Preface

Groundwater depletion is a pressing global issue, particularly in regions reliant on aquifers for agricultural, industrial, and domestic water supply. In the Indian subcontinent, overexploitation of groundwater resources has led to significant decline in water tables, threatening water security and sustainability of aquifers. Managed Aquifer Recharge (MAR) presents a viable and sustainable solution to augment groundwater levels through induced recharge of aquifers for later use or environmental benefit. However, planning and implementation of the MAR projects require a robust framework to ensure that recharge efforts are effective, efficient, and sustainable. This thesis proposes a comprehensive framework for MAR planning, integrating spatial and numerical tools to resolve groundwater depletion challenges. The framework provides a structured approach towards MAR project planning, focusing on the applications of these tools at every stage of the MAR process. The developed methodology was evaluated using the case study of Lower Betwa River Basin (LBRB) in central India, a region prone to severe groundwater stress.

Quantification of the long-term groundwater flow budget dynamics is a prerequisite of any management work and the first step in the proposed MAR planning process. The framework utilised loosely coupled Soil and Water Assessment Tool (SWAT) and numerical model MODFLOW-NWT to evaluate and quantify the groundwater budget components, groundwater depletion, flow budget and the influence of natural and induced stresses on aquifer storage from 2003 to 2020. The calibrated models were employed to reveal that even when the annual average stage of groundwater development was at only 64% during the study period, yet the LBRB aquifers were gradually losing water from storage at the rate of 3650 Ham/year. Analysis of the groundwater trends revealed that the north and central regions of LBRB (Jhansi and Tikamgarh districts) experienced progressive decline in groundwater levels (0.6 – 1.2 m/year). Assessment of Block-wise budget showed that out of the twenty blocks in the LBRB, seven blocks in Jhansi district and one in Tikamgarh district was under negative storage stress. Scenario analysis revealed that abstraction rates had more influence on storage component than natural recharge rates. It was observed that 20% reduction in annual abstraction rates could reduce storage loss by 29% and 16% in Bamaur and Gursarai blocks, respectively and that targeted replenishment of stressed aquifers was better suited to improve storage loss than general increase in natural recharge rates.

The second step of the proposed framework was the identification and quantification of source water for MAR. In case of the LBRB, the excess surface runoff generated during the high intensity rainfall that generally flowed away from the basin, was identified as the source water for recharge. While the annual water demand in the LBRB was around 116.5 Ham (76.8 mm/km^2), it was observed that that the northeastern region and few areas in the west generated runoff lower than 76.8 mm, indicating a dearth in the adequate availability of water for aquifer recharge. The SWAT model based subbasin scale monthly surface runoff output, estimated at 75% dependability was quantified as the surplus runoff for aquifer recharge. Spatial variations in generated surplus runoff were observed in the LBRB with over 85% of the subbasins generating about 182.5 Ham of water annually.

After the quantification of source water for MAR, the third step was the determination of safe aquifer recharge capacity. In case of unconfined aquifers such as in the LBRB, determination of safe recharge capacities is an important step to avoid the risk of water logging and soil salinity. A novel methodology was developed using numerical model, permissible/recommended groundwater levels, analytical relations between injection rates and developed groundwater mound, to estimate the Permissible Aquifer

Recharge Capacity (PARC) in the aquifers. The aquifer response to applied injection rates was accurately and efficiently mapped by the developed model. Based on the transmissivity values of different aquifer formations, the generated PARC values were larger for alluvial formations than weathered or fractured zones. The LBRB showed significant variation in the projected PARC values, with 80% of the basin having annual average PARC values in the rage of 9.85 to 343.10 Ham and about 50% of the basin had 127.75 Ham recharge capacity that could easily store the generated surplus runoff in the basin. The approach was computationally effective and could supplement the need for several model runs, and the real-world issue of determining appropriate recharge rates in the field.

The fourth step in the proposed framework, was the delineation of optimal recharge sites for MAR. An innovative approach was presented that classified any investigation area into clusters based on their surface and aquifer hydrologic properties using K-means clustering technique. The results were then employed to the LBRB groundwater model to assess the aquifer response to MAR at each cluster. Multiple combinations of surface features were analysed to study their influence in cluster formations. It was observed that the choice of surface parameters affected the cluster formations, and the best-suited combination depended upon the site-specific criteria of acceptable groundwater head change. In case of the LBRB, the combination of geomorphology, drainage density with aquifer parameter of hydraulic conductivity, specific yield and aquifer thickness allowed for maximum spatial coverage under least head change category. Applications of clustering techniques effectively reduced the computational time to evaluate potential MAR sites while considering the effect of surface and aquifer hydrologic properties.

The fifth and final step was the determination of suitable MAR rates and schedule. The present study explicitly incorporated the subbasin scale estimated surplus runoff and PARC values into a management model to determine the MAR schedule and suitability of each subbasin in the LBRB. It was observed that most of the basin in LBRB was under poor category i.e. either the surplus runoff was not adequate for groundwater recharge, or the permissible storage was not sufficient to store water. The recharge schedule in case of the LBRB was concentrated during the monsoon months of June to September when the rainfall was maximum in the region. The distribution of suitable recharge rates showed that about 10% of the subbasins had low suitable recharge rates of under 36.5 Ham/year, while 25% of the basin had large recharge rates of 182.5 Ham/year, with basin average of 162.25 Ham/year.

Assessment of the 17-year effect of MAR intervention in the LBRB resulted in 45% of the basin being able to generate 2000 Ham of surplus runoff at an annual average of 117.64 Ham which was enough to meet the water demand of the year 2020 (116.5 Ham). About 76% of the subbasin had recharge capacity of 100 to 500 Ham, with few subbasins showing very large recharge capacities (>500 Ham) due to the influence of other model features such as rivers and model boundary. The corresponding change in groundwater levels due MAR operation revealed that about 63% of the subbasins had less than 1.24 m of head change. Few basins in the central region of LBRB was sensitive to MAR with significant rise in groundwater levels of over 6.2 to 12.4m in 17 years. Overall, the study concludes that the vulnerable blocks in the LBRB generated enough surplus water and had enough storage to resolve groundwater storage loss and prevent aquifer depletion under the current stresses.

Overall, the present thesis puts forward a novel framework for planning MAR projects through integration of spatial, hydrological, and numerical modelling tools. The framework's successful application in the LBRB demonstrates its potential to significantly mitigate groundwater depletion and promote sustainable water management. The research contributes to the growing body of knowledge on MAR by offering a data-driven methodology that can be potentially adapted to various environmental contexts, making it a valuable tool for decision-makers and water resource managers.