

# 8

## **Suitable Aquifer Storage and Recovery Sites for Baseflow Restoration**

---

### **8.1 INTRODUCTION**

The selection of suitable sites for Managed Aquifer Recharge (MAR) is a complex process that involves multiple criteria and methodologies to ensure the effectiveness and sustainability of the projects. Various studies have employed Geographic Information System (GIS)-based Multi-Criteria Decision Analysis (MCDA) to create suitability maps for MAR site selection. These maps integrate hydrologic, hydrogeologic, and socio-economic factors to identify optimal locations for MAR implementation (Fuentes and Vervoort, 2020; Rahman et al., 2012; Jana Sallwey et al., 2019). For instance, the Namoi basin study in Australia utilized ten hydrologic and hydrogeologic criteria combined through Analytic Hierarchy Processes (AHP) and pairwise comparisons to construct a site suitability map validated by hydrograph data (Fuentes and Vervoort, 2020). Similarly, a review of 63 studies highlighted the variability in criteria and weighting used in GIS-MCDA, emphasizing the need for a structured approach to improve the reliability of suitability maps (Sallwey et al., 2019). Advanced tools like the Spatial Multi-Criteria Decision Analysis (SMCDA) software have been developed to streamline site selection by integrating non-compensatory screening, criteria standardization, and weighting with modern decision analysis techniques (Rahman et al., 2012). The application of simulation-optimization frameworks, as demonstrated in California's Central Valley, allows for the evaluation of cost-effectiveness and trade-offs in MAR site selection, providing stakeholders with a Pareto front to balance GW storage gains and project costs

(Kourakos et al., 2023a). Although, a large volume of research is available for the determination of suitable areas of MAR, the stream enhancement has never been taken as an objective.

The explicit parameterization of aquifer response has been found to be lacking, and very few studies discuss the inclusion of aquifer response. The recent development in the capture maps (Leake et al., 2010) has led to the inclusion of aquifer response in the site selection for GW development (Bajpai et al., 2023). After that, (Tewari et al., 2023) utilized the GW head response for each of the site clusters with a GW model to delineate the best clusters of areas suitable for ASR applications. Taking it further and based on the analysis of Shandilya et al. (2022), Kumar et al. (2024) have devised a methodology to determine suitable subbasins for ASR applications in the Lower Betwa Basin using PARC (Kumar et al., 2024; Shandilya et al., 2022b).

Based on the research gap in the site selection methodology for the ASR application explicitly focusing on restoring baseflow in rivers, we have formulated a framework for ASR site selection for baseflow restoration. The methodology utilizes the explicitly mapped response of the SW and GW systems to the ASR through BFER. The concept of PARR has been used to determine the maximum injection rates and corresponding stream flow enhancements. The framework utilizes the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) method coupled with the Entropy method for weight determination. The total cost, total streamflow enhancement, and GW storage enhancements have been used as decision criteria.

## 8.2 RANKING OF SITES BY TOPSIS

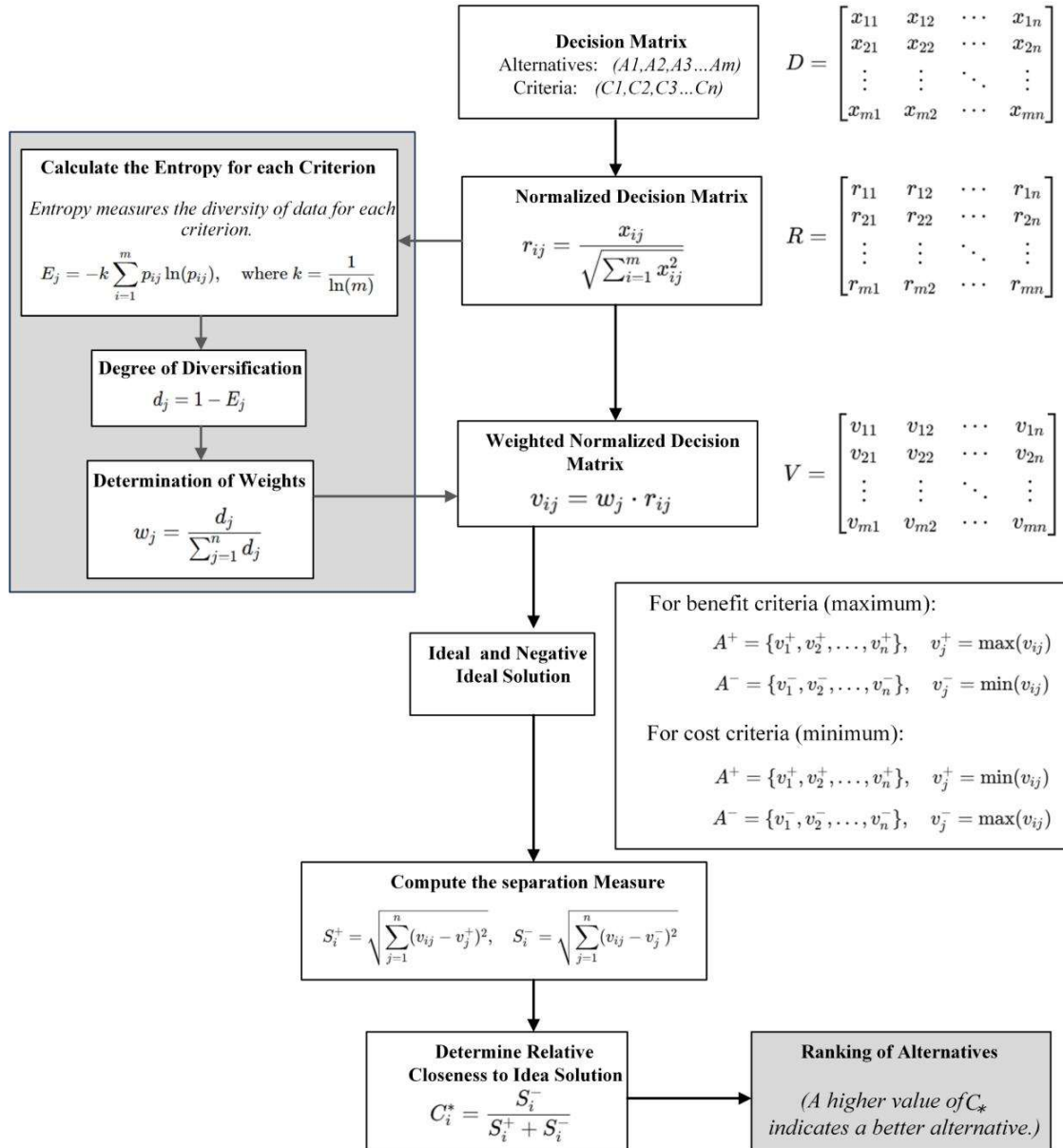


Figure 8.1. Flow chart for the implementation of the TOPSIS method with relevant formulas at each step

The TOPSIS is a widely used multi-attribute decision-making method. Combined with entropy weights, it becomes a powerful tool for objectively determining the importance of different attributes in decision-making. TOPSIS is a method that ranks alternatives based on their distance from an ideal solution, considering both the best and worst

possible scenarios. The entropy method calculates objective weights for the attributes by measuring the amount of information or uncertainty associated with each attribute. These weights, known as entropy weights, help in enhancing the decision-making process by emphasizing attributes with higher diversity in data and reducing the influence of less diverse attributes (C.-H. Chen, 2020; P. Chen, 2020; Lu et al., 2019). Apart from this, the TOPSIS with Entropy method provides additional advantages over other MCDM approaches such as:

- **Objectivity in Weighting:** Entropy weights provide an objective basis for determining attribute importance, reducing the bias that can occur with subjective weight assignments (Lu et al., 2019; Chen, 2020).
- **Enhanced Decision-Making:** By focusing on attributes with higher data diversity, entropy weights can improve the clarity and effectiveness of the decision-making process, although they may sometimes overly emphasize certain attributes (Chen, 2020; Lu et al., 2019).
- **Flexibility and Applicability:** The entropy-weighted TOPSIS method is versatile and can be applied in various fields, such as economic evaluations, supplier selection, and public blockchain assessments, demonstrating its broad applicability and effectiveness in different decision-making scenarios (Lu et al., 2019; Tang et al., 2019; Zeng et al., 2023).

### 8.3 CRITERIA FOR SUITABLE SITE SELECTION

#### 8.3.1 Baseflow Enhancement ( $\Delta Q_{bf}$ )

The baseflow enhancement from a location due to the injected water depends upon the aquifer and well design parameters and is represented by the baseflow enhancement ratio (BFER). The total percentage of baseflow enhancement is determined by multiplying the

BFER with the design injection rate of the ASR system. The total baseflow enhancement should be maximum to foster the restoration of baseflow in the river. To find a suitable area for ASR in VRB, total baseflow enhancement was used as a benefit criterion in the TOPSIS method.

The design injection rate for the given area depends upon the water source and the PARR. In case of recharge by the runoff, the surplus runoff available at the subbasin outlets will be conveyed to the recharge location and should be stored temporarily. The storage will facilitate sedimentation and treatment of the stored water. A design recharge rate ( $Q_d$ ) is obtained depending upon the incoming surplus water as:

$$Q_d = \begin{cases} \bar{Q}_{sp} & \bar{Q}_{sp} < PARR \\ PARR & \bar{Q}_{sp} \geq PARR \end{cases} \quad 8.1$$

Where  $\bar{Q}_{sp}$  is the mean available surplus runoff rate and is determined as the total surplus runoff available per unit of time. Since the surplus runoff is only accumulated during the monsoon season and has different values for each monsoon month, the  $\bar{Q}_{sp}$  can be determined as the arithmetic mean of the surplus time series data for the injection period:

$$\bar{Q}_{sp} = \frac{1}{n} \sum_{i=1}^n Q_{sp,i} \quad 8.2$$

In case of canals the aquifers can be recharged with their maximum potential and  $\bar{Q}_{sp}$  will be equal to  $PARR$ . Based on  $Q_d$  the maximum baseflow enhancement has been determined as:

$$\Delta Q_{bf} = Q_d \cdot BFER \quad 8.3$$

### 8.3.2 Increase in Aquifer Storage

The primary goal of any MAR project is to increase the GW storage of an area to meet the demands during the dry period. The GW storage is not a field measurable value and it can only be estimated via numerical simulations. The MODFLOW model can calculate the GW storage per grid cell. The aquifer storage gain under transient simulation models is a time series data. To obtain a decision value, the mean annual storage gain during the injection periods has been determined by simulating the injection well with the design injection rate ( $Q_d$ ). The simulated storage time series array is then subtracted with the business-as-usual case. The mean of the resulting storage enhancement time series data has been taken as the decision value.

$$\Delta GWS = \frac{1}{\sum_1^m \Delta t_i} \sum_{i=1}^m (GWS_{inj} - GWS_0)_i \cdot \Delta t_i \quad 8.4$$

The low GWS enhancement is associated with the loss of injected water to sinks, i.e., the rivers. To increase the efficiency of a MAR project, the storage enhancement has been taken as a benefit criterion, i.e., it should be maximum. This makes baseflow enhancement and GW storage a conflicting criterion for determining potential MAR sites.

### 8.3.3 Total Cost

Managed aquifer recharge (MAR) projects involve several major costs during their construction and planning phases. These costs can be broadly categorized into capital costs, operational and maintenance costs, and additional costs related to site-specific factors. The initial capital investment for MAR projects is significant and includes expenses related to infrastructure development such as the construction of recharge

basins, infiltration trenches, and injection wells. For instance, in Idaho's Eastern Snake Plain Aquifer, the state invested over \$16 million in infrastructure improvements to support MAR operations, which included increasing the recharge capacity significantly (Hipke et al., 2022). Similarly, the construction of recharge weirs and infiltration trenches in Northern Australia involves substantial capital costs, which are necessary to alter channel characteristics and enhance water infiltration into aquifers (Leslie, 2017).

Once the infrastructure is in place, ongoing operational and maintenance costs are incurred. These include costs for monitoring, managing water quality, and maintaining the recharge systems. In Idaho, the cost of conducting MAR, including capital, conveyance fees, operation, and maintenance, is reported to be ~1 rupees (USD 0.01) per cubic meter (Hipke et al., 2022). In Oman, the cost of MAR using treated wastewater varies between ~ 3.5 rupees (USD 0.353) and ~5.5 rupees (USD 0.550) per cubic meter, influenced by factors such as electricity costs and project lifespan (Zekri et al., 2014).

Site-specific factors can significantly influence the costs of MAR projects. These include the cost of sourcing water for recharge, which can vary depending on whether the water is sourced locally or from external basins. For example, in California's Central Valley, sourcing recharge water from outside local basins can increase total costs by 10% to 15% due to additional lift costs (Kourakos et al., 2023). Additionally, the cost of subsurface investigations, which are crucial for determining site suitability and aquifer characteristics, has increased due to supply chain issues and rising steel prices (Parker et al., 2022b).

The primary variable costs constitute critical criteria for the selection of suitable Managed Aquifer Recharge (MAR) sites. This research identifies the significant variable costs that generally arise during the planning and construction phases and utilizes them as key

decision-making criteria. Two major variable costs, i.e., land cost and conveyance cost, have been considered for calculating the total cost of the MAR construction ( $C_{total} = C_{land} + C_{conveyance}$ ).

### 8.3.3.1 Land Cost

Adequate land area is required for the construction of the major infrastructures such as the desilting reservoir, pump house, and well field. The feasibility of MAR also depends on the existing infrastructure and natural conditions. In Gotland, the potential for MAR in existing well fields was estimated to meet a substantial portion of the future water supply needs, highlighting the importance of integrating MAR with current water management systems (Dahlqvist et al., 2019). The land area required for MAR reservoirs and well fields must be evaluated in terms of both the physical space available and the capacity to store and recharge water effectively. This involves assessing the proximity to SW sources and the capacity of the underlying aquifers (Dahlqvist et al., 2019).

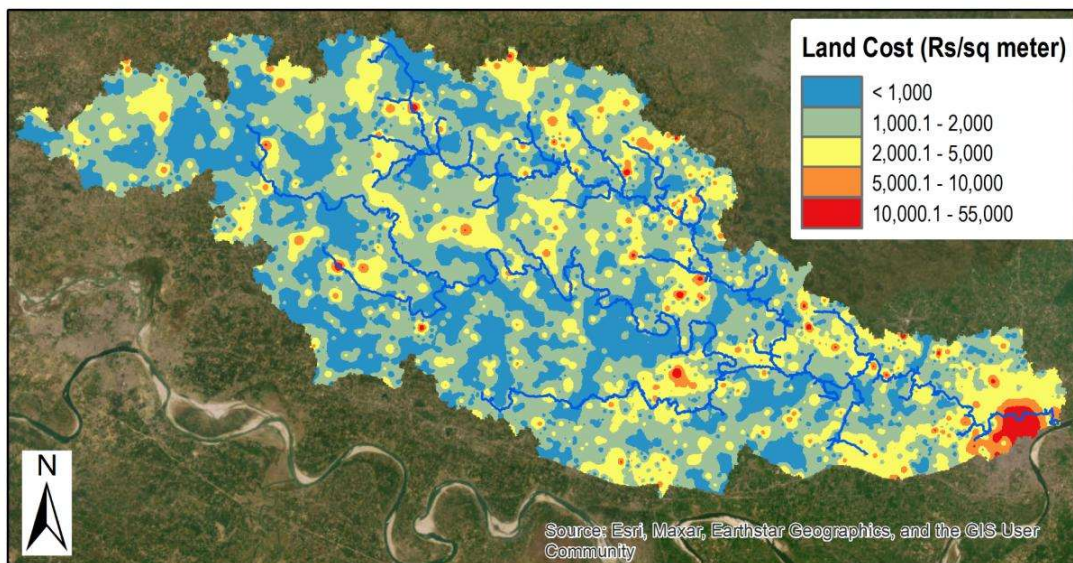


Figure 8.2. land cost per  $m^2$  in the study area

The two major infrastructures required for the construction of a MAR site (i.e. land area for desilting reservoir and well-field) have been considered for cost evaluation. Given that  $C_{land}$  is the total cost due to land requirement,  $A_{reservoir}$  is the area of the reservoir and  $A_{well-field}$  is the area required for well field design in a square grid pattern, the total land cost can be determined as:

$$C_{land} = P_{land}(A_{reservoir} + A_{well-field}) \quad 8.5$$

$$A_{reservoir} = \frac{Q_d}{D_{reservoir}} \quad 8.6$$

$$A_{well-field} = \frac{Q_d \cdot d_w^2}{Q_{crit}} \quad 8.7$$

Where  $P_{land}$  is the per unit land cost in the study area, the land cost has been taken arbitrarily, with high urban and lower costs in rural areas. The reference per m<sup>2</sup> rate of land has been taken from the stamp and registration department<sup>8</sup>, the government of Uttar Pradesh. The  $Q_d$  is the design recharge rate,  $D_{reservoir}$  is the depth of the reservoir,  $d_w$  is the distance between two wells in the well field (square grid pattern), and  $Q_{crit}$  is the critical injection rate of the injection well (taken as 0.43 m<sup>3</sup>/sec corresponding to the critical exit velocity ( $v_e$ ) of 0.46 m/sec in the well screens (Houben, 2015)).

$$v_e = \frac{Q_{crit}}{2\pi \cdot r \cdot L_s \cdot A_p} \quad 8.8$$

Where  $r$  is the radius of the well/screen (0.125 m),  $L_s$  is the screen length (6 meters) and  $A_p$  is the ratio of open slot area and total screen area (0.2).

---

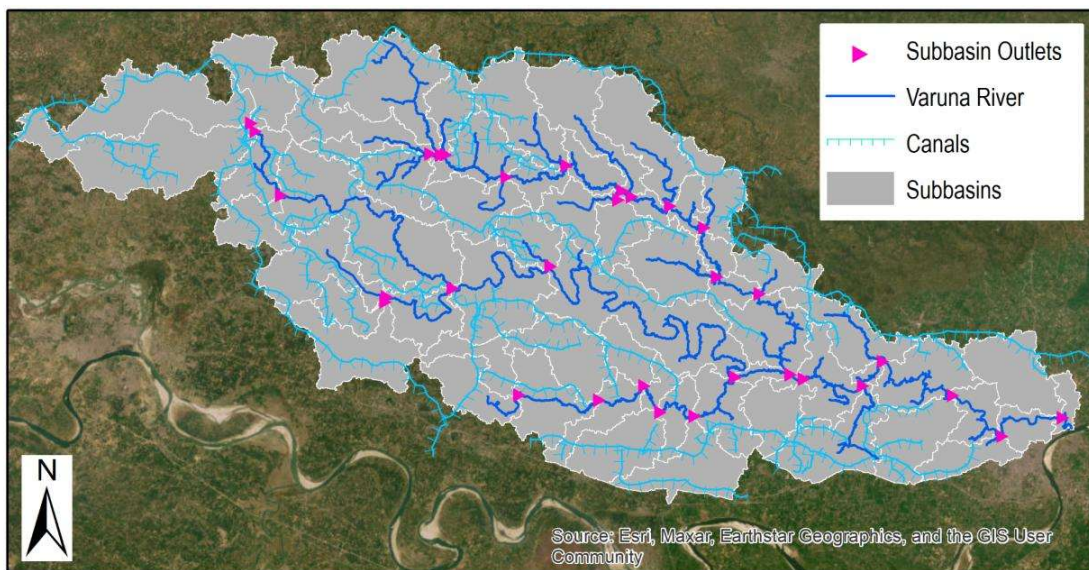
<sup>8</sup> <https://igrsup.gov.in/igrsup/getUploadedRateList.jsessionid=A11D02922DE25914FCD96454ED857151>

### 8.3.3.2 Conveyance cost

The conveyance cost ( $C_{conv}$ ) includes pipe, fittings, and pumping. The total cost per unit length ( $P_{conv}$ ) has been taken 800 rupees per meter of conveyance distance (arbitrary). The shortest distance between the water source (subbasin outlets or canal diversion) has been taken as the total conveyance length ( $l_{conv}$ ).

$$C_{conv} = l_{conv} \cdot P_{conv} \quad 8.9$$

## 8.4 SOURCE IDENTIFICATION



*Figure 8.3. Source of water in VRB for MAR*

The determination of the water source for the MAR application is one of the main steps. MAR projects utilize a variety of water sources to replenish GW supplies. Common sources include excess SW, stormwater, and treated wastewater, which are used to increase the natural recharge of GW reservoirs (Alam et al., 2021). In Latin America and

the Caribbean, river water and stormwater are the predominant sources of MAR, accounting for over 90% of cases (Valverde et al., 2018). In China, multiple water sources, such as the South-to-North Water Diversion Project, Yellow River, and Wohushan Reservoir, have been used, although they can impact GW quality (Zhang and Wang, 2020). In Mexico, reclaimed water and stormwater are considered vital for MAR, especially in semi-arid regions (Cruz-Ayala and Megdal, 2020). The mining industry also employs MAR using surplus water from operations, often in arid regions, to manage water volumes and preserve aquifers (Sloan et al., 2023). These diverse sources highlight the adaptability of MAR to different environmental and regulatory contexts, making it a versatile tool for sustainable water management.

The main source of water in the Varuna River Basin can be taken as the surplus runoff and the canal diversion from the Sharda Canal Network (Sharda Sahayak Major Irrigation Project (JI01838)).

#### **8.4.1 Surplus runoff at subbasin outlets**

The peak discharge in the Varuna River can rise up to 640 m<sup>3</sup>/sec during storm events, which causes floods in the Varanasi area. The utilization of excess runoff (generally in excess of the 75% dependable flow) can not only provide a source for the MAR project but also attenuate the flood event. The selection of subbasin outlets for diverting excess water to the injection well field will require a reservoir. The primary function of the reservoir would be to provide temporary storage of the excess water (which is variable depending upon the storm events) and desilting. The water treatment facilities can be installed at the subbasin outlets before injecting the water into the well field. Installing a desilting and treatment facility at the subbasin outlet helps prevent the clogging of the conveyance system. The conveyance cost depends upon the location of the subbasin outlet and the proposed well-field location.

The determination of excess surplus runoff has been discussed in Chapter 5 and presented in **Figure 8.4** for all climate scenarios in the Varuna River basin. The surplus runoff has been determined to correspond to the 25% exceedance limit. The spatial distribution of the 25% exceedance limit represents the disparity in the rainfall distribution and the impact of climate change on extreme events. It is evident from the range of the 25% exceedance limit in the four scenarios that the magnitude of extreme runoff events is higher in SSP370.

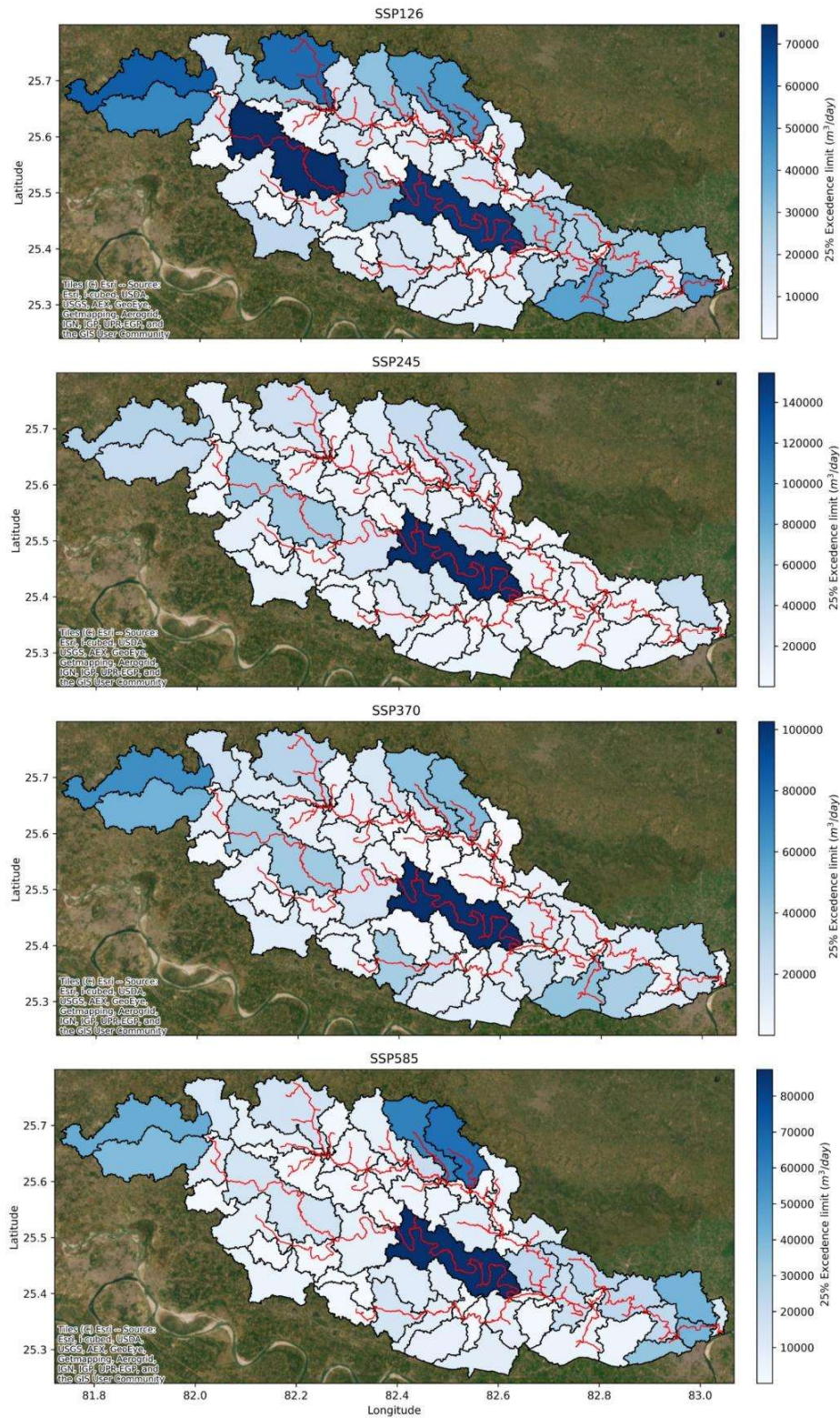


Figure 8.4. Runoff corresponding to the 25% exceedance limit at each subbasin outlet

At the same time, it is lower for SSP126, where the extreme values are more or less well distributed. The average surplus runoff for the 80-year forecasted period for the four scenarios (SSP126, SSP245, SSP370, and SSP585) were 16,871.9 m<sup>3</sup>/day, 19,098.4 m<sup>3</sup>/day, 15,529.7 m<sup>3</sup>/day and 15,806.0 m<sup>3</sup>/day respectively. Diverting the runoff above this limit ensures that only monsoonal flow is captured for MAR. The Euclidean distance from the subbasin outlets to the well field has been taken as the conveyance distance.

#### **8.4.2 Canal Diversions**

The study area lies in the command area of the Sharda Sahayak Canal system (**Figure 8.3**). The Sharda Canal system, established in 1928, stands as one of the largest and oldest irrigation systems in Uttar Pradesh, designed to irrigate an area of 2.55 million hectares while safeguarding the Ganga-Ghaghra doab region. Originating from the Sarda River at Banbasa in Uttarakhand's Champawat district, this extensive project benefits 15 districts, including Pilibhit, Lakhimpur Kheri, Shahjahanpur, and Varanasi, through its infrastructure, which comprises two significant barrages: the 716-meter-long Girija Barrage on the Ghaghra River and the 408-meter-long Lower Sarda Barrage. A 28-kilometer feeder channel, with a capacity of 480 cubic meters per second, connects these barrages, facilitating the diversion of floodwaters from the Ghaghra into the Sarda River. The canal system encompasses several major branches, including the Feeder Channel (Sarda Sahayak Canal System), Dariyabad, Barabanki, Faizabad, Tanda Main Canal, Doharighat Link, Sultanpur, Allahabad, and Pratapgarh branches, collectively extending over 258.80 kilometers, thereby contributing significantly to agricultural productivity and flood management in the region.

The dense network of the canal system in the area makes it suitable as a potential source of water for MAR. The surplus water in the Ghaghra and Sharda rivers can be recharged by diverting the flood waters through this canal system. Instead of the subbasin outlets,

the diversion can be constructed on the canal, resulting in lower conveyance costs. Further, since the water is already accumulated in the canal network, the injection wells can run at full capacity (i.e., recharge rate equal to PARR). The cost of diverted water has been taken as 4.67 rupees<sup>9</sup> per m<sup>3</sup>.

## 8.5 SUITABLE SITE SELECTION

Selecting potential sites for Managed Aquifer Recharge (MAR) projects requires a thorough evaluation of multiple criteria to ensure the project's feasibility and effectiveness. The primary factors considered in site selection usually include hydrologic, hydrogeologic, and socio-economic aspects. The Key Criteria for MAR Site Selection are as follows:

### 1. Hydrologic and Hydrogeologic Factors:

- *Water Availability*: The availability and frequency of water sources, such as rivers or floodwaters, are crucial for MAR projects (Fuentes and Vervoort, 2020; McCurry and Pyne, 2022).
- *Aquifer Characteristics*: The suitability of receiving aquifers, including their ability to accept and retain recharged water, is essential. This involves assessing the aquifer's permeability, storage capacity, and recharge rates (Fuentes & Vervoort, 2020; McCurry & Pyne, 2022).
- *Soil and Terrain*: Soil texture, land slope, and drainage density are important for determining the infiltration capacity and potential recharge efficiency (Jassim et al., 2023; Phankamolsil et al., 2022).

---

<sup>9</sup> <https://www.adriindia.org/images/newsletter/15659558322.pdf>

## 2. Technical and Environmental Considerations:

- *Water Quality Compatibility*: The compatibility of recharged water with the aquifer is necessary to prevent contamination and ensure environmental protection (McCurry & Pyne, 2022).
- *Infrastructure Proximity*: The proximity to existing infrastructure, such as wastewater treatment plants, can influence site suitability (Rahman et al., 2013).

## 3. Socio-Economic and Administrative Factors:

- *Land Use and Accessibility*: The current land use and accessibility of the site can impact the feasibility of MAR implementation (Tsangaratos et al., 2017).
- *Regulatory and Legislative Context*: Compliance with local regulations and policies is necessary for project approval and sustainability (Tsangaratos et al., 2017).
- *Project costs*: The initial costs, water costs, conveyance costs, maintenance costs, operational costs, etc., can be a major factor associated with the selected sites.

The above criteria have been reduced to only three major criteria with the parametrization of baseflow enhancements, i.e., (1) GW water storage enhancement, (2) Baseflow enhancement, and (3) Project cost. The primary objective of enhancing GW storage serves as the fundamental criterion necessary to substantiate the financial investment (which should be minimum as the third criterion) associated with the project, as well as

to evaluate the effectiveness of net recharge recovery. The improvement of GW availability is critical in addressing and fulfilling the increasing demand for water resources, particularly in the context of Managed Aquifer Recharge (MAR) projects. Such initiatives not only aim to augment the quantity of GW but also seek to enhance the sustainability of water resources in the face of growing consumption pressures and climatic variability.

The second objective justifies the enhancement of baseflow to the river, which indirectly affects the riverine ecosystem and water quality. Enhanced baseflow offers numerous benefits across various ecological and hydrological areas. One of the primary advantages is the increase in summer flows, which is crucial for maintaining water availability during dry periods (V. Ponce and Lindquist, 1990; V. M. Ponce and Lindquist, 1990). This augmentation supports healthier riparian areas by stabilizing channels and banks, reducing erosion, and decreasing sediment transport, which collectively improves water quality (Ponce & Lindquist, 1990; Ponce & Lindquist, 1990). Additionally, enhanced baseflow contributes to the creation of better habitats for fish and wildlife, as it lowers stream temperatures and improves stream aesthetics (Ponce & Lindquist, 1990; Ponce & Lindquist, 1990). In regions like Northern California, ascending baseflows have increased spawning habitats' availability and spatial variation, benefiting species such as the Chinook salmon by reducing the risk of habitat superimposition (Goodman et al., 2018).

The GW storage enhancement has been determined by simulating the injection well with the maximum possible recharge rate for the 30-year time steps. The baseflow enhancements have been calculated with the methodology discussed in the section 8.3.1. The total cost has been determined with the methodology presented in the section 8.3.3. The overall framework for suitable site selection with baseflow enhancement has been presented in **Figure 8.5**.

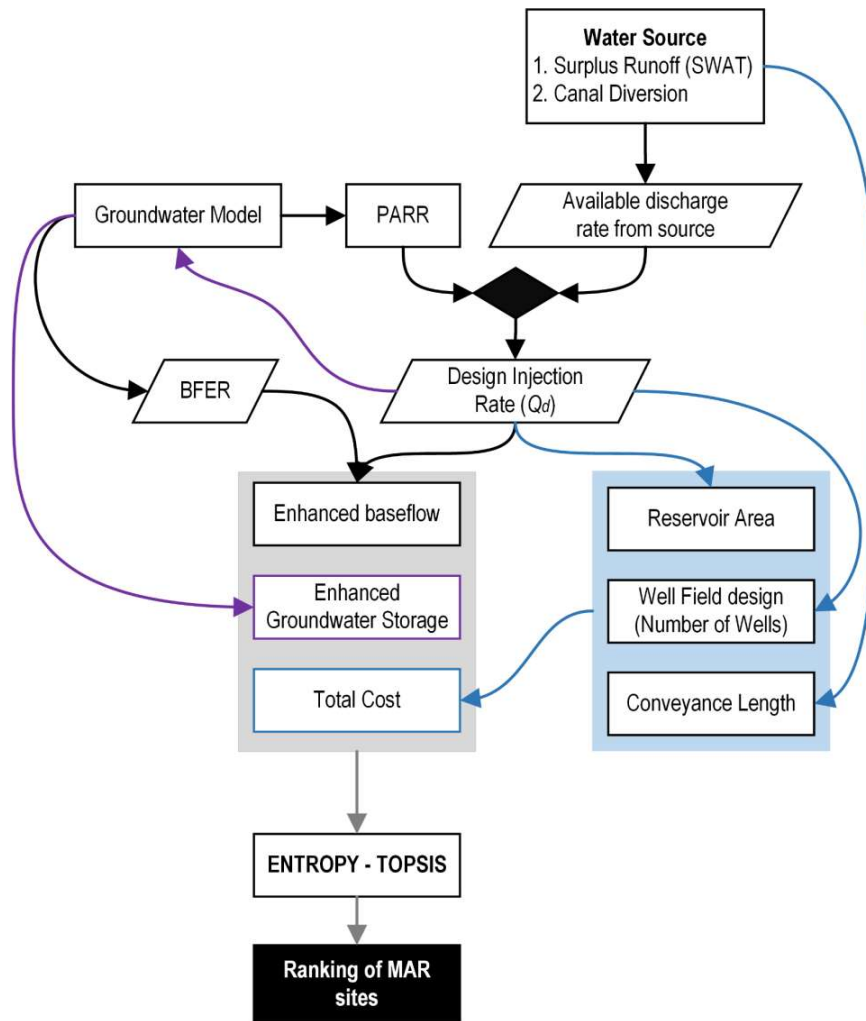


Figure 8.5. Flow chart for the ranking of MAR sites

## 8.6 RESULTS AND DISCUSSION

### 8.6.1 Suitable MAR sites

#### 8.6.1.1 Surplus Runoff as Water Source

The baseflow enhancement and the GW storage enhancement have been taken as the benefit criteria (maximize). In contrast, the total cost of the project has been taken as a loss criterion (minimized) to rank the GW model cells based on the closeness to the ideal MAR site with the TOPSIS method. The ranking of all the climatic scenarios in the Varuna basin is plotted in **Figure 8.6**. The right histograms represent the distribution of

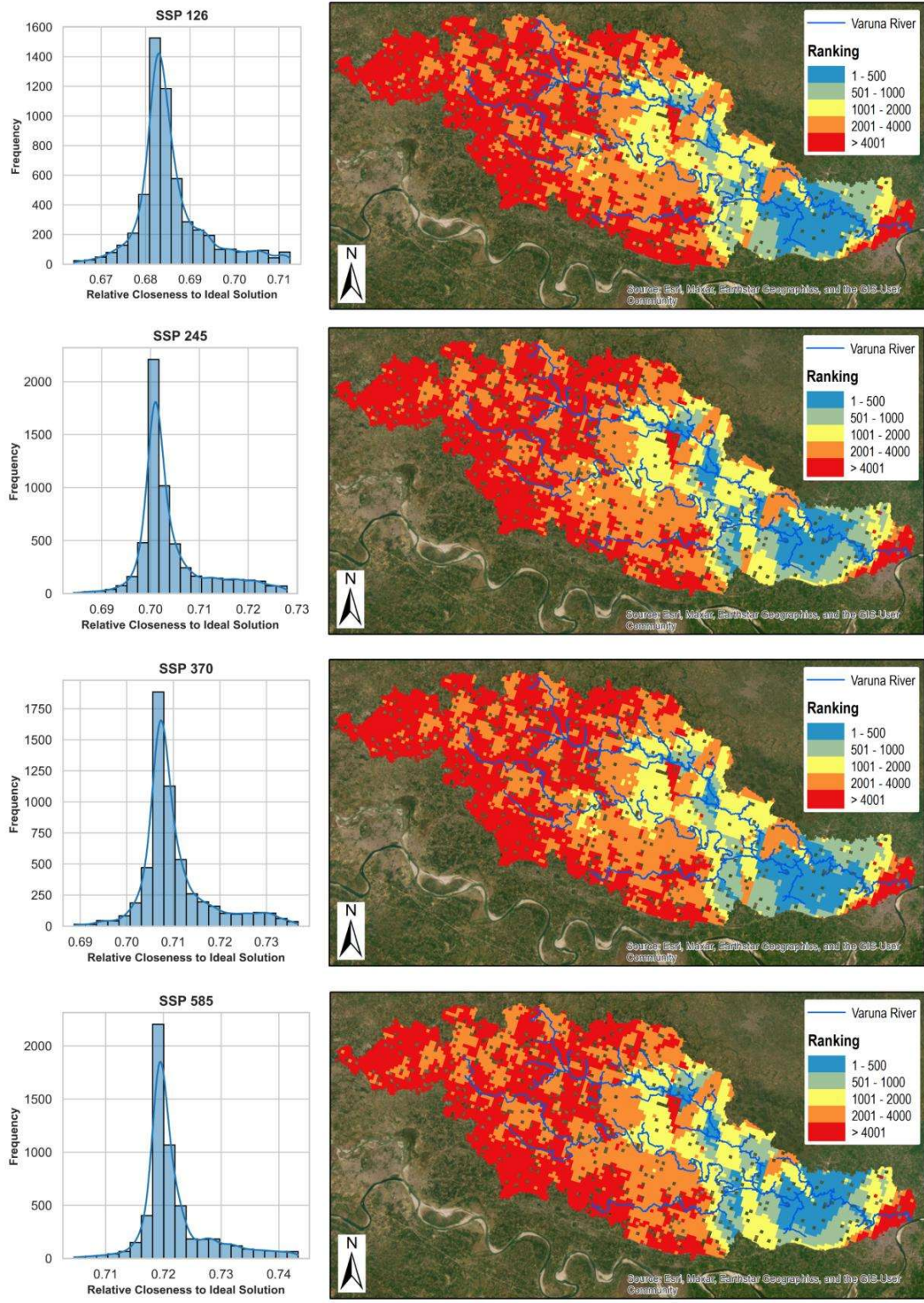
the Relative Closeness to the Ideal Solution (RCIS) values across the evaluated sites. The plots on the right side are the ranking of evaluated sites. The ranking has been classified based on **Table 8.1**, which highlights the best MAR sites.

**Table 8.1.** Classification of potential sites for MAR

Ranking class	Range	Suitability
1	1 – 500	Best sites
2	500 - 1000	High suitability
3	1000 - 2000	Moderately suitable
4	2000 - 4000	Low suitability
5	> 4000	Least suitable

The RCIS values are very narrowly distributed (0.65 – 0.74), which indicates a relatively consistent evaluation of MAR sites. The highest frequency of the RCIS occurs at 0.69, 0.70, 0.71, and 0.72 for SSP126, SSP245, SSP370, and SSP585, respectively. The increase in the RCIS for the peak shows the ranking improvement as we move from SSP126 to SSP585, which indicates the influence of climate variability on the ranking of sites. This phenomenon represents the high correlation between TOPSIS ranking and the distribution of surplus runoff.

A significant number of sites have lower rankings and are mainly distributed away from the stream network. 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. Climate change impacts the feasibility of the MAR sites with more suitable areas in higher emission pathways.

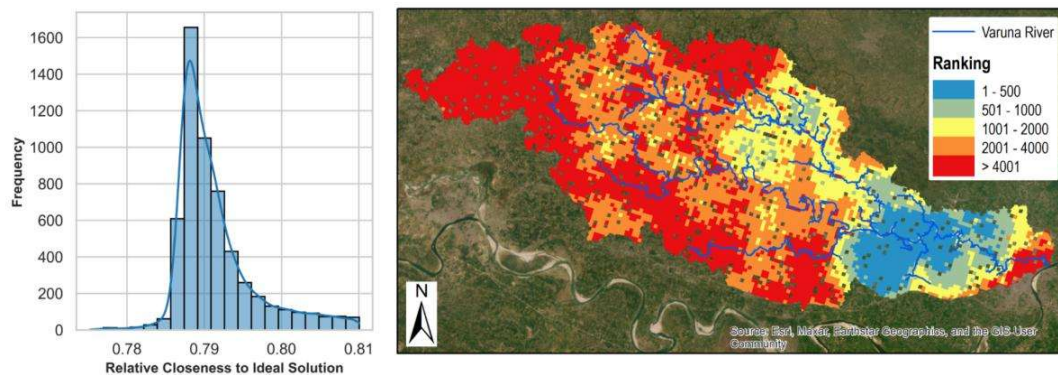


**Figure 8.6.** Ranking of MAR sites in VRB for all the climate scenarios with surplus runoff as the water source (the histogram represents the distribution of MAR sites with relative closeness to the ideal solution (RCIS))

### 8.6.1.2 Canal Diversion as Water Source

When the water from the canal network is used for the MAR, it has been assumed that the maximum recharge rates (i.e., PARR) can be achieved. Also, since the canal network is well distributed, the existing infrastructure can reduce the conveyance cost.

The RCIS in the case of canal water as a source ranges from 0.77 to 0.81, with a peak at 0.79. This is a narrower range with higher values than the distributions in all four SSPs with runoff as a water source. The top-ranked sites area is more concentrated near streams than in the runoff condition. In all scenarios, the top-ranked sites are more spread than the conditions with canal water. The area downstream of the confluence of Varuna and Basuhi has shown the best potential for MAR with canal diversion as the water source.

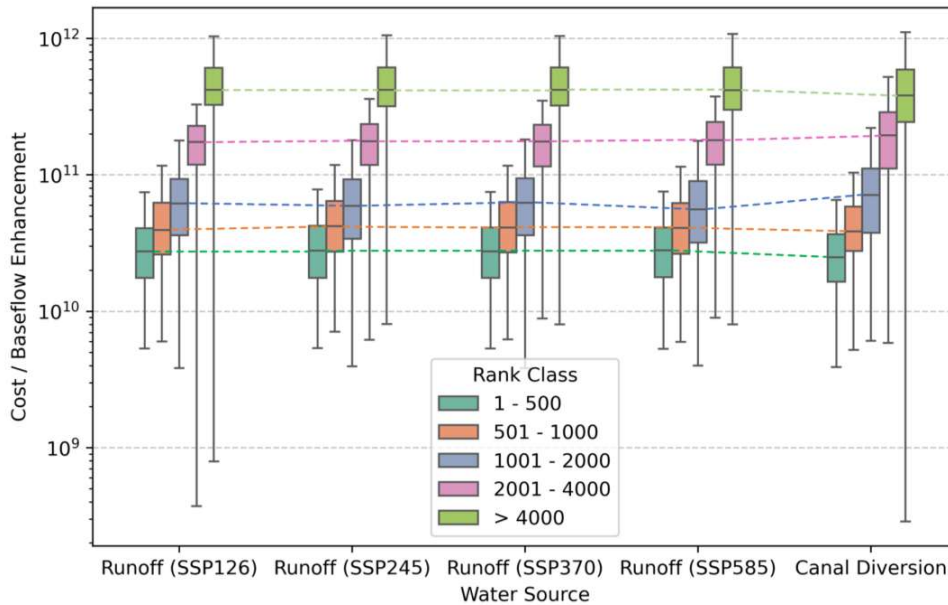


**Figure 8.7.** Ranking of MAR sites in VRB for all the climate scenarios with the canal as a water source (the histogram represents the distribution of MAR sites with relative closeness to the ideal solution (RCIS))

### 8.6.2 Best Source of Water for ASR

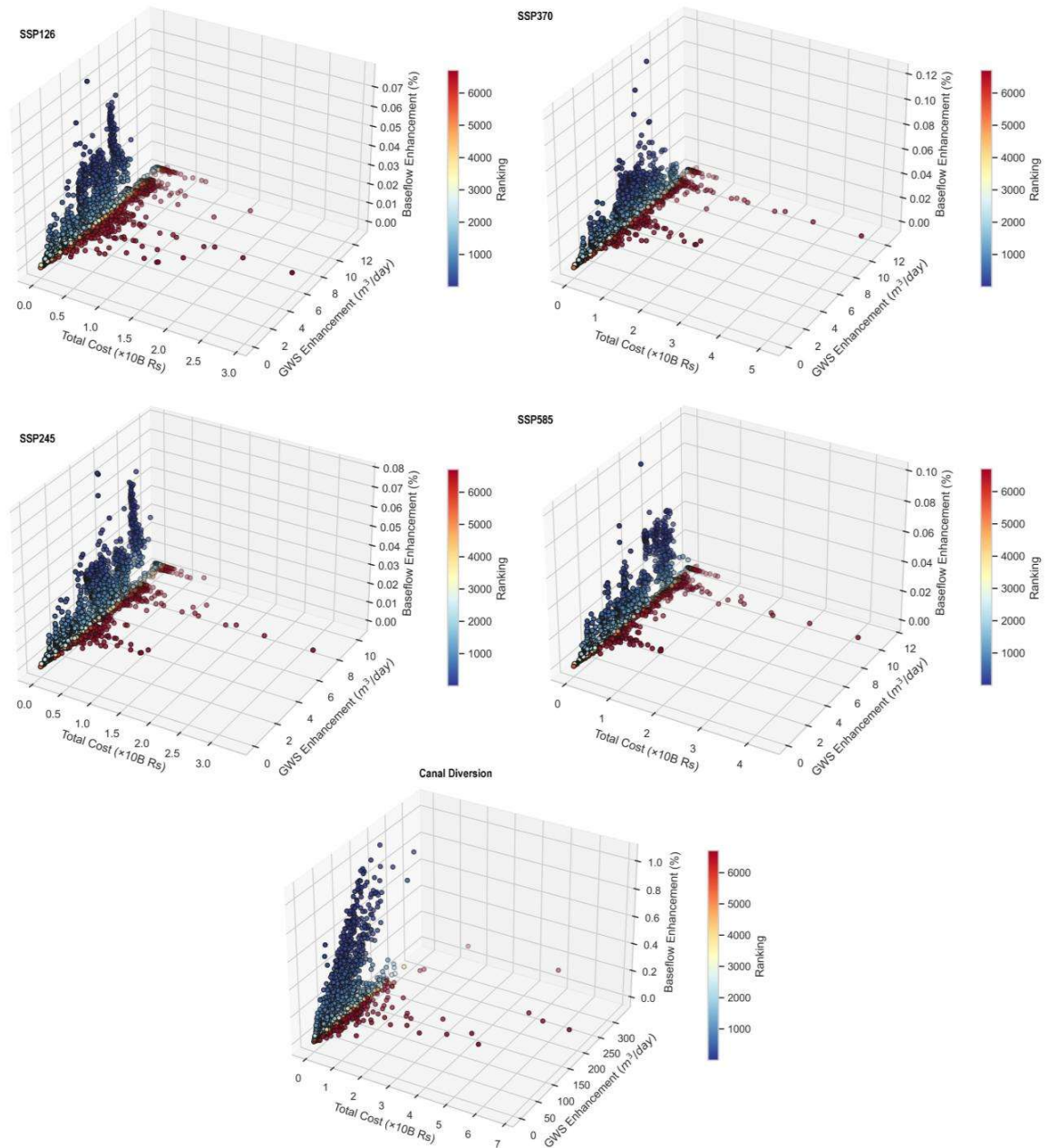
To evaluate the best water source for MAR in the VRB, we compared the project's costs to the enhancement of baseflow. We plotted the total project cost per percentage of baseflow enhancement using a boxplot for all water sources and Rank classes. The results indicate that as the rank decreases, the cost per unit of baseflow enhancement increases exponentially. After excluding outliers, the median, as well as the 25th and 75th

percentiles, for all scenarios utilizing runoff as a water source were relatively uniform. However, the minimum and maximum costs per unit of baseflow enhancement displayed variability across different climate scenarios.



*Figure 8.8. The boxplot of the Cost/baseflow enhancement percentage for each water source*

The Canal Diversion scenario presents a strong alternative compared to the SSP scenarios. Analyzing the scatter plots reveals that the GW Surface (GWS) Enhancement values in the SSP scenarios are significantly lower than the Canal Diversion range of 0.003 to 0.004. Canal Diversion outperforms all the SSP scenarios, achieving a maximum value of 1.0, which is considerably higher than the peak baseflow enhancements observed in the SSP scenarios. This substantial improvement in baseflow makes the Canal Diversion scenario particularly attractive, as it guarantees a significant and reliable boost in water availability, which is a critical objective. In contrast, the SSP scenarios offer much lower baseflow enhancements despite having comparable costs.



**Figure 8.9.** 3D scatter plots with decision criteria, each scatter point represents a MAR site

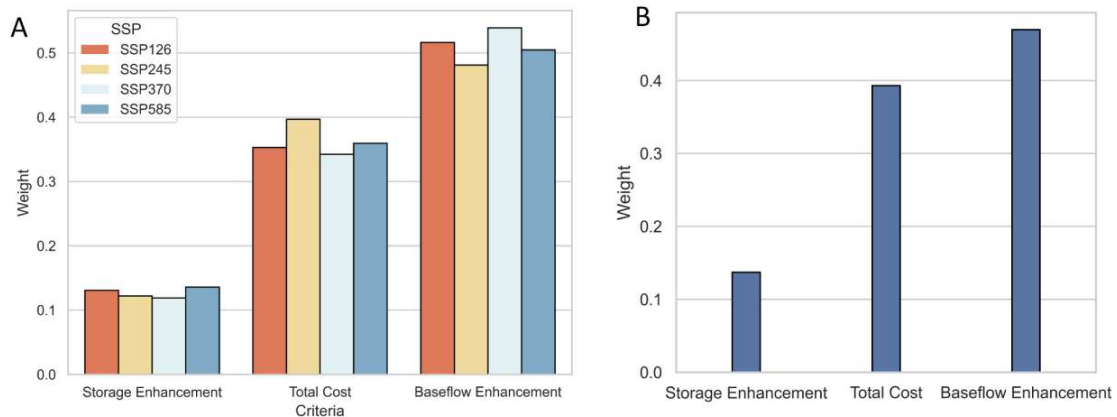
Although the total cost for the canal conversion scenario is high, this figure should be assessed in light of the substantial benefits it provides. The baseflow enhancement alone justifies the higher costs, especially when combined with Canal Diversion's superior GWS enhancement values. Therefore, the cost-benefit trade-off in this scenario is

favorable, as it achieves water-related targets much more effectively than the SSP alternatives.

Importantly, the cost per unit of baseflow enhancement from using a canal as a water source is lower than that from runoff. This advantage is due to reduced conveyance costs and higher injection rates associated with canal usage. In conclusion, canal diversion is the most effective water source for Managed Aquifer Recharge (MAR) projects in the Varuna River Basin. It can achieve an enhancement of up to 1.04% per year, whereas surface runoff can only restore a maximum of 0.12% of stream flow per year.

### 8.7 ADVANTAGE OF PRESENTED METHODOLOGY

The presented methodology combines the entropy weight calculation method with the TOPSIS method to rank the MAR sites based on three objectives—the GW storage enhancement, the baseflow enhancement and total cost. Due to the parameterization of baseflow enhancement with BFER and PARR, the presented methodology can be executed with TOPSIS. The alternative to the presented methodology would be to determine the baseflow change in each iteration with an optimization algorithm, which can be time-consuming for the complex model of this scale.



**Figure 8.10.** Entropy weights for all the climate scenarios for A. runoff as the water source and B. canal diversion as the water source

The entropy method eliminates the requirement of expertise to make the weights based on the variability and information content of the data, reducing the subjective biases. The criteria with higher variability represent more sensitivity, which the entropy method captures to assign higher weights. The weights determined have consistent values for all scenarios, which shows the robustness of the method (**Figure 8.10**). The baseflow has been found to be more diverse or sensitive to the location of injection and manifested by high weight by the entropy method. As the main objective of this research was to enhance the baseflow, the entropy method can be independently utilized for the proposed framework.

## **8.8 LIMITATION AND FUTURE SCOPE**

The study presented here is based on arbitrary variable costs only, which do not include various costs related to water treatment, initial capital, maintenance, and operation costs, etc. Since the total cost is an important criterion in the ranking of the alternatives, proper care should be taken while determining it. The results with proper cost estimation will differ from the current results, although the clustering of best sites will be more or less similar. Apart from the cost, the head loss is also important for the operation of MAR sites. The elevation difference between the source and the well field can cause additional stresses to the pumping system, which can lead to additional operational costs, which have been neglected in the study. Also, the framework of site selection should be integrated with water quality consideration since it is also a major criteria to control groundwater contamination.

The study presented here forms the basis for further analysis of different alternatives of water sources (such as treated wastewater and urban storm runoff) and algorithms (mainly

optimization). The TOPSIS method can be replaced with an optimization model to find the targeted outcomes. The parameterization of baseflow enhancement provides a new dimension to the targeted approach of baseflow restoration. Instead of finding several possible potential sites for MAR, the most adequate sites (number of sites based on the total budget) with given constraints and a fixed percentage of baseflow enhancement in the operational time period can be determined with an efficient optimization method.

## **8.9 SUMMARY**

The study presents a new framework for identifying suitable Managed Aquifer Recharge (MAR) sites aimed at restoring baseflow in the Varuna River basin. It utilizes the TOPSIS method to evaluate potential sites based on key factors including baseflow enhancement, storage enhancement, and overall project costs. This approach helps to identify locations that are closest to an ideal solution.

One of the main findings indicates that the Entropy-TOPSIS method is an effective and user-friendly multi-criteria decision-making (MCDM) tool for site selection. The study underscores the robustness of the entropy method, as the weightings assigned to various criteria remained consistent across different scenarios, yielding satisfactory results regarding the Baseflow Enhancement Ratio (BFER).

Additionally, 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. These sites are also noted to be sensitive to the impacts of climate change. Lastly, the findings suggest that canal diversion is the most effective water source for MAR initiatives within the Varuna River basin.

\*\*\*