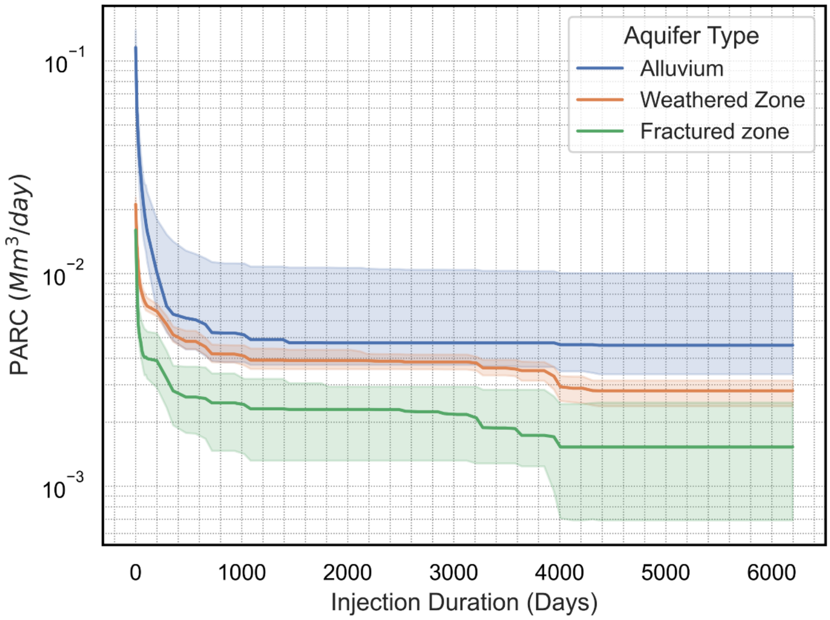

Figure 5.5 Variation of PARC w.r.t the pumping duration. The median value for the three aquifer types along with the range (shaded area) has been presented

The PARC has been calculated for each grid cell in the subbasin, and a mean value has been obtained for the subbasin. The estimated PARC values were highly variable across the LBRB, varying from as low as 0.2 m^3/day for the area with high water table to as high as 673,954 m^3/d for the areas with a low water table (**Figure 5.6**). Apart from the water table, the value of PARC is dependent on the aquifer hydraulic conductivity and nearby source/sink influence (pumping well and rivers). Highly water stressed area showed large PARC values to attain the permissible water level.

Analysis of the results revealed that grid cells sensitive to recharge rates showed low values of PARC and was due to the low hydraulic conductivity and low storage capacity of the aquifer resulting in quick head built up. Few cells with large PARC values were influenced by other boundary conditions like streams and model boundary which resulted in loss of water and lower head rise to corresponding recharge rates. The subbasins with groundwater levels equal and above permissible head was denoted as balanced subbasins and excluded from MAR interventions (**Figure 5.6**).

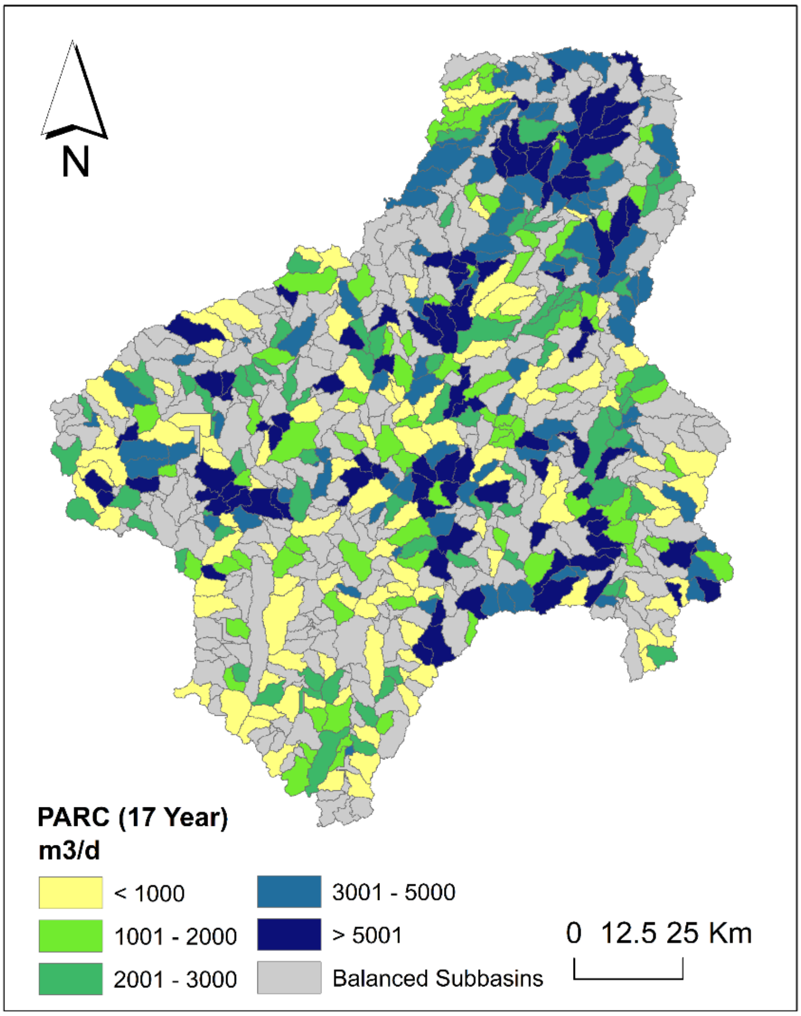

Figure 5.6 PARC distribution in the LBRB for the 17 years simulation period (2003-2020); The subbasins having average groundwater water head above the permissible head is omitted from the study and represented as balanced subbasins.

About 80% of the subbasins had PARC values in the rage of 270 to 9400 m^3/day and about 50% of the study area had a recharging capacity of over 3500 m^3/day which could be easily satisfied by the available surplus water. The PARC values were large for the Alluvium aquifers, due to the high conductivity and large aquifer thickness while it was lowest for the fractured aquifers (**Figure 5.5**). The values were found to be lower for the fractured aquifer system due to the low hydraulic conductivity of the formations. Although at some subbasins higher PARC values was also observed due to presence of highly fractured zone which can provide good storage capacity.

5.3. Summary

This study entails the effective utilization of hydrological model SWAT to quantify the available surplus water in the LBRB. Surplus water, estimated at 75% dependability of monthly generated surface runoff, showed spatial variability in threshold values for surplus runoff depending on the average annual rainfall rates. The east and the west regions with higher rainfall rates had larger annual groundwater recharge rates (85-351 mm/km^2) and were self-sufficient under the current annual water demand (77 mm/km^2). While few blocks in the northeast regions received the lowest rainfall, had the lowest threshold and the annual groundwater recharge was not adequate to satisfy the demand. Replanning to transfer water from high runoff potential upstream basins could be a viable solution. Overall, due to the topography, geomorphology and hard rock geology of the basin, high runoff rates were being generated and about 85% of the subbasins had over 5000 m^3/d of surplus water.

The study showed the development and application of PARC in case of unconfined aquifers. Linear regression models were effectively used to establish relation between the recharge rates and corresponding head change. PARC was developed to determine the maximum recharge rate for the injection operation in any MAR project. The developed methodology was effectively applied to estimate the PARC values in the LBRB. It was observed that about 50% of the selected subbasins had an average recharge capacity of 3500 m^3/day and that the PARC values were dependent on hydrogeology, aquifer thickness, groundwater level and the presence of nearby source/sink. The method was computationally efficient and could augment the practical problem of determining suitable recharge rates in the field.