Development of a framework for Managed Aquifer Recharge (MAR) planning using spatial and numerical modelling to resolve groundwater depletion challenges

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By

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CHAPTER 8
CONCLUSION AND FUTURE SCOPE

8.1. General

The stabilization of groundwater levels and storage decline is the most important process for sustainable groundwater resource utilization, and it could be achieved only through reduction in groundwater demand or increase in its replenishment. MAR has emerged as one of the most sustainable and worldwide adopted solution towards multi-faceted groundwater challenges. MAR implementation has been growing globally at the rate of 5% per year and in India alone, over 140 crore groundwater recharge structures has been proposed to ensure sustainable all-year-round water for agricultural and domestic purposes (CGWB 2021). Analogously, advancement in computational capability, availability of field and satellite data, competent modelling algorithms and models have made the MAR planning process more efficient, and the implementation process more cost effective.

The present study exhibits the applicability of soft computing techniques towards comprehensive MAR project planning. The study showcased that spatial, hydrological, analytical and groundwater models can be effectively applied at each stage of the MAR planning by taking up the case study of the LBRB, India. The overall thesis evolved around five important research objectives presented as the five steps towards comprehensive MAR project planning, to achieve the main aim of this study "Development of a Framework for Managed Aquifer Recharge (MAR) Planning using Spatial and Numerical Modelling to Resolve Groundwater Depletion Challenges". The following sections summarises the major findings associated with each objective and draws an overall conclusion to the undertaken study.

The main aim of this study was to develop and evaluate the performance of computationally efficient strategies to aid in the planning process of MAR projects. In the first step, the hydrological and groundwater models were developed and utilized to quantify the surface water and groundwater budget dynamics in the LBRB from 2003 to 2019. The analysis revealed that the average annual precipitation was 973mm and spatially varied (566 – 1035 mm) with the norther region of the LBRB receiving the lowest amount, consequently generating lower surface runoff and poor groundwater recharge. ET rates varied between 329 – 765 mm/y with basin average of 544 mm/year (56% of precipitation) and was the main source of water loss in the basin. Spatial distribution of generated surface runoff and groundwater percolation was in accordance with the distribution of rainfall in the basin and was 23% and 21% of precipitation, respectively. Groundwater budget analysis showed that natural recharge was the largest contributor to groundwater inflow into the LBRB aquifer system (64%), followed by recharge via river discharge (19%) and boundary inflow. Abstraction through pumping wells accounted for 41% of groundwater removal from the system, followed by minor streams outflow (21%), discharge into rivers (14%), groundwater ET (8%) and boundary outflow. The net groundwater balance was negative, and the LBRB aquifer was losing about 3650 Ham of water from storage every year. The northern doab region of Bamaur and Gursarai blocks in Jhansi district was identified as the most groundwater storage stressed zones in the basin, with progressive decline in groundwater levels (0.6 – 1.2 m/year). Zone budget analysis revealed that the abstraction rates had been exceeding recharge rates in both the blocks. Scenario analysis revealed that a reduction of 20% in abstraction rates could lower the storage depletion by 29% and 16% in Bamaur and Gursarai blocks, respectively. Yet it was not enough to counter storage loss and artificial recharge through MAR could be viable option to prevent further depletion in groundwater levels and improve storage while satisfying the water demand in the groundwater stressed regions of the LBRB.

The second step in the MAR process was the identification and quantification of source water for MAR. High intensity rainfall events caused floods in the downstream of the Betwa river and the water was being lost from the basin. The subbasin scale surplus water, estimated at 75% dependability of monthly generated surface runoff was identified as the potential source of water for MAR in the LBRB. Depending on the average annual rainfall rates, the threshold values for surplus runoff showed spatial variability. The east, west and the south regions with higher rainfall rates generated 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 the northern portions of the LBRB did not receive adequate rainfall to satisfy the demand. In these areas, inter-subbasin transfer from the upstream subbasins, with high runoff potential could redeem the groundwater requirements. Overall, due to the geography and hard rock geology of the basin, high runoff rates were being generated in about 85% of the subbasins that had over 5000 m^3/d of surplus water.

The third step involved determination of safe aquifer storage capacities. It is of utmost importance in case of unconfined aquifers to avoid the risk of soil salinity or water logging. In this study, a novel methodology, PARC was developed and evaluated to estimate the safe recharge capacity in aquifers. The model effectively mapped the aquifer response to injection rates with high accuracy ($R^2 = 0.99$). The PARC was calculated for each grid cell in the subbasin, and a mean value has been obtained for the subbasin. The PARC results varied spatiotemporally in the LBRB influenced by hydrogeology, aquifer thickness, groundwater level and the presence of nearby source/sink. About 80% of the LBRB 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 developed methodology was computationally efficient as it allowed for examination of different recharge rates without the repeated simulations of groundwater model. Additionally, it augmented the practical problem of determining suitable recharge rates in the field and could be utilized as a decision-making tool in AR projects.

The fourth step was identification of optimal sites for MAR interventions. A fresh methodology was presented that utilised K-means clustering technique to classify the basin into clusters based on similar surface and subsurface hydrological characteristics. Multiple combinations of surface (slope, drainage density, geomorphology and drawdown) and subsurface (hydraulic conductivity, specific yield and aquifer thickness) parameters were employed to gauge their influence in formation of clusters and the results were integrated into MODLFOW-NWT model to assess the impact of different recharge scenarios on groundwater levels. Among all the cluster combinations, CC3 had the maximum area spread (16%) under the least head change (<0.7 m) category and geomorphology and drainage density conjunction along with aquifer properties were found to be best suited combination for MAR site selection in case of LBRB aquifer systems. Under 1m head change category, CC1 performed better with cumulative 81% of the area under it and drawdown, slope along with aquifer properties the best suited combination. The methodology efficiently reduced the computational time to identify suitable MAR sites using groundwater models and further reduced the need for extensive field investigations.

The fifth and final step was determination of suitable recharge rates and the recharge schedule for the MAR intervention. A management model was developed based on the estimated PARC and surplus water availability. This was done to avoid excess consumption of surface water and the risk of water logging. The recharge schedule was designed around the monsoon season (June to September), when majority of the surface runoff was generated, ensuring only excess water is captured and recharged into LBRB aquifers. Based on the MAR suitability map, out of 768 selected subbasins in the modelled area, 316 subbasins were balanced subbasins (groundwater level >3 m below ground level), 15 subbasins was excellent and 50 subbasins was under good category. The mean head change after injection, in these subbasins was about 1.98 m and could store about 162 Ham of injected water. About 150 of the selected subbasins had poor MAR suitability due to inadequate surplus water. Analysis of the suitable recharge rates revealed that the LBRB aquifers had broad range of recharge rates (0-9 Ham/year) with an average of 0.45 Ham/year. About 10% of the subbasins had low recharge rates of under 0.1 Ham/day and 25% of the subbasins had a large recharge rate of over 0.5 Ham/day. Overall, the current hydrological patterns in the LBRB generated sufficient surplus runoff to offset the temporal mismatch of supply and demand in at least 45% of the subbasins. Additionally, around 76% of the subbasins could store up to 500 Ham of water in 17 years; 27 of which could store up to 25% of the water demand. The study presented an effective way of determining suitable recharge rates based on available surplus water and permissible storage capacity, which could augment the field problem of recharge rate determination and could be an effective tool in MAR project planning.

8.2. Generalised Framework for MAR Project Planning

This thesis presents a methodology for MAR project planning by taking up the case study of LBRB in central India, however the framework can also be generalised to be adaptable and transferable to other concerned areas as well. The generalised framework and the methods are presented in the sections below.

1. **Quantification of Groundwater Flow budget**

   Objective: To comprehend the flow budget dynamics, budget components and the effect of induced stresses

Method: Integrated or loosely coupled hydrological and numerical models.

Significance: Establishes a scientific basis for assessing the effects of natural and anthropogenic stresses on groundwater systems.

2. **Identification and Quantification of Source Water**

   Objective: To identify and quantify the potential sources of water for MAR.

   Method: Hydrological models in case of excess runoff and flood water as source water. Additionally, evaluate other potential sources such as treated wastewater in case of low rainfall regions.

   Significance: Ensures sufficient water availability for MAR without compromising existing water needs.

3. **Determination of Aquifer Recharge Capacity**

   Objective: Calculate safe recharge capacity in unconfined aquifers to avoid risk of water logging.

   Method: Permissible Aquifer Recharge Capacity (PARC), A novel method for estimating how much water can be safely recharged in unconfined aquifers.

   Significance: Protects aquifer integrity while maximizing recharge efficiency and sustainability. Saves computational time of repeated model runs.

4. **Delineation of suitable MAR sites**

   Objective: Identify locations with the best potential for successful MAR interventions.

   Method: Use MCDA, numerical model and K-means clustering to classify the area into clusters with similar surface and subsurface hydrological characteristics.

   Significance: Reduced computational time and cost in evaluating recharge site feasibility. Enhances decision-making by focusing resources on high-potential areas, improving MAR effectiveness.

5. **Determination of MAR Rates and Schedule**

   Objective: Establish suitable recharge rates and timing based on availability of source water and recharge capacity.

   Method: Integrate surplus water availability with PARC values into the management model

   Significance: Ensures sustainable water management by aligning water availability, recharge activities with natural excess water availability cycles.

8.3. Limitations of the Study

All groundwater flow models are limited by the conceptualization of their hydrologic system, assumptions taken and uncertainty of how the system is represented (Jones et al. 2017). The lack of any previous modelling studies in the area and sufficient data on aquifer properties resulted in conduction of multiple model runs with various conceptualizations to arrive at an acceptable solution. Lack of data on reservoir and lake water level variations led to their exclusion from the LBRB groundwater flow model. Information of irrigation return flow could have improved estimated results of groundwater recharge. Zonal distribution of aquifer hydraulic properties gave abrupt storage variation results and would require detailed field investigation to improve spatial distribution of aquifer properties. Lack of data on smaller rivers of the LBRB limited their conceptualization to drain package in the model, restricting estimation of their exchanges.

The study span across the site selection to the scheduling operations of an injection well. The limitation of the study arises due to temporal and spatial scale of analysis, which is constrained by the conceptualization of the groundwater flow model. A coarse model with 1000 m resolution made faster simulations but limited the precise determination of suitable injection well locations. Application of parent-child models can overcome this limitation. Well characteristics, such as partial penetration, skin, and screen loss, influences the injection capacity of recharge wells (Shandilya et al., 2022c), have not been considered in this study which resulted in overestimation of injection capacity. Although it was assumed that the estimated injection capacity could be achieved through single or battery of wells, however in case of real field applications care should be taken for pinpoint identification of recharge wells and injection rate. Apart from this, the assumptions in the Darcy's law and SWAT models are also inherited in this study.

8.4. Future Scope of Work

The present study offers a robust framework for planning Managed Aquifer Recharge (MAR) interventions using spatial and numerical modelling tools. While the application of the framework in the Lower Betwa River Basin (LBRB) demonstrates its feasibility and effectiveness, there remains significant potential for future refinement and extension. This research may be advanced in following directions in the future.

The current study employed loosely coupled SWAT and MODFLOW-NWT models to evaluate groundwater dynamics. Future research can focus on developing a fully integrated SWAT–MODFLOW platform to better capture interactions between surface and groundwater systems. Long-term scenario analysis incorporating climate projections (e.g., CMIP6-based rainfall and temperature datasets) could improve understanding of MAR performance under climate variability. Incorporation of land use and land cover change scenarios would allow assessment of how agricultural intensification and urban expansion influence recharge potential and groundwater depletion.

The identification of surplus runoff as a source of recharge can be extended by exploring alternative sources such as urban stormwater and treated wastewater to diversify MAR options in semi-arid and urbanizing regions. The clustering approach used for delineating optimal recharge sites can be enhanced through integration of advanced machine learning algorithms to incorporate additional surface and subsurface variables.

Validation of recharge zone prioritization using post-recharge groundwater response would strengthen model credibility.

Dynamic recharge scheduling based on real-time rainfall forecasts and runoff monitoring could be integrated to improve the timing and efficiency of MAR interventions. Uncertainty modelling using stochastic simulations can help assess the resilience of recharge strategies under extreme weather events, particularly delayed monsoon or prolonged drought conditions. Cost-benefit and multi-objective optimization models may be applied to identify recharge strategies that maximize groundwater storage per unit of investment.

The proposed MAR planning framework can be transformed into a GIS-based Decision Support System (DSS) to facilitate scenario visualization, data integration, and decision-making by planners and policy makers. The tool could include modules for aquifer budget analysis, site prioritization, recharge scheduling, and policy evaluation, supported by a user-friendly interface. Future frameworks may also integrate socio-economic and institutional factors such as land ownership, infrastructure availability, and stakeholder willingness to better align technical site suitability with implementation feasibility.

This future work outlines a comprehensive pathway for transforming the proposed MAR planning framework into a practical, adaptive, and scalable tool for sustainable groundwater management. The successful implementation of these enhancements would help bridge the gap between research and real-world policy, facilitating data-driven decision-making for aquifer recharge planning across diverse hydrogeological settings.