frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 22 November 2022
DOI 10.3389/fenvs.2022.916504

Check for updates

OPEN ACCESS

EDITED BY
Prosun Bhattacharya,
Royal Institute of Technology, Sweden

REVIEWED BY
Albert Casas,
University of Barcelona, Spain
Shahriar Shams,
University of Technology Brunei, Brunei

*CORRESPONDENCE
Gulraiz Akhter,
agulraiz@qau.edu.pk

SPECIALTY SECTION
This article was submitted to Water and Wastewater Management,
a section of the journal
Frontiers in Environmental Science

RECEIVED 09 April 2022
ACCEPTED 11 November 2022
PUBLISHED 22 November 2022

CITATION
Sardar H, Akhter G, Ge Y and Haider SA (2022), Delineation of potential managed aquifer recharge sites of Kuchlak sub-basin, Balochistan, using remote sensing and GIS.
Front. Environ. Sci. 10:916504.
doi: 10.3389/fenvs.2022.916504

COPYRIGHT
© 2022 Sardar, Akhter, Ge and Haider. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Delineation of potential managed aquifer recharge sites of Kuchlak sub-basin, Balochistan, using remote sensing and GIS

Hassan Sardar[1], Gulraiz Akhter[1,2]*, Yonggang Ge[3,4] and Syed Ammar Haider[5]

[1]Department of Earth Sciences, Quaid-i-Azam University, Islamabad, Pakistan, [2]China-Pakistan Joint Research Center on Earth Sciences, CAS-HEC, Islamabad, Pakistan, [3]Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, China, [4]Key Laboratory of Mountain Hazards and Earth Surface Processes, Chinese Academy of Sciences, Chengdu, China, [5]Department of Physical and Applied Geology, Eötvös Loránd University, Budapest, Hungary

RETRACTED

In the Kuchlak Sub-Basin (Pakistan), groundwater is overexploited, resulting in growing stress on groundwater resources. The water table level has declined rapidly due to intensive pumping. Artificial recharge methods and good management strategies are vital for the sustainable production of groundwater resources. Managed aquifer recharge is an artificial way of recharging the subsurface aquifers using surplus surface water, treated wastewater, and stormwater. It is a potential strategy for increasing freshwater supply and adapting to climate change. The present study proposes a method to delineate potential zones for MAR suitability in the Kuchlak Sub-Basin. INOWAS, a web-based tool, is utilized for narrowing down the available MAR techniques based on the hydrogeologic parameter and objectives of the study area. A geographic information system (GIS) coupled with the multi-criteria decision analysis (MCDA), commonly known as GIS-MCDA, is used to develop the MAR suitability map. Six criterion maps, including geology, land use, slope analysis, drainage density, soil, and rainfall, were created in ArcGIS for suitability mapping. The criterion maps are ranked and weighted based on their relative contribution to the groundwater recharge and published literature using the Multi Influence Factor (MIF) method. The final suitability map was developed by overlaying all the criterion maps using a weighted linear combination (WLC) technique. The MAR suitability map was divided into five zones, namely, very high, high, moderate, very low, and low. The unsuitable zones reflect the urban and slope constraints that reduce surface infiltration. The suitability map reveals that 45% of the Kuchlak Sub-Basin exists in a very high-high suitability zone, 33% in moderate, and 17% in a very low-low suitability zone, while 5% of the study area was unsuitable due to the urban and slope constraints. The MAR suitability map developed in this study can serve as a basis for conducting a focused analysis of MAR implementation. Furthermore, the technique and results of this study may aid in mapping MAR suitability in any arid or semi-arid region.

KEYWORDS

managed aquifer recharge, remote sensing, GIS, land use, slope, drainage density

RETRACTED

1 Introduction

Groundwater is considered among the most essential and reliable sources of drinking water worldwide (Todd and Mays, 2004). In arid regions, evapotranspiration exceeds average rainfall, making groundwater recharge dependent on high rainfall events, rainwater storage in depressions and streams, and rainwater's capacity to escape evapotranspiration through fissures, cracks, or solution channels (de Vries and Simmers, 2002). In dry regions like Balochistan, a province of Pakistan, sources of surface water are generally non-perennial, making groundwater the only reliable source of water for the household, agricultural, and industrial needs. The rise in population and the growth of farmlands have put growing stress on groundwater resources, which has resulted in the overexploitation of groundwater and deterioration of water quality (Watto, 2015; Mondal and Dalai, 2017). The situation is further exacerbated in dry regions, such as Balochistan, where the water table continues to decline rapidly causing the drying of karezzes and springs, and the destruction of orchards (Ashraf and Sheikh, 2017). The situation demands innovative approaches coupled with integrated watershed management to recharge groundwater and preserve sustainable production.

Water scarcity can be alleviated by subsurface storage of surplus water during wet periods for later usage during a dry season (Dillon et al., 2010, 2019; Arshad et al., 2020). Increasing the water storage under the surface is a viable strategy for increasing freshwater supply and resilience to climate change. This artificial increase in the groundwater can be realized through Managed Aquifer Recharge (MAR) techniques, defined as the "intentional recharge of water to aquifers for subsequent recovery or environmental benefit" (Dillon et al., 2019; Sendrós et al., 2020). MAR refers to a broad range of recharge techniques, including spreading methods (SM); well shaft, in-channel modifications (IM); rainwater and runoff harvesting (RWH); induced bank filtration (IBF); and borehole recharge (WSB) (Villholth, 2021). MAR offers a promising solution to alleviate the effects of the declining water table and replenish the subsurface aquifer (Dillon, 2005; Sprenger et al., 2017; Dillon et al., 2019) and can also alleviate drinking water problems associated with the consumption of groundwater with excessive levels of arsenic or salinity (Naus et al., 2021). It has been effectively used worldwide to improve the quality and quantity of groundwater resources, replenish the groundwater levels, avoid saltwater intrusion, manage land subsidence, alleviate floods, and boost ecological benefits (Stefan and Ansems, 2018). However, to design a MAR system, it is important to determine the soil infiltration rate and permeability of the unsaturated zones between the aquifer and surface land and ensure the lack of polluted zones (Bouwer, 2002). The selection of an appropriate recharge site is a vital step in MAR implementation since it influences the selection of a suitable recharge technique (Dillon, 2005). However, the selection of an appropriate MAR technique is challenging because it is dependent on several interrelated factors, including the source water availability for recharge (Alam et al., 2021), the subsurface soil type suitable for source water infiltration (Khan et al., 2020), the capacity of an aquifer to hold and discharge sufficient water (Maples et al., 2019), the quality of the source water (Rivett et al., 2008; Wiese et al., 2011; Alidina et al., 2014), and the total cost of the project (Perrone and Rohde, 2016). The site suitability analysis is carried out to find a suitable technique for a given location (Sallwey et al., 2019). The site suitability assessment for MAR is frequently determined by intrinsic characteristics like topography, hydrogeology, land use, soil type, and climate since these factors influence the recharge process of groundwater (Sallwey et al., 2019).

The traditional methods for locating, defining, and mapping MAR suitability zones mostly rely on expensive and time-consuming ground surveys utilizing geophysical, geological, and hydrogeological techniques (Israil et al., 2006). On the other hand, geospatial tools are cost-effective and less time consuming to model different kind of data in multiple geosciences fields (Oh et al., 2011). A literature review shows that the potential zones for ground water recharge have been identified and mapped using range of techniques. For instance, some researchers used probabilistic model like frequency ratio (Ozdemir, 2011; Razandi et al., 2015), certainty factor (Razandi et al., 2015), MCDA (Chowdhury et al., 2009; Rahmati et al., 2015), logistic regression (Ozdemir, 2011;Pourghasemi and Beheshtirad., 2015), decision tree (Chenini and Mammou 2010), evidential belief function (Mogaji et al., 2015), weights of evidence (Corsini et al., 2009; Ozdemir, 2011) Shannon's entropy (Naghibi et al., 2015), artificial neural network (Lee et al., 2012), and machine learning techniques like random forest (Rahmati et al., 2016). Remote sensing and GIS together provide a powerful tool that can be utilized for quick estimation of natural resources among the many techniques. The methodology is cost-effective and can be used to effectively explore groundwater before using intricate and expensive surveying techniques (Faust et al., 1991).

Several studies have used geographic information system GIS and remote sensing (RS) techniques to locate the potential groundwater zones. GIS and RS cover a large and remote area in a short time to determine the high potential groundwater zones for artificial recharge (Senthilkumar et al., 2019). GIS coupled with the multi-criteria decision analysis (MCDA),

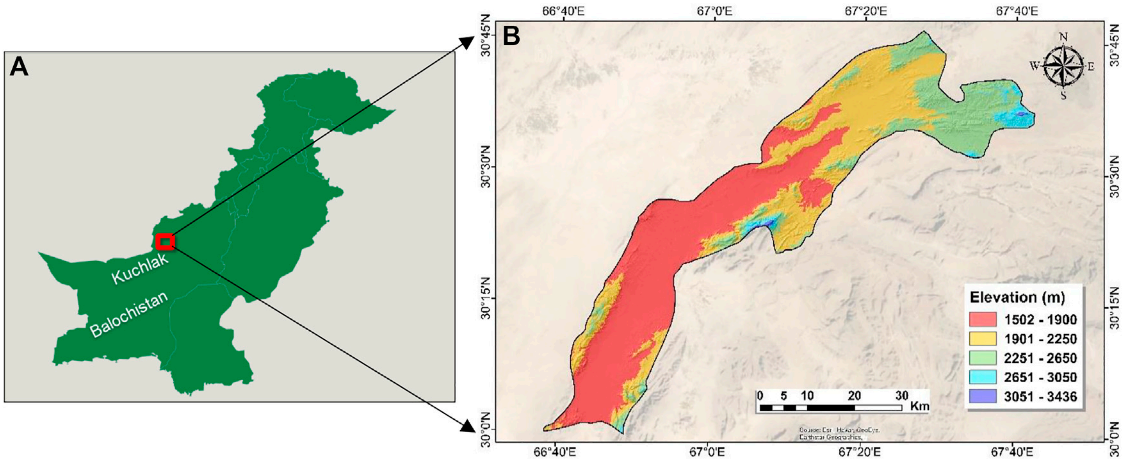

FIGURE 1
Map of Study area (Kuchlak Sub-Basin) showing **(A)** location, and **(B)** elevation.

RETRACTED

commonly known as GIS-MCDA, helps in finding a suitable location for MAR implementation (Rahman et al., 2012). The GIS-MCDA can be defined as a collection of tools for designing, evaluating, and prioritizing alternative decisions (Malczewski, 2006). In this method, the geospatial data are weighted against each other and overlayed to evaluate the study area. The process of assigning the weight is subjective and is defined by considering the expert opinion, personal preferences (Agarwal and Garg 2016), and objectives of the study area. GIS-MCDA is advantageous due to the increasing availability and the growing resolution of remote sensing data. Therefore, remote sensing data is useful for places with little geologic and field knowledge.

This study aims to address the water scarcity in dry regions using MAR techniques. To this end, the present work is divided into two sub-objectives. The first is to delineate suitable sites for MAR implementation using GIS-MCDA and the second is to suggest suitable MAR techniques. The main criteria used in this study for site suitability assessment are geology, slope analysis, drainage density, land cover, soil, and rainfall. The delineation of suitable MAR sites is performed using GIS-MCDA, whereas INOWAS, a web-based tool, is used to identify appropriate MAR techniques.

2 Materials and methods

2.1 Study area

The present study selected the Kuchlak Sub-Basin of the Pishin Lora basin in Pakistan's western province of Balochistan due to the significant decline in the groundwater table. The Kuchlak Sub-Basin extends between latitudes 30°N −30°45′N and longitudes 66°38′E–67°43′E, with an elevation range of 3430 m in the north to 1500 m in the south (Figure 1). It covers an area of approximately 2083 km^2 and extends from northeast to southwest. Annual rainfall is 217 mm, with considerable variability and the annual evaporation is approximately 1750 mm. The Kuchlak Sub-Basin is classified as arid due to low precipitation and drought episodes (Halcrow, 2007, 2008). Agricultural land consists of temporary crops (arable or cultivable land) and permanent crops (orchards like apples and grapes) covers around 276.8 km^2. Cultivable land which is part of agricultural land covers approximately 70.25 km^2, which is approximately 16.7 percent of the Kuchlak Sub-Basin. The Ghurkai Lora, Khanozai, Bibi Lora, Bostan, and Surkhab Rivers are the major streams in the study area and eventually flow into the Pishin valley *via* the Pishin Lora River (Ahmed et al., 2021).

There are two major aquifers in the Kuchlak Sub-Basin: one comprised of unconsolidated alluvial sediments that cover the majority of the study area, and another comprised of the bedrock of limestone (Ahmed et al., 2021). The primary stream's system in the Kuchlak Sub-Basin is ephemeral, and poor rainfall recharge means that agriculture must depend on groundwater for irrigation, resulting in significant water table decreases. Agriculture consumes 97 percent of Balochistan's water (Khair et al., 2010), and Kuchlak is no exception. Farming continues to offer employment for 31%–49% of the population in the Pishin district where the Kuchlak Sub-Basin is situated. (Halcrow, 2008b). The groundwater level in Kuchlak Sub-Basin has declined dramatically due to extended drought, overexploitation, and poor management (Ahmed et al., 2021). This grave scenario revealed the critical significance of water conservation in the area through MAR techniques.

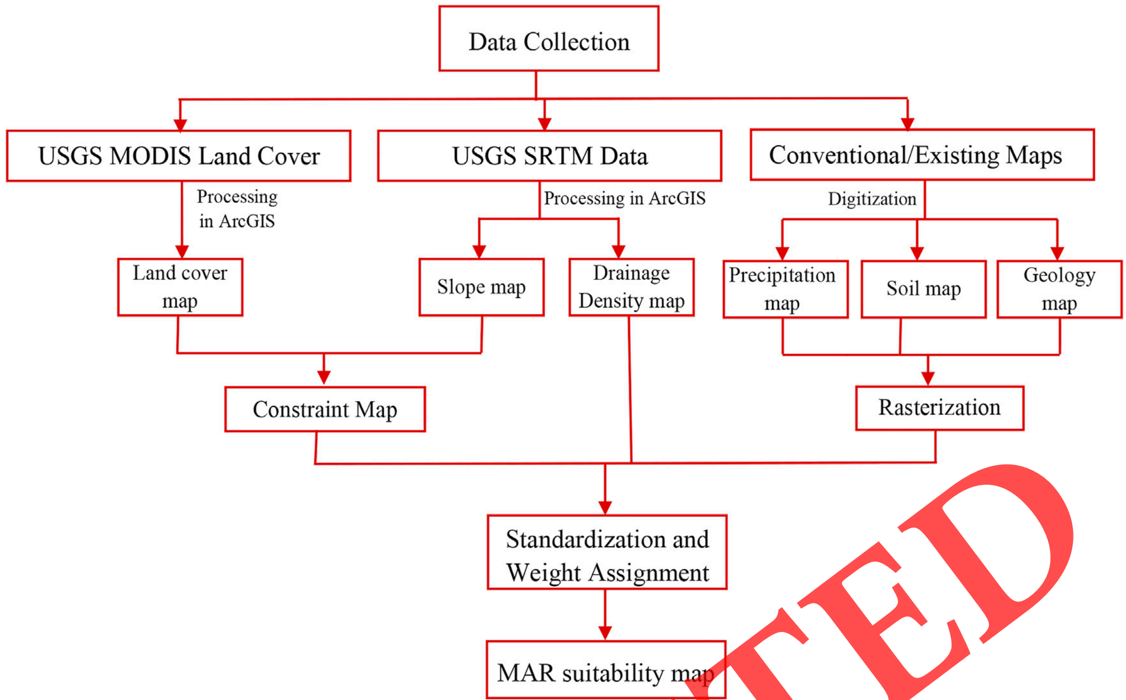

FIGURE 2
Workflow adapted for delineation of MAR suitability zones.

RETRACTED

2.2 Workflow

The detailed workflow adopted for this study is shown in (Figure 2), and the major steps are described below.

- Identifying suitable MAR techniques using INOWAS, a web-based tool for narrowing down the available MAR techniques
- Digitizing the conventional maps in ArcGIS, i.e., geology, soil, and rainfall.
- Preparation and reclassification of thematic (criteria) layers.
- Standardization of thematic layers to bring them to the same level.
- Assigning weight to each thematic layer using the Multi-Influence Factor (MIF) method.
- Generation of the final MAR suitability map using Weighted Linear Combination (WLC).

2.3 Managed aquifer recharge method selection

Since each MAR solution has unique site-specific needs, checklists comprising the selection criteria are classified according to MAR type. For instance, implementing an induced bank filtration MAR scheme is only practicable in the presence of a river or lake. By contrast, MAR schemes utilizing well, shaft, or borehole recharge are virtually independent of surface water. Because no generic selection criteria for MAR can be defined, this research develops selection criteria unique to the MAR type. INOWAS, a web-based data-driven tool, assists in the identification of appropriate MAR methods by analyzing hundreds of MAR case studies from around the world (Glass et al., 2021). The MAR method selection tool assists users in selecting an appropriate MAR method based on the features/properties of the selected MAR location. By selecting the research area's features, such as land use, soil type, MAR objectives, and the average scale of the study, INOWAS makes recommendations for appropriate MAR methodologies based on its library of MAR studies (Sallwey et al., 2019). The MAR methods suggested by the INOWAS are summarized in Table 1 and the suitability/unsuitability is decided based on the current climatic and hydrological conditions of the study area.

2.4 Collection of data and preparation of thematic/criteria layers

The data used for the preparation of the thematic layers comprises remote sensing data and existing conventional

TABLE 1 MAR methods suggested by INOWAS and their suitability for the study area.

MAR methods suggested by INOWAS	Suitability	Explanation
Infiltration ponds and basins	Unsuitable	High temperature and high sedimentation rate render these methods unsuitable
Trenches	Suitable	Economical to make and manage
Subsurface Dams	Unsuitable	The water table is very deep for most of the part (20–30 m)
Dune Filtration	Unsuitable	No dunes
Rooftop harvesting	Suitable	At the household level, it is an effective method
Ditches and furrows	Suitable	Economical to make and manage
Flooding	Suitable	Useful in times of heavy rainfall to prevent damage

data from existing. Thematic layers, alternatively referred to as criteria, are the spatial data that are used in GIS-MCDA. The criteria used in different studies vary between 4 and 21, but ninety percent of studies use less than ten criteria (Sallwey et al., 2019). The selection of criteria should be based not only on the availability of data and local attributes but also on the problem statement and expert opinion (Sallwey et al., 2019).

In this work, six criteria maps, namely, geology, land use/land cover (LULC), slope analysis, soil texture drainage density, and rainfall, were prepared using the existing conventional maps and satellite data. A detailed description of each of the above criteria is presented in the next section.

2.4.1 Geology

Regional geological characteristics, such as the porosity and permeability of different rocks, influence the occurrence and transport of groundwater. Consequently, the rock type considerably impacts groundwater availability and recharge. The geological map was prepared by digitizing the existing map in ArcGIS (Ahmed et al., 2021). The primary lithologies identified in the study area are conglomerate, fractured limestone, silty sandstone, and sandstone and shale. Conglomerate and fractured limestone have a high infiltration rate, while silty sandstone and mixed shale (sandstone and shale) have a low infiltration rate.

2.4.2 Land use land cover

Land use/land cover controls surface runoff and infiltration. Plant roots hold water in vegetation-covered places such as forests and agricultural traps, hence increasing the infiltration. In addition, urban areas and paved roads reduce infiltration by enhancing runoff during rainfall (Das et al., 2017). The land cover map was prepared from the Esri global land cover map with a spatial resolution of 10 m. The map was then reclassified into different land use classes based on the guideline provided by the Esri. The primary land use classes identified in the study area are shrubland, bare land, cropland, built area, and few water bodies.

2.4.3 Slope analysis

The slope of the terrain is an important parameter for suitability mapping. The most promising infiltration occurs in locations with little runoff, which is only valid in flat terrains. The slope map was prepared from ASTER-DEM with a spatial resolution of 30 m and then reclassified into five classes. The slope of most of the study area is less than 10%.

2.4.4 Soil texture

Soil texture defines the water retention capacity, permeability, and infiltration rate of the soil. Large particle size increases permeability and surface infiltration (Stephenson, 1979). The soil map was prepared by digitizing the existing conventional map (Soil Survey of Pakistan, Lahore 1993) in ArcGIS and reclassified based on the available codes. The primary soil types are Sandy Loam, loamy rock, and bare rocks (no soil).

2.4.5 Drainage density

The drainage density can be defined as the total length of all the streams in a unit area, irrespective of the stream network (Magesh et al., 2012). It can be used as an indicator for surface infiltration and runoff. High drainage density is related to low permeability, which leads to low infiltration and increased runoff. The drainage density was prepared from the ASTER-DEM using the line density tool in ArcGIS. The map was reclassified into three classes, i.e., high, medium, and low.

2.4.6 Rainfall

The rainfall map was prepared from the existing map (Ahmed et al., 2021) in ArcGIS. The MAR suitability mapping is highly dependent on the infiltration rate, which is determined by the rainfall distribution and slope angle. The rainfall map was reclassified into high, moderate, and low.

2.4.7 Criteria standardization

Each criterion is represented by a map of varying types, including classed maps (e.g., land use) and value maps (e.g., infiltration, slope); it is not easy to compare the two maps with

RETRACTED

RETRACTED

TABLE 2 Standardization of criteria and their suitability class.

Value/Common scale	Suitability class
5	Very high
4	High
3	Moderate
2	low
1	Very low
0	Unsuitable

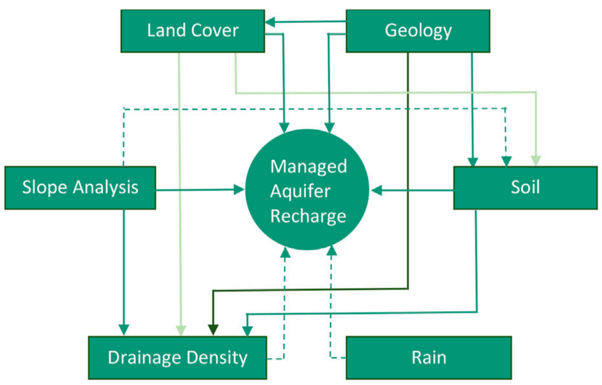

FIGURE 3
Interrelationship between the criteria showing the major (solid lines) and minor (dashed lines) influence using the MIF method.

distinct types in ArcGIS. For example, a land-use map with categories of urban, forest, and water bodies is not comparable to a slope map with categories of 20%, 50%, etc. But when each category on the criteria map is assigned a numerical value, based on its relative importance for MAR suitability, the comparison is easy. Standardization approaches such as step-wise and linear functions are commonly utilized in GIS-MCDA (Bonilla et al., 2016). The present study makes use of a step-wise function. The criteria are standardized on a scale of 0 (low suitability) to 5 (high suitability (Table 2). For example, flat surfaces facilitate infiltration, so they are standardized at a scale of 10 (high suitability for MAR). Similarly, the area with a high slope decreases the infiltration and increases run-off, so they are standardized at a scale of 0 (low suitability for MAR). The standard chosen for assigning the values to the criterion varies greatly and depends on the researcher's choice.

2.4.8 Criteria weighting

The weighting of criteria is critical for spatial multi-criteria decision analysis. Although GIS-MCDA is used for MAR suitability mapping by many studies, the criteria selection and weighting still lack a common understanding (Sallwey et al., 2019). Each criterion is weighted based on its relative importance for MAR within the set of criteria. There are several ways to assign weights to criteria, including the multi-influence factor (MIF), used in this study. In MIF, a higher score/weight is assigned to a criterion when it significantly influences other criteria (Figure 3). Solid lines represent the major influence with a score of 1, and the minor influence is represented by a dashed line with a score of 0.5. The final weight is obtained by adding the relative score of major and minor influence for each criterion (Table 3). The relative weight is then converted to a percentage.

2.4.9 Weighted overlay analysis

The final step in generating the MAR suitability map is the overlay analysis. In weighted overlay analysis, all the criteria are superimposed using the relative weight and standardized suitability score. This is done by multiplying the weight of each criterion with their standardized rank (1–5) for each cell and summing the result. Different overlay methods are available, including the weighted linear combination which is used in this study. The final suitability map is categorized into five levels from 1–5. The value of 1 indicates a very low suitability area for MAR implementation, while the value 5 indicates a very good suitability area.

3 Results and discussion

3.1 Evaluation of suitable MAR techniques

INOWAS, a web-based data-driven tool is used to select the appropriate MAR techniques for the study area. Table 1 summarizes the suitable MAR techniques suggested by INOWAS based on the input parameters related to the study area. The suitability/unsuitability of the proposed MAR techniques is decided based on the study area's existing climatic and hydrogeologic conditions. Some of the proposed techniques were not suitable given the Kuchlak climatic conditions. For instance, INOWAS recommends dune filtration as a potential MAR approach; however, the study area lacks dunes. The leaky dams MAR technique is also included in the suitability analysis because it is an effective MAR method applied in many areas of Balochistan (Ashraf and Sheikh, 2017), though INOWAS does not suggest this technique. The average annual rainfall in the study area is 217 mm, with extreme variability. During the summer monsoon period, heavy rainfall occurs, followed by severe drought in the pre-and post-monsoon period. Therefore, flooding is a possible MAR technique in the study area to capture the high rainfall during the monsoon period. Furthermore, the suitability of a specific MAR scheme at a proposed location requires a detailed study and depends on the hydrogeologic parameters and the target user group. The flooding technique is suitable for installation in the high suitability

RETRACTED

TABLE 3 Relative weight and score assignment of each criterion using the MIF method.

Criteria	Major influence	Minor influence	Combined relative weight	Proposed score (percentage)
Geology	1 + 1+1 + 1	—	4	32
Landcover	1 + 1+1	—	3	24
Soil	1 + 1	—	2	16
Slope Analysis	1 + 1	0.5	2.5	20
Rain	—	0.5	0.5	4
Drainage Density	—	0.5	0.5	4
Total			∑12.5	∑100

TABLE 4 Criteria reclassification and associated suitability score (rank) and weight.

Criterion	Categories (reclassification)	Qualitative rank (suitability)	Quantitative rank (common scale)	Weight
Geology	Conglomerate	Very High	5	32
	Fractured limestone	High	4	
	Silty Sandstone	Moderate	3	
	Sandstone and shale	Low	1	
Landcover	Sparse vegetation (Bare Land)	Very high	5	24
	cropland	High	4	
	Shrubland	Low	2	
	water bodies	Very low	1	
	Built-up area	Unsuitable	0	
Soil	Sandy loam	Very High	5	16
	Loamy rock outcrop	Moderate	3	
	Bare rock (no soil)	Very low	1	
Slope analysis	Flat (0–10)	Very High	5	20
	Gentle (10–15)	High	4	
	Moderate (15–25)	Low	2	
	Steep (25–35)	Very low	1	
	Very steep (>40)	Unsuitable	0	
Rain (mm)	High (230–250)	High	4	4
	Medium (215–230)	Moderate	3	
	Low (200–215)	Low	2	
Drainage density	Low (1–2)	Very High	5	4
	Medium (2–3)	Moderate	3	
	High (>3)	Low	2	

zones of the central and southern parts of the study area due to the high number of agricultural lands which can easily absorb water. The urban areas are used as a constraint in the study due to the scope of the study. However, rooftop rainwater harvesting is suitable for urban areas and is shown by the unsuitable zone in the final suitability map (Figure 5). This technique can be used in the high-moderate suitability zones of the central and North parts due to the high number of river and streams network.

3.2 Evaluation of criteria maps

The six parameters used in this study to delineate suitable locations for MAR implementation are described in detail. Table 4 summarizes the reclassification, weight assignment, and ranks of all criteria based on their importance to the MAR methods. Figure 4 demonstrates the criteria maps prepared to evaluate appropriate MAR locations. The land

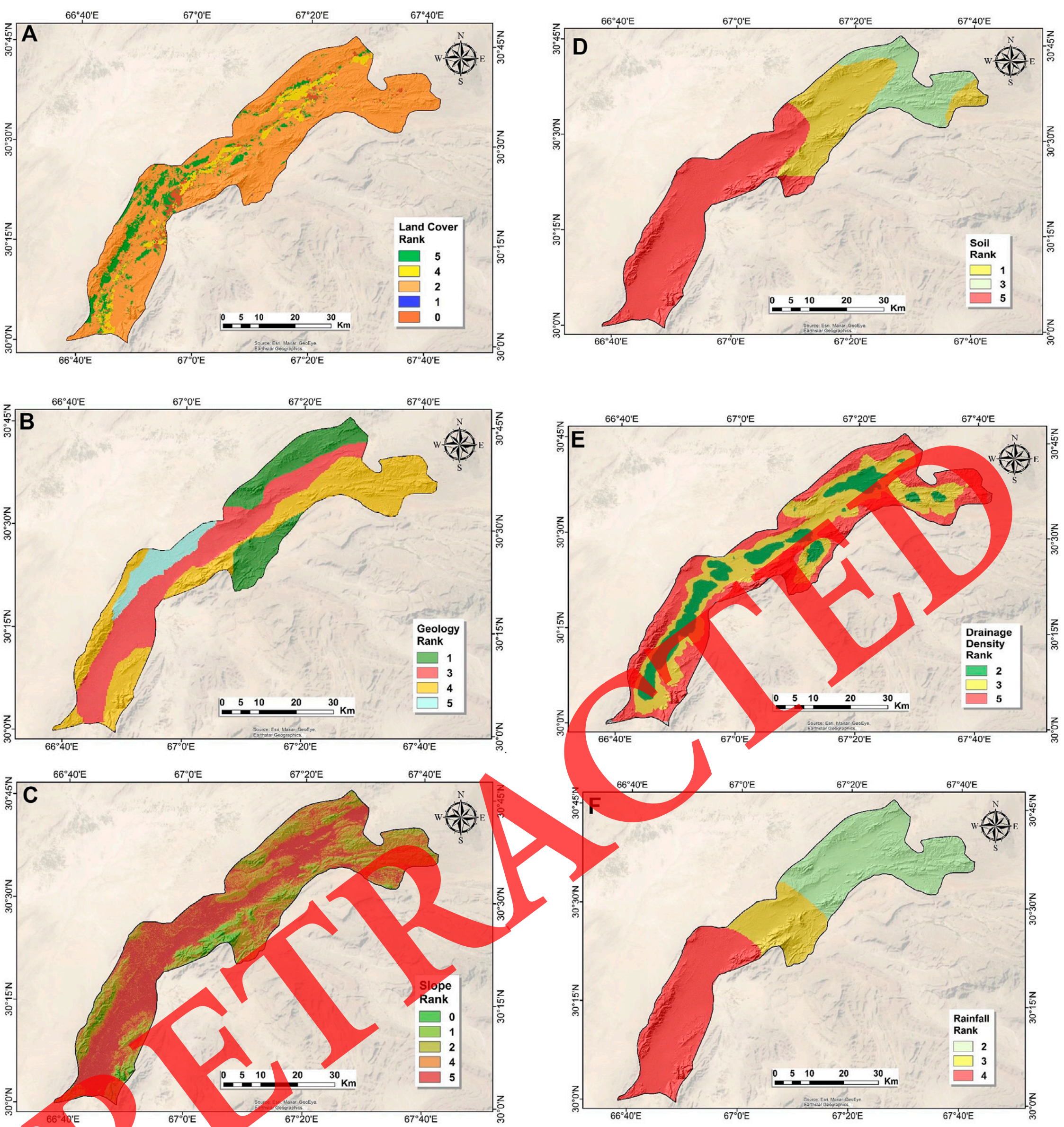

FIGURE 4
Criterion maps with standardized values used for the delineation of suitable MAR locations in the Kuchlak Sub-Basin: **(A)** Land use; **(B)** Geology; **(C)** Slope analysis; **(D)** Soil type; **(E)** drainage density; **(F)** rainfall.

RETRACTED

cover provides information on surface infiltration, groundwater potential, etc., (Das et al., 2017). The land cover map is classified into five main classes: shrubland, sparse vegetation (bare land), built-up area, cropland, and water bodies (Figure 4A). Shrubland covers most of the study area (80%), followed by bare land (10%), cropland (7%), built-up area (2.6%), and water bodies (0.4%). The bare land and cropland are assigned a high suitability score, as they are highly suitable for water infiltration. However, it is not easy to convince the landowners to sell their agricultural land for MAR, especially when their livelihood depends on farming. The built-up area is used as a constraint due to low infiltration and poor water quality.

Geology plays an important role in the occurrence and distribution of groundwater (Yeh et al., 2016). The study area is dominated by fractured limestone and silty sandstone followed by mixed sandstone and shale, and conglomerates (Figure 4B). The type and composition of rock significantly affect the infiltration rate and groundwater recharge. Karstic limestone and silty sandstone have high infiltration rates; therefore, most areas lie in the high-moderate suitability zone. Moreover, mixed

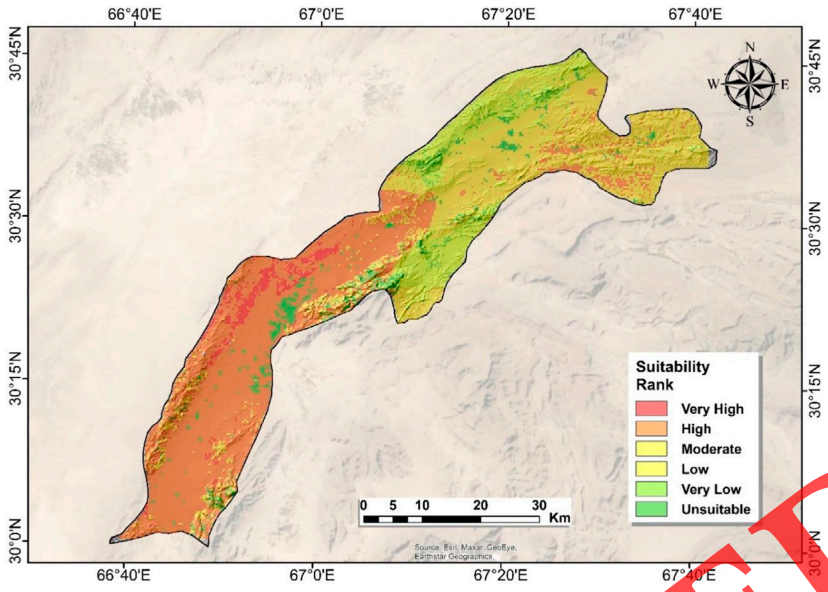

FIGURE 5
MAR suitability map of Kuchlak Sub-Basin, Balochistan, Pakistan.

RETRACTED

sandstone and shale have low permeability, limiting groundwater percolation; therefore, these areas are less suitable for MAR implementation.

The slope map is classified into five categories: flat (0–10), gentle (10–15), moderate (15–25), steep (25–35), and very steep (>40) (Figure 4C). The slope of an area directly affects the surface runoff. Flat areas permit the water to move slowly, increase the infiltration rate, and are highly suitable for aquifer recharge due to very low surface runoff. Conversely, a steeper slope reduces the infiltration and enhances surface runoff due to the fast movement of water. Therefore, high suitability rank was assigned to flat areas while a steeper slope was assigned a low suitability rank. Moreover, a slope higher than 40 was used as a constraint due to the very low infiltration rate.

The soil type and associated permeability control the water holding capacity of the soil and infiltration rate. The soil criterion map of the study area shows three categories: sandy loam, loamy rock outcrops, and bare rock (no soil) (Figure 4D). Sandy loam (55%) dominates the study area, followed by loamy rock outcrops (27%) and bare rocks (18%). The sandy loam is considered suitable for MAR since it has relatively high infiltration. Conversely, bare rock (no soil) is the least suitable for MAR due to the low infiltration rate. Therefore, high suitability rank was assigned to sandy loam while bare rock was given a low suitability rank. Moreover, soil act as a purifier when surface water infiltrates into the aquifer. Areas devoid of soil cover are unsuitable for implementing the MAR methods, as the absence of soil cover poses a significant risk of contamination. This risk grows further in the case of karstic aquifers, where water filtration is virtually non-existent. However, regions devoid of soil cover are included in the suitability mapping process since purification happens when water infiltrates through rocks, not just soil.

The drainage density and its pattern are regulated by surface geology and are therefore considered a significant indicator of surface runoff and infiltration (Gnanachandrasamy et al., 2018). The drainage density of the study area was classified into five categories, i.e., low (1–2), moderate (2–3), and high (>3) (Figure 4E). High drainage density is associated with low permeability, reducing infiltration, and increasing surface runoff. Therefore, areas with high drainage density were assigned a high rank (suitability score for MAR), indicating high runoff and low infiltration, and are considered least suitable for MAR. Contrarily, a high score was assigned to low drainage density areas, indicating high suitability for MAR.

Rainfall is the most dominant factor that influences subsurface recharge. Areas with high rainfall are considered highly suitable for MAR due to the large amount of water available for groundwater recharge. The rainfall criterion map of the study area was classified into three categories: low (200–215 mm), medium (215–230 mm), and high rainfall (230–250 mm) (Figure 4F). High rainfall is observed in the South-Western part of the study area, indicating high suitability for MAR. Other important parameters to be considered are the duration and intensity of rainfall; a prolonged period of 30 mm has a more significant effect on recharge than a brief 60 mm rainfall period.

3.3 Assessment of MAR suitability map

The final suitability map was used to delineate the regions suitable for MAR implementation by combining different criterion maps using GIS-MCDA. The suitability map was classified into five categories, i.e., very high, high, moderate, low, and very low (Figure 5). The final suitability map reveals that the highest MAR suitability in the Kuchlak basin covers the south and western part of the region. About 45% of the study area falls in the very high-high, 33% moderate, and 17% low-very low MAR suitability zone. The unsuitable zones contribute only 5% of the total study area The spatial distribution of the suitability zones typically demonstrates a mirror reflection of the significant contributing factors. The unsuitable zones are mainly concentrated in the Southeastern part, reflecting the urban constraint mapping. Similarly, the North and Northwestern part's unsuitable zones correspond to the slope constraint for steeper topography. The North and Eastern part shows relatively low MAR suitability due to the steeper slopes and presence of mixed shale and sandstone (geology), which are the major contributing criteria for MAR.

This study aims to provide a broad recommendation on the suitability of the Kuchlak sub-basin for MAR implementation, and it did not target any specific user group i.e., domestic, agriculture, and industrial (detail studies are required for each user group). However, the availability of data on the water table depth, lineament density in the case of fractured limestone, and precise information on the hydraulic conductivity of the soil will be critical for creating high-resolution MAR suitability maps at the local scale. In addition, data on water usage can further enhance the map, as the required water quality for drinking, agriculture, and industry varies significantly. Finally, while mapping the suitability of MAR is one component, socioeconomic factors such as cost, land requirements, expertise, and public acceptability all contribute to the success of MAR. By increasing the number of criteria, the accuracy of the MAR suitability map increases, but the data availability also influences it. Therefore, due to the data limitations and scope of the current study, the above parameters were not included in MAR suitability mapping.

4 Conclusion

The population growth and development of agriculture have put growing stress on groundwater resources, resulting in the overexploitation of groundwater. In Balochistan, the water table is declining rapidly due to intensive pumping. There is an urgent need to address this issue using MAR methods. In this study, the identification of appropriate MAR techniques and delineation of suitable MAR sites were performed using INOWAS and GIS-MCDA, respectively. The most suitable MAR techniques recommended by INOWAS include Trenches, flooding and ditches and furrows. The leaky dam MAR technique is also included as it is widely applied in many areas of Baluchistan though INOWAS does not suggest this method. For suitability analysis a total of six criteria, such as geology, land cover, soil, slope, rainfall, and drainage density, were used in this study. The MIF method was used to assign the weight to different criteria, and the highest weight was assigned to geology as it has a major influence on water infiltration. The final MAR suitability map was developed by overlaying all criterion maps based on the ranking and weighted values. The study area is divided into five categories based on MAR suitability, i.e., very high, high, medium, low, and very low suitability. The final MAR suitability maps show that the Kuchlak basin lies in a very high-high suitability zone (45%). Moderate and low-very low suitability zones cover an area of 33% and 17% respectively. The unsuitable zone accounts for only 5% of the total area Therefore, if correctly designed and managed, MAR has the potential to alleviate the water scarcity and increase the underground water storage in the Kuchlak basin. It is important to note that regions with low suitability scores should not be ruled out for MAR implementation, as MAR suitability mapping reveals the relative suitability of various components of an area. The MAR suitability map generated in this study can be used as a starting point for conducting focused studies on MAR implementation. The technique and results of this study may aid in mapping MAR suitability in any arid or semi-arid location. This study demonstrates that, despite its inherent shortcomings, GIS-MCDA is a helpful tool for resolving real-world groundwater problems.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

HS: Methodology, basic study design, formal analysis writing–original draft. GA: Methodology, software, resources, visualization, writing–review and editing. YG: Funding acquisition, project administration, resources literature review, manuscript writing, and giving valuable suggestions. SH literature review, rewriting revised manuscript, grammer, manuscript writing, and giving valuable suggestion.

RETRACTED

Funding

This research is financially supported by the International Science & Technology Cooperation Program of China (2018YFE0100100) and the Chinese Academy of Sciences President's International Fellowship Initiative (Grant No. 2021VCA0010).

Acknowledgments

The authors wish to acknowledge the Chinese Academy of Sciences President's. International Fellowship Initiative and the International Science and Technology Cooperation Program of China financially supported the current research. Special thanks of gratitude to the Director and Executive Director of the China-Pakistan Joint Research Centre (CPJRC) on earth Sciences for their encouragement, and support during the entire period of research.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

RETRACTED

References

Agarwal, R., and Garg, P. K. (2016). Remote sensing and GIS based groundwater potential & recharge zones mapping using multi-criteria decision making technique zones mapping using multi-criteria decision-making technique. *Water Resour. manage. Manag.* 30, 243–260. doi:10.1007/s11269-015-1159-8

Ahmed, W., Ejaz, M. S., Memon, U., Khair, S., Khilji, A. R., Tarin, R., et al. (2021). "Improving groundwater management to enhance agriculture and farming livelihoods in Pakistan," in *Groundwater resource management for the Kuchlak Sub-Basin, balochistan. Report no160* (Albury, Australia: Charles Sturt University).

Alam, S., Borthakur, A., Ravi, S., Gebremichael, M., and Mohanty, S. K. (2021). Managed aquifer recharge implementation criteria to achieve water sustainability recharge implementation criteria to achieve water sustainability. *Sci. Total Environ. Environ.* 768, 144992. doi:10.1016/j.scitotenv.2021.144992

Alidina, M., Li, D., and Drewes, J. E. (2014). Investigating the role for adaptation of the microbial community to transform trace organic chemicals during managed aquifer recharge. *Water Res.* 56, 172–180. doi:10.1016/j.watres.2014.02.046

Arshad, A., Zhang, Z., Zhang, W., and Dilawar, A. (2020). Mapping favorable groundwater potential recharge zones using a GIS-based analytical hierarchical process and probability frequency ratio model: A case study from an agro-urban region of Pakistan. *Geosci. Front.* 11 (5), 1805–1819. doi:10.1016/j.gsf.2019.12.013

Ashraf, M., and Sheikh, A. A. (2017). *Sustainable groundwater management in balochistan*. Islamabad, Pakistan: Pakistan Council of Research in Water Resources PCRWR, 36.

Bonilla, V. J. P., Blank, C., Roidt, M., Schneider, L., and Stefan, C. (2016). Application of a GIS multi-criteria decision analysis for the identification of intrinsic suitable sites in Costa Rica for the application of Managed Aquifer Recharge (MAR) through spreading methods. *Water* 8 (9), 391. doi:10.3390/w8090391

Bouwer, H. (2002). Artificial recharge of groundwater: Hydrogeology and engineering. *Hydrogeology J.* 10, 121–142. doi:10.1007/s10040-001-0182-4

Chenini, I., and Mammou, A. B. (2010). Groundwater recharge study in arid region: An approach using GIS techniques and numerical modeling. *Comput. Geosciences* 36 (6), 801–817. doi:10.1016/j.cageo.2009.06.014

Chowdhury, A., Jha, M. K., Chowdary, V. M., and Mal, B. C. (2009). Integrated remote sensing and GIS-based approach for assessing groundwater potential in West Medinipur district, West Bengal, India. *Int. J. Remote Sens.* 30 (1), 231–250. doi:10.1080/01431160802270131

Corsini, A., Cervi, F., and Ronchetti, F. (2009). Weight of evidence and artificial neural networks for potential groundwater spring mapping: An application to the Mt. Modino area (northern apennines, Italy). *Geomorphology* 111 (1-2), 79–87. doi:10.1016/j.geomorph.2008.03.015

Das, S., Gupta, A., and Ghosh, S. (2017). Exploring groundwater potential zones using MIF technique in semi-arid region: A case study of hingoli district, Maharashtra. *Spat. Inf. Res.* 25 (6), 749–756. doi:10.1007/s41324-017-0144-0

de Vries, J. J., and Simmers, I. (2002). Groundwater recharge: An overview of processes and challenges. *Hydrogeology J.* 10, 5–17. doi:10.1007/s10040-001-0171-7

Dillon, P. (2005). Future management of aquifer recharge. *Hydrogeol. J.* 13 (1), 313–316. doi:10.1007/s10040-004-0413-6

Dillon, P., Stuyfzand, P., Grischek, T., Lluria, M., Pyne, R. D. G., Jain, R. C., et al. (2019). Sixty years of global progress in managed aquifer recharge. *Hydrogeol. J.* 27 (1), 1–30. doi:10.1007/s10040-018-1841-z

Dillon, P., Toze, S., Page, D., Vanderzalm, J., Bekele, E., Sidhu, J., et al. (2010). Managed aquifer recharge: Rediscovering nature as a leading edge technology. *Water Sci. Technol.* 62 (10), 2338–2345. doi:10.2166/wst.2010.444

Faust, N., Anderson, W., and Star, J. (1991). Geographic information systems and remote sensing future computing environment. *Photogrammetric Eng. Remote Sens.* 57 (6), 655–668.

Glass, J., Schlick, R., and Junghanns, R. (2021). Web-based real-time modelling–Implementation of the web-based prediction analysis tool on the INOWAS platform. *Deliv. D4.5 SMARTControl Proj. Smart Framew. real-time Monit. control Subsurf. Process. Manag. aquifer recharge (MAR) Appl.* 3.

Gnanachandrasamy, G., Zhou, Y., Bagyaraj, M., Venkatramanan, S., Ramkumar, T., and Wang, S. (2018). Remote sensing and GIS based groundwater potential zone mapping in ariyalur district, Tamil nadu. *J. Geol. Soc. India* 92 (4), 484–490. doi:10.1007/s12594-018-1046-z

Halcrow (2007). *Basin-wide water resources availability and use.* Asian Development Bank: Supporting Public Resource Management in Balochistan.

Israil, M., Al-Hadithi, M., and Singhal, D. C. (2006). Application of a resistivity survey and geographical information system (GIS) analysis for hydrogeological zoning of a piedmont area, Himalayan foothill region, India. *Hydrogeol. J.* 14 (5), 753–759. doi:10.1007/s10040-005-0483-0

Khair, S. M., Culas, R. J., and Hafeez, M. (2010). The causes of groundwater decline in upland Balochistan region of Pakistan: Implication for water management policies. Proceedings of the 39 th Australian Conference of Econonomists, pp 1–11. Sydney, Australia

Khan, A., Govil, H., Taloor, A. K., and Kumar, G. (2020). Identification of artificial groundwater recharge sites in parts of yamuna river basin India based on remote sensing and geographical information system. *Groundw. Sustain. Dev.* 11, 100415. doi:10.1016/j.gsd.2020.100415

Lee, S., Kim, Y. S., and Oh, H. J. (2012). Application of a weights-of-evidence method and GIS to regional groundwater productivity potential mapping. *J. Environ. Manag.* 96 (1), 91–105. doi:10.1016/j.jenvman.2011.09.016

Magesh, N. S., Chandrasekar, N., and Soundranayagam, J. P. (2012). Delineation of groundwater potential zones in Theni district, Tamil Nadu, using remote sensing, GIS and MIF techniques. *Geosci. Front.* 3 (2), 189–196. doi:10.1016/j.gsf.2011.10.007

Malczewski, J. (2006). GIS-based multicriteria decision analysis: A survey of the literature. *Int. J. Geogr. Inf. Sci.* 20 (7), 703–726. doi:10.1080/13658810600661508

Maples, S. R., Fogg, G. E., and Maxwell, R. M. (2019). Modeling managed aquifer recharge processes in a highly heterogeneous, semi-confined aquifer system. *Hydrogeol. J.* 27 (8), 2869–2888. doi:10.1007/s10040-019-02033-9

Mogaji, K. A., Lim, H. S., and Abdullah, K. (2015). Regional prediction of groundwater potential mapping in a multifaceted geology terrain using GIS-based Dempster–Shafer model. *Arab. J. Geosci.* 8 (5), 3235–3258. doi:10.1007/s12517-014-1391-1

P. Mondal and A. K. Dalai (Editors) (2017). *Sustainable utilization of natural resources* (Boca Raton: CRC Press). doi:10.1201/9781315153292

Naghibi, S. A., Pourghasemi, H. R., Pourtaghi, Z. S., and Rezaei, A. (2015). Groundwater qanat potential mapping using frequency ratio and Shannon's entropy models in the Moghan watershed, Iran. *Earth Sci. Inf.* 8 (1), 171–186. doi:10.1007/s12145-014-0145-7

Naus, F. L., Schot, P., van Breukelen, B. M., Ahmed, K. M., and Griffioen, J. (2021). Potential for managed aquifer recharge in southwestern Bangladesh based on social necessity and technical suitability managed aquifer recharge in southwestern Bangladesh based on social necessity and technical suitability. *Hydrogeol. J.* 29 (2), 607–628. doi:10.1007/s10040-020-02264-1

Oh, H. J., Kim, Y. S., Choi, J. K., Park, E., and Lee, S. (2011). GIS mapping of regional probabilistic groundwater potential in the area of Pohang City, Korea. *J. Hydrology* 399 (3-4), 158–172. doi:10.1016/j.jhydrol.2010.12.027

Ozdemir, A. (2011). GIS-based groundwater spring potential mapping in the Sultan Mountains (Konya, Turkey) using frequency ratio, weights of evidence and logistic regression methods and their comparison. *J. Hydrology* 411 (3-4), 290–308. doi:10.1016/j.jhydrol.2011.10.010

Halcrow, Pakistan, and Cameos (2008b). Quetta: Supporting public resource management in balochistan, *Effectiveness of the delay action/storage dams in balochistan*, 53.

Perrone, D., and Rohde, M. M. (2016). Benefits and economic costs of managed aquifer recharge in California. *San Franc. Estuary Watershed Sci.* 14 (2). doi:10.15447/sfews.2016v14iss2art4

Pourghasemi, H. R., and Beheshtirad, M. (2015). Assessment of a data-driven evidential belief function model and GIS for groundwater potential mapping in the Koohrang Watershed, Iran. *Geocarto Int.* 30 (6), 662–685. doi:10.1080/10106049.2014.966161

Rahman, M. A., Rusteberg, B., Gogu, R. C., Lobo Ferreira, J. P., and Sauter, M. (2012). A new spatial multi-criteria decision support tool for site selection for implementation of managed aquifer recharge. *J. Environ. Manag.* 99, 61–75. doi:10.1016/j.jenvman.2012.01.003

Rahmati, O., Nazari Samani, A., Mahdavi, M., Pourghasemi, H. R., and Zeinivand, H. (2015). Groundwater potential mapping at Kurdistan region of Iran using analytic hierarchy process and GIS. *Arab. J. Geosci.* 8 (9), 7059–7071. doi:10.1007/s12517-014-1668-4

Rahmati, O., Pourghasemi, H. R., and Melesse, A. M. (2016). Application of GIS-based data driven random forest and maximum entropy models for groundwater potential mapping: A case study at mehran region, Iran. *Catena* 137, 360–372. doi:10.1016/j.catena.2015.10.010

Razandi, Y., Pourghasemi, H. R., Neisani, N. S., and Rahmati, O. (2015). Application of analytical hierarchy process, frequency ratio, and certainty factor models for groundwater potential mapping using GIS. *Earth Sci. Inf.* 8 (4), 867–883. doi:10.1007/s12145-015-0220-8

Rivett, M. O., Buss, S. R., Morgan, P., Smith, J. W., and Bemment, C. D. (2008). Nitrate attenuation in groundwater: A review of biogeochemical controlling processes in groundwater: A review of biogeochemical controlling processes. *Water Res.* 42 (16), 4215–4232. doi:10.1016/j.watres.2008.07.020

Sallwey, J., Bonilla Valverde, J. P., Vásquez López, F., Junghanns, R., and Stefan, C. (2019). Suitability maps for managed aquifer recharge: A review of multi-criteria decision analysis studies. *Environ. Rev.* 27 (2), 138–150. doi:10.1139/er-2018-0069

Sendrós, A., Himi, M., Lovera, R., Rivero, L., Garcia-Artigas, R., Urruela, A., et al. (2020). Geophysical characterization of hydraulic properties around a managed aquifer recharge system over the Llobregat River Alluvial Aquifer (Barcelona Metropolitan Area). *Water* 12 (12), 3455. doi:10.3390/w12123455

Senthilkumar, M., Gnanasundar, D., and Arumugam, R. (2019). Identifying groundwater recharge zones using remote sensing & GIS techniques in Amaravathi aquifer system, Tamil Nadu, South India zones using remote sensing & GIS techniques in Amaravathi aquifer system, Tamil Nadu, South India. *Sustain. Environ. Res.* 29 (1), 15–19. doi:10.1186/s42834-019-0014-7

Sprenger, C., Hartog, N., Hernández, M., Vilanova, E., Grützmacher, G., Scheibler, F., et al. (2017). Inventory of managed aquifer recharge sites in europe: Historical development, current situation and perspectives. *Hydrogeol. J.* 25 (6), 1909–1922. doi:10.1007/s10040-017-1554-8

Stefan, C., and Ansems, N. (2018). Web-based global inventory of managed aquifer recharge applications. *Sustain. Water Resour. Manag.* 4 (2), 153–162. doi:10.1007/s40899-017-0212-6

Stephenson, D. (1979). *Rockfill in Hydraulic Engineering*, Amsterdam: Elsevier Scientific Publ. Comp.Elsevier, 4.

Todd, D. K., and Mays, L. W. (2004). *Groundwater hydrology*. Hoboken, New Jersey, United States: John Wiley & Sons.

Villholth, K. G. (2021). An overview of features of the Managed Aquifer Recharge Case Studies aquifer recharge, Managing aquifer recharge. *A Showc. Resil. Sustain.*, 29.

Watto, M. A. (2015).The economics of groundwater irrigation in the indus basin, Pakistan: Tube-well Adoption, technical and irrigation water efficiency and optimal allocation. Crawley WA 6009, Australia: University of Western Australia. [Doctoral Thesis Desertation].

Wiese, B., Massmann, G., Jekel, M., Heberer, T., Dünnbier, U., Orlikowski, D., et al. (2011). Removal kinetics of organic compounds and sum parameters under field conditions for managed aquifer recharge. *Water Res.* 45 (16), 4939–4950. doi:10.1016/j.watres.2011.06.040

Yeh, H. F., Cheng, Y. S., Lin, H. I., and Lee, C. H. (2016). Mapping groundwater recharge potential zone using a GIS approach in Hualian River, Taiwan. *Sustain. Environ. Res.* 26 (1), 33–43. doi:10.1016/j.serj.2015.09.005

RETRACTED