

6

Injection-Induced Enhancement of River Aquifer Exchanges in VRB

6.1 INTRODUCTION

Baseflow, the portion of streamflow that GW contributes, is vital in sustaining water availability and ecological balance during dry periods. The rapid decline in the GW table, caused by climate and human-induced stresses, is causing a reduction in the baseflow of major river basins in India (Mukherjee et al., 2018; Surinaidu et al., 2016). The increased GW extraction to support the continued population growth has historically caused stream depletion, necessitating greater release from the SW reservoirs (Ronayne et al., 2017) or canals (as in the case of the Varuna River Basin). The evaporative loss, land area requirements, and construction cost make the utilization of SW reservoirs inefficient (Brown et al., 2019). An efficient management strategy is required to increase the water resource resilience to the probable climate change extremes and increased demands (Ferencz et al., 2024).

The shallow aquifer replenishment by recharge wells has been in practice since 600 AD, starting from the coastal areas of Tamil Nadu (Sakthivadivel, 2007) to the sandy dunes in Turkmenistan. The steep wells (*baoris*) in north India are the classic examples of rainwater harvesting and aquifer recharge by means of recharge wells. It was in the 1950s in California when the first injection well was installed to prevent seawater intrusion. After this event, many projects for Aquifer Storage and Recovery (ASR) and Aquifer Storage Transfer and Recovery (ASTR) have been initiated all around the world (Dillon et al., 2019) under the cap of Managed aquifer recharge (MAR). The utilization of ASR

is fueled by its low cost, low evaporation loss, and flexibility to store water from multiple sources, such as excess storm runoff, rivers, and treated wastewater at times of excess availability (Dillon et al., 2019). Generally, the volume stored with respect to the utilized surface area is much higher for the ASR compared to infiltration basins (Händel et al., 2014).

With the given advantage, the MAR has majorly been researched or implemented for the sole purpose of aquifer storage and later use (Ferencz et al., 2024). However, MAR has been getting recognition from researchers as a promising tool to manage and enhance the stream flow strategically (Asmael et al., 2023; Ferencz et al., 2024; Morrisett et al., 2024; Surinaidu et al., 2016). Artificially recharging alluvial aquifers has been shown to effectively sustain river flows during periods of drought. This was evidenced by the situation in the Garonne River (France), where shallow aquifer recharge led to a significant rise in GW levels, which, in turn, enhanced the baseflow of the river (Asmael et al., 2023). A study on the South Palette River (Colorado, USA), an alluvial river to augment low-flow with MAR using numerical modeling, illustrates the potential of increased stream flow accretion using an engineered recharge system (Ronayne et al., 2017). The present research work has been motivated by the aforementioned research outputs around the world that apply to the Varuna River basin. The study on the baseflow restoration with injection wells is limited and only covered by Ferencz et al. (2024) and has been applied to the arbitrarily chosen candidate locations.

The physically motivated, numerical GW flow models are widely applicable tools to simulate the surface-water and GW interaction (Anderson et al., 2015; Barlow and Leake, 2012; Leake et al., 2010; Webb and Leake, 2006). Numerical models are essential for simulating river-aquifer exchange (RAE) and evaluating the impacts of Managed Aquifer Recharge (MAR). These three-dimensional mechanistic simulations provide crucial

insights into hydrologic exchange dynamics, enhancing our understanding of how MAR influences baseflow (Anderson et al., 2015; Asmael et al., 2023). By accurately representing the interactions between SW and GW, these models capture the effects of varying GW levels and recharge rates on aquifer behavior and, hence, on the baseflow (Lee and Ajami, 2023). Compared to analytical solutions, which only represent the simplified GW dynamics, Numerical models can simulate multilayered and heterogeneous aquifers with complex stresses.

Based on the above discussion, it is evident that the efficacy of injection well systems for stream flow restoration is a new research dimension and needs comprehensive assessment. To bridge this gap this chapter discusses and demonstrates the detailed baseflow response to the injection signals. It is also evident that in most cases the weighted overlay analysis with multicriteria decision methods is used to determine the suitable site for MAR (Tewari et al., 2023), which often utilizes remotely sensed data with indirect field observations. Recent research works of R. Shandilya have demonstrated the use of analytical methods to map the aquifer response of injection and have shown promising results in determining the suitable recharge zone identification (Shandilya et al., 2022b). R. Kumar has extended the work of R. Shandilya to determine the suitable subbasins for MAR applications by utilizing the aquifer response to injection with a Numerical model (Kumar et al., 2024). With a focus on the base flow restoration potential of an injection well-field, we propose a metric named “Base Flow Enhancement Ratio (BFER)” to map the extent to which a baseflow restoration with MAR can enhance the stream flow. The research objectives addressed in this chapter are as follows:

- Determine the response of the baseflow of a stream to injected water.
- Framework to determine the BFER
- Assessment of MAR in VRB for the Baseflow Restoration.

6.2 RESPONSE OF INJECTION WELL TO STREAM FLOW

The analytical solution for the head dissipation by Jenkins et al. (2019) suggests that the dissipation of the head raised due to water injection into the aquifer depends on the time and aquifer conductivity. The response of the injected water pressure on stream flow is mainly determined by how quickly the pressure head travels from the injection point to the nearby stream cell. When water is injected into the aquifer, it elevates the GW potential, and this increased potential then spreads outward. The 1D propagation of the pressure head is given by the diffusivity equation (Boussinesq equation) (Freeze and Cherry, 1979):

$$\frac{\partial h}{\partial t} = D \frac{\partial^2 h}{\partial x^2} \quad 6.1$$

Where $D = K/S_y$ is the hydraulic diffusivity. The velocity of the pressure wave (v_p) in the unconfined aquifer is governed by the hydraulic diffusivity and can be approximately given as (Welch et al., 2013):

$$v_p \approx \sqrt{D} = \sqrt{\frac{K}{S_y}} \quad 6.2$$

The pressure waves propagate slower in unconfined aquifers than in unconfined aquifers since the Specific Yield (S_y) is larger than the Specific Storage (S_s). when compared to the actual seepage velocity of injected GW under the influence of the raised hydraulic gradient (i.e., darcy velocity/ porosity), the velocity of head propagation is much higher. This phenomenon results in a quick change in the hydraulic gradient in the aquifer (Lin et al., 2019; Zhu et al., 2024), resulting in the quick response of baseflow increase rather than actual water travel from the injection well to the stream.

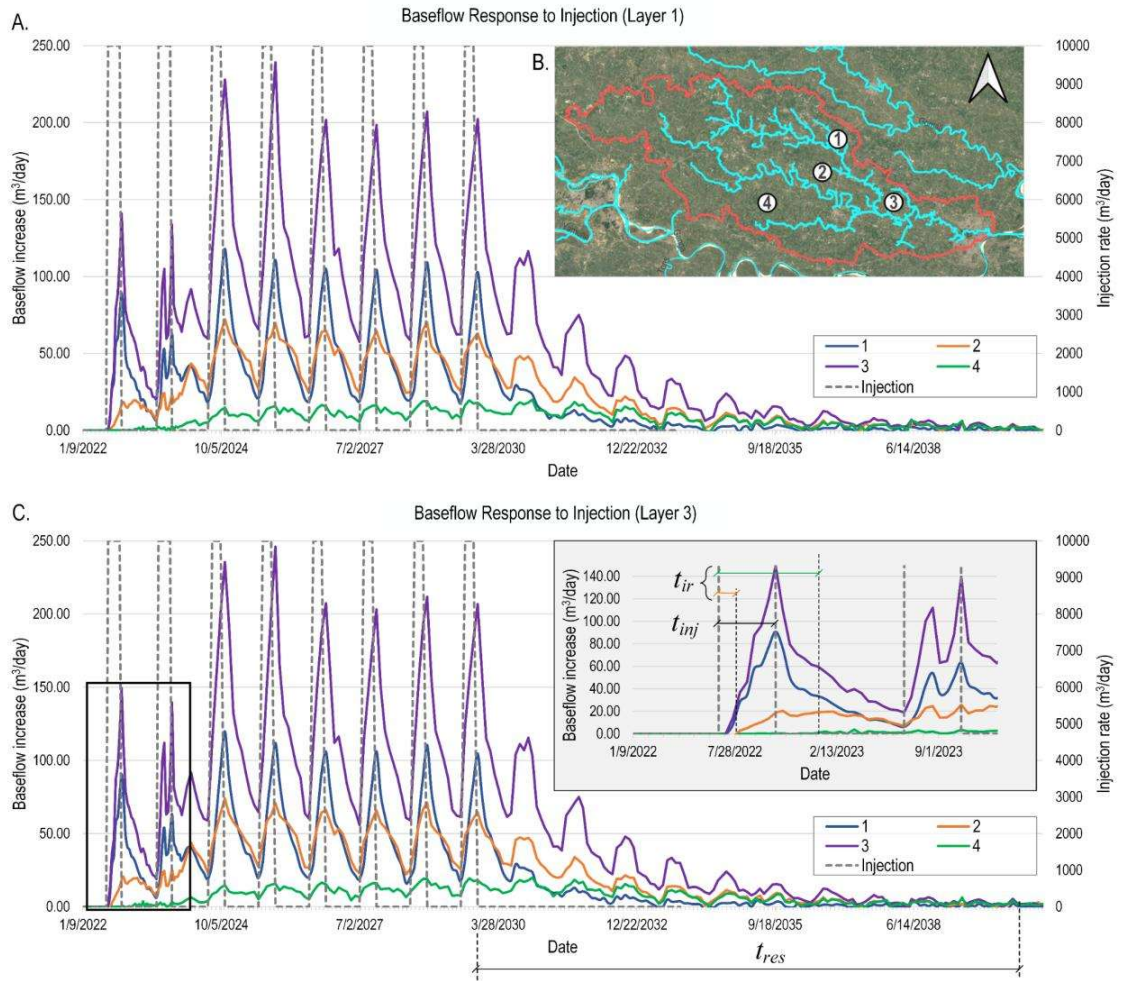


Figure 6.1. Plot of the change in stream flow due to an injection well with screen in Layer 1 (plot A) and Layer 3 (Plot C) as in Map B. Plot C has been enlarged to represent the different parts of the response curve.

The time lag between the start of the injection to the initial response (t_{ir}) depends upon the aquifer properties and the distance (Welch et al., 2013; Zhu et al., 2024). The effect of periodic injection signals on the stream flow has been simulated with a calibrated GW flow model and plotted for four different locations in VRB (**Figure 6.1**). The locations have been injected with a rate of 10^4 m³/day for the 3-month duration during monsoon season (July-September). Based on the heterogeneous aquifer properties of the VRB alluvium, all the response curves have shown different variations (Ferencz et al., 2024). The initial response lag for locations 1 and 3 is about 14 days due to the proximity to the

river, and it has a flashy response compared to others. Location 2 is situated between the Basuhi and Varuna rivers and has a response lag of approximately 31 days. In contrast, location 4 is far from the stream and has shown an initial response time (t_{ir}) of more than 6 months.

The magnitude of the baseflow increase or enhancement is highly variable and depends on the aquifer properties and regional GW hydraulic gradient and has been analyzed in the following sections. It is observed that the location that shows a flashy response during injection also attenuates rapidly after the injection has been stopped (**Figure 6.1**). Compared to others, the base enhancements attenuate slowly for location 2. The magnitude of stream enhancement has been found to vary with a minimal amount across different layers of injections. In the model conceptualized as a leaky aquifer, injecting water into the lower strata leads to slightly higher peaks due to the greater hydraulic conductivity of layer 3 compared to layer 1. The recession time (t_{res}) is the total elapsed time for the stream flow to shift from the excited state to the initial state in case of the end of the injection operations (**Figure 6.1**). The slope of the recession curve varies across the locations, following the antecedent hydraulic seasonality. The value of t_{res} has been observed to vary over the years depending upon the draining capacity of the aquifer and GW extraction.

6.3 BASEFLOW ENHANCEMENT RATIO (BFER)

The concept of “capture fraction” was introduced by Leaky et al. (2010) to determine the river fraction of extracted GW from a pumping well. The method to determine the map of these capture fractions (known as capture map) has also been presented with a 3D GW model, with Stream flow simulated with the SFR package. A similar terminology has been

presented by Ferencz et al. (2024) in the case of an injection well modeled into a regional GW model. Stephen B. Ferencz called the ratio of enhanced baseflow to the recharged volume of water the Return Ratio. The term closely resembles the general terminology of return flow from the agricultural Managed Aquifer Recharge (Ag-MAR) (Morrisett et al., 2024), which is the amount of recharged water coming to a nearby stream. Forwarding the work of Stephen B. Ferencz, we have explicitly defined the total baseflow enhanced due to the unit volume of water injected to an ASR system as the baseflow enhancement ratio (*BFER*).

If a well is being injected with a rate of Q_{inj} for a duration of t_{inj} the response curve of the stream flow follows the blue line in **Figure 6.2**. The initial delay in the response (t_{ir}) and the recession time for periodic injection systems (t_{res}) has been presented with respect to the response curve. Due to periodic injection operations, the stream flow response fluctuates, increasing from the antecedent discharge and reaching a maximum value due to a sudden increase in the GW head near the stream. The peak value depends on the head difference generated in the aquifer to the stream. The peak is achieved after a lag time after the injection has been stopped, and it is approximately equal to the initial response lag time (t_{ir}). The flow recedes to the antecedent flow rate or a value larger, depending upon recession time. If recession time is larger than the duration between injections, the response curve terminates above the antecedent flow rate, and the net stream flow follows an increasing trend due to periodic injection.

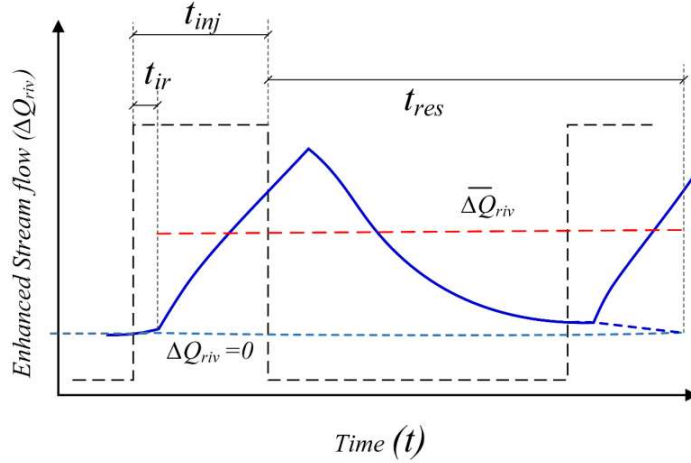


Figure 6.2. The conceptual response curve of baseflow enhancement

Based on the plot (Figure 6.2), the *BFER* has been determined as the area under the response curve for total response duration divided by the total injected water. For numerical models where the outputs are discretized into time steps, the *BFER* has been determined by taking mean stream flow enhancement for the response duration. Similar to the capture fraction, the non-linearity in the GW model due to external sources and sinks can impart uncertainty in determining *BFER*. The cumulative values of the multiple (30 years) periodic injection operations have been selected to minimize the uncertainty due to varied source sinks, as described by Nadler et al., (2018) for non-linear GW models for capture determination. For MODFLOW model outputs, the *BFER* is given as:

$$BFER = \frac{\text{Total volumetric RAE enhancement}}{\text{Total injected volume}} = \frac{\overline{\Delta Q_{riv}} \cdot T}{n \cdot Q_{inj} \cdot t_{inj}} \quad 6.3$$

Given,

$$\overline{\Delta Q_{riv}} = \frac{1}{T} \sum_{t=t_{ir}}^T \Delta Q_{riv,t} \cdot \Delta t_t \quad 6.4$$

$$\Delta Q_{riv,t} = \dot{Q}_t - Q_{0,t} \quad 6.5$$

and,

$$T = n \cdot t_{inj} + t_{res} - n \cdot t_{ir} \quad 6.6$$

Where Q_{inj} is the water injection rate; $\Delta Q_{riv,t}$ is the difference between stream flow rate with injection (\dot{Q}_t) and without injection i.e. baseline streamflow ($Q_{0,t}$) at time step t ; Δt_t represents the duration of the time step t ; T is the total time for which the stream flow has been enhanced and given by Eq.6.6; t_{inj} is the time steps during injection operation; t_{res} is the recession time after the injection is stopped, and t_{ir} is the response delay after the starting of the injection operation.

The *BFER* for the Varuna River basin has been determined using the calibrated MODFLOW-NWT model. A Python program has been prepared to simulate the injection well with seasonal injection (rate of 10^4 m³/day) during monsoon periods in each model grid. The stream flow change ($\Delta Q_{riv,t}$) for each time step was determined at the outlet of Varuna River, and the corresponding *BFER* for each cell was determined. The t_{ir} and t_{res} are important for determining *BFER*. The time series of the difference (say “signal”) between the stream flow in the initial state and the altered state (after injection) has been passed through the Savitzky-Golay filter (`savgol_filter` in `scipy.signal` class in the Scipy library) to get a smooth signal without the seasonality. A threshold signal value has been determined by taking the mean of the last 5-year signal. The time step at which the signal attains the threshold value is the end of the recession period. Using a 5-year signal in this study adequately removed the effect of noise on the simulated signals. The t_{res} were then determined by taking the time between the end of the injection and the

recession period. The t_{ir} has been determined by taking the difference between the start of the injection and the first non-zero signal.

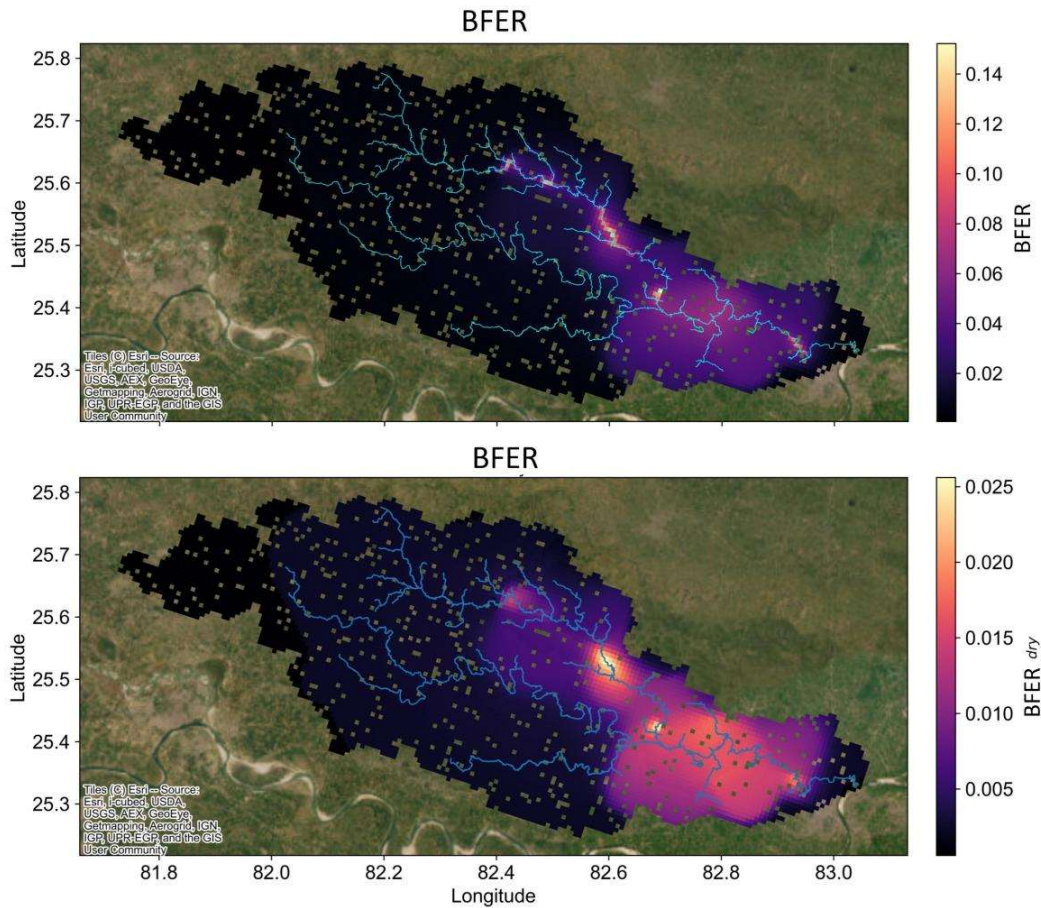


Figure 6.3. *BFER and BFER for the dry period in VRB*

The *BFER* values show a variation from 0.001 to 0.14 across the VRB when determined for the whole water year (**Figure 6.3**). The *BFER* for only dry season has also been determined to get the stream enhancement during low flow periods (**Figure 6.3**). The dry season *BFER* varies from 0.002 to 0.025, which is lower than the *BFER* for the whole water year. This represents the higher response of injection to the streams during the injection period and after the stream flow attenuates. The phenomena can be understood by revisiting the drawdown behavior after pumping in unconfined aquifers. During

injection, the buildup rate near the injection well is influenced by the elastic deformation of the aquifer, which transitions to gravity drainage in the influence of residual build-up in the aquifer after the injection has been stopped (Mao et al., 2011). The shift in the mechanism of stream flow response from head propagation to seepage under gravity results in delayed baseflow enhancement signals. As the buildup at the injection point diminishes, the seepage force decreases due to a reduced hydraulic gradient, resulting in a decline in the enhanced baseflow.

It is also observed that the number of locations of significant baseflow enhancement increases in the case of dry months. This is due to the fact that the delayed signals reach the streams during the recession time. The longer non-injection periods provide adequate time for the seepage signals to reflect as the enhanced baseflow. It is noted that the stream response was observed at the VRB outlet. The time required for the RAE flux to travel to the outlet has been neglected in the study as this time is significantly lower (approximately 2 -8 days) than the total response time (months). The stream responses should be measured at each river segment for local-scale studies.

6.4 DISCUSSIONS

6.4.1 Capture Fraction vs BFER

The *BFER* represents the total stream flow enhanced per unit of water injected into an ASR system. In contrast, when applied to injection wells, the capture fraction concept represents the stream flow enhanced during the injection period. The fundamental difference between the two can be understood by the conceptual diagram in **Figure 6.4(A)**. The capture fraction is determined by taking the overall stream flow increase/decrease due to continuous injection/pumping by a test well in the MODFLOW grid (Leake et al., 2010). This implies that the stream response considered in the determination of the capture fraction only corresponds to the shaded area in cyan (**Figure**

6.4(A)). In the case of *BFER*, the total stream flow enhancement, even after the injection is stopped, is taken into account (as represented by the area shaded in cyan and orange together). This makes *BFER* advantageous for accurately representing restored baseflow by considering the recession time of streamflow response, which capture-fraction neglects.

To compare the interrelationship between *BFER* and capture fraction, both parameters have been determined for the Varuna River in response to the yearly periodic (3 months of rainy season) injection for 10 years. The capture has been calculated using the method given by Leake et al. (2010). Both the data have been normalized to determine the yearly capture fraction or *BFER* (**Figure 6.4 C** and **D**). The recession time for the location far from the stream network is longer than the location near streams due to the time lag for the head attenuation (Welch et al., 2013). This extended response time from these locations influences the capture fraction, as numerous locations distant from the stream cells have had their contributions to stream flow underestimated (**Figure 6.4 D**). The *BFER* reflects the delayed response of injected water to streams by considering the total recession time, which indicates the overall contribution to stream flow (**Figure 6.4 C**).

The magnitude of *BFER* is approximately 57.4 times higher than the capture fraction. This can be justified because most stream enhancement takes place during a prolonged recession period after the injection has ended. The joint plot with the fitted regression line has been presented in **Figure 6.4 B**. The marginal histogram shows the skewed distribution of *BFER* and capture fraction, and the lower bins have most of the data population. The high values are low in numbers and mainly limited in the vicinity of the Basuhi River. The area after the confluence has also shown good stream enhancement capabilities.

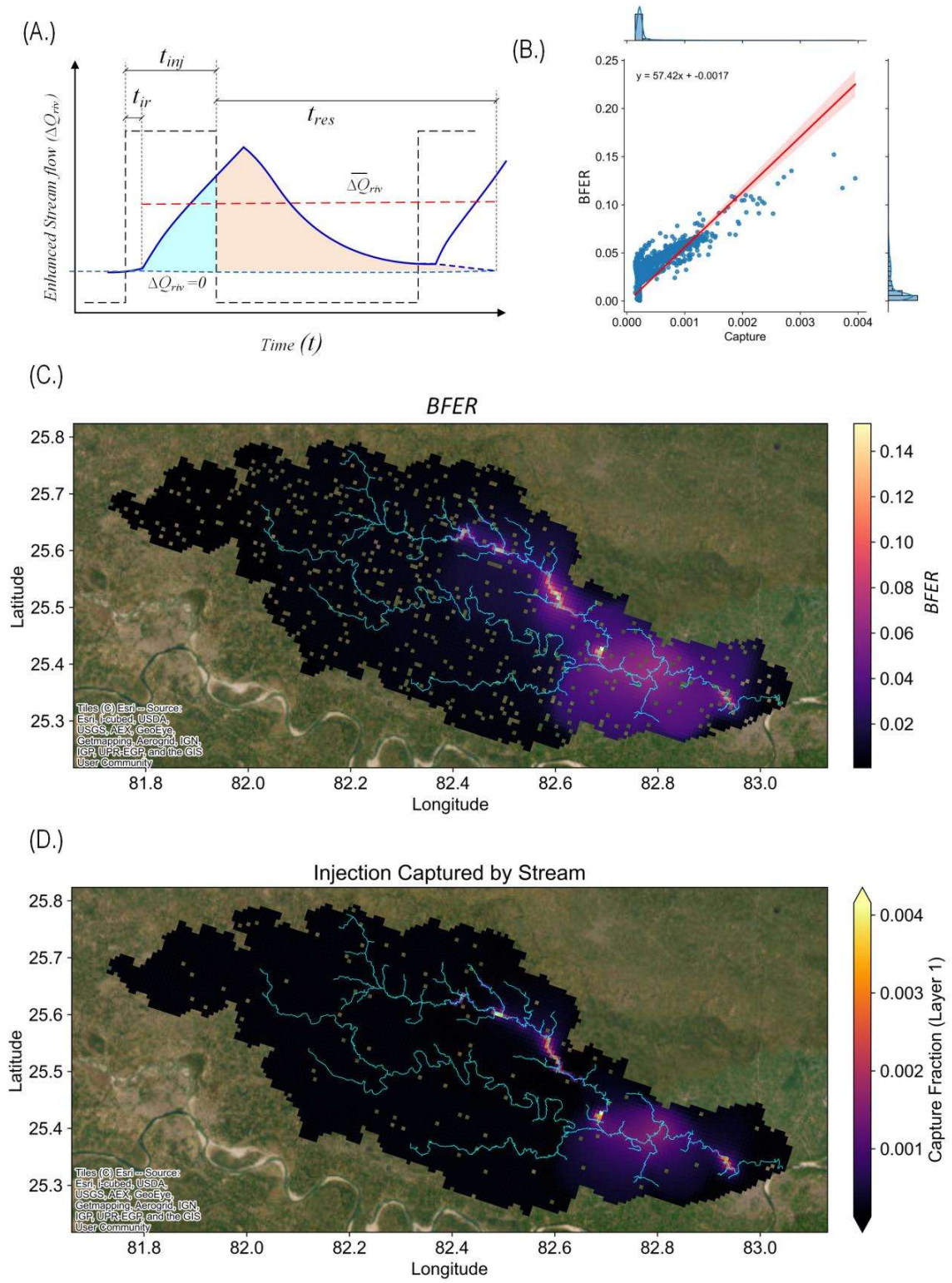


Figure 6.4. (A.) plot of stream response due to injection signals, (B.) scatter plot between capture fraction and BFER in VRB along with marginal histograms, (C.) The BFER in VRB plotted for each MODFLOW grid, and (D.) The capture fraction for Varuna River (plotted for each MODFLOW grid)

6.4.2 The initial response lag and recession time (t_{ir} and t_{res})

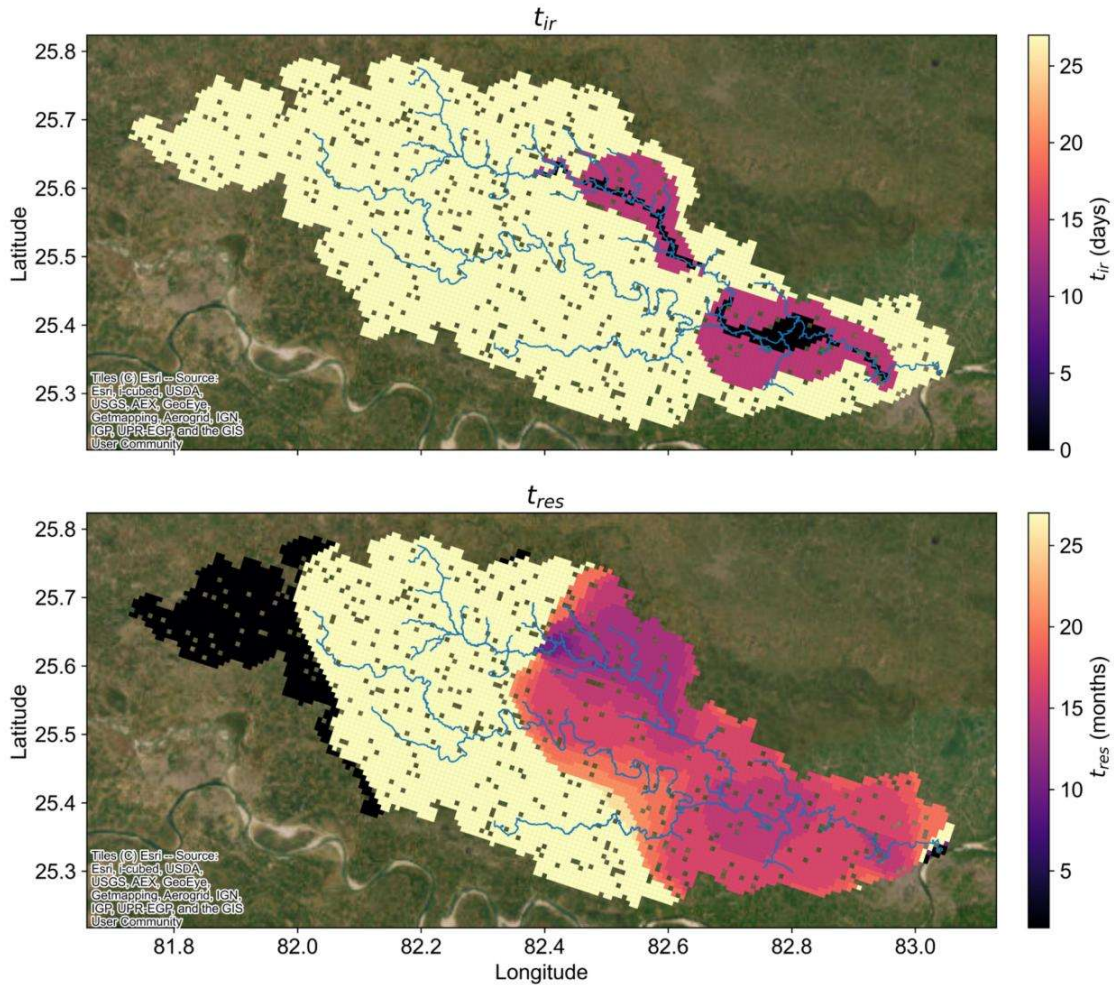


Figure 6.5. The spatial variation of initial response time (t_{ir}) and recession time (t_{res})

The initial response and recession time are important decision-making parameters for strategically retiming the surplus water to be stored as GW and further getting the delayed flow in the form of baseflow. It can be inferred that the quick response of baseflow enhancements is related to high-conductive aquifers. The recession time is generally low for the areas having a quick initial response time, leading to faster attenuation of enhanced

baseflow. This becomes significant in the case of areas with very high conductive aquifers such as alpine areas. The low recovery efficiency due to the rapid loss of recharged water to rivers makes it unsuitable for ASR projects.

The t_{ir} in VRB is fairly adequate, ranging from 2 days to 28 days (mean of 24 days). The temporal resolution of t_{ir} depends on the simulated time steps, leading to coarse estimates in this study (**Figure 6.5**). The highest t_{ir} values are concentrated in the western and central parts of the region. In contrast, the eastern areas have lower t_{ir} values. The areas with shorter initial response times appear to be clustered along lower Basuhi river networks and after confluence. The recession time in VRB has shown a variation of 3 to 27 months with a mean of 19.5 months (**Figure 6.5**). The longer recession time is distributed in the middle part of the basin, while the eastern part shows high variability, possibly due to the active hydraulic connection between the river and aquifer. The western part has a significantly low recession time.

6.4.3 Correlation of BFER to aquifer parameters and proximity to river

The variability of *BFER* with various conditioning parameters has been determined by plotting the marginal joint regression plots. The top and right side of the plot shows the histogram of the corresponding variable. A linear regression line has been fitted to determine the nature of correlation between the two variables.

BFER have right-skewed distribution, showing high values to the cells in close proximity to the river. The *BFER* shows a negative correlation to the proximity to the stream network (**Figure 6.6 B**). The histogram of proximity to the stream represents a left-skewed distribution with a uniformly decreasing number of grids. Most locations have low *BFER* values in the range of 0.0 to 0.07.

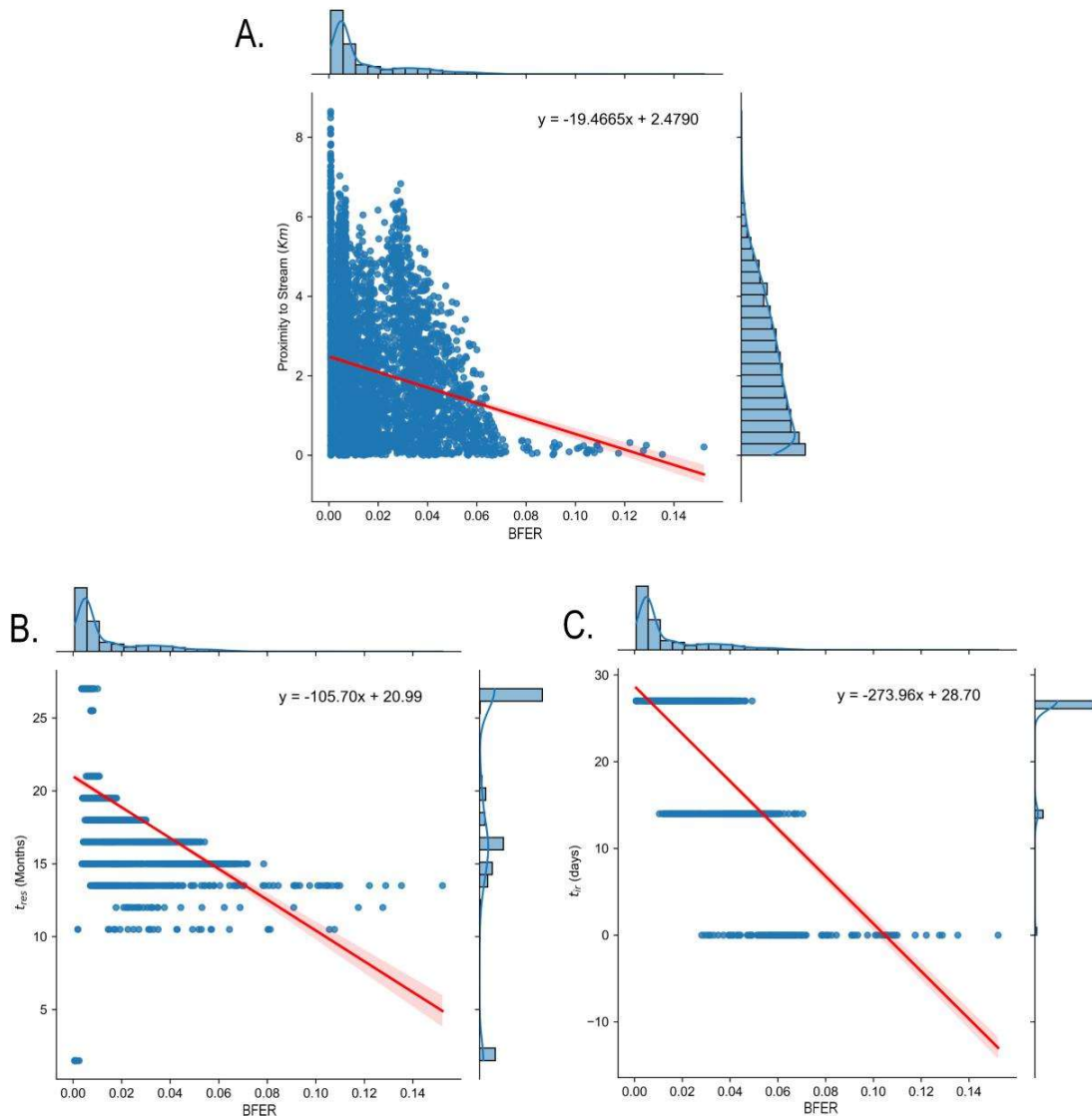


Figure 6.6. Marginal joint plots between *BFER* and (A.) Proximity to stream networks, (B.) the recession time (t_{res}), and (C.) the initial response time (t_{ir})

The t_{res} and t_{ir} have shown a strong negative correlation to the *BFER* (Figure 6.6 C and D). The high recession time does not ensure a high *BFER*. This is valid for low t_{res} also. It is found that the locations with a t_{res} from 10 to 15 months have shown high *BFER* values in VRB. Although the data is very sparse, the t_{ir} has shown a strong negative correlation to *BFER*. The lowest bin of t_{ir} corresponds to the highest *BFER* values.

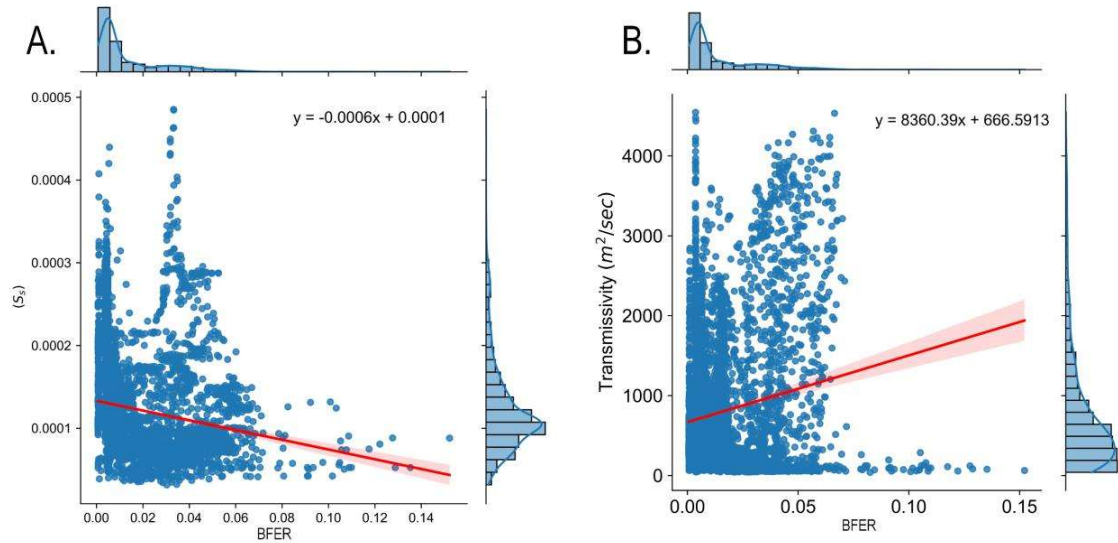


Figure 6.7. Marginal joint plots of *BFER* vs (A.) Storage coefficient (S_s) and (B.) Aquifer Transmissivity (T)

Aquifer properties can have a significant effect on the head propagation velocity (Welch et al., 2013). The storage coefficient has shown a weak but negative correlation with *BFER* (Figure 6.7 A). The S_s in VRB is normally distributed, with less frequent high values. Most grids have S_s values in the range of 0.000026 to 0.00018, which correlate with higher values of *BFER*. To examine the impact of aquifer thickness and hydraulic conductivity, the *BFER* has been correlated with Transmissivity. The relationship between transmissivity and *BFER* is positive, indicating that higher *BFER* values generally correspond to higher transmissivity. However, there are numerous outliers in the data, as proximity to rivers tends to negatively affect *BFER*. In areas near streams, lower transmissivity values can sometimes lead to elevated *BFER* readings.

6.4.4 The fate of baseflow restoration using ASR system in VRB

The analysis presented above shows that the baseflow restoration through ASR depends on many variables. The studies show that the natural baseflow generally decays exponentially with time after rainfall events, and this recession is highly dependent on the

geology groups, capacity for recharge, and transmissivity of bedrock and soils (Lacey and Grayson, 1998; Singh, 1968). Baseflow augmentation through ASR is justified in areas due to its benefits, such as increased summer flows, healthier riparian areas, and improved water quality and habitat (V. M. Ponce and Lindquist, 1990).

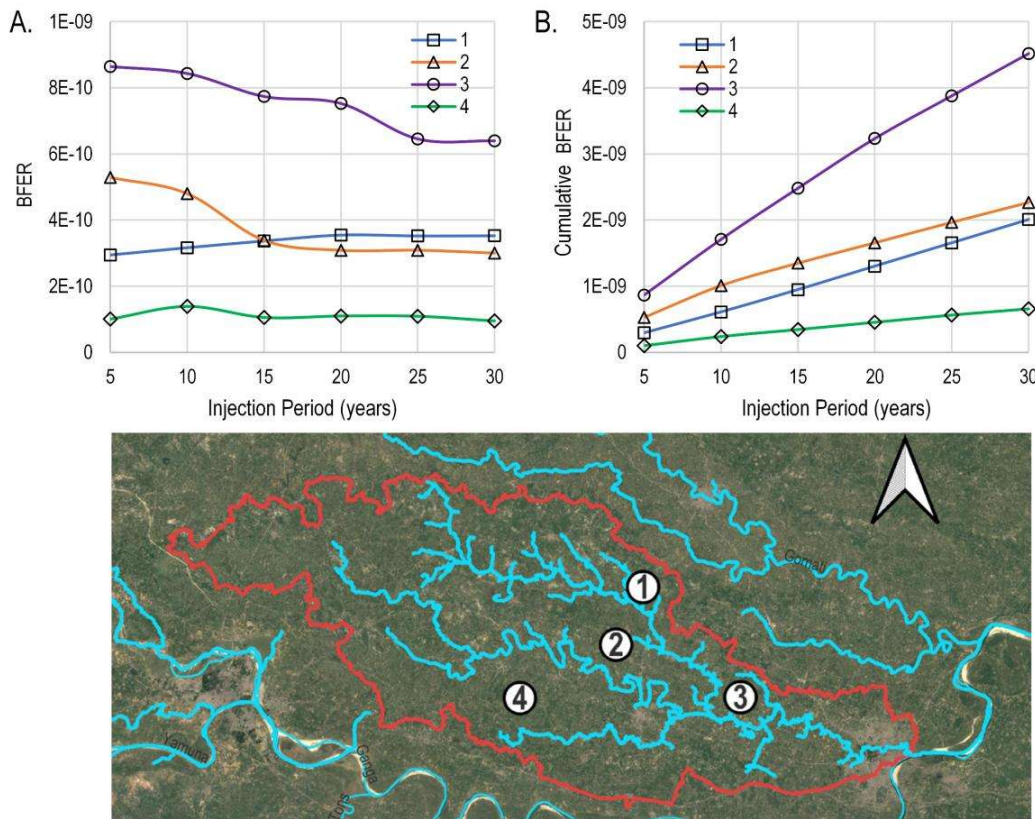


Figure 6.8. BFER Dynamics with respect to injection period (A) the BFER for each 5-year injection starting from the year 2021, (B) the cumulative BFER up to 30 years of injection.

The enhancement of the natural baseflow by the ASR system can be very beneficial in the case of small river basins such as the Varuna River. The main benefit of ASR projects is that they can achieve water security and sustainability under growing demand and climate change (Dillon, 2005). The buffer storage raised by storing surplus water reduces the stress on GW storage, resulting in the prevention of recent aquifer subsidence in the study area (Kelley et al., 2020; Tripathi et al., 2022).

The stream enhancement represented by *BFER* per 5-year injection has been plotted in **Figure 6.8A**. The *BFER* is significantly influenced by the hydrologic conditions associated with the interaction between aquifers and rivers. When the injection of water stops and the resulting enhanced streamflow begins to decrease, the response depends on the time interval associated with the injection periods. If the recession time (t_{res}) is longer than the interval between two injection periods, the streamflow starts to increase again, surpassing the previous enhanced flow level. However, if t_{res} is shorter than the injection interval, the streamflow will revert to its natural levels, and the next injection will again enhance the streamflow from these initial flow rates. This increase in the antecedent flow rate results in increased *BFER* for a longer injection duration.

Due to the dependency on the antecedent stream flow, the *BFER* varies along different injection durations because of increased GW demand and variability in the precipitation pattern in the basin (**Figure 6.8A**). Locations 1 and 4 manifest more or less stable *BFER* in each 5-year injection interval in the study area. Locations 2 and 3 have shown a decreasing *BFER*, which represents the influence of climate change and GW demand. The cumulative *BFER* of these recharge events represents total stream enhancements up to 30 years of injection (**Figure 6.8B**). As a secondary objective of Aquifer Storage and Recovery (ASR) in the area, it can restore the river's base flow by up to ~ 0.3 to 2.4 % of the current dry flow with a single ASR system. This assumes an injection rate of 10000 m³ per day for three months each year over a period of 30 years, which is conservative given the flood water availability and aquifer recharge capacity of the area.

6.4.5 Benefit of the GW Model-based Analysis

The measurement of stream response in the field is quite challenging and costly. The accurate determination of locations of RAE to monitor the baseflow enhancement is crucial before applying the ASR systems on the field. The analytical solutions to stream

depletion by a pumping well can be used for this study, such as changing the well extraction to injection. However, the simplified 2D approach of these analytical solutions limits their ability to simulate real field stresses. Numerical models, on the other hand, can offer several advantages over analytical solutions, particularly in their ability to handle complex and realistic scenarios. The key advantages such as (1) finite-difference and finite-element methods can handle three-dimensional, nonhomogeneous, and anisotropic conditions often encountered in real-world GW systems while analytical solutions are typically limited to simpler, idealized cases (Freeze and Witherspoon, 1966; Fujinawa, 1977; Meenal and Eldho, 2011), (2) the numerical models can incorporate nonlinear equations and heterogeneous conditions, which are common in natural GW systems. This capability is crucial for realistic simulations and accurate predictions (Hwang et al., 1985; Serrano, 2013), and (3) Numerical models can be easily adapted to real field conditions, allowing for the simulation of various scenarios such as pollutant transport, GW contamination, and thermal plumes. This adaptability is essential for effective GW management and decision-making (Fujinawa, 1977; Pophillat et al., 2020).

With the added advantage of simulating real field stresses and aquifer conditions, the determination of *BFER* from numerical GW models can be justified. However, proper care should be taken in the calibration of aquifer and river parameters for simulating RAE. The Numerical modeling, added to modern geophysical investigation methods, such as Transient Electromagnetic (TEM) surveys, can reduce the uncertainty in simulating river and aquifer dynamics and MAR (Parker et al., 2022a). The detailed aquifer and riverbed characterization of TEM systems can enhance the regional GW models (Lévesque et al., 2021). Development in continuous GW table monitoring along with stream discharge measurement with IoT devices in the study area enhances GW model calibration.

6.5 SUMMARY

This chapter introduces a framework for assessing baseflow restoration using a numerical model, highlighting the Baseflow Enhancement Ratio (BFER), which measures the stream's response to injection signals. This index is designed to facilitate easier decision-making and is detailed in terms of its background and sensitivity to aquifer parameters.

Key findings from the assessment indicate that the baseflow response, simulated with the MODFLOW model using an injection well and arbitrary signals, varies based on well locations. The response curve's characteristics allowed the mapping of total baseflow enhancement against the *BFER*. It was observed that the *BFER* displayed low enhancement rates in the Varuna River Basin (VRB), especially when injections targeted the shallow aquifer. Most areas in the subbasin 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 factors such as antecedent stream flow, increased GW demand, and variable precipitation patterns. The use of a single Aquifer Storage and Recovery (ASR) system, operating at an injection rate of 10,000 m³/day during the monsoon months, could potentially restore 0.3% to 2.4% of the current dry flow in the Varuna River.
