Preface

The River Aquifer Exchange (RAE) is an important process that influences the quantity and quality of water and, hence, the ecology of rivers. This intricate relationship between Surface Water (SW) and Groundwater (GW) is highly sensitive to climatic and anthropogenic stresses. The increasing GW demand and climate change have led to a drastic decrease in baseflow in the non-perennial tributaries of the rivers, particularly the Ganga River, which has led to degraded river health.

The introduction of Managed Aquifer Recharge (MAR) using injection wells in the mid-20th century marked a significant advancement in addressing water scarcity, particularly in water-stressed regions like India, the United States, Europe, and Australia, with a global annual execution increase of 5%. The MAR can be a vital tool for not only enhancing the GW storage but also river baseflows during dry periods, facilitating the artificial recharge of aquifers to maintain river ecosystems. Notably, the ecological benefits associated with improved baseflow often serve as secondary objectives. While many MAR systems focus on managing GW storage, they frequently overlook the critical aspect of baseflow restoration. This happens mainly due to the lack of a framework for quantifying RAE enhancements for its parametrization in decision-making, which arises from the complexity of subsurface flow processes. This highlights the urgent need for a comprehensive framework for baseflow assessment within MAR projects, which is essential for guiding effective GW management practices aimed at achieving meaningful baseflow restoration.

In this research work, the parameterization of baseflow enhancements induced by an injection well has been explored with the utilization of integrated SW and GW models in the Varuna River Basin (VRB). The GW storage anomalies derived using terrestrial water storage anomalies have been downscaled to the Hydrologic Response Unit (HRU) scale to facilitate the integrated assessment of GW variations. After assessing the need for MAR in the area, an integrated SW-GW model was developed for VRB using SWAT and MODFLOW-NWT. The impact of climate change on the SW-GW fluxes has been assessed and modeled using Global Circulation Models (GCM) outputs from the Coupled Model Intercomparison Project - Phase 6 (CMIP6). The coarse resolution climate scenario data of GCM have been downscaled to watershed scale (25km) using machine learning (ML) models and coupled with the integrated SW-GW model to simulate the impact of climate change on the basin hydrology and RAE. The impact of anthropogenic activities on the RAE has been simulated by forecasting the GW demand using the logistic growth method.

The baseflow response from the periodic water injection at the selected sites through the numerical GW model has been analyzed to determine the baseflow enhancement using a proposed novel index named "Baseflow Enhancement Ratio" (BFER). The BFER of an area represents the total baseflow flow enhancement due to unit water injection at an area. The sensitivity of the BFER to the aquifer and topographical parameters has been presented.

The determination of maximum possible RAE enhancements or maximum BFER due to MAR at a site depends upon the maximum possible injection rate. Using a novel adaptive learning-based optimization methodology, the maximum possible recharge rate at the location has been determined using Permissible Aquifer Recharge Rate (PARR). The PARR represents the maximum injection rate to an aquifer for a given operational time (and well characteristics) under the constraints of a permissible head. The design injection rate of MAR was determined by combining the PARR and the discharge rate of available water sources. The two water source – the canal diversion and surplus runoff has been considered and compared in this study. The maximum baseflow enhancement potential of an area was determined using the design injection rate and BFER.

Finally, the framework for determining potential sites for MAR to restore baseflow has been presented using the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) method after the parameterization of baseflow enhancement. The baseflow enhancement, GW storage enhancement, and total cost of the project have been taken as the criterion for TOPSIS ranking and weighted with the entropy method. Various water sources and climate change scenarios have been analyzed to determine the best location for the MAR site.

The results of the integrated SW-GW assessment suggest that GW extraction in the VRB is not sustainable, and the aquifer is losing GW storage at a rate of -1.4 mm to -6.9 mm annually. The natural recharge has shown a decline from 2025 to 2100 for all socio-economic pathways (SSPs), along with increasing disparity in spatial distribution amid climate change. This assessment determines the necessity of MAR in VRB for sustainable SW-GW management. Most areas in the VRB showed minimal baseflow enhancement, with significant contributions primarily found downstream of the Basuhi River and at the confluence of the Varuna and Basuhi Rivers. Furthermore, the BFER fluctuates with injection duration due to antecedent stream flow, increased GW demand, and variable precipitation patterns. Using a single injection well system, operating at an injection rate of 10,000 m^3/day during the monsoon months could potentially restore 0.03% to 0.24% of the current streamflow per year in the Varuna River.

The area downstream from the confluence of the Varuna and Basuhi rivers has been identified as a hotspot for high PARR values. The PARR is particularly affected by specific interactions among parameters, notably hydraulic conductivity and vertical anisotropy in unconfined aquifers. This underscores the importance of carefully managing unconfined aquifers, considering the interplay of these critical factors. For confined aquifers, the results indicate a more distributed sensitivity across multiple parameters, suggesting a broader influence on PARR.

The research highlights that the most suitable MAR sites tend to be located near streams, particularly along the Basuhi River and downstream of where the Varuna and Basuhi Rivers converge. Lastly, the findings suggest that canal diversion is the most effective water source for MAR within the Varuna River basin, which can restore the baseflow up to 1.04 % per year with the injection well installed at the best MAR site, compared to surface runoff, which can restore a maximum of 0.12 % per year.

The MAR presents a promising strategy for baseflow restoration within the VRB, particularly in light of the significant challenges posed by GW depletion and climate change. 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 discharge through the Sharda canal system, can significantly mitigate GW shortages and improve hydrogeological sustainability in VRB.

Keywords*: River Aquifer Exchanges, Managed Aquifer Recharge, Baseflow Restoration, Permissible Aquifer Recharge Capacity, Numerical Modelling, Hydrogeological Modelling, Climate Change Impact*