A DECISION-MAKING FRAMEWORK FOR MANAGED AQUIFER RECHARGE TO ENHANCE RIVER AQUIFER EXCHANGES

Thesis submitted in partial fulfillment for the
Award of Degree

Doctor of Philosophy

By

Ranveer Kumar
रणवीर कुमार

DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY
(BANARAS HINDU UNIVERSITY)
VARANASI - 221005
INDIA

Roll No. 20061501 2024

9

Conclusion and Future Scope

Increased GW abstraction and climate change have led to a significant decline in the Gangetic Plain, resulting in a loss of baseflow into small rivers, such as the Varuna River Basin. Managed aquifer recharge (MAR) has emerged as a potential solution to address GW decline. However, among the various frameworks available for planning MAR projects, the explicit consideration of baseflow restoration is often missing from the decision-making process. This oversight is largely due to lacking a framework that effectively quantifies baseflow enhancement in response to MAR initiatives.

To address this problem, a numerical GW model-based framework has been presented to determine the base flow enhancement ratio (BFER). The BFER represents the percentage of stream flow that can be enhanced with the unit injection of water through an aquifer storage and recovery system (ASR). Permissible aquifer recharge rate (PARR) has been estimated for each grid cell of the integrated SW (SW) and GW model to determine the maximum recharge rate. Apart from this, the proposed framework includes an assessment of current GW resources to determine the GW deficiency in the area. The river aquifer exchanges and current GW storage have been quantified using a calibrated SW-GW model, and their future projections will be based on downscaled global climate model (GCM) outputs. After accurately determining the streamflow enhancements in response to the injection wells, the total cost and GW storage enhancements have been determined at each model grid cell. A TOPSIS model has been employed with these criteria to find the ranks of MAR sites with respect to the ideal solution.

9.1 MAJOR FINDING

The objective-wise major findings of this thesis work are as follows:

- Assessment of GW decline through gravimetric methods and SWAT Model.
    - A novel methodology to determine the GWS at the HRU scale by integrating the SWAT model and GRACE-derived GW storage has been presented to reduce the requirement for complex GW models for GW assessment.
    - The ANN model effectively downscaled data, with HRU variables showing a strong correlation with GWS. The downscaled GWS has shown a high correlation with observed GW levels.
    - The study's findings indicated a decremental trend in GWS within the Gangetic Plain, ranging from -1.4 mm to -6.9 mm annually from 2001 to 2014. Water budgeting within the designated area suggested prevalent water stress among most blocks within the Gangetic Plain, necessitating interventions to augment natural recharge.

- Quantification of River Aquifer Exchanges and its assessment amid climate change
    - BCC-CSM2-MR, MIROC-ES2L, and MPI-ESM1-2-HR models from CMIP6 simulate the Indian monsoon better than other models studied in this research when compared to the IMD 2D gridded data.
    - Climate change impacts the intensity and spatial pattern of rainfall in all scenarios, with a maximum decrease in annual precipitation of -75 mm to -100 mm. The extreme temperature events are observed to be increasing

since the maximum temperature anomaly from the baseline period (1975-2020) is increasing by 2°C and the minimum temperature is also increasing by 2°C by the end of 2100.

- The sustainability of GW development under climate change has been assessed with GSR. Observing the variability of GSR across the VRB and its temporal fluctuations, it can be safely inferred that GW development in VRB is not sustainable for the future. Only 20% to 80% of the total GW demand is being fulfilled by the natural recharge (GSR: 0.2 – 0.8) and the rest water is coming from either the GW storage or upstream boundary leakage. The depletion of GW storage reserves resulting in the decreased GW table ranging from 3 to 8 meters across the VRB and IPCC scenarios. The decreased water table can have an adverse effect on the SW-GW interaction in the Varuna River.
- The surplus runoff (runoff volume in excess of the runoff events with an exceedance probability of 25%) from subbasins can be a vital source of water to cater to the additional GW demand, which is not replenished by the natural recharge. For all scenarios, the surplus runoff water can supply as much as 20% to 80% of the total GW demand in the VRB. This shows the MAR with storm runoff as a viable solution to GW depletion in the area.
- The RAE in Varuna River and its tributaries have been determined. The river shows a dynamic interaction with the GW system and has to be found in a losing state in the monsoon season and gaining in dry periods (pre-monsoon). The net contribution of RAE to the stream flow varies from ~2% to ~12%, depending upon wet and dry seasons, respectively.

  - The RAE has been found to be depleting with climate change. The decreasing natural recharge and increasing GW demand have led to a decline in the GW table, which resulted in a lost connection between the river and the aquifer. This phenomenon has shown a prominent effect on the baseflow of the Varuna River as most of the gaining river patches start diminishing after 2050.

- Quantification of injection-induced enhancement of River Aquifer Exchanges
  - The baseflow response has been measured by calculating the stream flow enhancement simulated with the MODFLOW model with an injection well with an arbitrary injection signal. The response curve shows different patterns depending on the location of the injection wells. The total baseflow enhanced has been mapped with the Baseflow Enhancement Ratio (BFER) by conceptualizing the response curve.
  - The BFER has been determined with the arbitrary injection signals to the MODFLOW model. In the VRB, the enhancement of baseflow per unit of injected water is low, particularly when injected into the shallow aquifer. Most areas of the subbasin do not significantly enhance baseflow, with notable contributions mainly found downstream of the Basuhi River and at the confluence of the Varuna and Basuhi Rivers.
  - The BFER fluctuates with varying injection durations due to its dependence on the antecedent stream flow, the increasing demand for GW, and the variability in precipitation patterns within the basin. The base flow in the Varuna River can be potentially restored by approximately 0.3% to

2.4% of the current dry flow using a single ASR system (given an injection rate of 10000 m3/day for monsoon months).

- Determination of permissible aquifer recharge rate (PARR) and its Sensitivity towards aquifer and well parameters.
    - The methodology for determining PARR with an adaptive learning rate based on the analytical solution to the well is efficient and requires less iteration than the conventional gradient descent method.
    - The combined effect of the location and size of the well screen on PARR suggests that the best location for the screen to be placed is near the bottom of the aquifer to get higher PARR.
    - The PARR is more sensitive to specific parameter interactions, particularly between hydraulic conductivity and vertical anisotropy in the case of an unconfined aquifer. This suggests that managing unconfined aquifers requires careful consideration of how these parameters interplay. In contrast, confined aquifers exhibit a more distributed sensitivity across multiple parameters, indicating a broader range of factors influencing PARR.
    - The implementation of the methodology in the Varuna River Basin highlights the applicability and spatial variability of PARR influenced by the aquifer characteristics. The area after the confluence of the Varuna and Basuhi and in the lower part of the basin has been shown as a hotspot with high recharge capacity. The large PARR values in this area represent suitable sites for planning any MAR project if an adequate water source is available.

- Determining suitable ASR candidates for baseflow restoration in VRB.
    - The Entropy-TOPSIS method is a simple-to-use MCDM approach for site selection and has shown satisfactory results with BFER. The weights determined have consistent values for all scenarios, showing the entropy method's robustness.
    - The best sites are more or less spread near the streams, on the Basuhi River, and after the confluence of the Varuna and Basuhi Rivers for both the water sources. The suitable MAR sites are also sensitive to climate change.
    - The canal diversion is the most effective water source for MAR projects in the Varuna River Basin.

In conclusion, the integration of Managed Aquifer Recharge (MAR) presents a promising strategy for baseflow restoration within the Gangetic Plain, particularly in light of the significant challenges posed by GW depletion and climate change. The development of a robust framework, such as the Base Flow Enhancement Ratio (BFER), facilitates the quantification of streamflow enhancements resulting from MAR, highlighting the importance of considering baseflow dynamics in GW management decisions. The assessment of river-aquifer exchanges indicates that effective MAR implementation, coupled with the utilization of surplus runoff, can significantly mitigate GW shortages and improve hydrological sustainability in the region. Ultimately, this approach addresses immediate GW deficits and supports the ecological health of river systems, underscoring the crucial role of science-based interventions in managing water resources amidst changing climatic conditions.

9.2 APPLICATIONS

The presented methodology parameterizes the baseflow responses due to the injection signal at a site. The quantification framework has a wide application in the decision-making regarding artificial recharge and GW extraction through scenario-based analysis. Some of the major applications have been discussed below:

- **Simulating the impact of MAR on water bodies**: The framework outlined in Chapter 6 can be applied to any MAR techniques, such as agriculture-MAR, percolation ponds, and rainwater harvesting, to assess the impact of artificial recharge on nearby streams. The enhancement of baseflow can be evaluated at the reach scale by calculating the baseflow enhancement on a cell-by-cell basis. Additionally, it is crucial to determine other fluxes, such as evapotranspiration losses combined with baseflow reductions, to accurately assess the recovery efficiency of MAR projects.
- **Integration with high-scale aquifer datasets**: The methodology's main advantage is scalability. The integrated SW-GW model can be scaled down to a parent-child approach. This will open a new dimension of the local-scale models with finer resolution. The data from transient electromagnetism tomography, integrated with the fine-scale model, will provide accurate estimates of aquifer recharge capacity (utilizing the concept of PARR). This will decrease the uncertainty in the decision-making.
- **Decision Support System**: The proposed framework can be directly implemented into a DSS. The BFER is a robust metric, and its map can be directly used to make decisions regarding MAR applications.

9.3 FUTURE SCOPE

- **Determining the suitable site and schedule with an optimization approach and accurate surrogate models.**

  Optimization algorithms are computationally intensive but provide accurate estimations. The simulation model can be transformed into a surrogate model, which can then be integrated with an optimization model such as Particle Swarm Optimization (PSO) or Multi-Objective Particle Swarm Optimization (MOPSO). However, developing accurate surrogate models that can effectively map stream flow enhancement and other relevant parameters can be challenging and requires thorough research.

- **Comprehensive cost estimation and optimization of the injection well field at a local scale with a parent-child approach.**

  The current research work only determines the suitable sites at the grid scale. The actual field implementation will require and local-scale model. The local-scale model can be built based on the boundary conditions of the regional models, and the exact well locations in the well field can be optimized to get the best injection rates.

- **Analytical solution to determine BFER.**

  The current solution of the baseflow enhancement is based on a numerical model. Although simulating the complex environment, the numerical models still have biases. The analytical formulation of the presented methodology can be very helpful in designing the analytical models.

- **The determination of MAR sites for targeted stream flow enhancement.**

  After parameterizing baseflow enhancement using BFER, we can determine suitable locations for project deployment. If the budget and constraints indicate that a specific number of Managed Aquifer Recharge (MAR) projects should be implemented, we can use a structured approach to identify the best combination of sites. For large-scale problems, the greedy method— which involves checking each combination—can be computationally intensive. Instead, we can effectively solve these issues using a multi-objective optimization algorithm.

***