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Introduction

1.1 BACKGROUND

Groundwater (GW) is a crucial component of the global water cycle, serving as the largest unfrozen freshwater resource on the planet. It plays a vital role in maintaining the balance of the hydrological and biogeochemical cycles, supporting ecosystems, and providing essential services to human societies. GW interacts with over half of the land surface areas, influencing the integrity of many dependent ecosystems and acting as a keystone ecosystem that preserves surface biomes and biodiversity (Saccò et al., 2023). It is integral to the sustainability of streams, lakes, and wetlands and supports plant life and SW bodies by redistributing water in the subsurface (Condon and Maxwell, 2015; Hiscock, 2011).

In addition to its ecological significance, GW is a critical resource for human consumption, agriculture, and industry. It accounts for 30% of the world's freshwater, with 97% of extracted GW used for drinking and other human needs (Frappart and Merwade, 2022; Herrera-Franco et al., 2022). GW is often the last available freshwater resource in regions where SWs are depleted, especially in semi-arid areas and densely populated countries (Frappart and Merwade, 2022). It supports a significant portion of the world's irrigated agriculture, essential for food production (Hiscock, 2011; Siebert et al., 2010). However, GW resources are increasingly stressed by human activities and climatic changes, leading to issues such as depletion, contamination, and reduced recharge rates (Frappart and Merwade, 2022; Gorelick and Zheng, 2015). Addressing these challenges requires advanced GW management models and improved governance strategies to ensure the sustainable use of this vital resource (Gorelick and Zheng, 2015; Hiscock, 2011).

Besides water scarcity, GW depletion has significantly reduced baseflow in GW-fed rivers, leading to various environmental and hydrological impacts. In the Murray-Darling Basin (MDB) in Australia, historical patterns of GW extraction have necessitated increased environmental releases of SW to maintain baseflow in some river valleys. This is particularly evident in valleys where SW storage is insufficient to compensate for stream losses to GW, thereby threatening ecosystem sustainability during dry periods (Walker, 2022). Similarly, in the Little Plover River basin in Wisconsin, USA, GW withdrawals have reduced baseflow below legally established minimums, prompting the development of collaborative management plans to restore river flow rates while balancing the needs of various stakeholders (Fienen et al., 2018).

In the Sao Francisco River Basin in Brazil, a significant reduction in baseflow has been observed, with over 86% of the decrease in streamflow attributed to declining GW contributions. This reduction is linked to increased evapotranspiration and agricultural water use, exacerbating terrestrial water storage depletion (Lucas et al., 2020). Additionally, in the Republican River basin in the USA, GW-fed irrigation has altered the interaction between SW and GW. This leads to decreased baseflow and increased variability in streamflow patterns. This shift has changed the seasonal regime of GW storage, further complicating water management efforts (Zeng and Cai, 2013). These examples illustrate the critical role of GW in sustaining river baseflow and highlight the need for integrated water management strategies to mitigate the impacts of GW depletion.

1.2 DYNAMICS OF RIVER AQUIFER EXCHANGES

River-aquifer exchanges are critical processes that influence the quantity and quality of water resources in various regions. These exchanges occur when water flows between rivers and adjacent aquifers, as GW discharges into the river (gaining conditions) or river water infiltrates the aquifer (losing conditions). Several factors, including geological and geomorphic features, river stage fluctuations, and climatic conditions, can influence these exchanges and it's spatio-temporal variability. For instance, significant GW discharge to rivers was observed in the Columbia Basin in volcanic terrains, while fluvial recharge was more prominent in sedimentary basins with shallow aquifers (C. P. Konrad, 2006). Similarly, monsoonal precipitation events in South Korea caused frequent flow reversals between gaining and losing conditions, significantly impacting local water quality and biogeochemical transformations (Bartsch et al., 2014).

Moreover, the interaction between river water and GW is influenced by various factors, including river morphometry and local hydrological conditions. In the Kosi River basin, for example, the river-aquifer exchange flux varies spatially, with certain zones predominantly losing water to the aquifer and others gaining water from it (Laveti et al., 2021). This dynamic interaction is essential for sustaining baseflow in non-perennial tributaries, especially in regions with stable GW levels due to high annual rainfall and limited historical GW use (Lapworth et al., 2021). However, the over-extraction of GW and the shift in water management practices pose potential threats to these delicate hydrological balances, emphasizing the need for sustainable GW management to ensure the long-term viability of baseflow in the Ganga's tributaries (Mukherjee et al., 2018).

The non-perennial tributaries of the Ganga River exhibit a significant dependency on GW to maintain their baseflow, particularly during dry seasons. GW recharge processes, including local rainfall and river seepage, are crucial in sustaining these tributaries. For instance, in the Gandak catchment, GW baseflow is a dominant contributor to river discharge during the peak dry season when barrage gates are closed, ensuring ecological flows for local wildlife (Lapworth et al., 2021). Similarly, GW discharge into the river is highest during the pre-monsoon season in the Ganges basin, contributing up to 30% of the total river discharge, while post-monsoon contributions drop to 25% (Das et al., 2021c). This seasonal variability highlights the critical role of GW in maintaining river flow during periods of low precipitation.

1.3 BASEFLOW DEPLETION

Natural recharge is the primary driving source of the GW cycle, which actively contributes to the quantity of baseflow in a river basin. The natural recharge in the Gangetic Plain has been decreasing due to climate change and rising demand. Climate change has led to alterations in precipitation patterns, resulting in reduced and irregular rainfall, which diminishes the natural recharge of GW (Ahmed et al., 2014; Srivastava et al., 2021).

Variations in terrestrial water storage further complicate the water availability scenario (Biemans et al., 2019; B. Liu et al., 2020). The growing population and agricultural demands have exacerbated the situation, leading to over-extraction of GW for irrigation, especially during the dry season (B. Liu et al., 2020; Singh et al., 2020). Over-extraction depletes GW levels and increases the energy required for deeper water pumping, adding economic burdens on the agricultural community (Ahmed et al., 2014). Consequently, the combined effects of climate change and rising demand are significantly reducing the natural recharge rates in the Gangetic Plain, posing severe socioeconomic and environmental challenges (Ahmed et al., 2014; B. Liu et al., 2020; Srivastava et al., 2021).

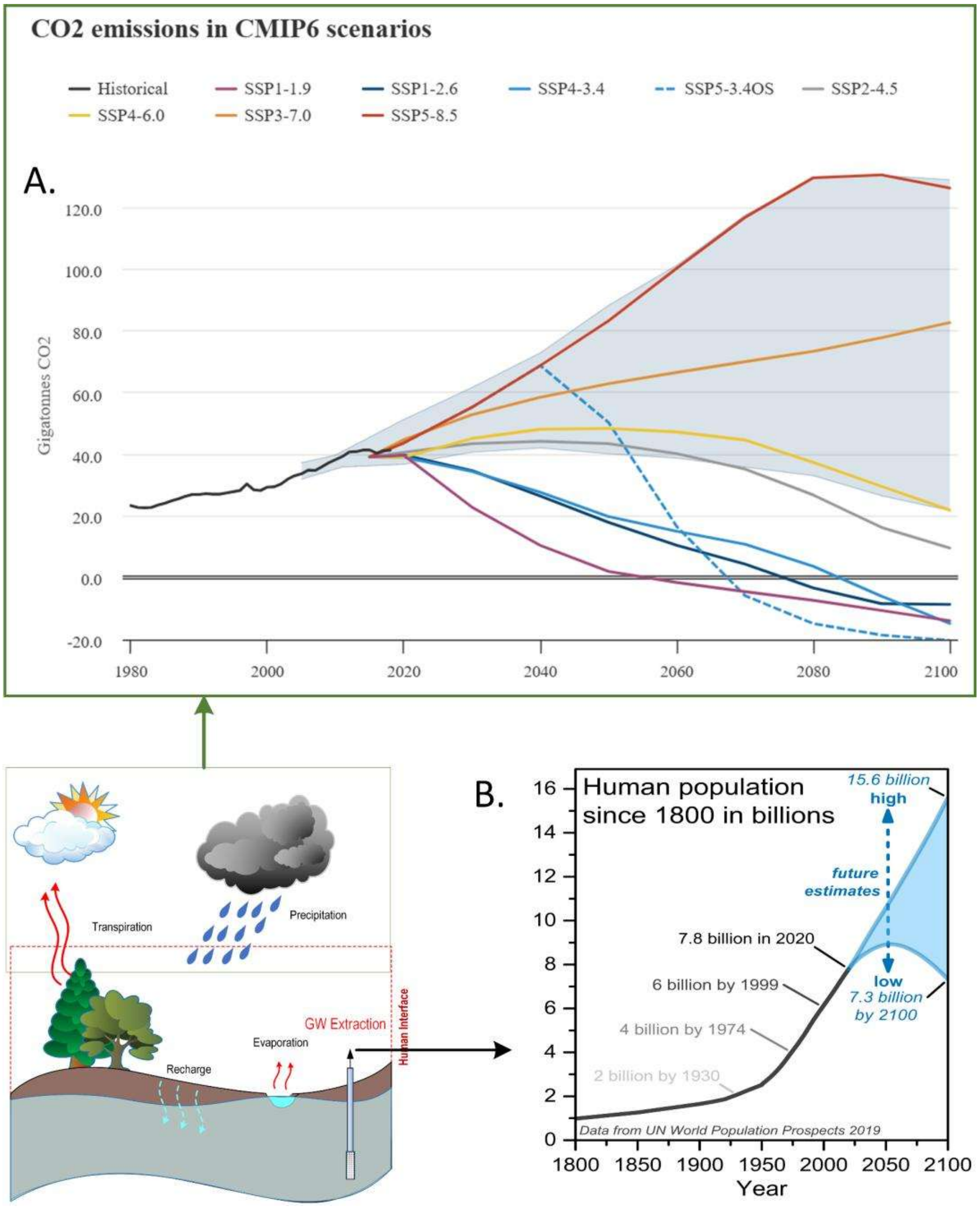

Figure 1.1. *The Impact of Rising Demand and Climate Change (A. The projected CO2 emissions*[1] *Under different Socio-economic Pathways (SSPs) and B. The projected human population growth*[2]*.)*

GW depletion in India has significantly reduced baseflow in GW-fed rivers, primarily due to reduced natural recharge and excessive GW extraction for irrigation and other

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[1] https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained/

[2] https://population.un.org/wpp/

anthropogenic uses (**Figure 1.1**). In regions such as northwest India, GW is being depleted at alarming rates, with studies showing a mean depletion rate of 4.0 ± 1.0 cm per year, which has led to a net loss of 109 km^3 of water over six years (Rodell et al., 2009). This over-extraction has reduced GW levels, reducing the baseflow that sustains river systems during dry periods.

For instance, the Betwa River basin has experienced a GW level decline of about 3-5 meters below ground level over the past two decades, mainly due to overexploitation for irrigation and reduced rainfall (Niranjannaik et al., 2022). Similarly, the Ganga River basin lost approximately 226.57 ± 25.22 km^3 of GW between 2002 and 2016, with non-renewable GW abstraction being the primary contributor (Dangar et al., 2021). These reductions in GW levels diminish the natural discharge into rivers, lowering baseflow and affecting the overall health of river ecosystems.

1.4 MANAGE AQUIFER RECHARGE AS A POTENTIAL SOLUTION

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 employing recharge wells. In the 1950s in California, 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). MAR methodologies (such as ASR, soil aquifer treatment, percolation tanks, bank filters, infiltration basins, and subsurface dams) are intended to purposefully introduce water into an aquifer from various sources for later use (Dillon, 2005). ASR has emerged as a popular water resource management strategy with a total 5% per year global increase in its implementation, especially in water-stressed areas of India, the US, Europe, and Australia (Dillon et al., 2019; Nättorp et al., 2016; Sprenger et al., 2017). 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 w.r.t the utilized surface area is much higher for the ASR when compared to infiltration basins (Händel et al., 2014).

MAR plays a crucial in restoring river baseflow by augmenting low flows during dry periods. This process involves artificially recharging and storing water in an aquifer, which can then be gradually released to maintain river flow. For instance, in the South Platte River, numerical modeling demonstrated that GW pumping during winter, followed by the pumped water delivered to recharge ponds, effectively increased streamflow during low-flow summer months. This retiming of streamflow helps to sustain river ecosystems during critical periods of low water availability (Ronayne et al., 2017). Similarly, in the Walla Walla Basin, MAR was shown to increase summer streamflow by raising GW levels, which enhanced GW discharge through springs and stream beds, benefiting aquatic habitats (Scherberg et al., 2014).

Moreover, MAR can be particularly beneficial in urban settings where stormwater is used as a recharge source. In London, a study explored the feasibility of using urban runoff for MAR, which could raise local water table levels and augment low river levels through baseflow. Although the study found limitations due to the insufficient thickness of the utilized unconfined aquifer, it highlighted the potential benefits of MAR in augmenting river flow, especially under more favorable conditions (Saleh et al., 2019). Additionally, in agricultural regions like California's Central Valley, MAR using agricultural lands for recharge (Ag-MAR) was shown to increase GW storage significantly and net GW contributions to streamflow, thereby enhancing baseflow during months with no recharge diversions (Kourakos et al., 2023b). These examples illustrate how MAR can be strategically implemented to restore and maintain river baseflow, supporting ecological and water supply needs.

1.5 RESEARCH MOTIVATION

Numerous MAR projects have been implemented worldwide, the main objective of which has been increasing GW storage for immediate or later use. The ecological benefits due to enhanced baseflow have always been secondary objectives or, many times, additional benefits. Baseflow restoration has not been taken as a primary objective in Managed Aquifer Recharge (MAR) (**Figure 1.2**).

One of the main reasons can be associated with the complex nature of the subsurface flow process, which makes it difficult to model the effects of various stormwater management techniques on catchment baseflow. This complexity arises from the interactions between physiographic and anthropogenic factors, which affect the baseflow response to urbanization (Hamel et al., 2013). There are significant uncertainties in baseflow responses due to inconsistencies in site assessment methodologies, including measurement techniques and the selection of indicators. The uncertainties make it difficult to accurately predict the outcomes of baseflow restoration efforts (Hamel et al., 2013). Major MAR systems are primarily designed to attenuate high-flow hydrology, such as reducing peak magnitudes and frequencies of stormwater runoff. While these systems may positively impact baseflow, their primary design objectives do not focus on baseflow restoration (Bonneau et al., 2017). There is a need for a clear framework for baseflow assessment for MAR projects. Without such frameworks, it is difficult to guide GW management practices effectively to achieve baseflow restoration (Hamel et al., 2013).

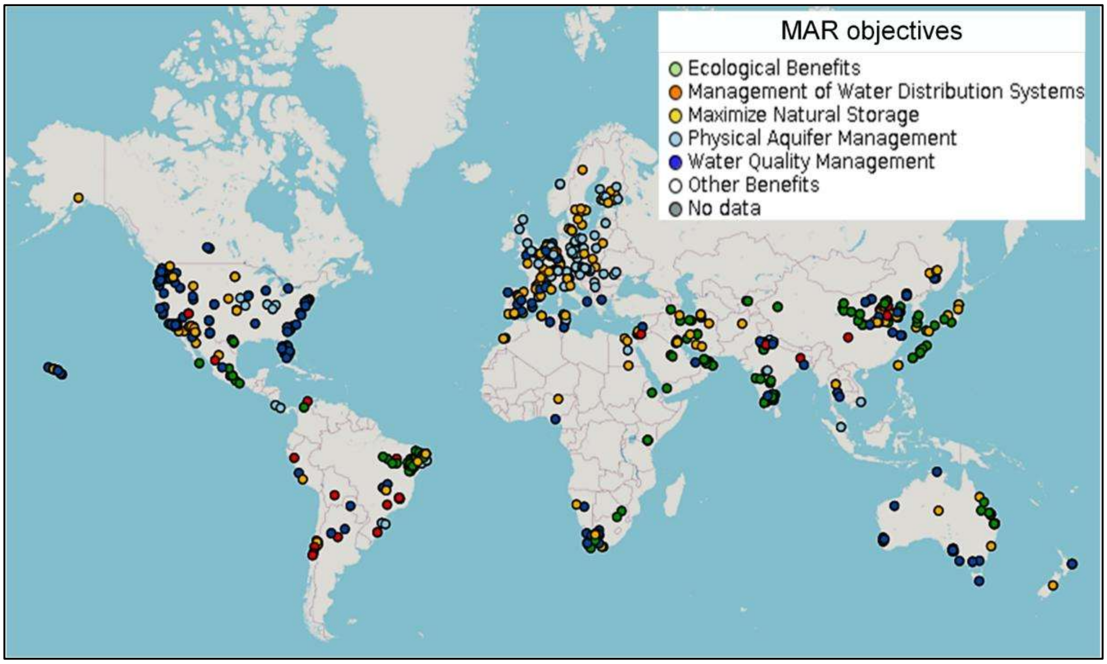

Figure 1.2*.MAR projects in the World (Source: https://ggis.un-igrac.org/view/marportal/)*

1.6 PROPOSED FRAMEWORK

Based on the research motivation and the gap in current literature, a framework to explicitly determine suitable MAR sites to restore the baseflow of a river has been proposed. The framework outlines a comprehensive GW and river management process, focusing on various aspects of water resource assessment, aquifer recharge capacity, and baseflow restoration potential. Each step of the framework has been outlined below.

1. **Assessment of GW Resources**:
    a. GW Availability Amid Climate Change: This involves evaluating GW's current and future availability under changing climatic conditions. Climate change impacts can influence rainfall patterns, evaporation rates, and GW recharge rates, necessitating robust models to understand how these changes affect GW resources.

b. GW Demand: This refers to estimating the demand for GW in the region, considering factors like agricultural and domestic water use, which helps manage and plan GW resources effectively.

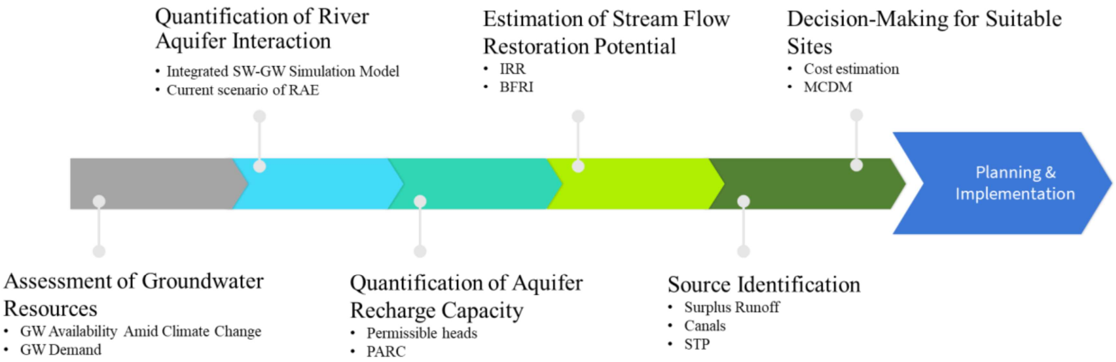

Figure 1.3. *The framework for suitable site selection of MAR to restore baseflow*

2. **Quantification of River-Aquifer Interaction**:

   a. Integrated SW-GW Simulation Model: This refers to integrating surface SW and GW models to simulate and understand the interaction between rivers and aquifers. This helps to determine how river flows influence GW recharge and vice versa.

   b. Current Scenario of RAE (River-Aquifer Exchange): This step involves evaluating the current state of river-aquifer exchanges, which can provide insights into the flow dynamics and the impact of SW on GW recharge.

3. **Quantification of the aquifer Recharge Capacity**:

   a. Permissible Heads: This involves determining aquifers' maximum allowable water levels (heads) to ensure the safety of confining layers or prevention of flooding during injection.

   b. Potential Aquifer Recharge Rate (PARR): This assesses the maximum recharge rate of an aquifer to store water during injection. PARR defines the maximum rate with which an aquifer can be injected.

4. **Estimation of Stream Flow Restoration Potential**: Stream flow enhancement is quantified using a numerical model in this step. It involves the determination of the Base Flow Enhancement Ratio (BFER), which represents the percentage baseflow enhancement per unit of injected water.
5. **Source Identification**: The step involves the determination of potential water sources and quantifying available flux.
   a. Surplus Runoff: Identifying surplus runoff from precipitation or river systems that could be captured and used for GW recharge.
   b. Canals diversion
   c. Treated sewage water (STP)
6. **Cost Estimation and Decision-Making for Suitable Sites**:
   a. Cost estimation: The detailed cost parameters should be determined before decision-making.
   b. MCDM (Multi-Criteria Decision-Making): This involves applying MCDM techniques to identify the most cost-effective and suitable sites for MAR.
7. **Planning & Implementation**: The overall framework culminates in planning and implementation, where the selected suitable candidates go through detailed field tests. The project is designed with the gathered data and implemented further.

1.7 RESEARCH OBJECTIVES

This thesis aims to conceptualize the baseflow response of a stream due to injection signals at ASR sites through a numerical GW flow model within a framework for determining suitable sites for MAR to restore baseflow in the Varuna River Basin (VRB). Novel SW and GW assessment methodologies have been developed with an integrated SW and GW model. The impact of climate change on the future water availability and River Aquifer Exchanges (RAE) has been determined to justify the need for MAR structures within the VRB. Given the need for MAR structures to sustain the GW demands, an additional objective of baseflow restoration has been used to determine suitable sites, such that the injected water not only enhances the GW storage (GWS) but also restores the baseflow in the Varuna River. To facilitate this goal, the stream flow response due to the induced recharge from the injection well has been conceptualized to determine the Baseflow Enhancement Ratio (BFER). The maximum possible injection rate at the site has been determined using the Permissible Aquifer Recharge Rate (PARR) (Kumar et al., 2024). The enhanced baseflow estimates are then utilized as a criterion in a TOPSIS model to rank the model grids for suitability. The specific objectives of the thesis are as follows:

I. Integrated assessment of GW decline through gravimetric remote sensing and field observations to facilitate GW assessment without using complex models.

II. Quantifying the river aquifer exchanges in the Varuna River Basin amid climate change to justify the need for managed aquifer recharge and future flood water (surplus runoff) availability.

III. Quantification of injection-induced enhancement of River Aquifer Exchanges in the Varuna River Basin.

IV. Determination of permissible aquifer recharge rate and its Sensitivity towards aquifer and well parameters.

V. Determining suitable ASR candidates for baseflow restoration in the Varuna River Basin.

1.8 ORGANIZATION OF THE THESIS

The thesis has been organized into nine chapters. The thesis has been structured in a way that each chapter from 4 to 8 is either published or going to be published as an individual research paper. Each research work (i.e. chapters 4 to 8) discuss corresponding objectives to satisfy the proposed framework for suitable MAR site determination to restore baseflow in VRB. The literature review for the overall objectives has been discussed in chapter 2, while the methodological literatures are presented in the individual chapters. The organization of the chapters is as follows:

Chapter 1. This chapter lays out the overall research background, motivation, and objectives.

Chapter 2. This chapter presents a comprehensive literature review, justifying overall research problem and objectives. The available literature on quantifying baseflow response to the MAR has been discussed, and the research gaps have been identified.

Chapter 3. This chapter goes through all the common methodologies used in the study to achieve individual objectives, including integrated SW and GW modeling, machine learning, trend analysis, TOPSIS model, and Sensitivity analysis. The novel methodologies developed to achieve individual objectives have been discussed in the following individual chapters. This chapter also discusses the brief introduction of the study area (VRB).

Chapter 4. This chapter introduces a new methodology to assess the SW and GW with SWAT models by integrating the gravimetric remote sensing data with the SWAT variables. This method aids a novel approach to the framework's first objective, i.e., the comprehensive assessment of the current and future GW water availability.

Chapter 5. This chapter discusses the detailed integrated modeling of SW and GW dynamics in VRB to facilitate the first and second objectives of the proposed framework, i.e., the assessment of GW and RAE in VRB.

Chapter 6. Motivated by the gap in the quantification of baseflow enhancement due to MAR, this chapter develops the theoretical background of the baseflow response to the induced recharge. This chapter determines the stream flow restoration potential of an area to satisfy the 4th step of the framework.

Chapter 7. The 3rd step of the framework has been discussed in this chapter, i.e., the determination of aquifer recharge capacity. It should be noted that steps 3 and 4 are independent and can be performed in any order.

Chapter 8. This chapter discusses the last two steps of the framework, i.e., source identification and Suitable site determination based on the decision criterion of Cost, baseflow enhancement, and GW storage enhancement.

Chapter 9. This concludes the present thesis with major findings, limitations of the study, and future scope.

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