Water Supply

Water Supply Vol 22 No 9, 7027 doi: 10.2166/ws.2022.297

Geographic information system and multi-criteria decision analysis for the determination of groundwater recharge potential: systematic review

Aji Ahmed Maghribi, Muhammad Dimyati* and S. Supriatna

Department of Geography, Faculty of Mathematics & Natural Sciences, Universitas Indonesia, Depok, Indonesia
*Corresponding author. E-mail: m.dimyati@sci.ui.ac.id

AAM, 0000-0002-1858-4492; MD, 0000-0003-4703-4227; SS, 0000-0003-2878-4532

ABSTRACT

The groundwater recharge area is one of the crucial components in regional development. Many studies in determining groundwater recharge areas with a combination of Geographic Information System and Multi-criteria Decision Analysis have been carried out. The development of studies over the last ten years is reviewed in this paper using the PRISMA systematic review method to find out the study's progress. A total of 31 studies were found in the previous ten years based on the review results. Information about the country of origin of the study, dominant geology, climatic conditions, criteria used, decision-making and weighting methods, and the validation process for each study were extracted. The results show 12 countries researching this topic, with five dominant geological classes and nine classes of climatic conditions, and 33 criteria are used in the 2011–2021 range with eight dominant criteria used. Four decision rules and the weighted method are used, and a validation process is commonly used with well data. From systematic review and meta-analysis, we conclude: India has become the country that has most researched this topic. Hard-rock-class geology is dominant and arid and semi-arid climate conditions have become the main focus of studies. The variability of criteria is up to 33 with 18 criteria still used only once in each study, and eight dominant criteria have been used. Analytical Hierarchy Process (AHP) and Multiple Influence Factor (MIF) have become the most-used methods for assigned weight, and Frequency Ratio (FR) is the newest method for assigned weight. Lithology has the highest weight compared with the other seven dominant criteria, and well data has become the most common data for verification of groundwater recharge.

Key words: GIS, groundwater recharge, meta-analysis, multi-criteria decision analysis, PRISMA, systematic review

HIGHLIGHTS

- GIS and MCDA for determination of groundwater recharge potential studies (2011–2021) reviewed using the PRISMA method.
- Dominant geology, climatic conditions, criteria used, decision-making and weighting methods, and the validation process extracted and combined for meta-analysis.
- Up to eight from 33 criteria dominant used, decision rules and weighted method process commonly used are AHP and MIF.

1. INTRODUCTION

The groundwater recharge area is one of the crucial components in regional development. This is because the groundwater recharge area functions as an area capable of infiltrating surface water or rainwater through pores or gaps in the soil or rock by gravity to the impermeable zone (Balek 1988; Zaidi *et al.* 2015; Yeh *et al.* 2016). So, it can be seen that in an area, groundwater recharge areas can reduce the risk of rising surface water causing flooding and maintain groundwater resources (Manna *et al.* 2017; da Costa *et al.* 2019). In the Presidential Regulation of the Republic of Indonesia No. 54 of 2008 concerning Regional Spatial Planning for Jakarta, Bogor, Tangerang, Bekasi, Puncak, and Cianjur, the water recharge areas are one of the criteria in planning priority protected areas. Groundwater recharge has two mechanisms, which are diffuse recharge by infiltration of atmospheric precipitation over a large area through the unsaturated zone to the aquifer and focused recharge by surface waterbodies such as rivers, streams, and lakes that lose water to aquifers or from water flow that moves through fractures (Ren *et al.* 2018; Reinecke 2022). In arid conditions, diffuse recharge becomes less important because of low precipitation and high evapotranspiration (Alley 2009; Ren *et al.* 2018).

Many studies in determining groundwater recharge areas have been carried out, such as by decision trees (Chenini & Ben Mammou 2010), weight-of-evidence (Lee *et al.* 2012) and frequency ratio (Ahmed *et al.* 2021) for those that are data-driven based, while for those that are physically based, one of them is the WetSpass model (Armanuos *et al.* 2016). Recent advances in digital image processing combined with conventional survey maps and multi-criteria analysis of the geospatial environment have allowed scientists to better identify areas. Natural groundwater recharge occurs using a combination of data such as geology, topography, land cover, soil type, lineament density, drainage density, slope, and rainfall (Lentswe & Molwalefhe 2020). The location selection procedure is carried out by combining and giving weight to geospatial data representing the research area according to the research objectives (Sallwey *et al.* 2019). The utilization of remote sensing and Geographic Information System (GIS) techniques can speed up and reduce costs in the qualitative determination of groundwater recharge areas (Adham *et al.* 2010). Multi-criteria analysis is a decision-making method to determine the best alternative from several alternatives that are evaluated based on specific criteria. Spatial analysis is generally used for the suitability of location selection (Malczewski 1999).

This paper review aims to determine the development of research on the application of GIS–Multi-Criteria Decision Analysis (GIS-MCDA) in mapping the potential for groundwater recharge. The analysis was carried out by knowing each location's dominant geological and climatic conditions, the criteria, decision-making methods, and the weighting used in obtaining the potential map in each case study, the weight of the criteria, and the validation process. A total of 31 case studies was obtained from the last ten years (2011–2021) on GIS-MCDA for determining the suitability of groundwater recharge using a systematic review and meta-analysis (PRISMA) procedure by taking English-based publications from the Scopus database. The development of research on the determination of groundwater recharge areas can be used as a lesson to practice in a sustainable spatial plan.

The limitation in conducting a review in selecting studies included in the inclusion criteria is that there are similarities, such as studies of artificial recharge and groundwater potential. To avoid these problems, after the abstract screening, full-text screening was carried out to determine the objectives of each study. With this process, we can obtain studies according to the inclusion criteria to be reviewed. In addition, the limitations in this systematic review limit the study sources to those only from journals so that other studies originating from conference papers are not included in the review process. The year used is only to review studies of the last ten years to determine the study's progress, so it is impossible to know the research condition before that year.

2. METHODS

The review writing method uses the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) methodology (Page *et al.* 2021). Based on these guidelines, there are several stages in the research, namely: (1) determining the eligibility criteria; (2) defining the source of information; (3) study selection; (4) data collection process; and (5) selection of data items. Figure 1 is a flow chart of the process of obtaining articles using a systematic review.

2.1. Eligibility criteria

The following inclusion criteria were used as a guide in writing the review. The first inclusion is articles with the final publication stage, document types from articles, and sources from journals, in English. The second inclusion is the research aims to determine the suitability of the groundwater catchment area using the spatial multi-criteria method. As for the exclusion criteria in writing a review, these are the research aims to determine the suitability of artificial groundwater recharge areas, groundwater potential areas, and Managed Aquifer Recharge (MAR).

The final publication stage is used as a criterion because the search for articles begins on August 3, 2021, with a search year spanning 2011–2021. The types of documents selected in the criteria are articles, types of journal sources, and those in English. Journal articles are the source of most of the data included in systematic reviews (Li *et al.* 2021). The use of journal articles as a criterion is due to having complete information about methods and results. Meanwhile, English was chosen because it is the common language used by researchers in scientific publications. Inclusion 2 is used to get answers in the development of research on the application of GIS-MCDA for groundwater recharge, while exclusion criteria are used to avoid ambiguity in the data processing.

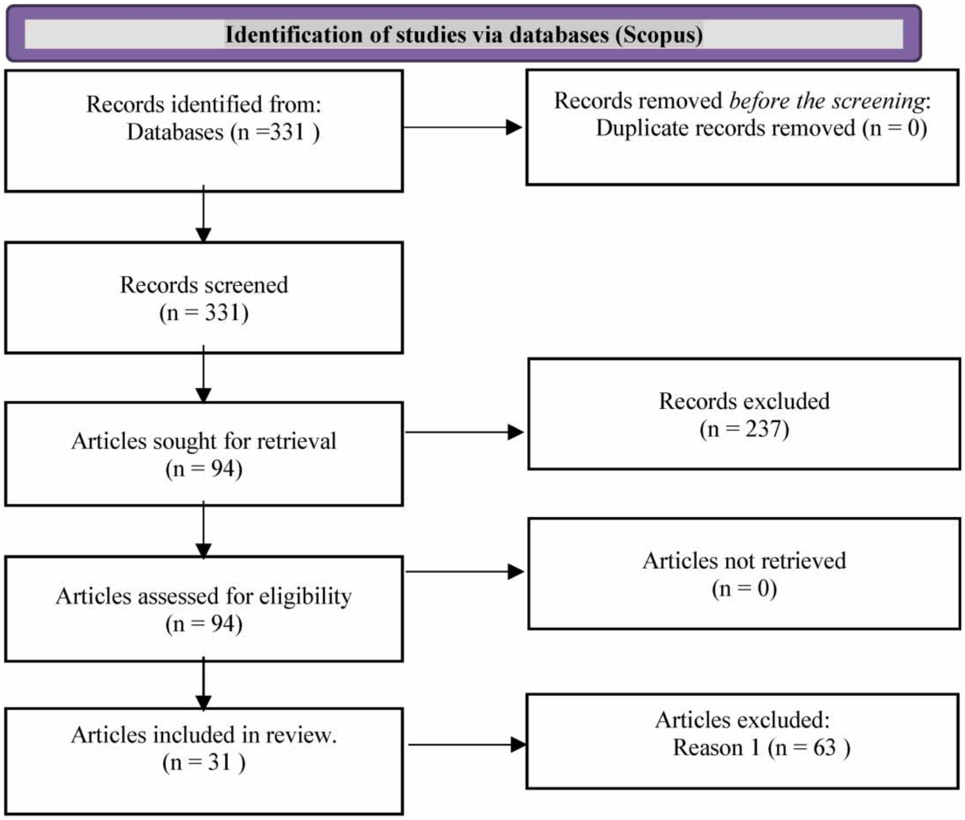


Figure 1 | Flow diagram for systematic reviews.

2.2. Source information

Scopus is the source of information used in the search for articles for writing a systematic review. Scopus is a multidisciplinary and selective database launched by Elsevier in November 2004 (Pranckutė 2021). Scopus has reproducible and documentable searches and has tools to analyze search results by author, affiliation, country, journal title, and broad subject categories (Gebre *et al.* 2021). Data was obtained on August 3, 2021. The search process uses the TITLE-ABS-KEY feature on the Scopus database with the string ((gis OR multi-criteria) AND ('groundwater recharge')) and published between 2011 and 2021 with document-type articles and sources from journals as well as in English and the final publication stage. Search results are exported and stored in MS Excel by listing the title, abstract, keywords, author and affiliation names, journal name, and year of publication.

2.3. Study selection

The results of the search obtained are screened based on the eligibility criteria that have been made. Initial screening is carried out on abstracts to eliminate those that do not meet the criteria. The results of the screening are then carried out in full text or partial reading on articles that have not been eliminated from the previous stage to determine whether the article meets the eligibility criteria or falls into the exclusion criteria.

2.4. Data collection process

Data collection is carried out from the export of Scopus database information sources using MS Excel based on the name of the journal, year, and country, and added manually from the selected articles in the form of dominant geological information in the research area, the climate of the research area, research criteria, research criteria weights, decision techniques, and the process of verification or validation of results.

2.5. Data items

Information taken from each article consists of (1) information on the geology and climate of the research area, and (2) the criteria used in the research, the weight of the criteria in the research, decision-making techniques, and the process of verifying or validating research results.

The information from number 1 is to determine what kind of dominant research was carried out on geological and climatic conditions, while the information from number 2 is to find out the development and number of criteria used during the last ten years, the weight of the criteria used from all research and based on the grouping of decision-making techniques, decision-making techniques used during the last ten years, and how the results validation process is carried out.

3. RESULTS AND DISCUSSION

Based on the search results from the Scopus database, 331 articles were obtained in 2011–2021 (August 3, 2021). After screening abstracts based on eligibility criteria, 95 articles were obtained; 31 articles were obtained after full-text and partial reading of articles based on eligibility and exclusion criteria. The 31 selected articles were used in the review.

3.1. Distribution of research by country, dominant geology and climate

Figure 2 shows the distribution of GIS-MCDA research for groundwater recharge areas by country in the last ten years (2011–2021). A total of 12 countries conducted research on this topic. India is one of the dominant countries in conducting research, with 43% (13 publications), followed by Nigeria, Algeria, Tunisia, Saudi Arabia, and Taiwan with 7% each (two publications), and Jordan, Morocco, Australia, Tanzania, Botswana, New Zealand, and Iraq each accounting for 3% (one publication).

Based on the dominant geology of each study, they are grouped into five classes, namely hard rock, soft rock, various deposits, volcanic deposits, unconsolidated deposits. Hard rock is a term for naming igneous and metamorphic rock types such as granite and gneiss, while soft rock names sedimentary rock types such as limestone and sandstone (Hall 2006). Volcanic deposits are the result of extrusive volcanic activity such as lava, and unconsolidated deposits are alluvial or eolian deposits. From the 31 studies, eight studies were obtained with dominant geology of hard rock and unconsolidated deposits, six studies with dominant geology of various deposits and soft rock, and three studies with dominant geology of volcanic deposits. Six of the eight studies with hard-rock-dominant geology are in India, Tanzania and Botswana. As for studies with dominant unconsolidated deposit geology, three are in India, two are in Saudi Arabia, and one is in New Zealand, Algeria, and Morocco. Studies with dominant geology of various deposits are in India for as many as three studies, and one study each in Taiwan, Egypt, and Nigeria. Studies with soft-rock dominant geology are in Taiwan, Tunisia, Iraq, Algeria, and Australia, with one study each. Studies with the dominant geology of volcanic deposits are in India with as many as two studies and one study is in Jordan. From all the geology or lithology types, the hard rock geological condition becomes the most-used in studies as a focus to determine groundwater recharge (Deepa *et al.* 2016; Kirubakaran *et al.* 2016; Fagbohun 2018; Patil *et al.* 2018; Mishra *et al.* 2020; Mussa *et al.* 2020; Fauzia *et al.* 2021).

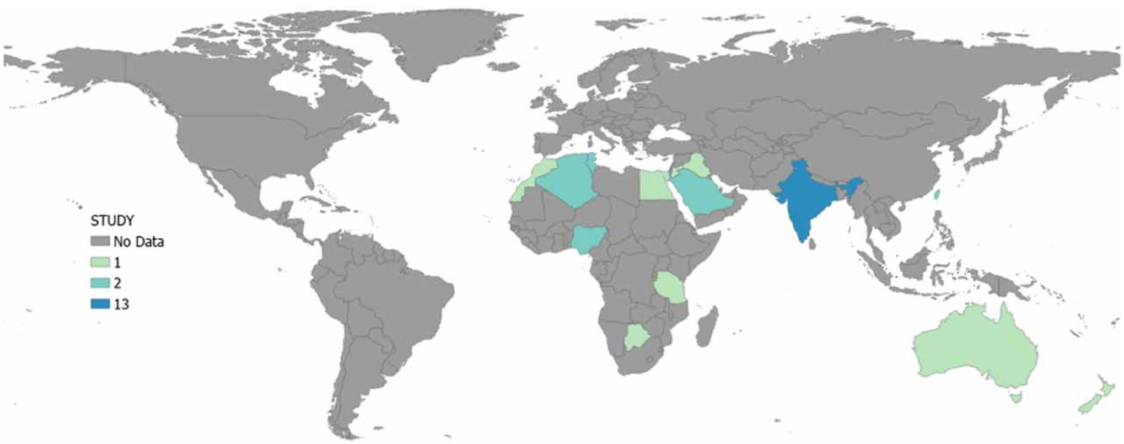


Figure 2 | Distribution of research articles by country.

Climate conditions were analysed using the Koppen Climate Classification, and the metadata for global climate data was obtained from Beck *et al.* (2018). Based on the Koppen Climate Classification and country distribution (shown in Figure 3), studies were done in Aw (tropical, savannah), all arid conditions (BWh, BWk, BSh, BSk), Csa (temperate, dry summer, hot summer), Cfa (temperate, no dry season, hot summer), Cfb (temperate, no dry season, warm summer), Cwa (temperate, dry summer, hot summer), Dfc (cold, no dry season, cold summer), and ET (polar, tundra) climate conditions. India has conducted studies with climate variations, namely BSh, Aw, and Cwa; and the same with New Zealand, and since the study was done in one country, the climate variations are Cfb, BSk, Dfc, and ET. The African continent and Western Asia mostly have semi-arid (BSh, BSk) and arid (BWh, BWk) climate conditions, one study with tropical (Aw) condition was done in Nigeria (Fagbohun 2018). In Australia, the study was only conducted under semi-arid (BSh-BSk) climate condition (Ahmed *et al.* 2021). Based on the climate conditions, arid and semi-arid climate conditions are usually used as a focus of study to determine groundwater recharge (Mahmoud *et al.* 2014; Ait El Mekki & Laftouhi 2016; Saidi *et al.* 2017; Al-Shabeeb 2018; Kadam *et al.* 2020; Lentswe & Molwalefhe 2020; Mussa *et al.* 2020; Zghibi *et al.* 2020).

3.2. Mapping criteria

Based on a study conducted between 2011 and 2021, it is known that 33 criteria were found to be varied. The least number of criteria used in a study is five criteria and the most is ten criteria, with the average used over the last ten years being seven criteria. Table 1 represents the combination of criteria for each study, while Figure 4 represents the number of studies based on the number of criteria used; the number of studies with eight criteria is the highest with a total of eight studies followed by six and seven criteria with a total of seven studies each.

There are eight dominant criteria used in each study, namely, slope, LULC/land use land cover, lithology/geology, drainage density, lineament density, soil, rainfall, and geomorphology. Figure 5 shows the number of dominant criteria used in a pie-chart. Each study generally has different combinations in criteria for determining groundwater recharge potential. Only four studies have the same combination of criteria, namely Huang *et al.* (2013) with Yeh *et al.* (2016), and Mahmoud (2014), Mahmoud *et al.* (2014), with the same author but different research locations. Based on the use of criteria, the criteria that have only been used once during 2011–2021 are 18 criteria, namely, water level fluctuation (Agarwal & Garg 2016), aspect, soil drainage (Singh *et al.* 2019), topography position index (Salar *et al.* 2018), TWI (Patil *et al.* 2018), HGSG, Qpeak, curve number (Maizi *et al.* 2020), hydrogeomorphology (Verma *et al.* 2020), curvature (Malik *et al.* 2021), number of infiltrations (Mishra *et al.* 2020), impermeable surface area (Chaudhuri *et al.* 2021), radar backscatter, stream network,

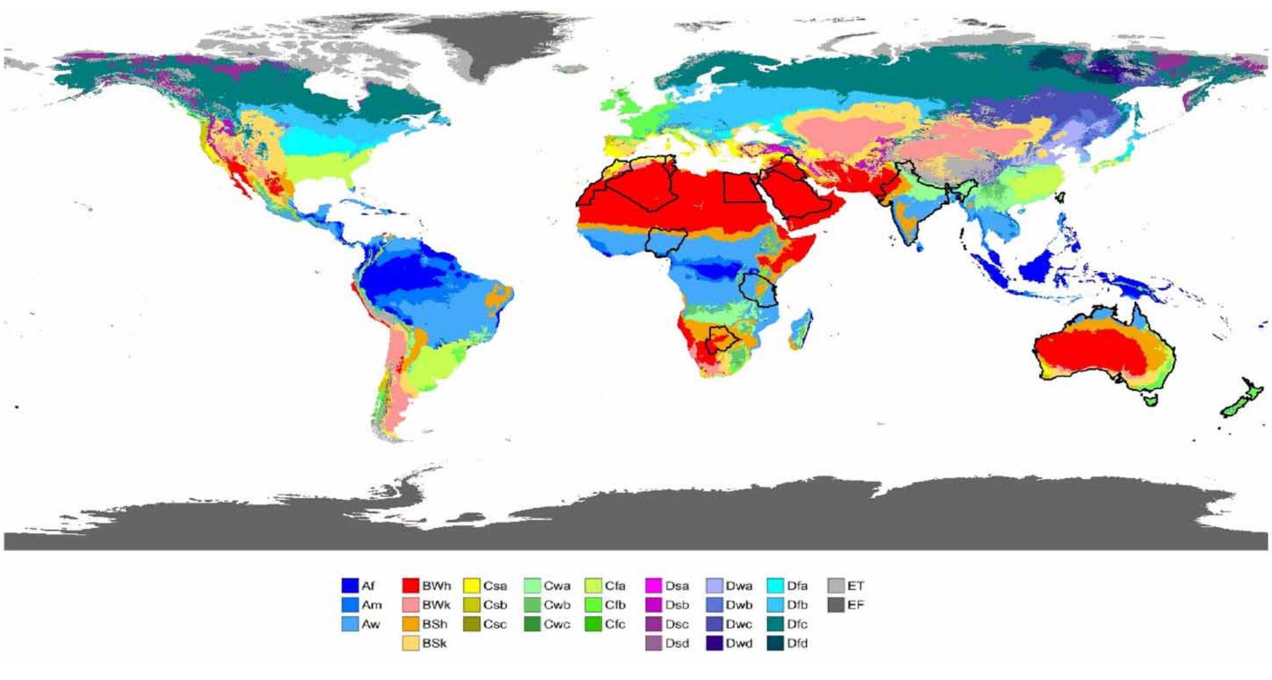


Figure 3 | Koppen Climate Classification and country distribution, modified from Beck *et al.* (2018).

Table 1 | Combination of criteria for each study of groundwater recharge potential

Criteria	Fauzia *et al.* (2021)	Abdullateef *et al.* (2021)	Abdelkareem & Al-Arifi (2021)	Chaudhuri *et al.* (2021)	Ahmed *et al.* (2021)	Panda *et al.* (2020)	Boufekane *et al.* (2020)	Zghibi *et al.* (2020)	Jena *et al.* (2020)	Mishra *et al.* (2020)	Mussa *et al.* (2020)
1. Geology/Lithology	•	•	•	•	•	•	•	•	•	•	•
2. Geomorphology	•					•		•	•	•	
3. LULC	•	•	•	•	•	•	•	•	•	•	•
4. Soil	•			•	•		•	•	•	•	•
5. Lineament Density/Fault Density	•	•	•		•	•		•	•	•	•
6. Drainage Density	•	•			•	•	•	•	•		•
7. Slope	•	•	•	•	•	•	•	•	•	•	•
8. Total Number of Fissures	•										
9. Depth to Basement Rock/ Aquifer Thickness	•								•		
10. Infiltration Rate	•										
11. Elevation/Topography		•	•								
12. Hydraulic Head		•									
13. Rainfall			•	•	•	•		•		•	•
14. Morphometric Analysis			•								
15. Stream Network			•								
16. Water Level Fluctuation											
17. ISA				•							
18. Water Depth/Vadose Zone				•			•				
19. Curvature										•	
20. NDVI				•							
21. Soil Depth/Thickness											
22. Curve Number											
23. Qpeak											
24. HGSG											
25. Soil Drainage											
26. Permeability							•				
27. Topography Position Index											
28. TWI											

(*Continued.*)

Table 1 | Continued

Criteria	Fauzia *et al.* (2021)	Abdullateef *et al.* (2021)	Abdelkareem & Al-Arifi (2021)	Chaudhuri *et al.* (2021)	Ahmed *et al.* (2021)	Panda *et al.* (2020)	Boufekane *et al.* (2020)	Zghibi *et al.* (2020)	Jena *et al.* (2020)	Mishra *et al.* (2020)	Mussa *et al.* (2020)
29. Potential Runoff Coefficient											
30. Hydrogeomorphology											
31. Radar Backscatter			•								
32. Number of Infiltrations										•	
33. Aspect											

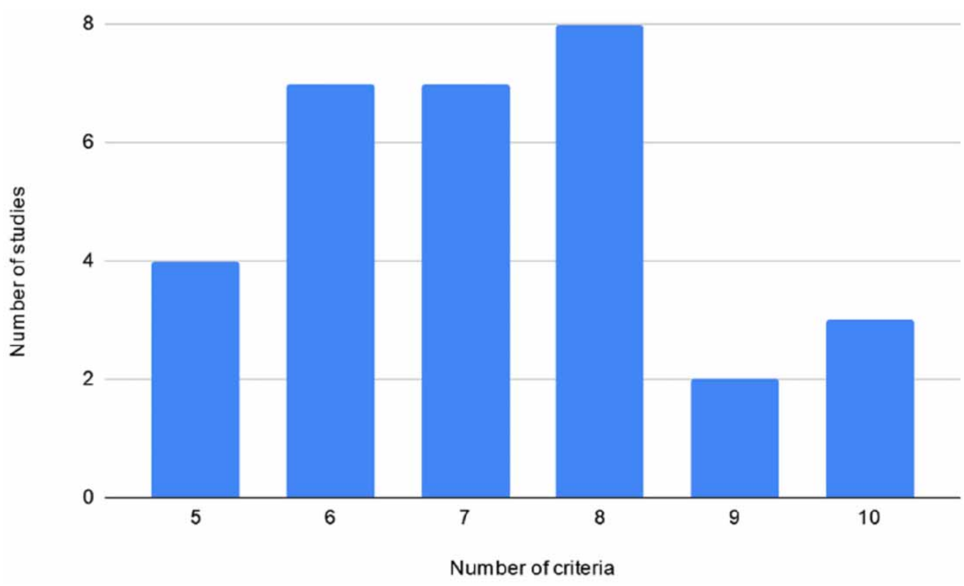


Figure 4 | The number of studies is based on the number of criteria used in the study of groundwater recharge potential.

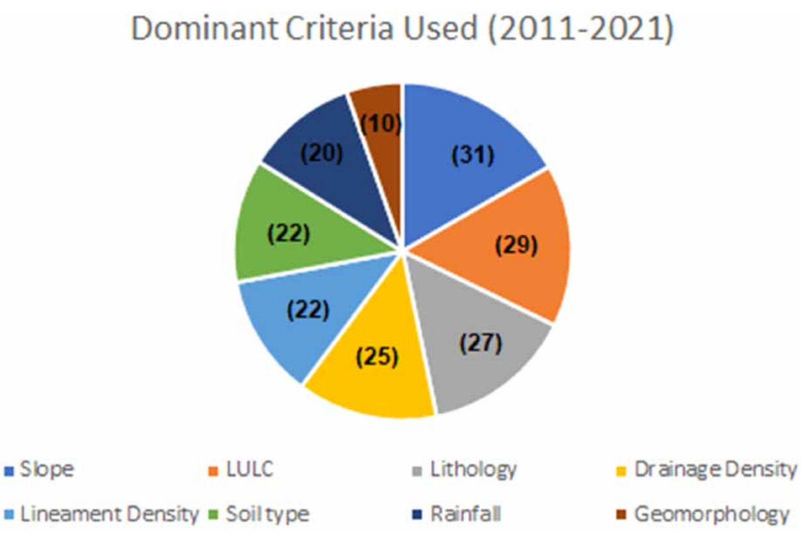


Figure 5 | Pie-chart for dominant criteria used.

morphometric analysis (Abdelkareem & Al-Arifi 2021), hydraulic head (Abdullateef *et al.* 2021), infiltration rate (Fauzia *et al.* 2021), total number of fissures (Fauzia *et al.* 2021).

3.3. Decision rules and weighted method

Based on 31 studies, the decision rules and weighted methods used include Weight Overlay Analysis (WOA) or weight linear combination, Analytical Hierarchy Process (AHP), Multiple Influence Factor (MIF), and Frequency Ratio (FR). Several studies combined previous research with the MIF method to obtain the weighted criteria (Yeh *et al.* 2016; Singh *et al.* 2019). Figure 6 represents the number of studies based on each decision rule and weighted method. Based on the number of studies, AHP is the most dominant used in determining groundwater recharge potential in as many as 15 studies, followed by MIF in as many as 14 studies, WOA in five studies, and FR in one study. The total number of studies exceeds 31 studies because some studies conducted studies of more than one method. Two studies used two methods (AHP and MIF) (Zghibi

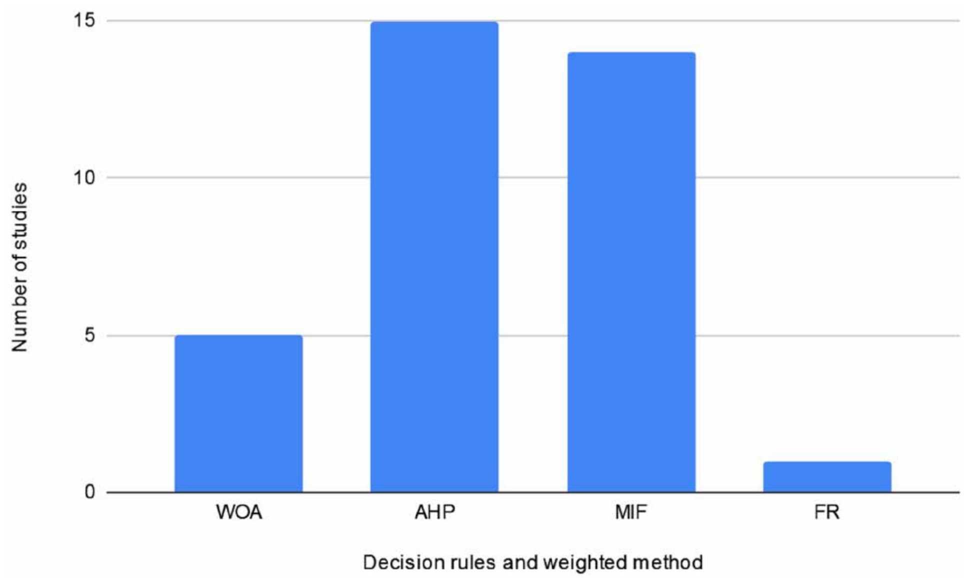
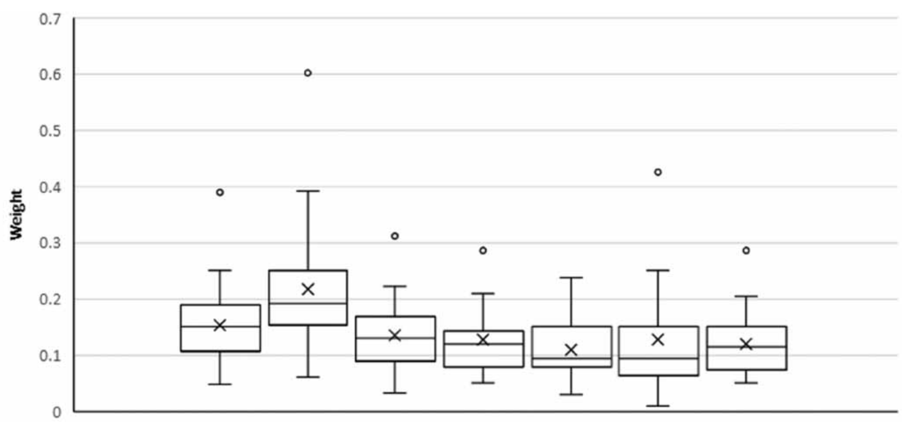


Figure 6 | The number of studies based on decision rules and weighted methods used in the study of groundwater recharge potential.

et al. 2020) and three methods (AHP, MIF and FR) (Ahmed *et al.* 2021) to make comparisons in determining groundwater recharge potential.

3.4. Weights assigned

The weights of all studies were evaluated by normalizing each weight first. Normalization is done by dividing the weight of the criteria by the total weight of the criteria in each study. The normalized weight results are displayed in a boxplot in Figure 7. The boxplot displays data by displaying the lower quartile (Q1), median (Q2 or m), and upper quartile (Q3), as well as the inter-quartile range (IQR) representing 50% of data centers (Krzywinski & Altman 2014). Only seven criteria were used in the evaluation because these criteria had many uses (>20). Based on the data distribution, lithology is the criterion with the highest average, and the median also has the highest value range of 0.33 (maximum–minimum, without outlier data). The second position is on the LULC criteria, and this criterion has a normal distribution compared with the other criteria.



Criteria	LULC	Litho logy	Slope	LD	DD	Soil	Rainfall
Total	30	29	33	23	27	23	22
Mean	0.153	0.218	0.131	0.126	0.110	0.128	0.119
Median	0.15	0.192	0.13	0.12	0.093	0.094	0.115

Figure 7 | Weight criteria distribution of 31 studies with boxplot.

The slope criteria more or less have the same data distribution characteristics as the LULC criteria. The weights have been ranked third when viewed from the average and median values. Lineament density has the lowest IQR among the other criteria, which is 0.06. The drainage density criterion becomes the lowest weight when viewed based on the average and median. In addition, this criterion is the only one that does not have outlier data.

3.5. Validation and sensitivity analysis

Validation is carried out after getting the groundwater recharge potential map results. Generally, this is done by verifying well data in the research area. A total of 15 studies verified the groundwater recharge potential map results with well data. Three studies used water level fluctuation data as verification data for the map of potential groundwater recharge. Several studies have used comparisons of the results of groundwater recharge potential maps with maps or other spatial data such as downstream maps and agricultural land (Abdelkareem & Al-Arifi 2021), electrical conductivity data (Panda *et al.* 2020), existing dam data (Salar *et al.* 2018), geological maps, and watershed flow data to obtain a quick flow index (Singh *et al.* 2019), and data on existing groundwater infiltration structures (Mahmoud 2014). Seven studies did not validate or verify the groundwater recharge potential map results. ROC analysis was carried out in two studies using well data to compare accuracy for each method. The results found that the AHP method out performs the MIF method (Zghibi *et al.* 2020) and the FR method out performs the AHP and MIF methods (Ahmed *et al.* 2021).

Sensitivity analysis was carried out in five studies from 31 existing studies. Sensitivity analysis is a method to determine the sensitivity of each criterion by removing one or more thematic maps (MRSA) (Lodwick *et al.* 1990) and to understand the contribution of each criterion to the map results with a Single Parameter Sensitivity Analysis (SPSA) (Napolitano & Fabbri 1996). Map removal analysis to determine the value of sensitivity analysis was carried out by Al-Shabeeb (2018), while the study from Jena *et al.* (2020) used the percentage change in the area of the potential zone to the thematic layer. Ait El Mekki & Laftouhi (2016) and Boufekane *et al.* (2020) used the effective weight obtained by multiplying each criterion's rating value and weight value divided by the potential groundwater index. Meanwhile, Zghibi *et al.* (2020) used two types of sensitivity analysis, namely map removal and single parameter or effective weight.

3.6. Discussion

Based on the systematic review results, a total of 31 studies sourced from journals on GIS-MCDA to determine potential groundwater recharge areas were carried out over the last ten years (2011–2021). India is the most dominant country in conducting studies to determine the potential for groundwater recharge. The dominant study of geology and climatic conditions of each area has variations. Some studies use geological conditions such as hard rock and arid and semi-arid climatic conditions as the study's focus. This is because the geological and climatic conditions are closely related to the presence and source of groundwater. Hard rock geological conditions prevent water from infiltrating to the aquifer because of low to impermeable conditions, groundwater recharge in hard rock depending on rocks that have weathered and secondary porosities, such as joints and fractures (Kirubakaran *et al.* 2016; Fauzia *et al.* 2021), while the conditions of arid and semi-arid climate are related to a lack of annual rainfall and high annual temperature (Ait El Mekki & Laftouhi 2016; Ahmed *et al.* 2021).

The development of criteria use over the last ten years has reached 33 variations of criteria. Of the 33 criteria, those generally used in each study are slope, LULC, lithology, drainage density, lineament density, soil, and rainfall. The seven criteria influence the value of the potential for groundwater recharge. In addition, these criteria have data availability and can be obtained through remote sensing and integrated with GIS and multi-criteria methods (Ahmed *et al.* 2021). In the last ten years from 2011 to 2021, there are about 18 new criteria that have been used only in one study, with the most recent study offering the integration of criteria from a conventional map with remote sensing, geophysical and borewell data (Fauzia *et al.* 2021). AHP and MIF have been commonly used for decision rules and weighting methods in the last ten years. Each method has advantages in determining the potential of groundwater catchment areas. The AHP method has an advantage because in determining the weights, it is determined by expert opinion and the consistency ratio for assessing the consistency of weights is $<10\%$ (Lentswe & Molwalefhe 2020). Meanwhile, MIF has the advantage of weighting based on the relationship between criteria (major or minor) (Huang *et al.* 2013). Frequency Ratio (FR) as the newest data-driven method in MCDA uses the ratio between the number of observational water wells and the criteria that influence groundwater recharge (Ahmed *et al.* 2021). FR result accuracy is shown to out-perform the AHP and MIF methods. However this method requires data availability to be performed.

The highest weight based on 31 studies on the seven criteria evaluated was the lithological criteria. Variations in the weight of the evaluation results occur due to differences in the location of the study, the method used, and the number of criteria used in the study. This affects the amount of weight in each criterion used in the study. The groundwater recharge potential map validation results based on MCDA have variations for the last ten years. The development of validation supports determining the accuracy of the groundwater recharge potential map results. However, only five out of 31 studies carried out sensitivity analysis and two studies carried out ROC analysis.

Variations in the geological and climatic conditions of each study and the number of criteria used lead to different assessments of each criterion. The AHP method considers weights based on expert opinion in each study country with different geological and climatic conditions that can cause differences in decision-making for the weight of the criteria. The MIF method considers weights based on the relationship between each criterion. In the weighting process, the difference in the number of criteria will affect the weight results of the criteria.

4. CONCLUSIONS

The systematic review findings on practice imply that the results collected can be used to determine the process in determining the potential for groundwater recharge areas, especially with the multi-criteria GIS method. The development of MCDA and GIS for groundwater recharge studies from 2011 to 2021 show that 12 countries are already doing this research, with India becoming the country of most research on this topic, five classes of geology condition occurrence with hard rock class becoming the main focus of studies, and 11 climate conditions with arid and semi-arid becoming the main focus of studies. There is variability of criteria of up to 33 with 18 criteria still used only in single studies and eight dominant criteria have been used; AHP and MIF have become the method most used for assigned weight and FR is the newest method. Lithology has the highest weight compared with the other seven dominant criteria, and well data has become the most-used data for verification of groundwater recharge. As for further research, this finding can be used as reference for finding new novelty in MCDA and GIS for determining groundwater recharge potential.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abdelkareem, M. & Al-Arifi, N. 2021 The use of remotely sensed data to reveal geologic, structural, and hydrologic features and predict potential areas of water resources in arid regions. *Arabian Journal of Geosciences* **14** (8), 704. https://doi.org/10.1007/s12517-021-06942-6.

Abdullateef, L., Tijani, M. N., Nuru, N. A., John, S. & Mustapha, A. 2021 Assessment of groundwater recharge potential in a typical geological transition zone in Bauchi, NE-Nigeria using remote sensing/GIS and MCDA approaches. *Heliyon* **7** (4), e06762. https://doi.org/10.1016/j.heliyon.2021.e06762.

Adham, M. I., Jahan, C. S., Mazumder, Q. H., Hossain, M. M. A. & Haque, A. M. 2010 Study on groundwater recharge potentiality of Barind Tract, Rajshahi district, Bangladesh using GIS and remote sensing technique. *Journal of the Geological Society of India* **75** (2), 432–438. https://doi.org/10.1007/s12594-010-0039-3.

Agarwal, R. & Garg, P. K. 2016 Remote sensing and GIS based groundwater potential & recharge zones mapping using multi-criteria decision making technique. *Water Resources Management* **30** (1), 243–260. https://doi.org/10.1007/s11269-015-1159-8.

Ahirwar, S., Malik, M. S., Ahirwar, R. & Shukla, J. P. 2020 Application of remote sensing and GIS for groundwater recharge potential zone mapping in upper Betwa watershed. *Journal of the Geological Society of India* **95** (3), 308–314. https://doi.org/10.1007/s12594-020-1430-3.

Ahmed, A., Ranasinghe-Arachchilage, C., Alrajhi, A. & Hewa, G. 2021 Comparison of multicriteria decision-making techniques for groundwater recharge potential zonation: case study of the Willochra Basin, South Australia. *Water* **13** (4), 525. https://doi.org/10.3390/w13040525.

Ait El Mekki, O. & Laftouhi, N.-E. 2016 Combination of a geographical information system and remote sensing data to map groundwater recharge potential in arid to semi-arid areas: the Haouz Plain, Morocco. *Earth Science Informatics* **9** (4), 465–479. https://doi.org/10.1007/s12145-016-0268-0.

Alley, W. M. 2009 Ground water. In: *Encyclopedia of Inland Waters* (G. E. Likens, ed.), Elsevier, Amsterdam, the Netherlands, pp. 684–690. https://doi.org/10.1016/B978-012370626-3.00015-6.

Al-Shabeeb, A. R. 2018 The selection of groundwater recharge sites in the arid region of northern Badia, Jordan, using GIS-based multicriteria decision analysis. *Indonesian Journal on Geoscience* **5** (3), 199–209. https://doi.org/10.17014/ijog.5.3.199-209.

Armanuos, A. M., Negm, A., Yoshimura, C. & Valeriano, O. C. S. 2016 Application of WetSpass model to estimate groundwater recharge variability in the Nile Delta aquifer. *Arabian Journal of Geosciences* **9** (10), 553. https://doi.org/10.1007/s12517-016-2580-x.

Balek, J. 1988 Groundwater recharge concepts. In: *Estimation of Natural Groundwater Recharge* (I. Simmers, ed.), Springer, Dordrecht, the Netherlands, pp. 3–9. https://doi.org/10.1007/978-94-015-7780-9_1.

Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A. & Wood, E. F. 2018 Present and future Köppen–Geiger climate classification maps at 1-km resolution. *Scientific Data* **5** (1), 180214. https://doi.org/10.1038/sdata.2018.214.

Boufekane, A., Meddi, H. & Meddi, M. 2020 Delineation of groundwater recharge zones in the Mitidja plain, north Algeria, using multi-criteria analysis. *Journal of Hydroinformatics* **22** (6), 1468–1484. https://doi.org/10.2166/HYDRO.2020.082.

Chaudhary, B. S., Singh, P., Verma, P. & Rai, S. C. 2021 Computation of groundwater recharge prospect in urban environment for sustainable water security. *Arabian Journal of Geosciences* **14** (7), 606.

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

da Costa, A. M., de Salis, H. H. C., Viana, J. H. M. & Pacheco, F. A. L. 2019 Groundwater recharge potential for sustainable water use in urban areas of the Jequitiba River Basin, Brazil. *Sustainability* **11** (10), 2955. https://doi.org/10.3390/su11102955.

Deepa, S., Venkateswaran, S., Ayyandurai, R., Kannan, R. & Vijay Prabhu, M. 2016 Groundwater recharge potential zones mapping in upper Manimuktha sub basin Vellar river Tamil Nadu India using GIS and remote sensing techniques. *Modeling Earth Systems and Environment* **2** (3), 137. https://doi.org/10.1007/s40808-016-0192-9.

Fagbohun, B. J. 2018 Integrating GIS and multi-influencing factor technique for delineation of potential groundwater recharge zones in parts of Ilesha schist belt, southwestern Nigeria. *Environmental Earth Sciences* **77** (3), 69. https://doi.org/10.1007/s12665-018-7229-5.

Fauzia, Surinaidu, L., Rahman, A. & Ahmed, S. 2021 Distributed groundwater recharge potentials assessment based on GIS model and its dynamics in the crystalline rocks of South India. *Scientific Reports* **11** (1), 11772. https://doi.org/10.1038/s41598-021-90898-w.

Gebre,, S. L., Cattrysse, D. & Van Orshoven, J. 2021 Multi-criteria decision-making methods to address water allocation problems: a systematic review. *Water* **13** (2), 125.

Hall, R. B. 2006 Hardrock versus softrock geology. In: *General Geology* (C. W. Finkl, ed.), Kluwer Academic Publishers, Boston, MA, USA, p. 331. http://doi.org/10.1007/0-387-30844-x_55.

Huang, C. C., Yeh, H. F., Lin, H. I., Lee, S. T., Hsu, K. C. & Lee, C. H. 2013 Groundwater recharge and exploitative potential zone mapping using GIS and GOD techniques. *Environmental Earth Sciences* **68** (1), 267–280. https://doi.org/10.1007/s12665-012-1737-5.

Jena, S., Panda, R. K., Ramadas, M., Mohanty, B. P. & Pattanaik, S. K. 2020 Delineation of groundwater storage and recharge potential zones using RS-GIS-AHP: application in arable land expansion. *Remote Sensing Applications: Society and Environment* **19**, 100354. https://doi.org/10.1016/j.rsase.2020.100354.

Kadam, A. K., Umrikar, B. N. & Sankhua, R. N. 2020 Assessment of recharge potential zones for groundwater development and management using geospatial and MCDA technologies in semiarid region of Western India. *SN Applied Sciences* **2** (2), 312. https://doi.org/10.1007/s42452-020-2079-7.

Kirubakaran, M., Johnny, J. C., Ashokraj, C. & Arivazhagan, S. 2016 A geostatistical approach for delineating the potential groundwater recharge zones in the hard rock terrain of Tirunelveli taluk, Tamil Nadu, India. *Arabian Journal of Geosciences* **9** (5), 382. https://doi.org/10.1007/s12517-016-2419-5.

Krzywinski, M. & Altman, N. 2014 Visualizing samples with box plots. *Nature Methods* **11** (2), 119–120. https://doi.org/10.1038/nmeth.2813.

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

Lentswe, G. B. & Molwalefhe, L. 2020 Delineation of potential groundwater recharge zones using analytic hierarchy process-guided GIS in the semi-arid Motloutse watershed, eastern Botswana. *Journal of Hydrology: Regional Studies* **28**, 100674. https://doi.org/10.1016/j.ejrh.2020.100674.

Li, T., Higgins, J. P. T. & Deeks, J. J. 2021 Chapter 5: Collecting data. In: *Cochrane Handbook for Systematic Reviews of Interventions Version 6.2* (Higgins, J. P. T., Thomas, J., Chandler, J., Cumpston, M., Li, T., Page, M. J. & Welch, V. A., eds), Cochrane. Available from: https://training.cochrane.org/handbook/current/chapter-05 (accessed February 2021).

Lodwick, W. A., Monson, W. & Svoboda, L. 1990 Attribute error and sensitivity analysis of map operations in geographical informations systems: suitability analysis. *International Journal of Geographical Information Systems* **4** (4), 413–428. https://doi.org/10.1080/02693799008941556.

Mahmoud, S. H. 2014 Delineation of potential sites for groundwater recharge using a GIS-based decision support system. *Environmental Earth Sciences* **72** (9), 3429–3442. https://doi.org/10.1007/s12665-014-3249-y.

Mahmoud, S. H., Alazba, A. A. & Amin, M. T. 2014 Identification of potential sites for groundwater recharge using a GIS-based decision support system in Jazan Region – Saudi Arabia. *Water Resources Management* **28** (10), 3319–3340. https://doi.org/10.1007/s11269-014-0681-4.

Maizi, D., Boufekane, A., Ait Ouali, K. & Aoudia, M. 2020 Identification of potential area of recharge using geospatial and multi-criteria decision analysis in the Macta watershed (Western Algeria). *Arabian Journal of Geosciences* **13** (3), 127. https://doi.org/10.1007/s12517-020-5076-7.

Malczewski, J. 1999 *GIS and Multicriteria Decision Analysis*, Wiley, New York, USA.

Malik, M. S., Shukla, J. P. & Mishra, S. 2021 Effect of groundwater level on soil moisture, soil temperature and surface temperature. *Journal of the Indian Society of Remote Sensing* **49** (9), 2143–2161. https://doi.org/10.1007/s12524-021-01379-6.

Manna, F., Walton, K. M., Cherry, J. A. & Parker, B. L. 2017 Mechanisms of recharge in a fractured porous rock aquifer in a semi-arid region. *Journal of Hydrology* **555**, 869–880. https://doi.org/10.1016/j.jhydrol.2017.10.060.

Mishra, A. K., Upadhyay, A., Srivastava, A. & Rai, S. C. 2020 Probabilistic groundwater recharge zonation in hard rock terrain using geospatial techniques in Veniar watershed, South India. *Ecohydrology and Hydrobiology* **20** (3), 456–471. https://doi.org/10.1016/j.ecohyd.2019.01.004.

Mussa, K. R., Mjemah, I. C. & Machunda, R. L. 2020 Open-source software application for hydrogeological delineation of potential groundwater recharge zones in the Singida semi-arid, fractured aquifer, central Tanzania. *Hydrology* **7** (2), 28. https://doi.org/10.3390/HYDROLOGY7020028.

Napolitano, P. & Fabbri, A. G. 1996 Single-parameter sensitivity analysis for aquifer vulnerability assessment using DRASTIC and SINTACS. In: *HydroGIS 96: Application of Geographic Information Systems in Hydrology and Water Resources Management* (K. Kovar & H.P. Nachtnebel, eds), IAHS Publication 235, IAHS Press, Wallingford, UK, pp. 559–566.

Page, M. J., Moher, D., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., McGuinness, L. A., Stewart, L. A., Thomas, J., Tricco, A. C., Welch, V. A., Whiting, P. & McKenzie, J. E. 2021 PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. *BMJ* **372**, n160. https://doi.org/10.1136/bmj.n160.

Panda, B., Sabarathinam, C., Nagappan, G., Rajendiran, T. & Kamaraj, P. 2020 Multiple thematic spatial integration technique to identify the groundwater recharge potential zones – a case study along the Courtallam region, Tamil Nadu, India. *Arabian Journal of Geosciences* **13** (24), 1284. https://doi.org/10.1007/s12517-020-06223-8.

Patil, N., Reddy, V. P., Patangray, A. & Singh, S. K. 2018 Mapping groundwater recharge potential using GIS approach in Darwha block. *Arabian Journal of Geosciences* **11** (1), 8. https://doi.org/10.1007/s12517-017-3324-2.

Pranckutė, R. 2021 Web of Science (WoS) and Scopus: the titans of bibliographic information in today's academic world. *Publications* **9** (1), 12. https://doi.org/10.3390/publications9010012.

Reinecke, R. 2022 Groundwater – global abundance and distribution. In: *Encyclopedia of Inland Waters: Volume 3*, 2nd edn (T. Mehner & K. Tockner, eds), Elsevier, Amsterdam, the Netherlands, pp. 306–314. https://doi.org/10.1016/b978-0-12-819166-8.00133-x.

Ren, X., Zhu, B., Liu, M., Zhang, Y., He, Z. & Rioual, P. 2018 Mechanism of groundwater recharge in the middle-latitude desert of eastern Hunshandake, China: diffuse or focused recharge? *Hydrogeology Journal* **27**, 761–783.

Saidi, S., Hosni, S., Mannai, H., Jelassi, F., Bouri, S. & Anselme, B. 2017 GIS-based multi-criteria analysis and vulnerability method for the potential groundwater recharge delineation, case study of Manouba phreatic aquifer, NE Tunisia. *Environmental Earth Sciences* **76** (15), 511. https://doi.org/10.1007/s12665-017-6840-1.

Salar, S. G., Othman, A. A. & Hasan, S. E. 2018 Identification of suitable sites for groundwater recharge in Awaspi watershed using GIS and remote sensing techniques. *Environmental Earth Sciences* **77** (19), 701. https://doi.org/10.1007/s12665-018-7887-3.

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

Selvam, S., Magesh, N. S., Chidambaram, S., Rajamanickam, M. & Sashikkumar, M. C. 2015 A GIS based identification of groundwater recharge potential zones using RS and IF technique: a case study in Ottapidaram taluk, Tuticorin district, Tamil Nadu. *Environmental Earth Sciences* **73** (7), 3785–3799. https://doi.org/10.1007/s12665-014-3664-0.

Singh, S. K., Zeddies, M., Shankar, U. & Griffiths, G. A. 2019 Potential groundwater recharge zones within New Zealand. *Geoscience Frontiers* **10** (3), 1065–1072. https://doi.org/10.1016/j.gsf.2018.05.018.

Verma, P., Singh, P. & Srivastava, S. K. 2020 Development of spatial decision-making for groundwater recharge suitability assessment by considering geoinformatics and field data. *Arabian Journal of Geosciences* **13** (8), 306. https://doi.org/10.1007/s12517-020-05290-1.

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

Zaidi, F. K., Nazzal, Y., Ahmed, I., Naeem, M. & Jafri, M. K. 2015 Identification of potential artificial groundwater recharge zones in Northwestern Saudi Arabia using GIS and Boolean logic. *Journal of African Earth Sciences* **111**, 156–169. https://doi.org/10.1016/j.jafrearsci.2015.07.008.

Zghibi, A., Mirchi, A., Msaddek, M. H., Merzougui, A., Zouhri, L., Taupin, J.-D., Chekirbane, A., Chenini, I. & Tarhouni, J. 2020 Using analytical hierarchy process and multi-influencing factors to map groundwater recharge zones in a semi-arid Mediterranean coastal aquifer. *Water* **12** (9), 2525. https://doi.org/10.3390/w12092525.

First received 30 December 2021; accepted in revised form 7 August 2022. Available online 13 August 2022