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Literature Review

Baseflow restoration is not a primary objective in managed aquifer recharge (MAR) planning due to the complexities of GW (GW) flow processes, uncertainties in baseflow responses, ambiguity in the aquifer capacity, and the lack of clear assessment frameworks. The assessment framework to define suitable MAR sites for baseflow restoration needs accurate quantification of baseflow enhancements after the MAR operations. Additionally, quantifying aquifer recharge capacity is vital to determine the maximum injection rates during aquifer storage and recovery (ASR) operations. Both the parameters quantifying the aquifer capacity and the baseflow enhancement should be integrated to determine the inter-relationship between injected water and baseflow enhancement. The literature review has been organized into four sections to align with the research objectives, which are discussed in the following subsections.

2.1 SUITABLE CANDIDATE AREAS FOR MAR TO RESTORE RAE

2.1.1 Methodologies for the MAR site selection

2.1.1.1 Multi-Criteria Decision Analysis (MCDA)

The GIS-Based Multi-Criteria Decision Analysis (MCDA) method is a powerful tool for determining suitable sites for MAR. This approach integrates geographic information systems (GIS) with MCDA to create suitability maps that help identify optimal locations for MAR implementation. The method involves evaluating various criteria, such as hydrologic and hydrogeologic factors, and assigning weights to these criteria to reflect their relative importance. This process allows for a structured and systematic assessment

of potential sites, accommodating local contingencies and specific project needs (Fathi et al., 2021; Jana Sallwey et al., 2019; J Sallwey et al., 2019). The flexibility of GIS-MCDA makes it particularly useful in semi-arid regions where water scarcity is a pressing issue, as it can incorporate diverse data inputs and stakeholder preferences (Fathi et al., 2021).

However, the GIS-MCDA method also has its disadvantages. One major challenge is the lack of standardized guidelines for conducting suitability mapping, leading to variability in the factors assessed and their weighting (Jana Sallwey et al., 2019). The quality of the suitability maps heavily depends on the quality of input data and the expertise of the decision-makers involved (J Sallwey et al., 2019). Additionally, the process can be complex and time-consuming, requiring significant technical expertise to manage and interpret the data effectively (J Sallwey et al., 2019).

The Analytic Hierarchy Process (AHP) is a structured technique used for organizing and analyzing complex decisions, particularly in the context of determining suitable sites for MAR. AHP involves breaking down a decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently. The process includes defining the problem, structuring a hierarchy of criteria and sub-criteria, conducting pairwise comparisons to establish priorities, and synthesizing these to determine the best decision. In the context of MAR site selection, AHP is used to weigh various factors, such as hydrological, geological, and environmental criteria, to identify the most suitable locations for recharge activities (Fuentes and Vervoort, 2020; N Kazakis, 2018; Mouhoumed et al., 2023).

The advantages of using AHP for MAR site selection include its ability to handle both qualitative and quantitative data, providing a comprehensive framework for decision-making that incorporates expert judgment and stakeholder preferences. AHP is

particularly beneficial in complex scenarios where multiple criteria must be considered, as it allows for a systematic comparison of these criteria and their relative importance (Rahman et al., 2013, 2012). However, the method also has disadvantages, such as its reliance on expert judgment, which can introduce subjectivity and potential bias into the decision-making process. Additionally, the process can be time-consuming and complex, requiring careful structuring and analysis to ensure consistency and accuracy in pairwise comparisons (Banai-Kashani, 1989; Koseoglu et al., 2023). Despite these challenges, AHP remains a valuable tool in the strategic planning and implementation of MAR projects.

2.1.1.2 Fuzzy Logic Approaches

The fuzzy analytical hierarchy process (FAHP) is an extension of the traditional AHP that incorporates fuzzy logic to handle the uncertainty and vagueness inherent in decision-making processes (Ishizaka, 2014). FAHP is particularly useful in situations involving subjective judgments, as it allows decision-makers to express their preferences more flexibly using linguistic terms rather than precise numerical values. This method is advantageous in complex multi-criteria decision-making scenarios, such as selecting the optimal underground mining method, where it helps determine the weights of various criteria by considering the subjective judgments of decision-makers (Y. Liu et al., 2020; Naghadehi et al., 2009). The FAHP can provide different solutions compared to AHP, which can be beneficial in capturing the nuances of human judgment, although it does not necessarily guarantee a better solution (Y. Liu et al., 2020).

The Fuzzy Inference method, often used in conjunction with FAHP, further enhances decision-making by applying fuzzy logic to infer conclusions from a set of fuzzy rules. This method is particularly useful in determining Managed Aquifer Recharge (MAR) sites, where multiple environmental and socio-economic factors must be considered. The

advantages of using FAHP and Fuzzy Inference include the ability to handle imprecise data and achieve consensus among decision-makers, as demonstrated by the Guaranteed-Consensus Posterior-Aggregation FAHP method, which ensures consistent and precise estimation of fuzzy weights (Chen, 2019). However, these methods also have disadvantages, such as the complexity of the model and the potential for inconsistent fuzzy pairwise comparisons, which can complicate the decision-making process (Chen, 2019). Despite these challenges, the FAHP and Fuzzy Inference methods remain valuable tools for addressing uncertainty in complex decision-making environments.

2.1.1.3 Integrated Models

The Integrated TOPSIS Model, combined with various MCDA methods such as AHP and entropy, is a sophisticated approach to determining potential MAR sites. This model leverages the strengths of different decision-making techniques to address the complex site selection task, particularly in regions facing water scarcity. The AHP is used to establish the relative importance of various criteria through pairwise comparisons, which helps in structuring the decision problem and quantifying the weights of each criterion (Feizi et al., 2017; Mouhoumed et al., 2023). The entropy method, on the other hand, provides an objective way to determine the weights by measuring the amount of information each criterion contributes, thus reducing subjectivity (Feizi et al., 2017; Islam et al., 2022). The TOPSIS method is then employed to rank the potential sites by calculating the geometric distance of each option from an ideal solution, integrating the weighted criteria to prioritize areas for MAR activities (Demesouka et al., 2013; Mouhoumed et al., 2023).

The advantage of using an integrated TOPSIS model with AHP and entropy lies in its ability to combine subjective judgments with objective data, leading to a more balanced and comprehensive decision-making process. This integration allows for a robust analysis

that can accommodate various types of data and preferences, making it particularly useful in complex environmental and spatial planning scenarios (Islam et al., 2022; Mouhoumed et al., 2023). However, the model also has its disadvantages. The complexity of integrating multiple methods can lead to increased computational demands and the need for specialized knowledge to interpret the results accurately. Additionally, the reliance on accurate data inputs and the potential for subjective bias in the AHP process can affect the reliability of the outcomes (Demesouka et al., 2013; Feizi et al., 2017). Despite these challenges, the integrated approach remains a powerful tool for identifying suitable MAR sites, as demonstrated in various case studies (Mouhoumed et al., 2023; Feizi et al., 2017).

The Integrated Spatial Multi-Criteria Decision Analysis (SMCDA) Model is another sophisticated tool designed to determine potential sites for MAR. This model integrates various decision-making techniques to evaluate and rank potential sites based on multiple criteria. The SMCDA model combines non-compensatory screening, criteria standardization and weighting, and the Analytical Hierarchy Process (AHP) with Weighted Linear Combination (WLC) and Ordered Weighted Averaging (OWA) to facilitate a comprehensive analysis. This integration allows for a flexible approach that can accommodate a wide range of decision-maker preferences. The model is implemented within a Geographic Information System (GIS) framework, which enhances its capability to process and display spatial data effectively. This GIS integration is crucial for visualizing the spatial distribution of potential MAR sites and for conducting spatial analyses that are essential for site selection (Fathi et al., 2021, 2020; Rahman et al., 2013, 2012).

The advantages of the SMCDA model include its adaptability and comprehensiveness, making it applicable to various site-selection problems beyond MAR. Its user-friendly interface and explicit decision steps, such as constraint mapping and criteria overlay,

make it accessible to users with different levels of expertise. Additionally, the model's ability to incorporate GW flow and transport modeling provides a more holistic approach to site selection, ensuring that selected sites are not only suitable but also sustainable in the long term (Rahman et al., 2013, 2012). However, the model also has some disadvantages. The complexity of integrating multiple decision-making techniques can be challenging, requiring significant expertise and computational resources. Furthermore, the model's reliance on accurate and comprehensive data inputs means that its effectiveness can be limited in regions where such data is scarce or unreliable. This can lead to uncertainties in the site selection process, potentially affecting the reliability of the outcomes (Hani et al., 2023a, 2023b; Rahman et al., 2013).

2.1.1.4 Simulation-Optimization Frameworks

The Simulation-Optimization (SO) framework for determining potential MAR sites is a sophisticated approach that integrates simulation models with optimization techniques to identify optimal locations for MAR implementation. This framework is particularly useful in balancing multiple objectives, such as maximizing GW storage while minimizing costs. For instance, in California's Central Valley, an SO framework was employed using an evolutionary multi-objective genetic algorithm coupled with a hydrological simulation model. This approach allowed for the creation of a Pareto front, which helps stakeholders evaluate different MAR site options based on cost, benefits, and trade-offs. The framework demonstrated that recharging GW from high-magnitude flows could be achieved at varying marginal costs, depending on the source of recharge water and the scale of the operation (Kourakos et al., 2023a).

The advantages of the SO framework include its ability to handle complex, multi-objective problems and provide a clear visualization of trade-offs through the Pareto front. This makes it a powerful tool for decision-makers who need to consider various factors

and constraints in MAR site selection. However, the framework also has some disadvantages. It requires significant computational resources and expertise in both simulation modeling and optimization techniques, which can be a barrier for some organizations. Additionally, the accuracy of the results is highly dependent on the quality of the input data and the assumptions made in the models, which can introduce uncertainties in the decision-making process (Fatkhutdinov and Stefan, 2019; Kourakos et al., 2023a).

2.1.2 General objectives of MAR projects

The determination of suitable sites for MAR involves several key objectives that are crucial for the successful implementation and sustainability of MAR projects. One primary objective is to ensure the availability and quality of water for recharge. This involves assessing the potential sources of water, such as excess SW, stormwater, or treated wastewater, and evaluating their suitability for recharge based on quality and quantity criteria (Alam et al., 2021; McCurry and Pyne, 2022). Additionally, the compatibility of the recharged water with the receiving aquifer is essential to prevent adverse effects on water quality and aquifer health (McCurry and Pyne, 2022). Another critical objective is to evaluate the physical and hydrogeological characteristics of potential sites. This includes analyzing factors such as soil type, aquifer properties, depth to GW, and hydraulic conductivity, which influence the aquifer's ability to store and transmit water (Alkhatib et al., 2021; Nerantzis Kazakis, 2018). The use of GIS- MCDA is a common approach to integrate these factors and create suitability maps that guide site selection (Sallwey et al., 2019; Rahman et al., 2012).

Another significant objective in determining suitable MAR sites is to address environmental and socio-economic considerations. This includes minimizing potential negative impacts such as land subsidence, saltwater intrusion, and disruption to existing land use (Alam et al., 2021; Kazakis, 2018). The selection process often involves a trade-off analysis to balance the benefits of increased GW storage against potential costs and environmental impacts (Kourakos et al., 2023). Furthermore, the integration of MAR into broader water resource management strategies, such as Integrated Water Resources Management (IWRM), is crucial to ensure that MAR projects contribute to long-term water sustainability and resilience against climate variability (Rahman, 2011).

The primary objectives in determining suitable sites for MAR are optimizing the balance between maximizing GW storage and minimizing costs while considering the complex interplay of various hydrological and geological factors. A key goal is to identify locations that offer the best trade-offs between these competing factors, often using multi-objective optimization frameworks that incorporate both surface and subsurface characteristics (Alkhatib et al., 2021; Kourakos et al., 2023a). These models aim to map out cost-effectiveness frontiers, allowing stakeholders to evaluate different MAR site options based on potential benefits and associated costs (Kourakos et al., 2023). Additionally, the models consider the impact of MAR on GW levels and the prevention of issues such as seawater intrusion, especially in coastal areas (Russo et al., 2015). Overall, the objective is to ensure that MAR sites are selected in a way that maximizes efficiency and sustainability, considering current and future water resource needs.

2.2 STREAM FLOW ENHANCEMENT THROUGH MAR

MAR site selection has not traditionally focused on streamflow enhancement due to several factors. MAR has been implemented to increase GW storage and availability rather than directly enhancing stream flow. This is evident in studies where MAR is used

to mitigate GW depletion and improve water security in regions facing water shortages due to climate change and increased demand (Ferencz et al., 2024; Kourakos et al., 2023a; Lee et al., 2019). Additionally, the complexity of hydrological systems and the variability in water availability make it challenging to align MAR operations with stream flow enhancement objectives. For instance, the availability of SW for recharge is a critical factor, and in many cases, MAR is conducted in areas where water rights and availability are prioritized for agricultural or urban use rather than ecological benefits (Kourakos et al., 2023a; Morrisett et al., 2024). Furthermore, the technical and institutional challenges associated with managing water rights and ensuring the legal feasibility of using MAR for stream flow enhancement can be significant barriers (Morrisett et al., 2024). As a result, while MAR has the potential to enhance baseflow and support ecological objectives, its implementation has often been driven by immediate water supply needs rather than long-term stream flow enhancement goals.

There is a vast scarcity of research on MAR site selection with the objective of stream flow enhancement. In the Namoi basin, Australia, a study utilized MCDA to create a site suitability map for MAR projects. This approach involved selecting ten hydrologic and hydrogeologic criteria, which were reclassified and combined using AHP and pairwise comparisons. The study highlighted the importance of high spatio-temporal variability in natural recharge rates, which are heavily dependent on the Namoi River streamflow. The selected area of interest (AOI) demonstrated high recharge rates, particularly in the paleochannel surrounding the river, indicating the effectiveness of the proposed methodology in identifying suitable MAR sites for stream flow enhancement (Fuentes and Vervoort, 2020).

In another study, MAR was evaluated as a strategy to redistribute excess surface flow to baseflow in snowmelt hydrologic regimes. This research focused on the Treasure Valley

aquifer in Idaho, USA, where a regional GW model was used to identify favorable locations for baseflow enhancement. The study simulated MAR at 197 candidate locations to assess their effectiveness in meeting water management objectives. The findings emphasized the importance of selecting sites where GW recharge can flow back to the SW system in a lagged manner, thus enhancing baseflow during periods of low SW availability. This approach not only aids in stream flow enhancement but also addresses the challenges posed by climate change, such as reduced snowpack and altered snowmelt timing (Ferencz et al., 2024).

2.3 ASSESSMENT OF RAE WITH INTEGRATED SW-GW MODEL

2.3.1 Quantification of RAE

In a well-connected, undisturbed river aquifer system, GW that enters the aquifer through recharge will traverse its way to the sink (i.e., Rivers). The extraction by the vegetation and humans creates non-linearity in the GW flow process, which makes it difficult to quantify the net-enhanced river aquifer exchanges. Analytical solutions for GW flow, while valuable for theoretical insights and simplified scenarios, often fall short in real-world applications due to their inherent assumptions and limitations. These solutions typically rely on idealized conditions such as homogeneity of aquifer properties, simplified boundary conditions, and linearity of flow equations, which rarely match the complex and heterogeneous nature of actual subsurface environments. For instance, analytical models may not adequately capture the variability in hydraulic conductivity and porosity, leading to inaccuracies in predicting flow and transport behaviors in heterogeneous aquifers (Perez et al., 2021; Zoua et al., 1996). Additionally, they often fail to account for vertical flux and complex interactions between multiple layers and recharge sources, which are critical in realistic settings (Cihan et al., 2011; Pophillat et al., 2020).

The simplifications necessary for analytical solutions, such as assuming uniform flow or neglecting vertical leakage, can result in significant errors when applied to natural systems with irregular boundaries, variable recharge rates, and anisotropic conditions (P. Omar et al., 2020; Zhao et al., 2016). Consequently, while analytical solutions provide a useful starting point, they must be supplemented with numerical models and field data to achieve reliable and accurate predictions in real-world GW management scenarios.

The use of MODFLOW for simulating river-aquifer exchanges offers several advantages, particularly its ability to dynamically couple SW and GW models. This integration allows for a comprehensive simulation of saturated and unsaturated zones, which is crucial for accurately determining recharge rates and flow exchanges between rivers and aquifers (Zeinali et al., 2020). Head-dependent boundaries condition in MODFLOW is specifically designed to handle river-aquifer interactions, enabling the simulation of spatiotemporal distributions of GW recharge rates and aquifer evapotranspiration, which are essential for understanding the hydrological dynamics in a given area (Kim et al., 2008). Additionally, MODFLOW's capability to simulate complex flow fields, including vertical and lateral exchanges, provides a more detailed and accurate representation of river-aquifer interactions compared to simpler models (Ghysels et al., 2021). This detailed modeling is beneficial for water resource management, as it allows for the assessment of various management scenarios and the planning of sustainable GW use (Movahedian et al., 2016). Furthermore, MODFLOW's flexibility in handling different hydrological conditions, such as connected and disconnected streams, enhances its applicability across diverse environmental settings (Brunner et al., 2010). Overall, MODFLOW's robust modeling capabilities make it a valuable tool for simulating river-aquifer exchanges, aiding in effective water resource management and planning.

The SFR2 package offers significant advantages for simulating river-aquifer exchanges, particularly in complex hydrological settings. One of the primary benefits is its ability to model unsaturated flow beneath streams, which is crucial in regions where streams are hydraulically disconnected from aquifers due to GW withdrawals. This capability allows for more realistic simulations in areas with deep unsaturated zones, as it accounts for the hydraulic conductivity of the unsaturated zone, which can restrict seepage loss from streams (Niswonger and Prudic, 2005, 2010). Additionally, the SFR2 package is integrated with MODFLOW, a widely used GW modeling software, enhancing its utility in various hydrological studies, such as those involving the Okavango Delta, where it aids in evaluating water management and climate change scenarios (Milzow et al., 2009). Furthermore, the SFR2 package supports the simulation of solute transport in stream-aquifer systems, which is essential for assessing water quality issues related to nutrient and trace element transport in agricultural settings (Qurban et al., 2018). These features make the SFR2 package a powerful tool for researchers and water resource managers aiming to effectively understand and manage stream-aquifer interactions.

2.3.2 Integrated SWAT and MODFLOW Model

The integration of SWAT with the MODFLOW offers significant advantages in simulating river-aquifer exchanges and assessing the impacts of climate change. This integrated approach allows for a more comprehensive understanding of the interactions between SW and GW systems. The SWAT (Soil and Water Assessment Tool) model does not inherently simulate GW dynamics, such as distribution and recharge rates. To address this limitation, SWAT is often coupled with GW models like MODFLOW or AEM to better capture SW and GW interactions (Sangeetha et al., 2022). By linking SWAT's semi-distributed watershed modeling capabilities with MODFLOW's fully-distributed GW modeling, researchers can simulate detailed GW recharge rates and aquifer

evapotranspiration, which are crucial for understanding river-aquifer interactions (Ehtiat et al., 2018; Guzman et al., 2015; Kim et al., 2008). The SWAT-MODFLOW model has been successfully applied in various regions, demonstrating its ability to simulate spatiotemporal distributions of GW recharge and levels and to capture the dynamics of GW discharge into river systems, especially during low flow periods (Chunn et al., 2019; Kim et al., 2008; Yifru et al., 2020).

In the context of climate change impact assessment, the integrated SWAT-MODFLOW model provides a robust framework for evaluating how climate variables affect River Aquifer interactions. Studies have shown that while climate change may have a negligible impact on RAE patterns in some regions, the addition of anthropogenic factors, such as increased GW withdrawals, can significantly alter these interactions (Abbas et al., 2022; Akbarpour and Niksokhan, 2018; Chunn et al., 2019). The model's ability to incorporate downscaled climate projections and simulate future scenarios makes it a valuable tool for predicting the potential impacts of climate change on water resources. For instance, in the Dee River catchment in Wales, the SWAT-MODFLOW model was used to predict future surface-water abstraction scenarios under climate change conditions, providing insights into unmet water demands and streamflow requirements (Abbas et al., 2022).

Moreover, the SWAT-MODFLOW model enhances the accuracy of hydrological simulations by providing more realistic outputs than standalone models. It has been shown to improve the prediction of low stream flow and GW level, which is critical for effective water resources management (Molina-Navarro et al., 2019; Yifru et al., 2020). The model's ability to simulate the effects of GW abstraction on streamflow, as demonstrated in a Danish catchment, highlights its utility in supporting decision-making for environmental assessments and sustainable GW management (Molina-Navarro et al., 2019). Overall, integrating SWAT and MODFLOW offers a powerful tool for researchers

and policymakers to address the challenges posed by climate change and develop strategies for sustainable water resource management.

2.4 THE PERMISSIBLE AQUIFER RECHARGE RATE

The determination of aquifer recharge capacity is crucial for MAR projects because it directly influences the effectiveness and sustainability of these initiatives. Understanding the recharge capacity helps select suitable sites and design systems that can efficiently store and recover water, thereby enhancing water supply resilience in the face of increasing water stress and climate variability (Alam et al., 2021; Parker et al., 2022a). An accurate assessment of recharge capacity ensures that the aquifer can accommodate the intended volume of water without causing adverse effects such as GW mounding or reduced water quality (Tzoraki et al., 2018). It also aids in optimizing the cost-effectiveness of MAR projects by aligning the recharge efforts with the aquifer's natural capacity, thus preventing over-extraction and ensuring long-term GW sustainability (Kourakos et al., 2023; McCurry & Pyne, 2022). Additionally, knowledge of recharge capacity is essential for mitigating potential challenges such as clogging and ensuring the compatibility of recharged water with the aquifer's existing conditions (Ringleb et al., 2016; Kazakis, 2018).

The rate of injection at a site is dependent on the aquifer properties as well as the well-design parameters (Kumar et al., 2024; Shandilya et al., 2022b, 2022a). The hydrogeological evaluation necessitates determining the aquifer capacity for assessing site suitability and design recharge rate during the feasibility assessment and conceptual design phase of ASR development (Pyne, 2017). The knowledge of the optimal injection rate during aquifer recharge is vital information required for the site selection, design, and operation of ASR projects (Tiwari and Yadav, 2024). The aquifer storage capacity is the maximum volume of water that can be injected into an aquifer at an optimal rate under

the constraint of a permissible head change and operational parameters (well characteristic and Injection duration) (Shandilya et al., 2022a). The aquifer recharge rate through injection wells can be determined using various methods, including temperature-depth profiles (Rushton and Srivastava, 1988), sinusoidal functions (Li et al., 2020), incremental increases in recharge head (Dillon et al., 1994), field tests (Dillon et al., 2019; Martinez and Widdowson, 2023), analytical methods (Shandilya et al., 2022b) and numerical modeling (Kumar et al., 2024; Tewari et al., 2024). Most recent studies by Shandilya et al. (2022b) demonstrate the determination of aquifer-scale recharge capacity based on analytical solutions for a pumping well in confined aquifers. The methodology presented by Shandilya et al. (2022b) does not consider the effect of sources and sinks. Apart from field tests, which are time-consuming and expensive, solutions based on 3D GW flow models better represent the real field scenarios with respect to the available analytical solutions considering nearby sources and sinks. The numerical model was used to analyze the injection capacity for ASR systems by Myoung-Rak et al. (2020) (Myoung-Rak et al., 2020). The available literature does not offer any studies that determine the injection capacity of aquifers. To the author's knowledge, no study has utilized a numerical model to explicitly identify the optimal injection rates for confined and unconfined aquifers.

2.5 RESEARCH GAPS

Based on the literature review, the following research gaps have been identified:

1. There is a lack of GW parameterization in SWAT models, which limits their utilization in integrated SW and GW assessment.

2. The impact of climate change and rising GW demand on RAE has not been clearly defined and is often analyzed for baseflow at gaging stations using hydrograph separation methods, which do not account for spatial variations.
3. The effect of MAR through injection wells on the baseflow has not been conceptualized, and explicit quantification measures of baseflow enhancement are lacking.
4. The methodology to determine Permissible Aquifer Recharge Rate (PARR) through numerical methods assumes a regression surrogate model, which reduces the accuracy of PARR.
5. No research is available that explicitly quantifies the potential of a recharge site to restore baseflow.
