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Article

Introducing a Managed Aquifer Recharge Feasibility Index (MARFI): A Tool for Discursive Decision Making

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Key Points:

- (i) Groundwater Resources are under threat globally.
- (ii) Pakistan is 4th largest user of groundwater globally, where groundwater is meeting almost 50% irrigation, 90% drinking and industrial demands.
- (iii) In Pakistan groundwater levels and quality are deteriorating
- (iv) Large scale Managed Aquifer Recharge (MAR) using abandoned canals/channels can contribute significantly to the sustainable management of groundwater for irrigated agriculture is imperative
- (v) Decision making for investment in MAR is complex.
- (vi) A new Index called Managed Aquifer Recharge Feasibility Index (MARFI) is introduced.

Abstract

Water is fundamental to the economy of Pakistan, and to many of the country's 250 million people. Increasing groundwater use in Pakistan is occurring against a backdrop of climate change, dwindling surface water, and human population growth. Historically there has been little groundwater resource management in the country, and that little has mainly related to its use, that is to demand side management. There is some potential for Managed Aquifer Recharge (MAR) to contribute to groundwater supplies, that is, to supply side management. MAR is a complex process which to be effective requires consideration of social, institutional, environmental, technical, financial, and economic parameters. This paper introduces a methodology that has been developed to assess and sum the effect of multiple parameters into single numerical value, to enable the feasibility of proposed MAR projects; the "Managed Aquifer Recharge Feasibility Index (MARFI)". MARFI was developed using a case study of an MAR project currently being implemented by the Punjab Irrigation Department in the bed of Old Mailsi Canal. MARFI is a suitable tool for examining the pre-project feasibility of any MAR scheme for contributing to wise investment decision making.

Keywords: managed aquifer recharge; MARFI; groundwater; Old Mailsi Canal; Punjab; Pakistan

1. Introduction

Only 1% of the total water on earth is suitable for use by humans (Qureshi & Ashraf, 2019). With the increasing population and climate change, water scarcity has become one of the major global issues of the 21st century (Maheshwari, 2023; Pahl-Wostl et al., 2013; Rockström et al., 2009). Around 96% of the planet's unfrozen freshwater is available as groundwater (Giordano, 2009; Reinecke et al., 2020). Most of the 750-800 billion m³/year global groundwater withdrawals are used

for agriculture; indeed, groundwater has become the mainstay of irrigated agriculture in many parts of Asia, especially in South Asia (**Maheshwari, 2023; Qureshi, 2018**)

Water is of crucial importance to the economy of Pakistan, and to many of the country's 250 million people. The primary water sources of Pakistan are glacial melt, rainfall, and groundwater (**WB, 2019**). Over 70% of Pakistan's surface water resources are from the Indus River Basin (IRB) (**Qureshi, 2015**). The IRB has an arid to sub-arid climate with an average annual rainfall of 240 mm. Around 90% of Pakistan's food production is from irrigated agriculture (**Qureshi & Ashraf, 2019**).

An extensive network of diversion structures, link canals, main canals, minor canals, and watercourses is collectively called the Indus Basin Irrigation System (IBIS). The IBIS conveys water across Pakistan; however, this surface supply is now insufficient for Pakistan's needs, and groundwater has become significantly important. The reduction in surface water supplies and the increased use of groundwater of marginal quality poses a significant risk to Pakistan's food security (**Watto & Muger, 2016**).

The demands for food and fiber for its rapidly increasing population have led Pakistan to become fourth largest user of the groundwater globally (**Muzammil et al., 2020; Zakir-Hassan, Shabir, Hassan, et al., 2022**). Groundwater management in Pakistan has historically focused on seeking technical solutions related to its use, that is, on how to manage the demands on groundwater through reduced extractions (**Bhatti et al., 2017; Zakir-Hassan, Akhtar, et al., 2022**). There is, however, some potential to manage the supply of groundwater. In the Indus Basin groundwater is sourced from a large aquifer, which is replenished naturally by rivers, canals and irrigated fields (**Punthakey et al., 2016**). Floods are also important hydrological event which cause aquifer replenishment (**Ashraf, 2022**).

Artificial or managed aquifer recharge (MAR) is the planned human activity for augmenting the amount of groundwater available through works designed to increase the natural replenishment of surface waters into the groundwater aquifers, resulting in a corresponding increase in the amount of groundwater available for abstraction as and when required (**Ahirwar et al., 2020; El Moneam, 2022; IRI, 2009; Singh et al., 2017**)

There is rapidly gaining interest in MAR as a tool for replenishing depleted aquifers, improving water quality, and combating water scarcity in many regions of the world (**Dillon et al., 2018**). While MAR has potential as a reliable supply side management tool (**Glaude et al., 2023**) there are many associated costs and risks. For example, artificial recharge may contaminate groundwater with organic and inorganic pollutants (**Madhavan et al., 2023**), and MAR schemes are usually costly, so it is always necessary to evaluate the potential anticipated barriers/risks to implementation of any MAR (**Diedhou et al., 2023**). MAR is a complex undertaking, and its feasibility depends on a range of multi-sectoral parameters, including social, institutional, environmental, technical, financial, and economic considerations. The essential elements for assessing the feasibility of MAR projects include hydrogeological considerations, institutional feasibility, and economic analysis (**Govt of Australia, 2008; Halytsia et al., 2022**). It is also important to consider infrastructure-related considerations and institutional design (**Tiwari & Yadav, 2023; Ulibarri et al., 2021**). Therefore, assessing the overall feasibility of any MAR project involves multidisciplinary and multi-parameter analysis and evaluation (**Dashora et al., 2019**). At present a comprehensive methodological framework for this purpose is generally not available and experts in different discipline deal with feasibility assessment in a piecemeal fashion.

This paper presents the first iteration of an index developed to assist with assessing the pre-project feasibility for any MAR scheme before heavy investments of time, money and other resources are made. The development of this "Managed Aquifer Recharge Feasibility Index (MARFI) is presented below, followed by reflection on its potential use and future improvement.

2. Methods

MARFI was developed as part of a larger study that examined MAR using the case of a government initiated large-scale project in the Punjab province of Pakistan. As part of that project

144 recharge wells have been constructed in the bed of the long-disused Old Mailsi Canal (OMC). Pre-existing structures enable flood water, when available, to be diverted into the OMC, and via these wells into the aquifer. Although there have been small scale aquifer recharge projects undertaken in Pakistan, especially in urban areas, the OMC is the first large scale MAR in Pakistan's Punjab (Zakir-Hassan, Shabir, Yasmin, et al., 2022).

2.1. Study Site

The case study includes the area around a proposed MAR experimental site that is part of the Vehari district, Punjab province, Pakistan as shown in Figure 1. The area is located between latitude 29.9719 °N, longitude 72.4258 °E, with an area of 1522 km². The elevation is roughly 140 meters above sea level, and the area includes both rural and urban areas. The population of district Vehari is approximately 2.9 million, with a 2.23 percent annual growth rate, and the majority of people rely on agriculture for their income (GOP, 2018b; Sindhu, 2010). The nearest large town is Multan, which is approximately 130 km from the study area. The average annual rainfall ranges from 160 mm to 186 mm with an annual average of 173 mm (IRI, 2015). Water is supplied to the area by the Sutlej River and Pakpattan Canal. The river is subject to extreme variations of flow, with the mean monthly discharge during the summer months about 15-20 times that of the winter months (IRI, 2019; Zakir-Hassan, 2023).

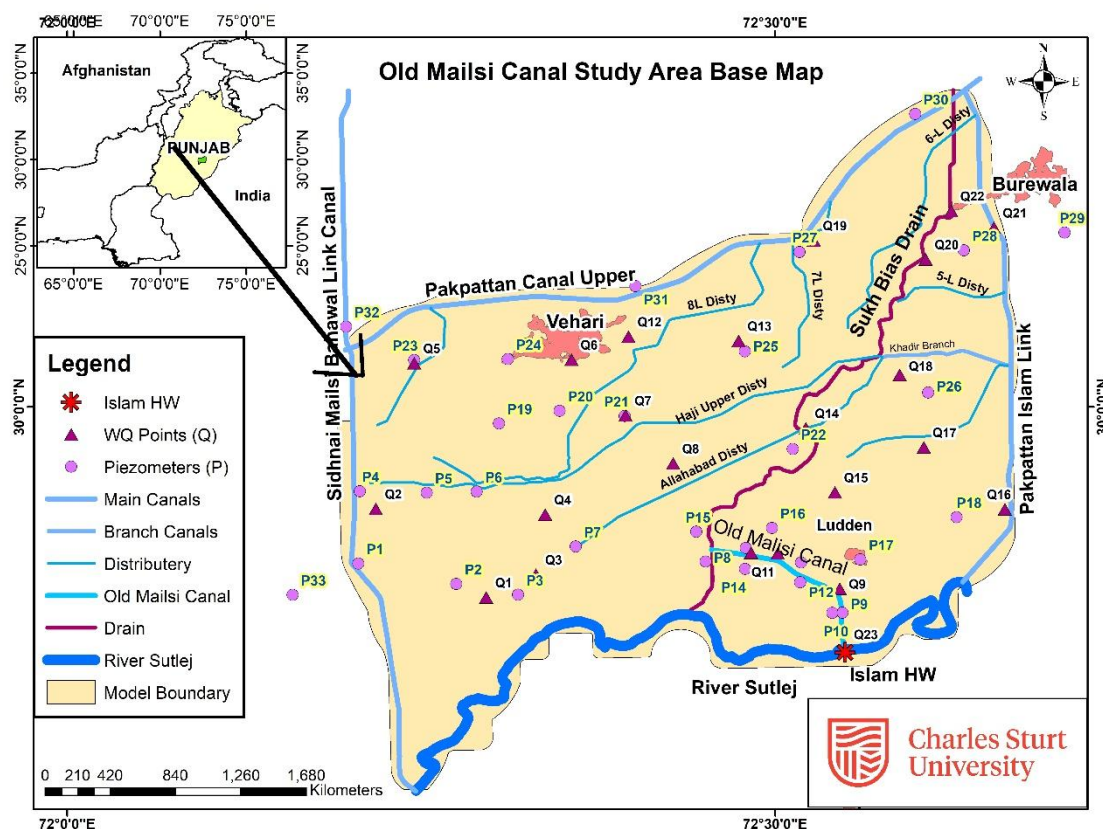


Figure 1. Study area map showing major features and boundaries.

The climate of the study area is generally hot and dry during the summer season that starts in April and continues until October. May, June, and July are the hottest months, with mean maximum and minimum temperatures for these months about 47 °C and 28 °C respectively. The Vehari district is located within an agricultural region of the country, with limited industrial development. The agriculture in the study area depends upon groundwater supply due to a shortage of canal water (WAPDA, 2009). Only 32% of irrigation requirements are fulfilled through non-perennial canal and rainfall (Fatima et al., 2018). Wheat is the major winter crop grown in the area followed by cotton,

fodders, rice, maize sunflower and sugarcane during summer (Sindhu, 2010). Until 2012, the main farming pattern in Vehari was cotton-wheat. The district’s predominant planting pattern, however, has recently emerged as maize-wheat (Khalid et al., 2020). Vehari is the food basket for the province as well as being called the city of cotton and is an intensively cropped area (GoP_BoS, 2019; GoPb_P&D, 2009). Major food crops include wheat, rice and maize, and cash crops comprise cotton and sugarcane and orchards. The fodder crops broadly include Kharif and Rabi fodder like jowar, maize, bajra, berseem, lucerne, shaftal.

2.2. Experimental Layout of MAR Site

The Figure 2 shows the schematic layout of the proposed MAR site in the OMC. This is the first of its kind large-scale MAR project that aims to augment the supply side for irrigated agriculture and to decrease the rate of decline in groundwater in the Vehari district.

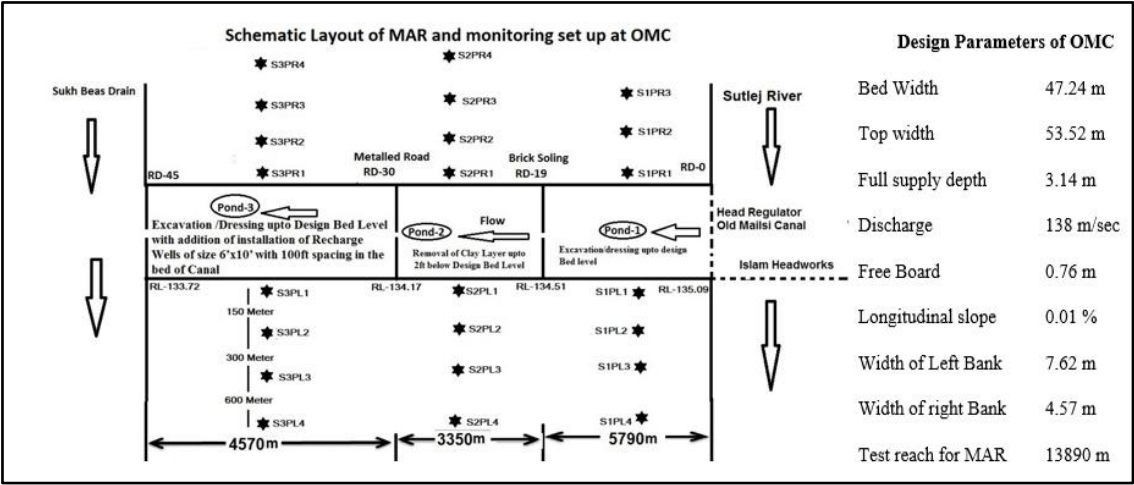


Figure 2. Schematic Layout for large scale MAR in Old Mailsi Canal.

2.3. Developing MARFI

Because MAR is a complex undertaking there is a wide spectrum of parameters which need to be considered while examining the feasibility, which can be broadly considered as technical, social, institutional, financial, economic, legal, and environmental (Arshad et al., 2014). Different aspects of these were addressed by the range of different research approaches used in the larger study.

As summarized in Figure 3 the research included a wide range of components including developing and interrogating a groundwater model (MODFLOW) to estimate the water balance components and future response of the aquifer to different scenarios up to 2035 including with and without MAR situations (Zakir-Hassan, Punthakey, et al., 2025); water quality assessments of source water (river/flood) and ambient water (aquifer). Other physical parameters evaluated include the storage potential of the aquifer (Zakir-Hassan et al., 2024), availability of water for MAR, subsurface lithology/soil profile, sediment concentration in source water, and soil chemistry. Field surveys, investigations and sampling were carried out for ground-trothing of data observations and performance geohydrological tests. In addition, literature was reviewed, and a detailed institutional analysis included a desktop-review of major policy documents and semi-structured interviews 31 water experts from different levels, sectors, and categories (Zakir-Hassan, 2023). Groundwater governance is the biggest challenge for its sustainable management and utilization (Zakir-Hassan, Allan, et al., 2023), to address and mitigate this challenge some tools like MARFI are imperative.



Figure 3. Learning sources for development of MARFI.

Together these inquiries suggest six main feasibility parameters for consideration before undertaking MAR; technical/physical social, economic, financial, environmental, and the institutional arrangements for these.

Technical/Physical Parameters

Effective MAR relies on suitable physical conditions, and technical capabilities. Physiographic characteristics such as drainage density, surface geology, lineament/topography, rainfall patterns, and land cover/use, soil texture, soil structure have a direct influence on MAR (Vaddadi et al., 2023), with aquifer characteristics playing a vital role in success of any AMR scheme (Tiwari & Yadav, 2023). Technical parameters of importance include the aquifer characteristics supporting infiltration and then recovery, availability of ‘surplus’ water, adequate underground storage potential, and means to transport the surplus water to the target aquifer. These physical and technical parameters can be assessed through field investigations/tests, such as drilling, soil sampling, geophysical investigation, pump test, well logging, permeability test, and infiltration tests, and through analysis of historical hydrological data including frequency analysis of hydrological extreme events, groundwater levels, surface water flows. Laboratory analyses will also be required, including permeability, grainsize distribution and bore logs. The availability of and natural characteristics of the landscape also need consideration. High infiltration rates support easy and fast storage, and whether the flow to recharge can occur by gravity or if some lift is required; these types of parameters influence social and economic considerations.

Social Considerations

MAR requires land and infrastructure, and public or other investment of resources, with benefits such as increased access to water not necessarily distributed equally across the region or province. Projects are more likely to be successfully used and maintained if there is social acceptance or social ‘licence,’ to operate (Gehman et al., 2017), although care is needed with this term and concept

paralleling the need for physical investigations, the knowledge and views of various stakeholders should be assessed. Approaches such as Social Impact Assessment (**Becker, 2001**) can highlight negative and positive impacts ideally the people most impacted by the potential development should have some mechanism to contribute to the assessment and planning. Beyond simple acceptance and licence to operate, there may be opportunities for stakeholders, including individual and community, participation in monitoring operational aspects of the MAR proposal if it went ahead. Social research methods may include surveys, including Participatory Rural Appraisal (**Khair et al., 2021**) and is best situated in an adaptive, systemic social-ecological framework (**Mitchell et al., 2021**).

Economic Feasibility

Economic and financial parameters are generally considered together but as financial feasibility deals with the benefits and costs of a particular investment/business, and economic feasibility deals with a range of costs and benefits to the whole economy they should be considered separately. (**Maliva, 2014**) has provided details of various types of costs and benefits involved in the economic, social, and financial analysis of a MAR project, noting that economic parameters are most often approached through cost benefit analysis (CBA) are generally performed by calculating the net present value (NPV) of the project considering with-project and without-project scenarios. Some economic approaches measuring the willingness to pay (WTP) and willingness to accept compensation (WTA) of all positive and negative impacts of a project. CBAs of MAR schemes also incorporate the uncertainties and risks involved in design and execution of MAR schemes (**Govt of Australia, 2008**).

Financial Analysis:

Financial feasibility differs from the economic feasibility as it deals with the market prices while economic analysis deals with the economic costs and values (**Ulibarri et al., 2021; WMO, 2007**). The financial analysis of any project includes the monetary components which include the project (rather than general) cost benefit ratio (CBR), internal rate of return (IRR), financial internal rate of return (FIRR), and other financial aspects of MAR. Through a financial feasibility study, the decision-makers arrive at the conclusion that what are the expectations about the success of the project. Such a type of feasibility involves the costs of the project which are generally known/calculated and the benefits of the project which are expected. The costs components involve the capital costs and the maintenance costs after completion of the project. Benefits can be tangible and non-tangible, including the monetary value of water recharged to aquifer, and/or water improved by MAR systems.

Environmental Aspects

There are a range of assessments currently used to consider the impacts of large projects that can be used for MAR to assess positive and negative impacts on groundwater dependent and landscape ecosystems and natural habitats. These include initial environmental impact assessment (IEIA), environmental impact assessment (EIA), and strategic environmental assessment (SEA) (**Halytsia et al., 2022; WMO, 2007**)...

Institutional Arrangements

Institutional feasibility is a wide term and covers many important parameters which can play significant role in success of a MAR project. 'Institutions' in this sense include organizations, policies, rules, laws, norms, traditions, and customs which influence MAR and the legal aspects supporting or hindering the MAR (**Mukherji & Shah, 2005**). It covers a broad spectrum of important parameters; for example, any policy which supports the MAR, laws and rules which illustrate the legal aspects of MAR, regulatory framework which advocates the governance of MAR related activities. Other important attributes include the local customs, traditions, cultural trends, and religious thoughts which strengthen the MAR objectives and scope. Organizations may include departments, ministries,

authorities, divisions, and units, at international, national, provincial, and local level in public sector and the INGDs, NGOs, CBOs, WUAs, FOs in private sectors. Organizational capacity with respect to human resource, infrastructure, computer-based knowledge management systems, and groundwater models prerequisite for the monitoring, modelling and management of the MAR schemes play a vital role in the institutional feasibility of the MAR projects. Resource monitoring, information storage, data retrieval its accessibility and sharing the key factors towards the institutional strength. Organisational norms can also support or oppose the MAR projects and are required to be evaluated for assessing the viability of a MAR project.

2.4. The Design of MARFI

MARFI has been designed by quantifying the different as shown in Figure 4. Different types of feasibilities have been grouped together to come up at a single numerical value for quick and prompt decision making.



Figure 4. Feasibility framework of a typical MAR project-.

All parameters identified above are linked with the feasibility of any MAR project, have been linked together using a rank (R) and weight (W) system Appendix 1 (supplementary material). The R and W have been assigned to each parameter based on the significance and role towards as determined through the multi-disciplinary case study. This system of weights and ranks is flexible having wide range. Assigning ranks is a relative action and no absolute ranks can be assigned to the physical properties related to feasibility of MAR. Allocation of ranks and weights is subjective, and depends upon the wisdom, vision, and expert knowledge of the rankers. The suggested relative ranks between 1 and 5 assigned to parameters are justified in Appendix 2 (supplementary material)

The weights and ranks method is used when there are several factors having variable effects and importance, their combined impact is converted into a single numerical value to make suitable decision about success or failure of any process. This is done by assigning weights and ranks to different parameters and their weighted impact is calculated. (Mondal et al., 2012; Noshin et al., 2018; Zakir-Hassan, Hassan, et al., 2022). The weighted index –MARFI- can be calculated by using Equation (1).

$$MARFI = \frac{1}{n} \sum_{i=1}^n Ri * Wi \quad (1)$$

where, n is the number of factors/parameters ($F_1 - F_{24}$) ($n = 24$), R_i is the rank of i th parameter, W_i is the weight of i th parameter (F). Keeping in view the ranks and weight system of parameters, a classification of feasibility of MAR schemes based on MARFI has been proposed as given in Table 1.

Table 1. Proposed classification of MARFI.

MARFI Value	Class of MAR
400-500	Highly Feasible
200-400	Feasible
100-200	Low feasible
10-100	Not feasible

3. Results and Discussions

The first iteration of MARFI has been applied to the case study site. Although the logic is somewhat circular, doing so is useful to demonstrate how MARFI can be used, and to check its overall congruence. In the sections below some details of the case study are provided, followed by how these are converted in the MARFI to provide a feasibility ‘score’.

The Irrigation Research Institute (IRI) of Punjab Irrigation Department (PID) is executing a MAR project at OMC in in Vehari district, Punjab province of Pakistan, at latitude 29.9719°N, longitude 72.4258°E. The district’s population is approximately 2.9 million, growing annually by over 2 percent annual growth rate, and with the majority relying on agriculture for their livelihood (GOP, 2018b; Sindhu, 2010). The river Sutlej originates from India and enters Pakistan downstream Ganda Singh Wala. The Mailsi Canal had been diverting water from the Sutlej River at Islam Headworks since 1928 but was abandoned in 1960 due to Indus Water Treaty between India and Pakistan (WB, 1962) . It is now referred to as the Old Mailsi Canal (OMC). The OMC is 53.4 km long, and the first 15 Km have been taken for an MAR project. The aim is to use the existing Islam Headworks to divert Sutlej floodwaters into the bed of the canal where 144 recharge wells have been constructed. OMC is about 47 m wide and 4 m deep existing channel, into which the floodwater from Islam Headworks is diverted during rainy/flood season (July-September).

At this site, the land is available except for a small reach which has been occupied illegally by local people. Infrastructure in the shape of the abandoned Old Mailsi Canal (OMC) is also available, which is not being used for any purposes and can be utilized for MAR after rehabilitation. Flood water is available during monsoon period. Groundwater levels are depleting at about 0.5 to 1 m per year (Zakir-Hassan, Shabir, et al., 2023), increasing the cost of groundwater extraction, an example is shown in Figure 5.

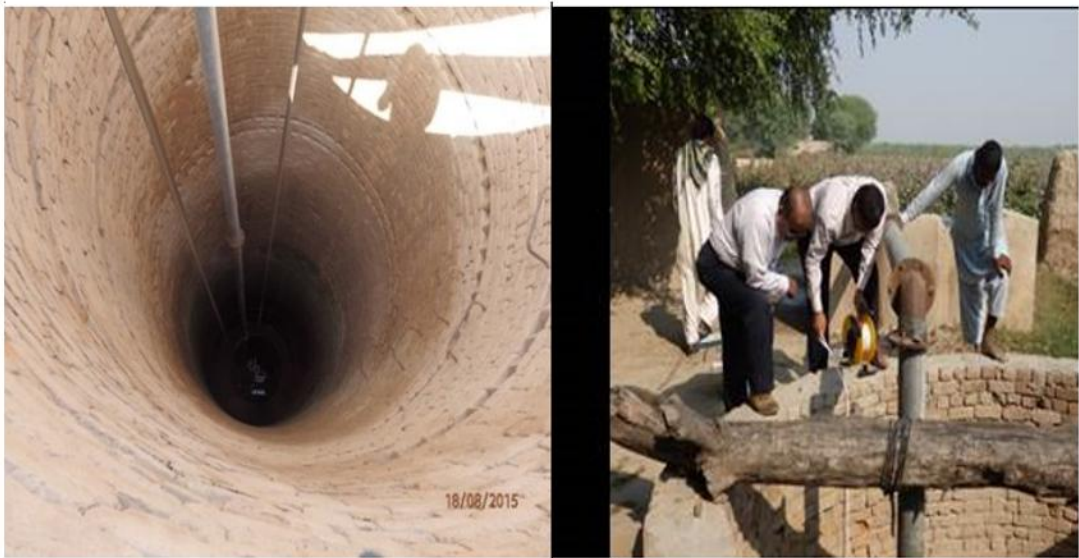


Figure 5. Depleted groundwater levels in district Vehari Punjab Pakistan (Zakir-Hassan, 2023).

In addition to agricultural purposes groundwater is being used for drinking, industrial, livestock, fish-farming and other miscellaneous functions. Groundwater quality is also a challenge. Groundwater is not suitable for drinking purposes, how is fit for irrigation uses (Zakir-Hassan, Baumgartner, et al., 2025; Zakir-Hassan, Shabir, et al., 2025). Sediment loads in the floodwater are higher as compare to normal flows in the river (IRI, 2023). The topography of the study area is very mild i.e., 0.02% with suitable geologic characteristics having sandy aquifer after few meters’ depth. Local people are generally supportive of the MAR project as the cost of extraction of groundwater has increased due to falling water levels.

It this case study improved water quality has been anticipated to have a positive environmental impact on human and crops health. There were no adverse impacts of the OMC MAR projects identified as per environmental impact assessment (EIA) conducted by (WAPDA, 2009) as the OMC was an existing canal.

The anticipated benefits of the project include increase in crop production, opportunities for increasing area under high value cash crops, improved drinking water and other household needs of the community, improved financial conditions of the farmers by income from raising of livestock and livestock products, *increased volume of water in the aquifer, reduced pumping cost due rise in water table and* tax receipts of the government in the form of water rates and income tax will increase due to higher cropping intensities. The project has created *some jobs for labour during execution and in the long run employment opportunities will be created in agriculture sector* (Hassan et al., 2016). The Water and Power Development Authority carried out the economic and financial analysis of this MAR project and the estimated values of different parameters include i) Economic Internal Rate of Return (EIRR) = 23%; Financial Internal Rate of Return (FIRR) = 13.71%; Benefit Cost Ratio (BCR) = 1.82; and opportunity cost of capital = 12%. They noted that the project is economically viable as it yields EIRR higher than the opportunity cost of capital, and BCR is greater than 1. They further reported that the project is financially viable as FIRR is 13.71%. (IRI, 2019; WAPDA, 2009)

While there were some short-term impacts on livestock during the construction works the project does not pose any long-lasting significant threat to the existing highly modified environment. To mitigate the few trees removed from the bed of canal, one percent of the project cost has been earmarked for tree planation at the project site (IRI, 2019). Another, minor adverse impact for the community is disturbance in village roads and water courses which were crossing the OMC. Culverts have been constructed on such points to facilitate the local community.

Results from the water analysis have indicated that groundwater as well as the river water are suitable for irrigation use. *Overall, it has been noted that the project will not have any sever threats or long-lasting adverse impacts; however minor impacts have been safeguarded by ensuring mitigation measures.*

Institutionally the National Water Policy (GoP, 2018a), Punjab Water Policy (GoPb_PID, 2018), and Punjab Water Act 2019 are the major legal instruments which cover and support the MAR. Rules and regulations are also being framed in this context. As per classification of the projects under (GoP_EPA, 1997), the project has been classified as “Category A” (WAPDA, 2009).

These various factors assigned Ranks (1 to 5) and weights (10 to 100) at the case study site are listed in Table 2, which shows the application of MARFI at OMC.

Table 2. Application of MARFI to case study of MAR at Old Mailsi Canal in Punjab Pakistan.

ID	Factor/parameter (F) with description	Ranks (R) (Most important-R=5; least important-R =1)	Weights (W) Maximum = 100 Minimum = 10	Weights assigned for OMC MAR project.
F1	Geophysical Conditions (Land slope, topography-flow possible under gravity or required lift, infrastructure, site accessibility)	4	- Accessible with gravity flow: 100 - Difficult to access, but gravity flow possible: 80.	90

			• Very remote/hard area but gravity flow possible: 50. • Hard area and lift/pump required: 10	
F2	Subsurface Lithology/ Soil Texture and structure (Texture -sandy, clayey, silty, mixed; infiltration rate-low or high; structure- well graded or poorly graded)	4	• Sand, poorly graded with high infiltration rate: 100. • Sandy with high infiltration rate, with normal gradation: 100 • Clayey sand with moderate infiltration rate: 80 • Sandy clay with low infiltration rate: 40 • Sand-silt-clay mixed with very low infiltration rate: 30. • Silty with impermeable layer, well graded: 10	80
F3	Aquifer Parameters/type (Aquifer type, transmissivity, porosity)	3	• Highly Transmissive: 100 • Medium Transmissive: 50 • Low Transmissive, unconfined: 30 • Low Transmissive and confined aquifer: 10	70
F4	Water Availability (Historic surplus water, quantity, frequency, duration, Source of water rainfall, floodwater, wastewater, seawater)	5	• Adequate volume of water is available: 100. • Medium availability: 50 • Low water availability: 20 • No water available: 10	90
F5	Water Recovery (Option for aquifer storage and recovery)	2	• Stored water can be recovered as, when and where required: 100. • Partial recovery: 50 • Poor recovery: 10	80
F6	Suitable Recharge Method (Infiltration, injection, spreading)	1	• All methods are suitable: 100. • Only infiltration is possible: 50. • Injection is the only way: 10	70
F7	Sediments (Physical and chemical properties like, suspended load in source water, chances of clogging, sediment load, concentration, sediment size, sediment type, turbidity level)	3	• Low sediment concentration, less chances of clogging: 100 • Medium chances: 50 • High chances of clogging (more concentration of sediments, more silt load, natural filtration possible): 30 • Heavy silted water, high chances of clogging, not possible to use without costly artificial filtration: 10	70
F8	Underground Storage Potential (How much water can be stored in aquifer)	5	• Sufficient potential: 100 • Medium Potential: 50 • Low Potential: 10	100
F9	Groundwater Depletion Rate (Historical water table depletion trends, annual depletion rates)	4	• Highly depleted: 100 • Medium depletion: 50 • Low depletion: 30 • Waterlogging: 10	100

F10	Climatic Conditions (Rainfalls, floods, droughts)	2	• More droughts, low rainfall, low floods: 100 • Moderate: 50 • No droughts, high rains, and floods: 10	
F11	Quality of Source Water (Quality of source water to be recharged into the aquifer- chemical, biological, physical)	4	• Suitable for irrigation/drinking: 100 • Marginally fit for irrigation/marginally fit for drinking: 80 • Marginally fit for irrigation/not fit for drinking: 50 • Not fit for irrigation/drinking: 10	90
F12	Quality of Sink/target Water (What is quality of host water in the aquifer- physical, chemical, and biological quality for different uses)	4	• Suitable for irrigation/drinking: 100 • Marginally fit for irrigation/marginally fit for drinking: 80 • Marginally fit for irrigation/not fit for drinking: 50 • Not fit for irrigation/drinking: 10	80
F13	Resultant Water Quality (Quality of water in aquifer after recharge- Physical, chemical, biological quality for different uses)	3	• Suitable for irrigation: 100 • Marginally fit: 50 • Not suitable: 10	70
F14	Environmental Impacts (Rehabilitation of wetlands, groundwater dependent ecosystems, improvement in value of the place, improved landscape, cutting of trees, temperature controlled, new plants, greenery, temperature control, Recreational value addition, EIA, IEE, loss of flora and fauna, improvement of Aesthetic value of place)	4	• Positive impacts/environmentally sound: 100 • Some positive Impacts: 70 • No impacts (positive or negative): 50 • Some adverse impacts: 30 • Adverse impacts: 10	80
F15	Soil Chemistry (Chemistry of soil /vadose zone through which recharge water will flow before reaching the saturated zone/groundwater. It might be saline, sodic, or good soil. For example, soil pH, Ec)	3	• Good soil: 100 • Medium good: 50 • Saline or Sodic: 10	80
F16	Monitoring System for MAR (Monitoring system is in place or not- as no management without monitoring, pre and post monitoring)	3	• Adequate monitoring system in place: 100 • Partial system in place: 50 • Poor or no system: 10	60
F17	Organizational Capacity (Capacity of agencies for implementation, adequate HRs)	4	• Adequate capacity: 100 • Medium capacity: 50 • Poor capacity: 10	60

F18	Policy and Legal Support (Legal aspects including policy, regulatory framework, Laws, Rules, supporting MAR). b	3	- Policy supports MAR regulation in place with implementation framework = 100 - Only policy- no regulation or implementation: 50 - Policy regulation exist but poor implementation: 30. - Not supported by policies and no regulatory framework = 10	70
F19	Social Aspects (Social license, cultural/social considerations, improved livelihood; displacement of people, plants, animals; alternate land for community, livelihood, water is life, business of opportunities, creation of jobs, drinking water for animals,) Increase Crop Production Opportunities for increasing area under high value cash crops.	4	- Community willing/support MAR, benefits for community: 100 - Some positive impacts: 70 - Partially willing positive and adverse impacts more or less are: 50. - Least willing/no ownership: 10	90
F20	Demand for Groundwater (Irrigation, and others- like drinking, livestock, industries, aquaculture)	3	- High demand for all sectors: 100 - Moderate demand/limited uses: 50 - Medium demand/only few uses: 30 - Low demand/ not much use: 10	90
F21	Economic Analysis Cost Benefit Analysis (CBA), anticipated returns on the investment (ROI), Economic internal rate of return-EIRR and other parameters, increase in cropped area, more crops, manpower required, economic value of water through MAR0, Contribution to GDP)	5	Economically viable and feasible: 100 Medium feasibility/viability: 50 Low viability/feasibility: 30 Not feasible: 10	70
F22	Financial Viability (Cost benefit ratio-CBR, Financial internal rate of return-FIRR, reduction in pumping cost,)	5	Financially viable: 100 Not viable: 10	70
F23	Site/Land Availability (Land for construction of recharging system, Alternate use of land)	5	- Land available -state land = 100 - Land donated by community= 80 - Land to be purchased: 30. - Suitable Land not available: 10	90

F24	Funding	2	• Top priority: 100	60
	(Priority of the Govt for		• Moderate: 50	
	funding, funds available or not)		• Least priority: 10	

Different ranks and weights have been assigned to all factors, after due examination, deliberation, and assessment as per case site conditions at OMC project. Detailed calculations on MARFI for OMC project are given in Table 3. It is an example of application of the MARFI to the study area with specific site conditions. Equation 1 has been applied to the case study site.

Table 3. Calculation of MARFI for MAR project at OMC.

Factor ID	Old Mailsi Canal Ranks (R)	Old Mailsi Weights (W)	R x W
F1	4	90	360
F2	4	80	320
F3	3	70	210
F4	5	90	450
F5	2	80	160
F6	1	70	70
F7	3	70	210
F8	5	100	500
F9	4	100	400
F10	2	90	180
F11	4	80	320
F12	4	70	280
F13	3	70	210
F14	4	80	320
F15	3	80	240
F16	3	60	180
F17	4	60	240
F18	3	70	210
F19	4	90	360
F20	3	90	270
F21	5	70	350
F22	5	70	350
F23	5	90	450
F24	2	60	120
Sum			6760
n =	24		
MARFI =	282		

The calculated MARFI for the MAR project of Old Mailsi Canal is 282, which suggests the project has overall feasibility.

4. Conclusions and Recommendations

MAR has potential to contribute to supply side management of groundwater, and thus to enhanced water security, not just in Pakistan but in all areas reliant on groundwater for continued survival. However, MAR undertaken at scales that can make a major contribution is resource heavy, and not without risks. This study has shown how multiple parameters can be combined to aid decision making about whether to implement a MAR project The MARFI presented here is a first attempt. Because MARFI has been developed and tested in a real case study, it goes beyond theory into something that could be effective in the field. MARFI is particularly suited for large scale MAR projects designed for replenishing aquifers which are heavily exploited for irrigation, which is a significant emerging challenge in South Asia. The methodology developed is an innovation which

can be applied for any MAR project in Pakistan, the South Asia region, and globally because the details of the fields and weighting decisions can be varied over time and across regions.

Assessing the feasibility of any MAR scheme is very complex, laborious, costly, and time consuming exercise. Before investing the huge amounts for replenishment of the stressed aquifers through MAR; detailed investigations including drilling at site, sampling, and lab analysis are required. The hydrogeologists always look for a framework to declare any site suitable for detailed investigations and design of a MAR project. Under these circumstances quick assessment of any site is imperative before making heavy financial and HR commitments for MAR systems. The methodology developed under this research is a quick check-list arranged under a framework which guides the decision makers about the fate of a site before going into detailed design and construction for any MAR intervention. The index, MARFI, designed and introduced here provides a vital role in planning and designing any MAR project. This index can be used widely in Indus River Basin in Pakistan and other regions as well where MAR is gaining importance for combating the challenges of water scarcity.

Data Availability Statement: All the data pertaining to the study has been made part of the paper, however, any requests for further information, clarification, comments can be referred to the corresponding author.

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Note: Views expressed in the article are those of the authors, and do not reflect the point of view of any organization/department.

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