CHAPTER 7
EVALUATION OF THE MAR FRAMEWORK ON LBRB

7.1. Introduction to the MAR Framework

The main goal of this research was to develop and apply a comprehensive framework for MAR planning using a combination of spatial and numerical modelling tools. Groundwater depletion is a critical issue worldwide, and MAR has emerged as a sustainable solution to restore groundwater levels. However, the success of MAR projects relies on effective planning, which requires accurate tools to quantify groundwater resources, identify optimal recharge locations, and manage surplus water efficiently. This research aimed to address these challenges by creating a step-by-step framework that integrates hydrological modelling, groundwater flow analysis, regression models and clustering techniques to improve the efficiency and feasibility of MAR projects. The framework was applied to a drought prone, high intensity rainfall region of central India, the LBRB, providing a practical case study to validate its effectiveness and showcasing how these methodologies can be adapted for real-world MAR project planning.

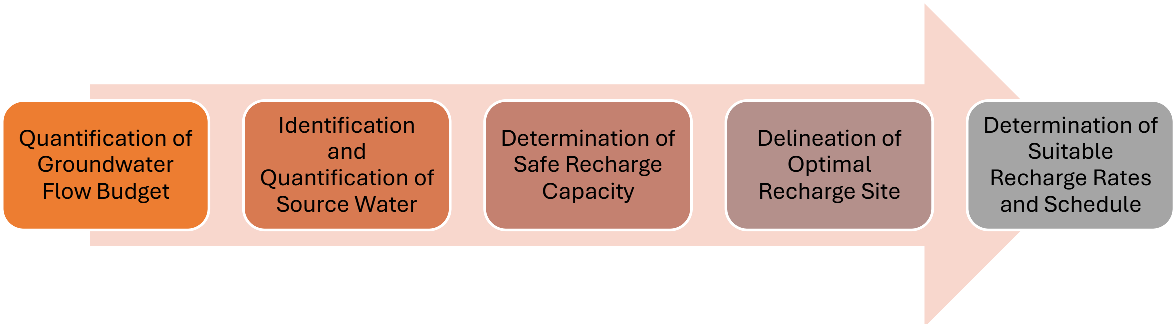

Figure 7.1 Proposed MAR Framework

The framework was structured in a sequence of interconnected steps, each building upon the findings of the previous step. Each step was designed to progressively refine the understanding of the basin's groundwater dynamics, surplus water availability, and potential recharge sites, rates and schedule while ensuring sustainable management of groundwater resources. Below is a detailed overview of how each step was implemented in the LBRB accompanied by the important observations obtained during its application.

STEP 1: Quantification of Groundwater Budget dynamics

The first step in the proposed MAR framework is to assess the current state of groundwater resources in the study area by quantifying the groundwater flow budget. Since surface and groundwater resources are components of a single system, loosely coupled hydrological model (SWAT) and numerical groundwater model (MODFLOW-NWT) was employed to quantify and understand the long term (2003-2020) surface and groundwater budget dynamics. Both models were calibrated using historical climate data, streamflow records, and groundwater level observations.

The integrated models revealed critical insights into the water budget components. The LBRB was found to be under significant groundwater stress, with regions in the central and northern parts showing high levels of groundwater depletion and storage loss. The models quantified the aquifer storage decline over the past few decades and identified areas where groundwater recharge had failed to keep pace with extraction rates. These findings provided a foundation for targeting recharge interventions in the most stressed regions. The most vulnerable blocks in accordance with storage loss in the LBRB were – Bamaur, Gursarai, Niwari, Moth, Chiraigao, Bangra and Mauranipur.

STEP 2: Estimation of Surplus Water for MAR

In this step, the surplus water generated during heavy rainfall events was identified as the source water for MAR in the basin. High intensity rainfall in the LBRB, caused soil erosion and movement of water out of the basin. The excess runoff generated during the monsoon season was identified as the source water for MAR. SWAT estimated monthly surface runoff (SURQ_CNTmm) was utilised to generate surplus runoff of each subbasin at 75% dependability. 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 study found out that low groundwater infiltration rates existed in the LBRB due to geological factors such as rugged terrain, dissected topography, underlain rock formations, and hydrogeomorphology of the region where short length of overland flows resulted in high runoff velocities into streams. It was observed that about 85% of the subbasins generated an average surplus runoff of 182.5 Ham/year. Surplus water generated in the vulnerable blocks is given in **Table 7.1.**

STEP 3: Aquifer Storage Quantification

Following the estimation of surplus water, the next step in the proposed framework was quantification of the safe aquifer recharge capacity in the LBRB aquifers. This step, requisite for unconfined aquifers, involved calculating the volume of water that can be safely injected into the aquifers without exceeding permissible groundwater levels, which would otherwise lead to issues such as waterlogging or soil salinity. A novel methodology (PARC) was developed to determine the permissible recharge capacity in each subbasin of the LBRB, based on the linear regression model and numerical model.

The results revealed spatiotemporal variations in the PARC values of the LBRB subbasins. PARC values were transmissivity dependent and higher for alluvial formations than weathered and fractured formations in the LBRB. Annual average PARC values ranged from 9.85 Ham to 343 Ham in 80% of the subbasins. About 50% of the subbasins had average recharge capacity of 127.75 Ham. The aquifer storage capacity at the end of 17-year study period in 7 subbasins is given in **Table 7.1.** This quantification was crucial in ensuring that the recharge activities such as MAR would not lead to detrimental effects such as flooding or soil salination. The identification of safe storage limits allowed for the design of MAR systems that maximized recharge efficiency while safeguarding environmental integrity.

STEP 4: MAR Site Selection

The fourth step involved the identification of optimal recharge sites where MAR interventions would be most effective. This was done by classifying the basin into clusters based on similar surface and subsurface hydrological characteristics using the K-means clustering technique. Multiple combinations of surface features—such as slope, drainage density, geomorphology and drawdown—were analysed, along with aquifer properties like hydraulic conductivity, specific yield and aquifer thickness. The clustering results were integrated into the MODFLOW-NWT model to assess how different recharge scenarios would impact groundwater levels in each cluster.

The clustering analysis resulted in the delineation of multiple optimal recharge zones across the basin. The surface hydraulic properties greatly influenced cluster formations, with low variations in slope, drawdown and drainage density properties resulting in formation of large clusters. Based on the groundwater head response to applied recharge, geomorphology and drainage density along with aquifer parameters were the best suited combination for MAR site selection in the LBRB. About 16% of the LBRB was under least head change category (>0.7 m) and 81% of the basin was under 1m head change. The methodology efficiently reduced the computational time to identify suitable MAR sites using groundwater models and further reduced the need for extensive field investigations.

STEP 5: MAR rate and schedule

Once the optimal recharge sites are identified, the final step is to determine appropriate recharge rates and schedules based on the availability of surplus water and the storage capacity of the aquifers. Direct recharge through injection wells have been selected as the appropriate method of MAR in this study. By incorporating the surplus runoff data and PARC values, suitable recharge rates were calculated for each subbasin within the LBRB, so as to avoid both, excess consumption of surface water and the risk of water logging. The recharge schedule was designed around the monsoon season, when majority of the surface runoff was generated, ensuring only excess water is captured and recharged into LBRB aquifers.

Analysis of the results revealed that the suitable recharge rates varied from 0 to 3285 Ham/year in the LBRB, with an annual average rate of 164.25 Ham/year. Spatially, about 10% of the selected subbasins had very low recharge rates of 36.5 Ham/year, while 25% of the subbasins had large recharge rates of 182.5 Ham/year. Apart from the low mean annual rainfall from 2005 to 2010, most of the years between 2003 and 2020 had runoff excess for at least two months (median value). The recharge rate time series showed ephemeral recharge rates, which was only possible during high storm event in the LBRB.

7.2. Potential Impact of the Framework

Evaluation of the proposed MAR framework for the LBRB is a critical step in ensuring the framework's effectiveness, scalability, and sustainability. The evaluation focused on both technical performance of developed models, the generated results and analysis, especially on the vulnerable blocks in the LBRB. Firstly, the SWAT and MODLFOW-NWT model's robustness was tested through multiple performance metrics and the acceptable results indicated the model's ability to represent hydrological and groundwater flow dynamics of the LBRB with fair accuracy.

Quantification of the block flow budget dynamics indicated that seven out the 22 blocks in the LBRB was under groundwater stress, with the aquifers losing water from storage (**Table 7.1**). However, upon evaluation of the generated surplus runoff at 75% dependability, it was adequate to offset the storage loss in the vulnerable blocks. Similarly, the estimated aquifer storage capacity in 17- year study period, indicated that almost all the blocks had the storage capacity to store all of the generated surplus runoff without the risk

Table 7.1 Estimated values at the end of 17-year period

Sub-basin	Area (Ha)	Storage loss (17yrs) Ham	Surplus Runoff Generated in 17 years Ham	Aquifer storage capacity (PARC*injection duration)
Bamaur	82100	13365	44448	210493
Gusarai	71400	10142	64459	60315
Moth	30200*	8612	18974	147810
Chiraigao	28800*	4264	17315	19799
Niwari	65600	9758	34950	65625
Bangra	45700	10124	34866	32335
Mauranipur	61800	10013	42437	36058

*Area within model boundary

of water logging. Although few blocks, such as Gursarai, Bangra and Mauranipur lacked the adequate storage to accommodate all the surplus water yet had enough storage to resolve the storage loss and stop further aquifer depletion.

Hence, it can be concluded that enough surplus water was being generated, and adequate storage was available to store this generated water to offset storage depletion and minimize groundwater storage stress in most of the LBRB blocks.

7.3. Effect of MAR on the LBRB

The overall impact of the applied intervention can be understood by the changes in the groundwater levels below the recharge structure. The effect of MAR in the LBRB was assessed with respect to total volume of surplus water available, total injected volume and the corresponding change in groundwater head from 2003 to 2020. The total volume of surplus water available during the study period has been plotted in **Figure 7.2**. It was observed that about 45% of the subbasins had the surplus water of more than 2000 Ham during the 17-year study period, which was greater than the average groundwater requirement of 2003 – 2020 (1980.5 Ham), if we take the total demand for the year 2020 as average (116.5 Ham/year). The results revealed that the LBRB has sufficient runoff that could be stored underground to offset the mismatch of supply and demand.

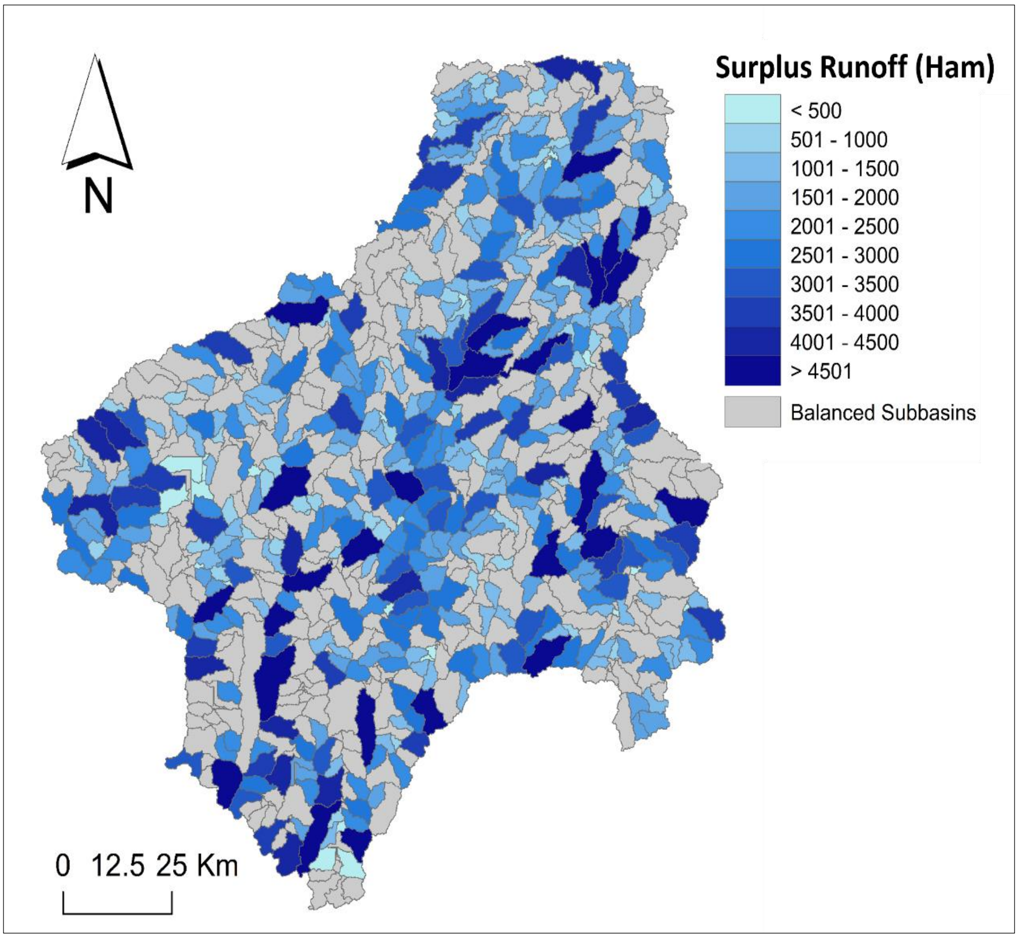

Figure 7.2 Total surplus runoff volume generated in the LBRB (2003-2020)

The total volume of water injected during the MAR operation in the study area is termed as injection capacity (Shandilya et al. 2022a). Excluding the balanced subbasins, the LBRB showed a spatially varied range of injection capacities (**Figure 7.3**). The frequency distribution plots revealed that about 18% of the selected subbasins had a low recharge capacity of less than 100 Ham in 17 years, due to the low PARC values. About 40% of the subbasins had a varying recharge capacity of 100 to 200 Ham, 36 % had varying capacity of 200 to 500 Ham and rest has the recharge capacity greater than 500 Ham. A total of eight subbasins had large injection capacity of over 1000 Ham due to the influence of other features like streams and model boundary. When compared to the water demand in the LBRB, 27 subbasins had the capacity to store more than 25% of total water demand and out of these 27 subbasins, eight had the capacity to store more than 50% of total water demand.

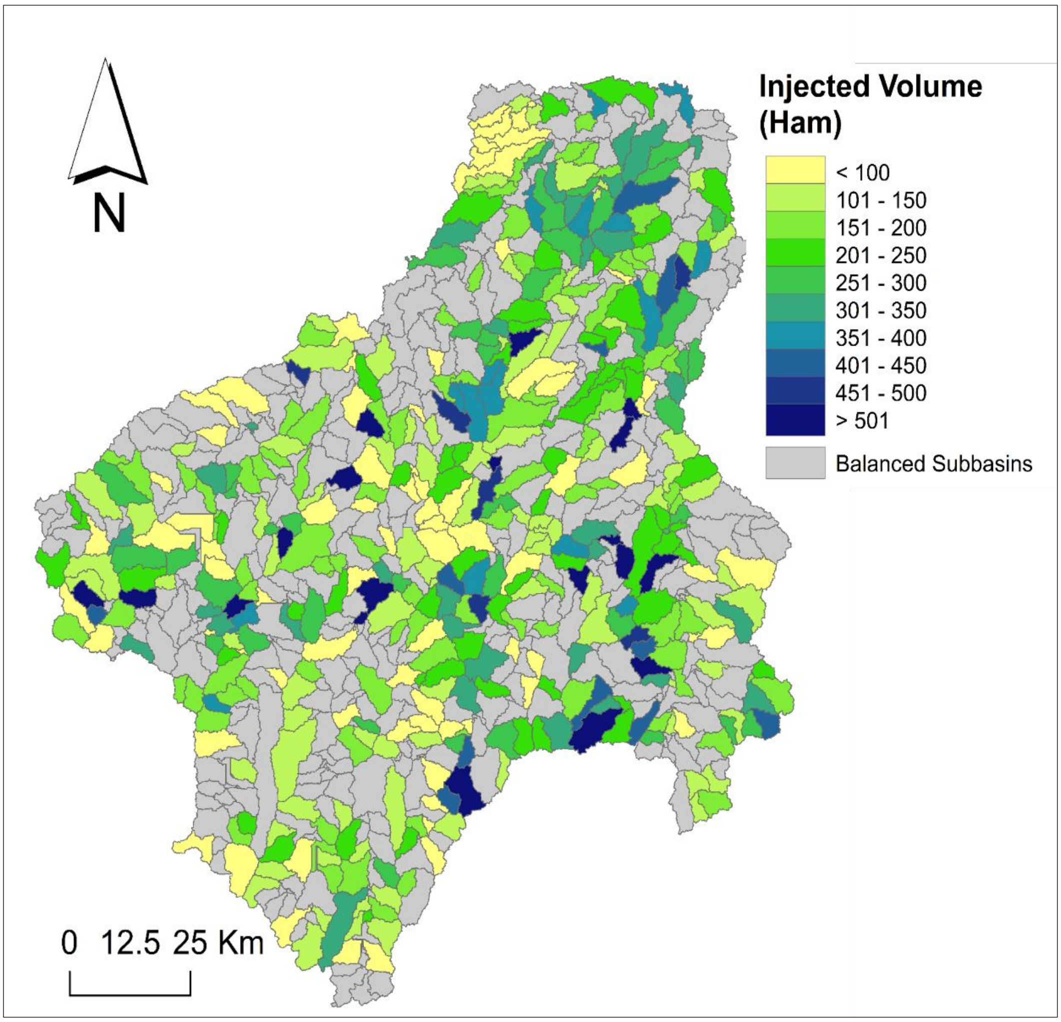

Figure 7.3 Injected volume of water per subbasin

The corresponding change in groundwater levels after MAR operation w.r.t to the initial scenario (without MAR) has been represented spatially as change in head (**Figure 7.4**). Almost 63% of the subbasins had a change in head of less than 1.24 m. The aquifers in the central region of the LBRB were sensitive to MAR with many subbasins showing significant changes in groundwater head (over 6.2 m to 12.4 m). Overall, an average head change of about 1.46 m was recorded for the LBRB at the end of the simulation period.

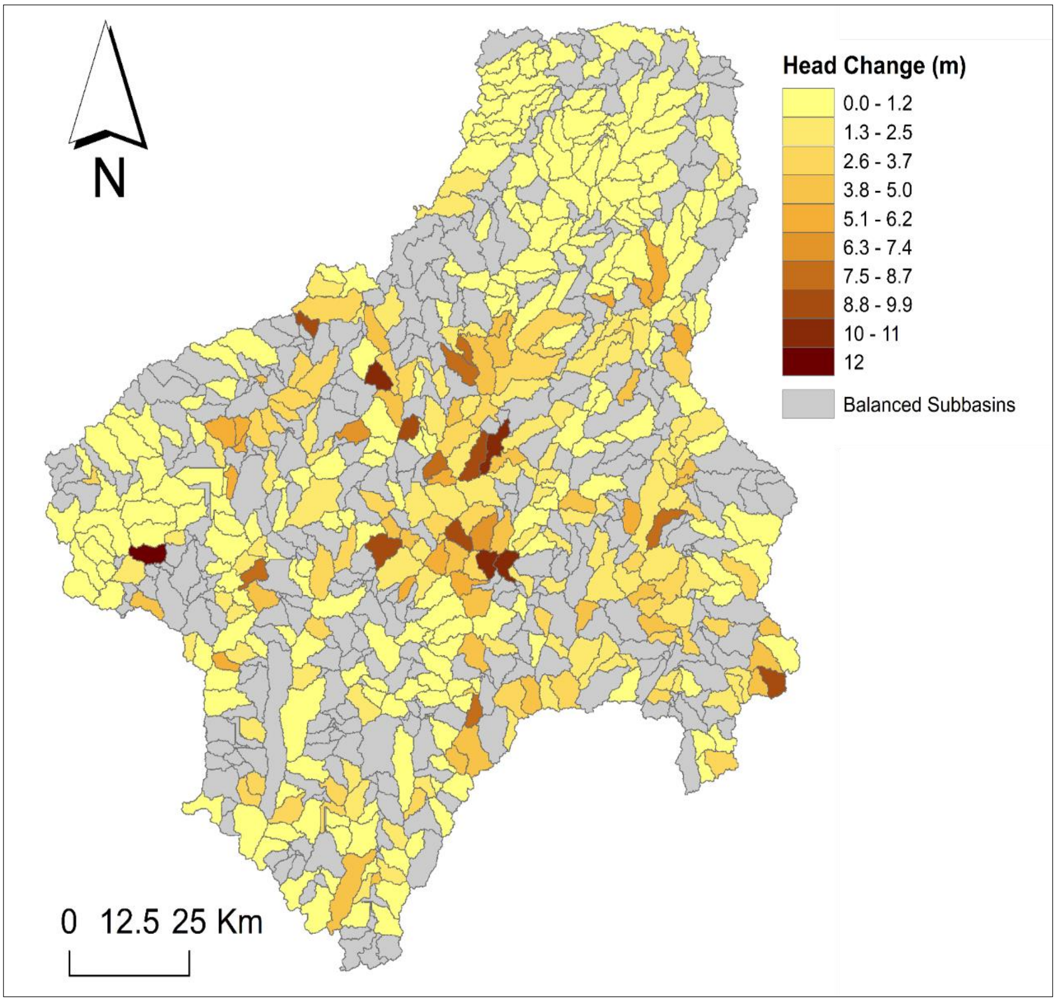

Figure 7.4 Observed head change due to MAR in the LBRB

Assessment of the overall effect of the MAR in the LBRB, it was observed that 45% of the LBRB generated sufficient surplus water to meet the average groundwater demand. About 76% of the subbasin showed storage capacity of up to 500 Ham in 17 years of study. The overall head change in the LBRB varied from less than 1.2 m to over 12 m with the aquifers in the central region being more sensitive to artificial recharge.

7.4. Adoptive Action for Storage Stabilization in the LBRB

After the quantification of the available surplus runoff, safe recharge capacity, and the MAR rates and schedule, several mitigative actions can be proposed based on the estimated values to stabilize the storage depletion in vulnerable blocks of LBRB. Some of the mitigative actions that can be adopted in the LBRB is discussed in the following sections.

1. The existing (dried/polluted) shallow dug wells in the LBRB can be converted into groundwater recharge structures.
2. The linear quartz reefs that exist in almost all of the LBRB region acts as a natural groundwater flow barrier and can be utilised to design underground water harvesting structures.
3. Utilization of high recharge capacity blocks to capture and store the generated surplus runoff.
4. Minimization of surface runoff structures in blocks with poor storage capacity to allow for more water retention in the downstream blocks with larger storage capacities.
5. Prioritization of water conservation and induced recharge structures in the most vulnerable blocks of LBRB through utilization of subbasin scale information on surplus water and recharge capacity.
6. Incorporation of the research findings into existing and new groundwater management plans to improve the success of MAR projects.