Quantification of Baseflow Enhancement due to Managed Aquifer Recharge

Quantification de l'amélioration du débit de base due à la recharge gérée des aquifères

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RÉSUMÉ

Les critères de conception des ouvrages de recharge des aquifères manquent souvent de paramétrage adéquat des augmentations des débit de base suite à la recharge en raison de l'absence de méthode de quantification. Dans cette étude, la quantification des échanges nappes - rivière a été étudiée à l'aide d'un modèle hydrogéologique numérique couplant eaux de surface et eaux souterraines. La réponse positive des débits de base des cours d'eau dues à l'injection périodique d'eau dans la nappe sur plusieurs zones d'un bassin versant a été analysée pour déterminer l'augmentation du débit de base à l'aide d'un nouvel indice appelé Baseflow Restoration Index (BFRI). Le BFRI représente le pourcentage d'augmentation du débit en lien avec le débit d'injection unitaire d'eau. Le volume d'augmentation du débit de base a été déterminé par le taux de retour d'injection (IRR), qui représente l'augmentation totale du débit du cours d'eau due à l'injection d'eau unitaire. Le BFRI a été dérivé du IRR. Les sensibilités du BFRI et de l'IRR aux paramètres de l'aquifère (transmissivité et stockage spécifique) ont été étudiées en détail. Ce travail a été mis en œuvre dans le bassin versant de la rivière Varuna en Inde. Les résultats montrent qu'une surface Importante du bassin versant de la Varuna présente de faibles valeurs de BFRI, ce qui indique une faible potentialité de nombreuses zones aux projets de restauration du cours d'eau.

ABSTRACT

The design criteria for managed aquifer recharge structures often lack adequate parameterization of baseflow enhancements due to the absence of a quantification method. The river aquifer exchanges in the complex groundwater systems have been determined using a coupled surface water and groundwater model. The response of the baseflow enhancements due to the periodic injection of water from an area has been analyzed to determine the baseflow enhancement using a novel Index named Baseflow Restoration Index (BFRI). The BFRI represents the percentage of streamflow enhancement with unit injection of water. The volume of baseflow enhancement has been determined by injection return ratio (IRR), which represents the total stream flow enhancement due to unit water injection. The relationship between BFRI and IRR has been established. The sensitivity of the BFRI and IRR to the aquifer parameters (Transmissivity and Specific Storage) has been presented. The framework has been implemented in the Varuna River Basin in India. The results show that a large part of the Varuna River Basin has low values of BFRI, rendering them less suitable for stream restoration projects.

KEYWORDS

Baseflow Restoration, Baseflow Restoration Index (BFRI), Injection Return Ratio (IRR), Managed Aquifer Recharge, Varuna River Basin

Restauration du débit de base, indice de restauration du débit de base (BFRI), taux de retour d'injection (IRR), recharge gérée de l'aquifère, bassin de la rivière Varuna

1 INTRODUCTION

Baseflow, the portion of streamflow that groundwater contributes, is vital in sustaining water availability and ecological balance during dry periods. The rapid decline in the groundwater 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 groundwater extraction to support the continued population growth has historically caused stream depletion, necessitating greater release from the surface water reservoirs (Ronayne et al., 2017) or canals (as in the case of the Varuna River Basin). The evaporative loss, land area requirements, and the cost of construction make the utilization of surface water reservoirs inefficient (Brown et al., 2019). To increase the water resource resilience to the probable climate change extremes and increased demands, an efficient management strategy is required (Ferencz et al., 2024).

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). 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.

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 research work discusses and demonstrates the detailed baseflow response to the injection signals. With a focus on the base flow restoration potential of an injection well-field, we propose an index named “Base Flow Restoration Index (BFRI)” to map the extent to which a baseflow restoration with MAR can enhance the stream flow. The research objectives are focused on three key areas: first, to determine the response of a stream's baseflow to injected water; second, to establish a framework for calculating the Baseflow Restoration Index (BFRI); and third, to assess Managed Aquifer Recharge (MAR) in the Valley River Basin (VRB) for the purpose of baseflow restoration.

2 INJECTION RETURN RATIO (*IRR*)

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 2.1. 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 groundwater 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.

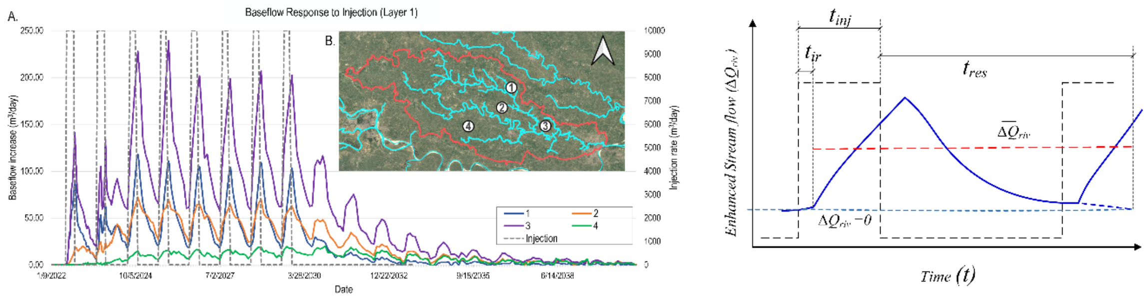

Figure 2.1. The simulated and conceptual response curve of baseflow enhancement

Based on the plot (Figure 2.1), the *IRR* will be 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 *IRR* will be determined by taking mean stream flow enhancement for the response duration. Similar to the capture fraction, the non-linearity in the groundwater model due to external sources and sinks can impart uncertainty in determining IRR. The cumulative values of the eight injection operations have been selected to minimize the uncertainty due to varied source sinks, as described by Nadler et al., (2018) for non-linear groundwater models for capture determination. For MODFLOW model outputs, the IRR is given as:

$$IRR = \frac{\overline{\Delta Q}_{riv}.T}{n.Q_{inj}.t_{inj}} \tag{2.1}$$

Given, $$\overline{\Delta Q}_{riv} = \frac{1}{T}\sum_{t=t_{ir}}^{T} \Delta Q_{riv,t}.\Delta t_t \tag{2.2}$$

$$\Delta Q_{riv,t} = \acute{Q}_t - Q_{0,t} \tag{2.3}$$

$$T = n.t_{inj} + t_{res} - n.t_{ir} \tag{2.4}$$

Where Q_{inj} is the water injection rate; $\Delta Q_{riv,t}$ is the difference between stream flow rate with injection ($\acute{Q}_t$) and without injection ($Q_{0,t}$) 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.2.4; 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.

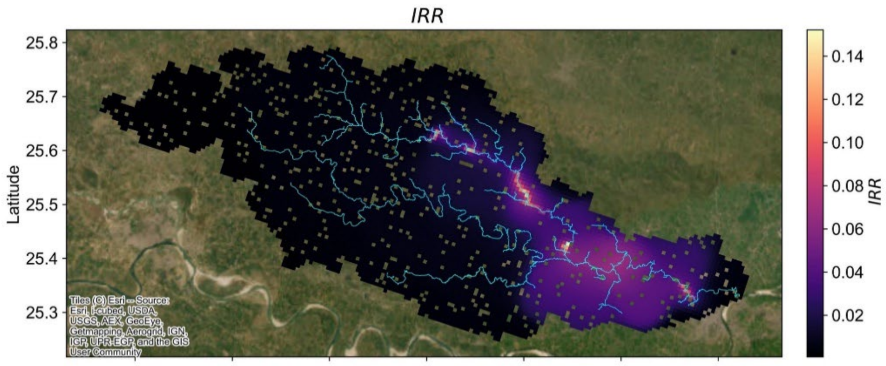

Figure 2.2. IRR in VRB

The IRR values show a variation from 0.001 to 0.14 across the VRB when determined for the whole water year (Figure 2.2). The number of locations of significant baseflow enhancement increases in the case of dry months. This is because the delayed signals reach the streams during the recession time. The longer non-injection periods allow 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.

3 BASE FLOW RESTORATION INDEX (*BFRI*)

Based on the response curve of stream flow to the given injection (Figure 2.1), The BFRI is given as the ratio of the mean enhanced stream flow rate ($\overline{\Delta Q}_{riv}$) to the initial stream flow rate (Q_{riv}) during time T. Similar to *IRR*, BFRI can also have uncertainty due to the non-linear behavior of the groundwater flow model. This study has used the cumulative response of multiple injection signals to minimize the uncertainty. If the n injection operation has been performed at a location, each having equal injection duration of t_{inj} and the mean streamflow rate during total response duration (T) BFRI is given as :

$$BFRI = \frac{\overline{\Delta Q}_{riv}}{\bar{Q}_{riv}}.\frac{100}{Q_{inj}} \tag{3.1}$$

Rearranging Eq. 6.3 for $\overline{\Delta Q}_{riv}$, the BFRI can be determined in terms of IRR as:

$$BFRI = \frac{100.IRR.n.t_{inj}}{\bar{Q}_{riv}.T} \tag{3.2}$$

The BFRI for the VRB has been determined using Eq. 3.1 (Figure 3.1). The BFRI exhibits a similar spatial pattern to the IRR. The percentage of baseflow enhancement per unit of injected water is very low in the VRB when injected into the shallow aquifer. Most parts of the subbasin do not significantly contribute to the enhancement of baseflow, as most of the significant locations are either near downstream of the Basuhi River or after the confluence (Varuna and Basuhi). The BFRI for the dry periods is ~20% lower than the whole water year.

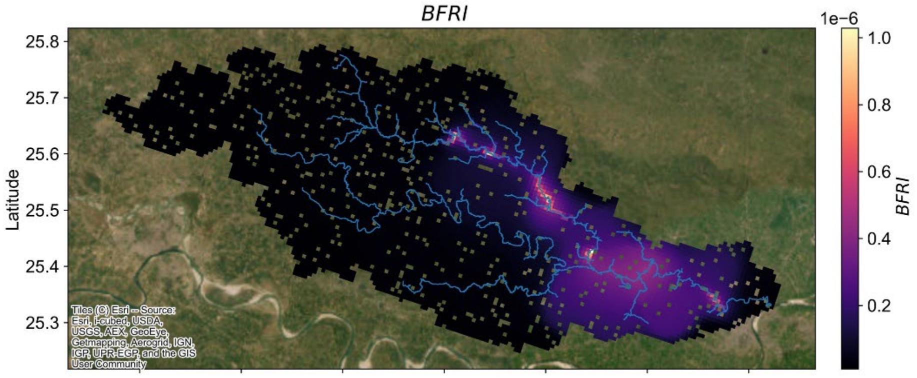

Figure 3.1. BFRI in VRB

4 CORRELATION OF BFRI AND IRR TO AQUIFER PARAMETERS

The variability of the Irrigation Return Rate (IRR) based on various conditioning parameters has been analyzed through marginal joint regression plots, which reveal a direct proportionality between the Base Flow Recharge Index (BFRI) and IRR. Both BFRI and IRR show right-skewed distributions, indicating higher values near rivers, while IRR has a negative correlation with proximity to the stream network. Most locations exhibit low IRR values between 0.0 and 0.07. Both transit time (t_{res}) and time of rise (t_{ir}) demonstrate strong negative correlations with IRR, with higher IRR values typically found in areas where t_{res} is between 10 and 15 months. Additionally, the specific storage shows weak negative correlations with IRR, while transmissivity has a positive relationship with IRR, suggesting that higher transmissivity usually corresponds to higher IRR values. However, outliers are present as proximity to rivers can lower IRR readings, even in areas with high transmissivity.

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