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ORIGINAL ARTICLE

Groundwater delineation for sustainable improvement and development aided by GIS, AHP, and MIF techniques

Muhsan Ehsan[1,2] · **Haider Shabbir**[1] · **Ayad M. Fadhil Al‑Quraishi**[3] · **Nadhir Al‑Ansari**[4] · **Zulfiqar Ahmad**[5] · **Kamal Abdelrahman**[6] · **Muhammad Tayyab Sohail**[7,8] · **Zaira Manzoor**[9] · **Ahsan Shafi**[10,11] · **Ahmed Elbeltagi**[12]

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Abstract

Exploration of groundwater is an integral part of viable resource growth for society, economy, and irrigation. However, uncontrolled utilization is mainly reported in urban and industries due to the increasing demand for water in semi-arid and arid regions of the world. In the background, groundwater demarcation for potential areas is vital in meeting necessary demand. The current study applied an integrated method comprising the analytical hierarchy process (AHP), multiple influence factors (MIF), combined with a linear regression curve and observatory well data for groundwater prospects mapping. Thematic maps such as flow direction, flow accumulation, elevation map, land use land cover, slope, soil texture, hill shade, geomorphology, normalized vegetation index, and groundwater depth map were generated utilizing remote sensing techniques. The relative weight of each parameter was estimated and then assigned to major and minor parameters. Potential zones for groundwater were classified into five classes, namely very good, good, moderate, poor, and very poor, based on AHP and MIF methods. A spatially explicit sensitivity and uncertainty analysis method to a GIS-based multi-criteria groundwater potential zone model is presented in this research. The study addressed a flaw in the way groundwater potential mapping results are typically presented in GIS-based multi-criteria decision analysis studies, where discrete class outputs are used without any assessment of their certainty with respect to variations in criteria weighting, which is one of the main contributors to output uncertainty. The study region is categorized based on inferred results as very poor, poor, marginal, and very good in potential ground quality 3.04 km^2 is considered extremely poor, 3.33 km^2 is considered poor, 64.42 km^2 is considered very good, and 85.84 km^2 is considered marginal zones, which shows reliable and potential implementation. The outcomes of AHP and MIF were validated by linear regression curve and actual water table in a study area. The study results help to formulate the potential demarcation of groundwater zones for future sustainable planning and development of groundwater sources. This study may be helpful to provide a cost-effective solution to water resources crises. The current study finding may be helpful for decision-makers and administrative professionals for sustainable management of groundwater resources for present and future demands.

Keywords Groundwater · Multiple influence factors (MIF) · Analytical hierarchy process (AHP) · Thematic maps · Remote sensing

Introduction

Water is essential for human life and global economic growth (Akhter et al. 2021; Wen et al., 2024; Qiu et al., 2023). Groundwater (GW) is the major freshwater resource for industrial, domestic, and irrigation practices globally, as 97% of freshwater resources are in GW (Ravenscroft and Lucy 2022; Li et al., 2023). Currently, GW meets 40% of agriculture demand, one-third of the total population depends on GW for drinking, while 700 million will require GW in the future (https://iah.org/education/general-public/groundwater-hidden-resource). However, with an ever-increasing population, unplanned anthropogenic activity, rapid urbanization, industrialization, and agricultural modernization etc., render GW overexploitation (Gleeson et al. 2012) and contamination (Foster and Willetts 2018). World Bank has reported contamination as one major reason for depletion and insisted that long-term sustainability will not be possible without GW planning and investments supported by strong institutions and an

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Extended author information available on the last page of the article appropriate legislative framework (Ravenscroft and Lucy 2022). These not only harm ecosystems resulting in loss of habitats, impaired ecology, and reduced biodiversity (Colvin et al. 2019) at large but also endanger human well-being, food production, and economic development from socio-economic perspective and sustainable deployment of the nation. It is a matter of concern for densely populated areas and developing countries around the world, especially India, Pakistan, and China. Due to uncontrolled exploration, depletion of the GW table is quite common in many parts of the world. Moreover, the drastic impacts of climate change have intensified the strategic nature of GW resources (Ahmad et al. 2023; Vinke et al. 2017; Rasul and Sharma 2015). Therefore, the decision-makers and scientists are looking for cost-effective methods to meet freshwater demands (Brazier 2015). Moreover, the drastic impacts of climate change have intensified the strategic nature of GW resources, specifically in arid and semi-arid areas (Wang and Qin 2017; Zhu et al., 2022; Ahmed et al., 2019). In the current scenario, GW crises in the highest importance for any state of the world, and with this scenario this research takes Pakistan as a case study.

The excessive unplanned extraction of GW is disrupting the global balance between aquifer recharge and withdrawal, causing a disturbance in the availability of freshwater sources. This imbalance results from rapid population growth, urbanization, and industrialization, which have collectively impacted the availability of clean water resources over time. However, its depletion occurs due to excessive exploitation to meet water demand, alongside the shortage of other natural resources. GW is essential and considered a reliable global water source in all climatic areas. GW, a precious natural resource, is crucial for human civilization, serving as a primary source of potable water in various climatic regions. It plays a vital role in meeting freshwater demands, especially for drinking water. It also supplies irrigation water to approximately one-quarter of the world's irrigated farmland, a significant portion in Asia. In numerous regions, particularly rural areas, wells, and springs are the sole water sources for communities. However, despite the Earth's surface being predominantly water, freshwater resources are limited, underscoring the importance of sustainable management and conservation efforts (Yamazaki and Trigg 2016; Falkenmark et al. 2019; Mojid et al. 2019; Talukdar et al. 2022; Priya et al. 2022; Fatema et al. 2023).

Pakistan is the 6th most populated country globally, has weak land use governance and reforms (Shafi et al. 2022), and lacks a comprehensive water policy, resulting in unsustainable exploitation of GW. International Monetary Fund (IMF) has reported Pakistan to be one the most water-stressed countries, which will become water-scarce by 2050 (Team 2015). Although the country is mainly irrigated through one of the largest canal systems, GW provides 56 MAF for agricultural usage through 1,562,568 wells (data taken from an Economic Survey of Pakistan, 2021–2022; finance.gov.pk) from 20.18 million Hectors, 3.98 million Hectors is irrigated through GW wells. Moreover, this canal system causes degradation of GW through salinity, water logging, and seepages. In coastal areas, the intrusion of saline water is very high, reducing the productivity of the soil. Hayat et al. (2020) reports water scarcity due to a lack of management, as 57% of farmers faced problems like salinity, aquifer depletion, and restriction of using canal water. Here, the fundamental issues remain the unsupervised over-exploitation of aquifers causing declining water levels, high level of salinity and nitrate, intrusion of salt water in coastal areas, flood irrigation resulting in water wastage caused by the absence of comprehensive GW management policies and practices. Currently, sudden shifts in the irrigation system caused by climate change and growing urbanization and industrialization have prompted severe worries about the Indus Basin's accessible water sources in Pakistan, on which millions of people depend for their survival (Jabeen et al. 2020). Pakistan is concerned about water contamination and quantity and the country is among the countries whose GW discharge exceeds recharge, and GW is considered highly insufficient to meet irrigation requirements (Mehmood et al. 2021). The GW table in Pakistan's Rachna Doab sub-catchment of the Indus River basin is declining every year, and if the same situation continues for the next three decades, the GW level will drop by 10 m (Khan et al. 2008; Dawood et al. 2021). Though National Water Policy 2018 has standardized the criteria of GW utilization, the policy lacks implementation and execution through executives pointing toward incompetent political and bureaucratic institutions.

According to the authors' information and literature survey, it was concluded that there was no study done in the research area related to AHP and MIF in the study area. However, a few studies, e.g., assessing the environmental influence on diminishing groundwater resources: A case study from a semi-arid and dry climatic zone in Pakistan was done by Rahman et al. (2022). Numerous studies worldwide have integrated different approaches (e.g., Singh et al. 2021; Ajayi et al. 2022). Over the past two decades, the GW chemistry in Punjab (study area), part of the upper Indus Basin, has significantly changed (Bonsor et al. 2017). Punjab is mainly relying on shallow GW located 20–200 feet below the ground surface for various purposes such as drinking, agriculture, industry, and farming. However, the current state of Punjab's GW presents several challenges (Tiwari et al. 2009), which including depletion, salinization, and harmful substances (Bajwa et al. 2017). The current study area, Nankana Sahib is located in Punjab Province, Pakistan, between the major water tributaries of Ravi and Chenab. It is commonly known as Rachna Doab. Despite being between two tributaries, the area mostly depends on GW for irrigation and domestic usage because it lacks surface irrigation resources. Though river Ravi is the primary source of the aquifer recharge of the area, the river mainly carries sewerage and wastewater, which is not processed, causing GW contamination (Khan and Khan 2020).

Remote sensing (RS) and geographical information system (GIS) are entirely benefitting from integrating basic and numerical data sets (Shailaja et al. 2019; Ahmad et al. 2022; Tian et al., 2019, 2020; Zhou et al., 2023). Researchers have used various modern techniques to analyze traditional methods, like thematic mapping and many more (Maity and Mandal 2019; Guan et al., 2023; Dong et al., 2023a; b; Yang et al., 2022). The combined approach of geospatial was processed to define GW (Qadir et al. 2020). RS has played an important role in mapping and analyzing a synoptic-scale (Chen et al., 2019; Zhou et al., 2022a; b). Different methods have been adopted to describe suitable locations for groundwater using MIF and AHP techniques (Ghimire et al. 2019; Brazier 2015). The integration of fundamental and numerical data sets benefits both remote sensing (RS) and geographic information systems (GIS) by Kumar et al. (2022a). RS combined with hydrological data was grouped into a statistical approach to analytical classification methods (Şener et al. 2018). AHP and MIF techniques were utilized for the potential GW zone, so they provide accurate estimations and reduce the chances of human errors such as (Pande et al. 2021). The surface flow in hard rock areas is very high, and rainwater is not easily infiltrating broken rocks and reservoirs. Therefore, most groundwater is preserved and stored in cracks, fractures, and weathered rocks (Díaz-Alcaide and Martínez-Santos 2019). Therefore, sustainable development of freshwater resources requires attention has been paid to it by using GIS and RS (Arabameri et al. 2019).

The World Bank produced a study on water shortage and water security in Pakistan in 2019. These two words, shortage and security, allude to the amount of water accessible to each individual depending on the total supply, as well as the overall accessibility and safety of the available water. These two concerns are intertwined, and the latter has an impact on the former (Young et al. 2019). Recent studies relevant to sustainable development and improvement of GW in Pakistan last 5 years 2023–2018 is shown in Table 1. GW delineation for sustainable improvement and development is crucial to water resource management worldwide. Integrating GIS, AHP, and MIF techniques can provide valuable insights into groundwater availability and potential areas for sustainable development. In the case of Nankana Sahib District (study area), Pakistan, located in the Rachna Doab region, these techniques can be applied to support informed decision-making regarding sustainable GW management. This study may be helpful to decision-makers and water resource managers in Nankana Sahib can comprehensively understand GW resources and their spatial distribution. This knowledge can aid in formulating sustainable development plans, identifying suitable locations for new wells, managing groundwater extraction rates, and promoting water conservation practices to ensure groundwater's long-term availability, sustainable development of GW resources and quality in the study area.

Various methods are used for assessing groundwater delineation, and the choice of method depends on factors such as the study's specific objectives, site conditions, available resources, and the accuracy required. Here are some commonly used methods: Groundwater Monitoring Wells, Geophysical Methods, RS, GIS, Pumping Tests, etc. (Ajayi et al. 2022). From this context, delineating GW perspective is vital in preserving the balance quantity in reservoirs, industry, agriculture, sustainable and economic development. Furthermore, changing the water table to rainy and dry seasons needs to be analyzed for sustainable watershed development and planning. The current study's main objective is to apply an integrated method comprising the AHP, MIF, combined with a linear regression curve and observatory well data for GW prospects mapping. Therefore, this study's specific objective is to highlight the change in GW table issues within an aquifer system, identify groundwater zones for potential exploration by RS combined with new techniques, and present less economical and reliable solutions.

Location of the study area

Nankana Sahib District is part of the Rachna Doab, is a Tehsil of Lahore, Pakistan, situated in latitude 31° 45′ 12″ to 31° 25′ 1″ N, and longitude 73° 39′ 48″ to 73° 55′ 30″ E (Fig. 1), and located in Pakistan's arid and agricultural region. The study area is dominated by high rainfall during monsoon spells, and the elevation ranges from 190 to 230 m above sea level, with a total basin area of 1096.8 Km^2. The study area is a part of the Ravi Floodplain, which is the ultimate recharge source of aquifers in the study area. The basin mainly consists of agricultural land with flat topography; whereas, agriculture is the dominant sector in this area, to meet water requirements for irrigation canal system has been utilized.

Nankana Sahib is located in the province of Punjab, Pakistan, between the Ravi and Chenab waterways, sometimes known as the Rachna Doab. Although the Ravi River is the primary source of subsurface aquifer recharge, several geochemical investigations in the area have revealed indications of salty water intermixing with fresh water aquifers (NESPAK 2014). The declining trend in the availability of fresh water resources has already highlighted serious problems in the study region, necessitating prompt management of limited water resources.

Table 1 Recent studies relevant to sustainable development and improvement of GW in Pakistan last 5 years 2023–2018

Authors	Research technique	Research aspect	Basic purpose and theme of the study
Mahmud et al. (2022)	Electrical resistivity sounding and Dar Zarrouk parameters	Investigation of groundwater resources	To explore and evaluate the nature of GW, saline water and intrusion of seawater in Uthal area, of Baluchistan, Pakistan
Arshad et al. (2020)	Mapping: Potential recharge zones, potential recharge index, Analysis: analytical hierarchical process (AHP) and area under the curve (AUC)	Delineation of groundwater in agro-urban areas	This study aims at pinpointing the recharge zones, so that sustainable usage of GW be ensured as artificial recharge of aquifers be made possible
Hasan et al. (2019)	Integrated geophysical approach: vertical electrical sounding (VES) and electrical resistivity tomography (ERT)	Delineate the intrusion boundary between the fresh and saline aquifers	This study aims to utilize the geophysical methods to cut the expensive borehole methods, where homogeneous and heterogenous aquifers can be segregated
Shakoor et al. (2020)	DRASTIC model for agriculture application	Delineation of contaminated aquifers	The article aims to map the vulnerability potential of aquifers with most dominant factors, and suggests that different regions require different approach to tackle the contamination ratio; site-specific solutions
Nasir et al. (2018)	GIS and multi-influence factor (MIF)	Assessment of GW potential	This paper explains the GW potential through ArcGIS utilizing weighted overlay method, where planning and management of GW is targeted with recognition of potential zones with proscribed method
Hasan et al. (2020)	Integrated geophysical study of VES and ERI methods	Delineation of contaminated water	To utilize the integrated geophysical approach to pinpoint the intrusion of salt water into freshwater in upper Bari Doab region of Pakistan
Soomro et al. (2017)	Physiochemical analysis	Occurrence of contamination in freshwater	To delineate the occurrence of high nitrate factor in drinking water in Tharparkar district of Sidh, Pakistan, where livestock manure is the basic reason of high nitrate factor in GW contamination
Khan et al. (2021)	Integrated geophysical and hydrological investigation	Aquifer vulnerability	To evaluate the source rocks, check the flow rates and exploitation measures in Braham Bahtar area of Lesser Himalayas. The chemical analysis suggests the quality of the water to be potable
Hasan et al. (2018)	Non-invasive geoelectric method	Delineation of potable water and saline intrusion	The study provides with geochemical and geophysical analysis of potable aquifers
Sarwar et al. (2021)	Geospatial analysis: multi-influencing factor	Mapping GW potential	The study utilizes GIS and Remote sensing to point out the potential areas of GW usage for agricultural purposes in District Lower Dir, Pakistan and finds the GW availability differs in different areas refer from shallow to deep
Islam et al. (2023)	GIS and remote sensing	GW mapping	For exploration, management, and supply of freshwater, this study maps the aquifers in Kohat district, Pakistan to ensure the quality and quantity of GW
Dars et al. (2023)	Electrical Resistivity Survey	Quantum and quality of GW	For irrigation purposes this study conducts the quality check of the GW and suggests the canal water should also be utilized to enhance the productivity as the GW is hazardous

Table 1 (continued)

Authors	Research technique	Research aspect	Basic purpose and theme of the study
This study	GIS, AHP, and MIF techniques	Delineation	This study will explore change in GW table issues within an aquifer system and identify GW zones for potential exploration by remote sensing combined with new techniques and present less economical and reliable solutions

The study area is covered by thick alluvial and river deposits (Shah et al. 2022), it includes the terrigenous sedimentary rocks of streams, flood plains, and detrital sedimentary rocks. Borehole data suggest sediments coexist in different proportions and alternate from sandy clay to clayey sand, mainly grey to brownish-grey (Akhtar et al. 2016; Jabeen et al. 2020). The sand, gravel, and their admixtures serve as water-bearing strata. Most of the aquifers in this region are confined by Shah et al. (2022). However, unconfined aquifers characterize some places with gravels and boulders at the top. Moreover, the aquifers are recharged mainly due to watercourses, unlined canals, irrigation practices, and rainfall and ponds, which are the other recharge elements. The water table in the area fluctuates depending upon seasonal recharging. The total maximum rainfall is between 65 and 242 mm (Source: Pakistan Meteorological Department. 2016 (PMD) http://www.pmd.gov.pk/cdpc/home.htm).

Data set and methodology

The study used these datasets in combination with other spatial analysis techniques in ArcGIS to process and analyze the information. The analysis involved generating derivative maps and performing spatial overlays to identify relationships and patterns between the variables. To validate the results, a linear regression curve was used to assess the relationship between the predicted GW depth based on the analyzed datasets and the actual measured GW depth from field surveys. This validation helps assess the accuracy and reliability of the GW depth estimation method used in the study. Overall, by integrating different datasets and utilizing ArcGIS for spatial analysis, the study aimed to understand the spatial distribution and relationship between GW depth and various influencing factors, such as topography, land use, soil type, vegetation, and geology.

The datasets used in this study were acquired from Shuttle Radar Topography Mission (SRTM) and field survey, shown in (Table 2), which included Digital Elevation Model (DEM), soil type, water table depth, vegetation index, and geology. DEM, land use, soil types, geomorphology, flow direction, hill shade, and groundwater depth of the aquifer were processed in ArcGIS ver 10.5. Geological and hydrogeological information plays an essential role in spatial groundwater circulation. The results validation has been made with a linear regression curve and actual groundwater depth.

Ten thematic layers have been considered for the study area. The dataset and methodologies used are presented in Table 3 and Fig. 2. The DEM was downloaded from the U.S. Geological Survey earth explorer website (https://earthexplorer.usgs.gov/). Geology and soil texture were prepared from Water and Power Development Authority (WAPDA)

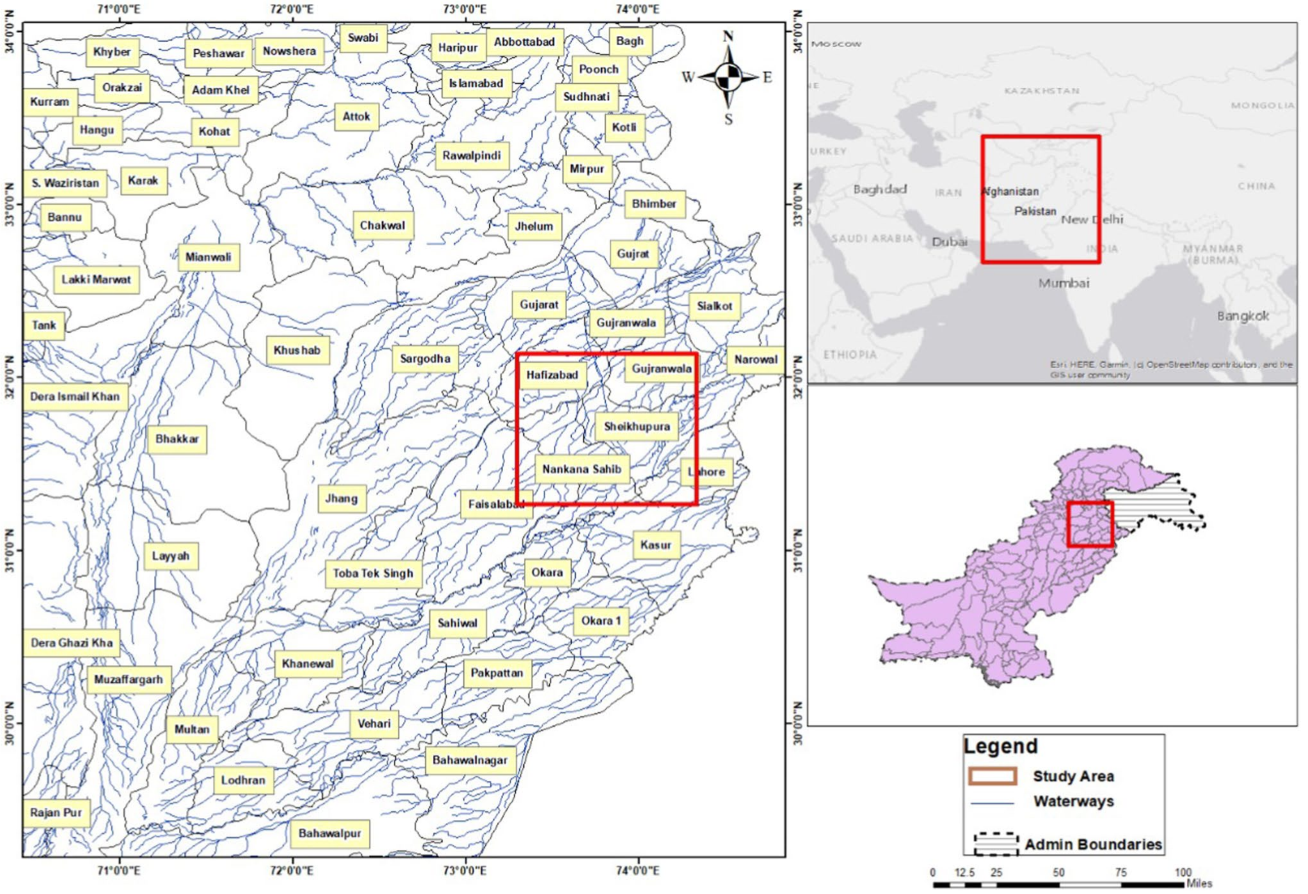


Fig. 1 Location map of the study area (Nankana Sahib District)

published Report 1968, collected Pakistan Council for Research in Water Resources (PCRWR) (https://pubs.usgs.gov/wsp/1608i/report.pdf). The groundwater depth was measured using observation wells. The AHP and MIF results were validated through the linear regression method and actual water depth. This analytical approach gives a reliable and authentic approach to determining potential zones for groundwater (Negnevitsky 2005).

AHP ranking and weight assigning

We calculated the weight of the thematic layers based on their parameters by using the AHP (Saaty 2008). Each layer has its characteristics, and capacity to hold water, as per Saaty's scale. The AHP technique was used for the multi-parameter calculation based on their formations or categories (Bhatla et al. 2019). An interpolation method was adopted to divide the groundwater depth map into four sub-classes defined by slope, hill shade, and DEM values. Among the Jenks optimization method sorting technique, the 0 and 1 class was prominent in creating slope, hill shade, and DEM maps (Arulbalaji et al. 2019).

The parameter calculation for thematic maps is shown in Table 4. Based on the literature survey geopolitical weight values were assigned in Table 4. Relative groundwater availability (Tables 5 and 6) for each sub-class of thematic layers was assigned a rank (0–15). In the context, relative groundwater availability for each sub-class of thematic layers was assigned a rank ranging from 0 to 15. Assigning ranks is a common practice in various analytical methods, such as the AHP or multi-criteria decision-making approaches. Ranks are used to represent the relative importance or preference of different factors or categories within a given context. In this case, the thematic layers likely represent different factors or attributes related to groundwater availability. Each sub-class within these thematic layers was assessed and assigned a rank, which serves as a measure of its relative importance or suitability for groundwater availability Janković and Popović (2019). The specific methodology for assigning these ranks may vary depending on the study or analysis being conducted. It could involve expert judgment, statistical analysis, or a combination of both. The ranks assigned to each sub-class can then be used

Table 2 Dataset, indices, methodology, and references utilized for this study

Spatial thematic parameter	Methodology	Descriptions	Multicollinearity check	References
Normalized difference, Land use, Rainfall, NDVI, Geology, slope, groundwater level, Soil texture, stream link, elevation	There are several models of multimodal decision making, including the AHP, and knowledge-based models	Maps of natural resources and hydrological data were used as inputs for the development of groundwater zones	Not executed	Gueretz et al (2020)
NDVI, depth of groundwater, soil, slope, drainage density, geomorphology, and geology	GIS weighted method based on remote sensing	With the combination of remote sensing and GIS, this weighting method uses multiple parameters based on remote sensing	Not executed	Shailaja et al. (2019))
Geomorphology, geology, and slope; elevation, flow accumulation	Remote sensing and GIS weighted method	These parameters describe leading characteristics along with other influences	Not executed	Chen et al. (2019))
Slope, geomorphology, geology and accumulation of flows	Satellite and Geospatial data	Remote sensing and GIS benefit of joining different digital data set	Not executed	Rani et al. (2019))
Geomorphology, soil, landforms, slopes, flow accumulations, and soils	MIF and AHP method	The advanced and traditional methods were utilized to mark groundwater potential zones	Not executed	Pande et al. (2020)
Hydrological dataset through GIS and RS	A statistical approach, AHP, and groundwater flow modeling	RS and GIS and statistical methods applied with AHP technique to demarcate groundwater potential suitable sites	Not executed	Sashikkumar et al. (2017)
Geology, drainage density, slope, land use classes, geomorphology and soil type	AHP and GIS	RS and GIS methods applied with AHP technique	Not executed	Ajay Kumar et al. (2020)
Geology, lineament, aquifer depth, slope, land use classes, geomorphology, soil, rainfall, stream density and soil type	GIS weighted method based on remote sensing	Geological parameter with RS and GIS methods to identified groundwater potential zones	Not executed	Arivazhagan et al. (2021)
Rainwater, groundwater depth, landform, surface water bodies, topography, topography, surface elevations, and land use	GIS weighted method based on remote sensing	All thematic related parameter plays a key role in developing groundwater planning	Not executed	Pande and Moharir (2017)
Flow accumulation and geomorphology Land cover, groundwater level, slope, drainage, and direction of flow	WOA, MIF and GIS weighted method	RS and GIS methods applied with MIF technique to demarcate groundwater potential zones	Not executed	Mehra et al. (2016)

Table 3 Parameters and sources used in the current study

Parameter	Data type	Data sources	Data details	Data acquisition/ years	Generated map type	References
LULC	Raster	NRCS Soil maps	Dem 30-m, Land use land cover analysis	2021	LULC map	Bhatla et al. (2019)
Soil texture	USGS published report	USGS 1968 published reports	Dem 30-m, Soil map	1968	Soil map	USGS published reports
Geomorphology	Raster	Digital elevation model (DEM), resolution 30 m	Dem 30-m, geomorphology map	2021	Geomorphology map	Pande et al. (2020)
Flow direction	Raster	Digital elevation model (DEM), spatial analyst tool in ArcGIS 10.5 software	Dem 30-m, flow direction	2021	Flow direction	Rani et al. (2019)
Hill shade	Raster	Digital elevation model (DEM), spatial analyst tool in ArcGIS 10.5 software	Dem 30-m, Hill shade map	2021	Hill shade map	Arulbalaji et al. (2019)
Slope	Raster	Digital elevation model (DEM), slope map	Dem 30-m, Slope Map	2021	Slope map	Jothibasu and Anbazhagan (2016)
NDVI	Raster	NDVI maps developed by Sentinel-2 data	Dem 30 m, NDVI map	2021	NDVI map	Mehra et al. (2016), Pande et al. (2021)
Aspect	Raster	Digital elevation model (DEM), by spatial analyst tool in ArcGIS 10.5 software	Dem 30-m, Aspect Map	2021	Aspect map	Mahato and Pal (2018)
Groundwater depth	Raw, survey	Groundwater map by the interpolation method	Data acquire from filed survey, Groundwater depth map	PCRWR,2016	Groundwater depth map	Pande and Moharir (2017)
Geospatial software	Raster	Arc map 10.7, Overlay Analysis method	N/A	2021	N/A	Ajay Kumar et al. (2020)

to compare and prioritize them, informing decision-making processes related to groundwater management or resource allocation. Several methods for estimating the consistency ratio (CR) were used to verify the resultant thematic maps (Saaty 1990).

$$\mathrm{CI}=\frac{(\lambda_{\max}-n)}{(n-1)} \tag{1}$$

$$\mathrm{CR}=\frac{\mathrm{CI}}{\mathrm{RI}} \tag{2}$$

where RI = random index, CI = consistency index If CR value ≤ 0.10, it is acceptable and If CR = 0, it is the perfect level.

Each layer has a weight and a rank, and the groundwater zones can be determined by overlaying multiple maps using ArcGIS 10.5's weighted overlay technique using Eq. (3).

$$\mathrm{GPZ}=\sum_{i=1}^{n}(W_iXR_i) \tag{3}$$

$$\begin{aligned}\mathrm{GWPZ} =&(\mathrm{ST_w}\times\mathrm{ST_{wi}})+(\mathrm{GM_w}\times\mathrm{GM_{wi}})+(\mathrm{SL_w}\times\mathrm{SL_{wi}})\\&+(\mathrm{D_w}\times\mathrm{D_{wi}})+(\mathrm{FD_w}\times\mathrm{FD_{wi}})+(\mathrm{LULC_w}\times\mathrm{LULC_{wi}})\\&+(\mathrm{HS_w}\times\mathrm{HS_{wi}})+(\mathrm{NDVI_w}\times\mathrm{NDVI_{wi}})+(\mathrm{Espect_w}\times\mathrm{Aspect_{wi}})\\&+(\mathrm{GD_w}\times\mathrm{GD_{wi}})\end{aligned} \tag{4}$$

In Eq. (4), GWPZ represents the areas that can be identified using factors such as soil texture (ST), geomorphology

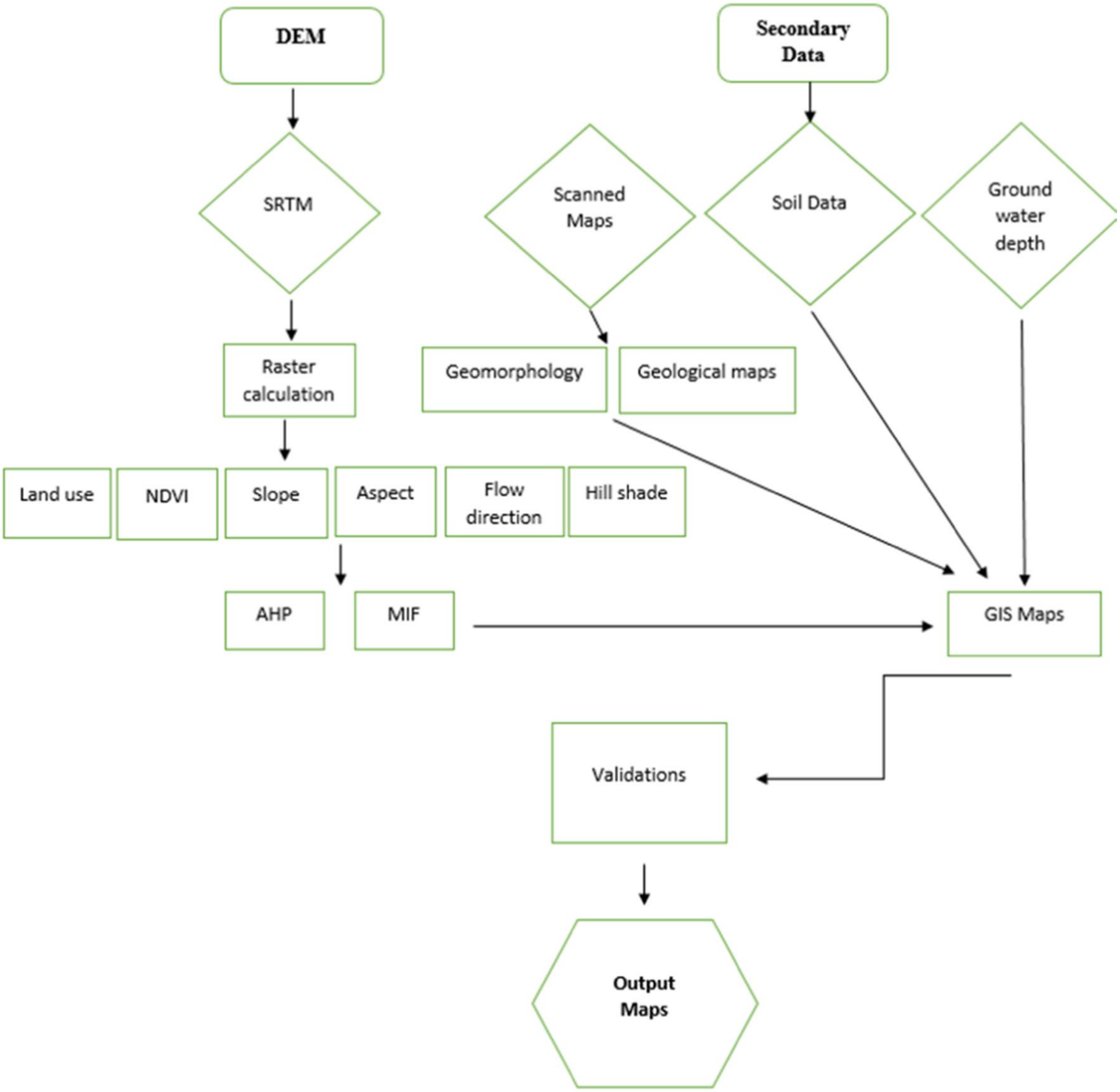


Fig. 2 Methodology and workflow adopted for the current study

(GM), DEM (D), hill shade (HS), slope (SL), NDVI, aspect, and groundwater depth (GD). Each sub-class of thematic layers was assigned a weight in accordance with the weight layer of each class.

In current study, both recent and previous data were used for groundwater assessments to ensure the reliability and validity of the results. Also incorporated recent RS data can provide valuable insights into changes in land use, vegetation cover, and other parameters that can impact groundwater dynamics.

Multi-influencing factors (MIF)

The important parameters are listed in Table 7. If an impact has a maximum value, then a 1.0 score is assigned. If it has a minimal impact, those elements perform poorly, receiving a 0.5 score. They are defined as potential groundwater zones via the relation between major and minor parameters. The relative score helps to calculate the individual impact of each parameter (Eq. 5). Table 7 delineates the potential groundwater areas based on a weighted influencing factors classification.

$$D = \left(\frac{(A + B)}{\sum (A + B)} \right) * 100 \tag{5}$$

The suggested mark for each influencing factor is D; while, A represents the major relationship between the two factors, and B represents the minor relationship between the two factors (Ghosh et al. 2016). We have assigned the required scores based on groundwater data and hydrogeology knowledge as mentioned in Manap et al., (2014).

Table 4 Study's parameters calculation for the thematic maps

Factors	Soli texture	LULC	DEM	Flow direction	Hill shade	Slope	NDVI	Aspect	Groundwater depth	Weight	λ	λ max	CI	CR
Soil texture	15/15	15/15	15/15	15/15	15/15	15/15	15/15	15/15	15/15	0.15	10	10	(10–10) /(10–1) = 0	0/1.48 = 0 < 0.10
LULC	15/10	15/10	15/10	15/10	15/10	15/10	15/10	15/10	15/10	0.1	10			
Geomorphology	15/10	15/10	15/10	15/10	15/10	15/10	15/10	15/10	15/10	0.1	10			
DEM	15/10	15/10	15/10	15/10	15/10	15/10	15/10	15/10	15/10	0.1	10			
Flow direction	15/10	15/10	15/10	15/10	15/10	15/10	15/10	15/10	15/10	0.1	10			
Hillshade	15/10	15/10	15/10	15/10	15/10	15/10	15/10	15/10	15/10	0.1	10			
Slope	15/10	15/10	15/10	15/10	15/10	15/10	15/10	15/10	15/10	0.1	10			
NDVI	15/10	15/10	15/10	15/10	15/10	15/10	15/10	15/10	15/10	0.1	10			
Aspect	15/10	15/10	15/10	15/10	15/10	15/10	15/10	15/10	15/10	0.1	10			
Groundwater depth	15/10	15/10	15/10	15/10	15/10	15/10	15/10	15/10	15/10	0.1	10			

Table 5 Assigned weight for each studied factor's thematic maps

Sr No#	Factors	Weight
1	Soil texture	15
2	LULC	15
3	DEM	10
4	Flow direction	10
5	Hill shade	10
6	Slope	10
7	NDVI	10
8	Aspect	10
9	Groundwater depth	10
10	Total	100

Table 6 Weight for each sub-class has been done based on thematic layers integrated into a single frame to delineate groundwater potential

Sr #	Factors	Weight	Groundwater potential areas
1	Soil texture	15	Very poor to very good
2	LULC	15	Very poor to very good
3	DEM	10	Very poor to very good
4	Flow direction	10	Very poor to very good
5	Hill shade	10	Very poor to very good
6	Slope	10	Very poor to very good
7	NDVI	10	Very poor to very good
8	Aspect	10	Very poor to very good
9	Groundwater depth	10	Very poor to very good

The single influence parameters planned scores were separated for each reclassified sub-parameter. Based on the map removal technique, the GWPZ map was constructed by identifying the most sensitive layer utilizing the algebra function in ArcGIS 10.5.

GWPZ accuracy and validation

From the field survey, various ten (10) hand pump and tube well GW depths were collected for validation (Mandal et al. 2021). Equation 6 was given below:

$$\text{Accuracy of high GWP(\%)} = \frac{\text{Wellwith low GWF in high GWPZ}}{\text{Total no. of wells in low GWP}} * 100 \tag{6}$$

Table 7 Percentage of each influencing factor allocated weight

Sr #	Factors	Major effect (A)	Minor effect (B)	Relative weight (A + B)	Allocated weight
1	Soil texture	3	0.5	3.5	15
2	LULC	3	0.5	3.5	15
3	Digital Elevation Model	2	0	2	10
4	Flow direction	2	0	2	10
5	Hill shade	3	0	3	10
6	Slope	3	0.5	3.5	10
7	NDVI	3	0	3	10
8	Aspect	3	0.5	3.5	10
9	Groundwater depth	4	0.5	4.5	10

Results and discussions

The study area is covered by thick alluvial and river deposits; whereas, it includes the terrigenous sedimentary rocks of stream deposits, flood plain deposits, and detrital sedimentary rocks (Shah et al. 2022). The geologic units' high permeability and porosity increase groundwater storage and yields (Yildirm 2021). It has been inferred from the results, that the study area is classified based on potential ground quality. The classification is very poor, poor, marginal and very good 3.04 km^2 area are classified as very poor, 3.33 km^2 as poor, 64.42 km^2 as very good, and 85.84 km^2 as marginal zones. The AHP map of groundwater potentiality indicates that a total of 22.44% of the area is very poor and poor. At the same time, alluvium represents good groundwater potential. While in the MIF map, 19.21% of the area was considered very poor or poor. According to MIF and AHP techniques, the area is close to 19.33% and 15.33% semi-critical zones representing good to very well potential groundwater zones, respectively. The detail's interpolation is given below:

Aspect

It is a simulation of rock bedding's moisture retention and slope. The aspect is flat which indicates positive groundwater potential; while, the east part of the study area contains steeper slopes and negative groundwater potential (Fig. 3a).

Curvature

Curvature, hill shade, and elevation are important factors in assessing GW availability due to their influence on topography, surface water movement, and groundwater recharge processes. By integrating information on curvature, hill shade, and elevation, groundwater professionals can identify areas that are likely to contribute to groundwater recharge and discharge processes. This knowledge helps in delineating GW flow paths, locating potential recharge zones, and understanding the connectivity between surface water and GW systems. It also aids in predicting areas where GW availability may be limited due to factors such as steep slopes, low elevations prone to flooding, or areas with limited recharge potential (Saravanan et al. 2021). Curvature represents the measurable characteristic of a surface's profile, manifesting as either a concave upward or convex upward shape. Water tends to slow down and accumulate more in areas with convex profiles, while concave profiles tend to encourage water to gather (Arulbalaji et al. 2019). Based on Fig. 3b, the estimated curvature value ranged from 0.35 to 1.9.

Elevation

The elevation of the land surface plays a crucial role in GW replenishment. It is the primary driver of water movement through gravity (Gebreyohannes et al. 2017). We can identify the areas contributing to GW flow by studying the elevations (Maqsoom et al. 2022). Elevation is a topographic feature that can be used as a surface indicator to investigate the potential of groundwater. The STRM DEM has been utilized to develop the study area's elevation map. The climate can change depending on altitude, which leads to variations in rainfall pattern, and soil quality, etc. (Melese and Belay 2022). Elevation gradients impact the direction and flow of groundwater, whereas elevation changes across a landscape contribute to groundwater recharge and movement. These data are critical for making sound decisions about water resource management and sustainability (Ashwini et al. 2023). Plain surface areas generally have less irruption than

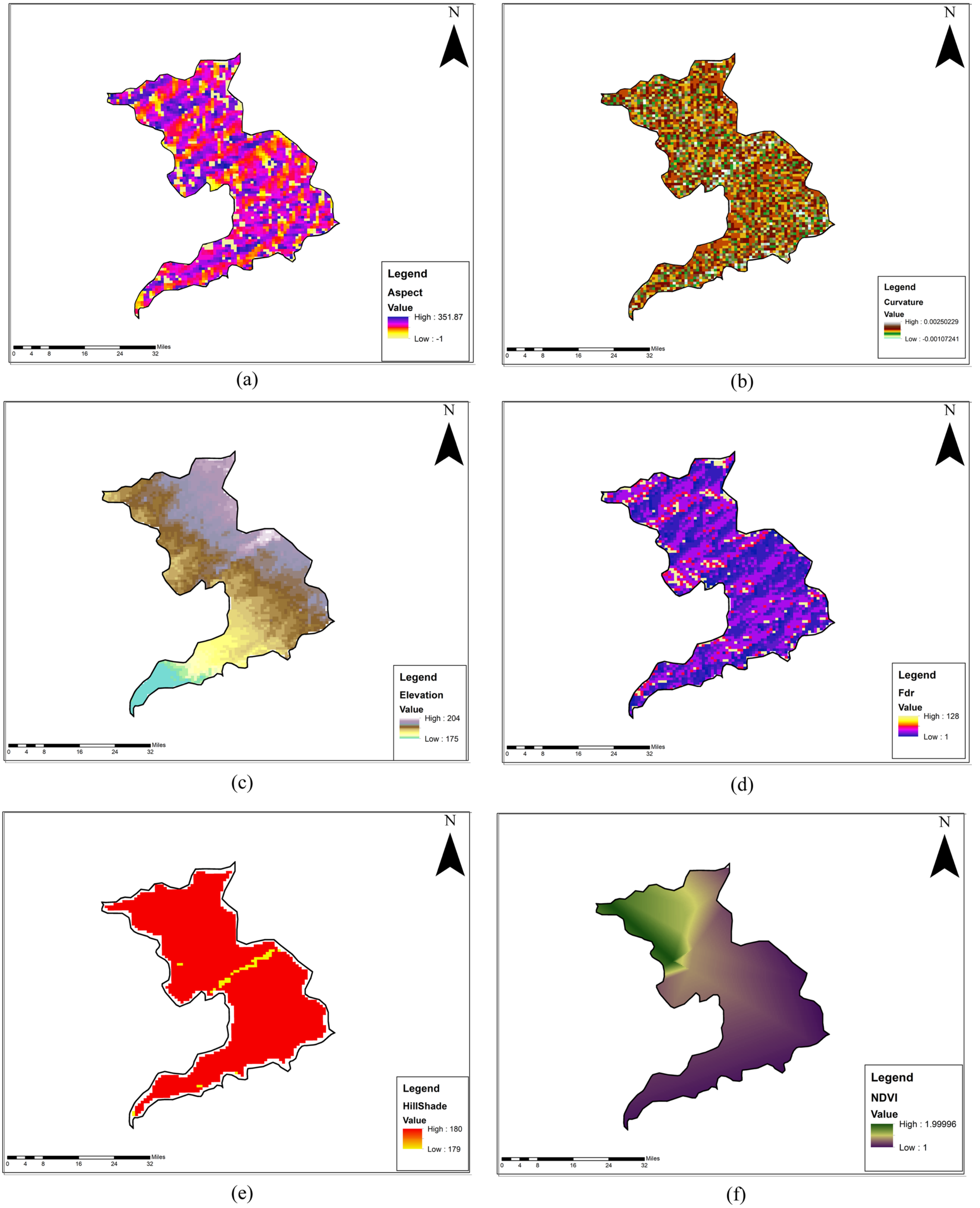


Fig. 3 **a** Aspect, **b** curvature, **c** elevation, **d** flow direction, **e** hill shade, **f** NDVI, **g** slope, **h** soil texture, and **i** geomorphology map for the study area

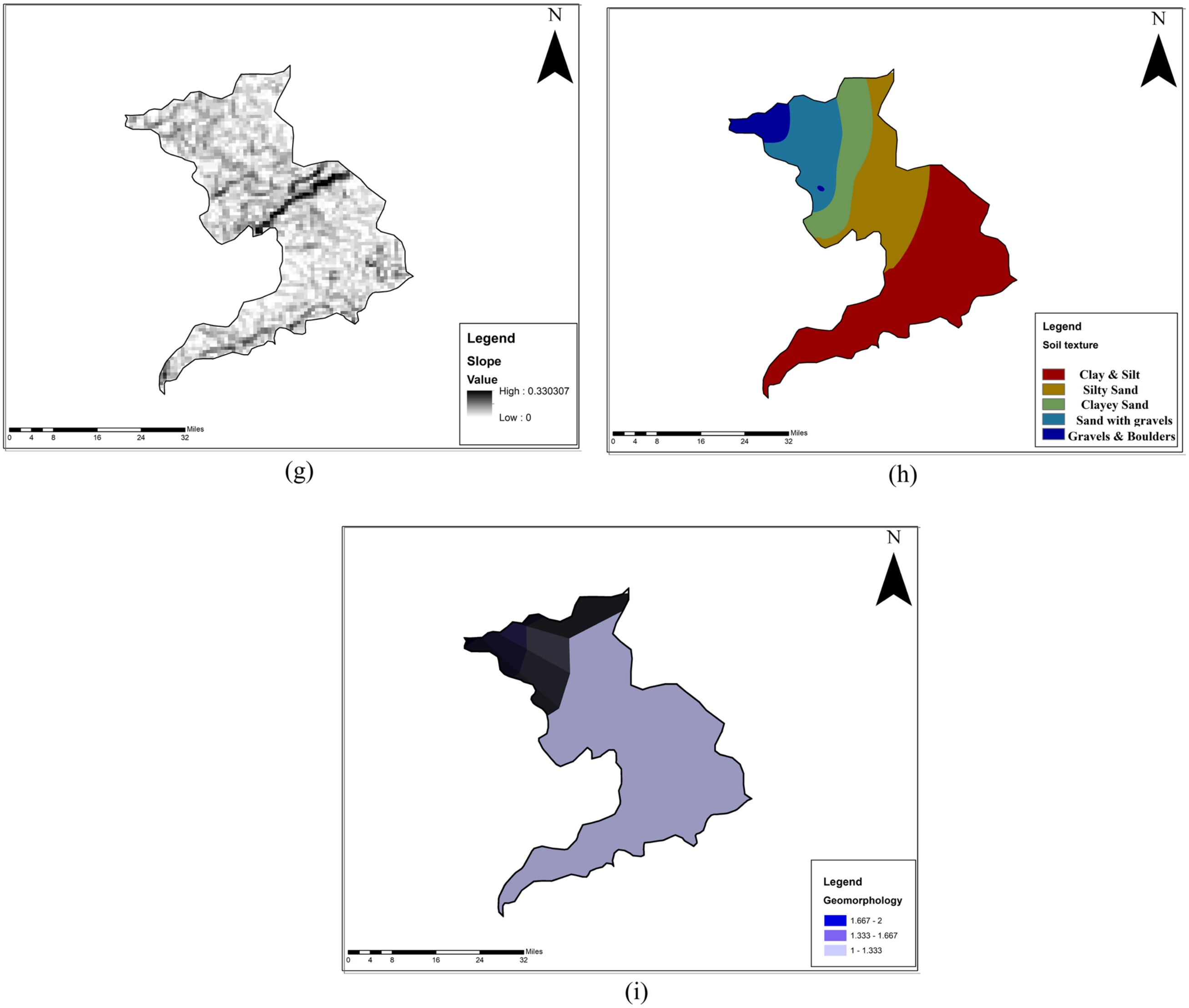


Fig. 3 (continued)

moderate and high elevated points, whereas ranges vary between 190 and 23m above sea level (Fig. 3c).

Flow direction

Flow direction is being consider fundamental parameter in groundwater mapping using GIS and RS. It provides critical insights into the movement of GW within an aquifer system, which is essential for effective management and sustainable use of natural resource (Kalhor et al. 2019). Water moves under the action of gravity toward the southward side due to the terrain factor. The high elevation demonstrates extra runoff and reduces the quantity of water infiltration. The movement of water under the influence of gravity is generally determined by the topography or slope of the land. Water tends to flow from higher elevations to lower elevations, following the path of least resistance. As shown in Fig. 3d, values varied from 1 to 128.

Hill shades

Hill shade map is a crucial parameter for understanding the topography and hilly places of the study area. An altitude and azimuth tools define the way of the sun using a three-dimensional grayscale depiction of the surface. Hill shade map serves as a powerful tool for enhancing our understanding of both topography and GW dynamics (Pande et al. 2021). The current study area hill shade map shown in Fig. 3e indicates no significant variation in numerical values.

NDVI

An essential parameter for assessing the quality of an eco-system is the normalized difference vegetation index (NDVI), which is classified into four groups: very good, good, moderate, and poor. As shown in Fig. 3f, NDVI varies from 0.21 to 2. 0 represents an area with poor groundwater potential, and 2 represents a zone with good groundwater potential (Mukherjee and Singh 2020). Measuring the density can determine whether large amounts of the canopy could lead to better groundwater harvesting in poor aquifers (Archibald et al. 2019).

Slope

Generally, plain land surfaces have low runoff than moderate and high elevated points (Fig. 3g); whereas, it varies from 0 to 0.4% (Fig. 3g). An area with a flat slope will infiltrate > 1 with a steep slope or 1 with a moderately steep slope.

Soil texture

Land water uses the voids in soil to penetrate to reach the aquifer. The fundamental aspect in determining potential groundwater zones is the soil. Therefore, many technologies and techniques, such as remote sensing, GIS, and AHP, are used in groundwater research (Rajesh et al. 2021). The average size of solid particles in the soil, such as sand, silt, and clay, has been used to build soil type maps (Pande et al. 2021). The soil has high infiltration rates assigned high weights that why sand, gravel, and boulders receive a higher weightage (Fig. 3h).

Geomorphology

The science of geomorphology is a study of how landforms are created, altered, configured, and related to underlying structures by using satellite images. Based on satellite images, landforms are categorized into geomorphic units/landforms. Geomorphology gives us an obvious picture of the environment definition and classification of topography using SOI topographic maps (Moharir et al. 2020) (Fig. 3i). The morphology of land surface topography is reflected by the curve of peak slopes, which is an important characteristic for detecting prospective groundwater fields, and assessing water hydrology (Pande et al. 2021). Most of the study area falls in the plain region and only a minor fall in the hilly area.

Land use and land cover (LULC)

LULC maps were developed by classifying the raster datasets for different years (2000, 2010, and 2020) as shown in Fig. 4. Five classes were made according to land use type for different past years. Figure 4a–c shows that the area exhibits very good groundwater potential zones. LULC comparisons for the years 2000, 2010, and 2020 are shown in Table 8.

Groundwater depth

A groundwater depth analysis is the most significant aspect of defining potential groundwater areas. During monsoon season, groundwater depth is measured; it serves as a valuable tool in determining safe groundwater boundaries. Inverse distance weighted (IDW) interpolation was used to create groundwater depth, which ranges between 4.5 and 14 m (Fig. 5).

Groundwater calculation

Groundwater recharge areas in the field of study were delineated using weighted overlay methods and categorized into five types: very poor to very good possible groundwater zones. In order to reduce grid marking on the map, the ArcGIS system was used as a standard fit. The groundwater map depends on several parameters, including soil texture, DEM, flow direction, geomorphology, hill shade, slope, and groundwater depth. The AHP and MIF techniques were employed for the potential groundwater areas map to categorize the potential groundwater areas as very poor to very good (Fig. 6).

Discussions

Several studies have emphasized the dangers of groundwater reduction associated with access to groundwater for agricultural use (Chindarkar and Grafton 2019). In the current study, ten observations of groundwater levels have been covered on the groundwater potential area map (Fig. 6 and Table 8). Saranya and Saravanan (2020) studied the Kanchipuram District of India using AHP and GIS techniques. They reported that the AHP, MIF, and remote sensing techniques proved 86% and 80% correct for groundwater potential zones mapping, indicating the study's reliability. An analysis of groundwater prospects was carried out using observatory well data with AHF and MIF and finding out the coefficient of determination (R^2) by linear regression curves (Fig. 7).

A linear regression model observed wells data with AHF and MIF shows that every idea on the arc corresponds to a threshold referring to the sensitivity pair. An area under curve (AUC) value ranging from 0.6 to 0.7, 0.7 to 0.8, 0.8 to 0.9, and 0.9 to 1 indicates good forecasting accuracy, respectively (Ajay Kumar et al. 2020). On the linear regression curve of the potential areas, the validation of outcomes for good prediction was 0.52 (Fig. 7).

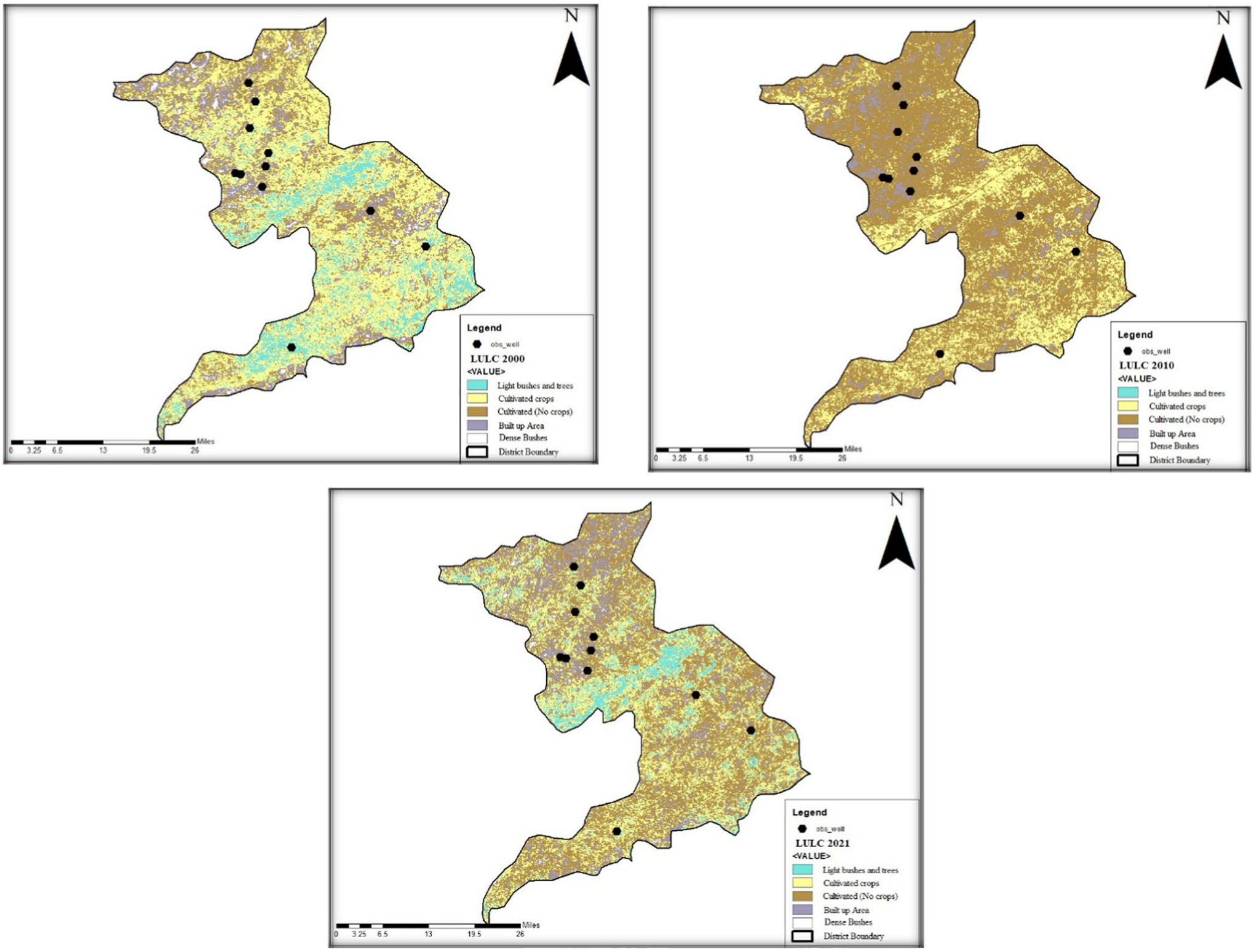


Fig. 4 LULC pattern map for the years 2000(**a**), 2010(**b**), and 2021(**c**)

Table 8 LULC comparison for the years 2000, 2010 and 2020

SR #	Year	Percentage (%)					
		Light bushes	Cultivated crops	No crops	Built-up area	Dense bushes	Total area
1	2000	10	55	20	10	5	100
2	2010	5	40	25	25	5	100
3	2021	2.5	20	40	35	2.5	100

The correlation between observed and estimated data refers to the degree of association or similarity between the actual (observed) values and those predicted by a model or estimation method. It indicates how well the estimated values align with the actual values. The validation of the results demonstrated a reasonable correlation with the linear regression model. Specifically, the linear regression model achieved an accuracy of 0.86 when utilizing the analytic hierarchy process (AHP) and multiple influence function (MIF) procedures proposed by Bhanja et al., in 2019. This suggests that the linear regression model, when incorporating these procedures, exhibited a strong correlation with the observed data or target variable. Other factors, such as the quality and representativeness of the data, model assumptions, and potential sources of error, should also be considered when evaluating the model's performance.

Water resources in basin areas can be extracted using this information by drilling new wells in the appropriate locations. More accurate results may be obtained by considering parameters like hydrogeology and landform maps (landforms and water levels). Groundwater use, water management, water withdrawal restrictions, advanced water

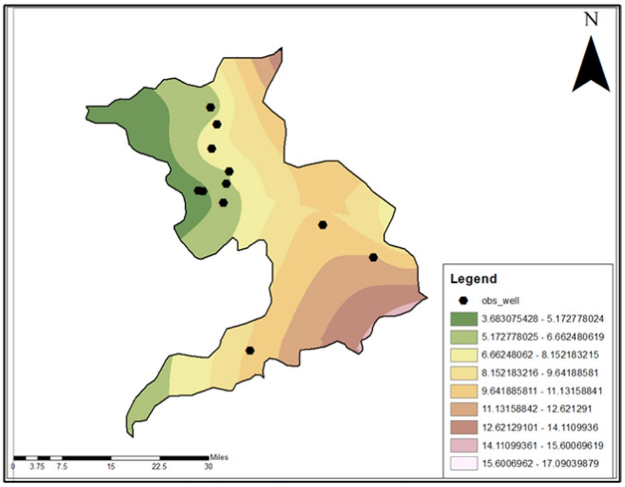


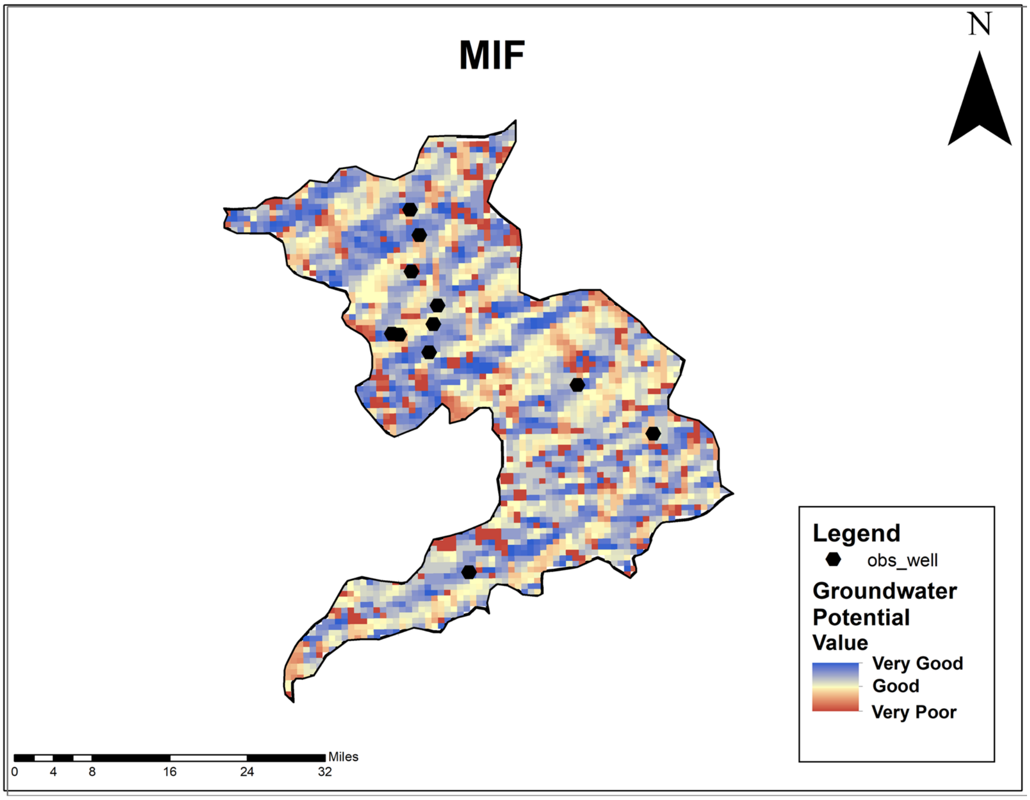
Fig. 5 Groundwater depth (meter) map of the study area

structures, water resource awareness, and preserving domestic and industrial water are key sustainability factors.

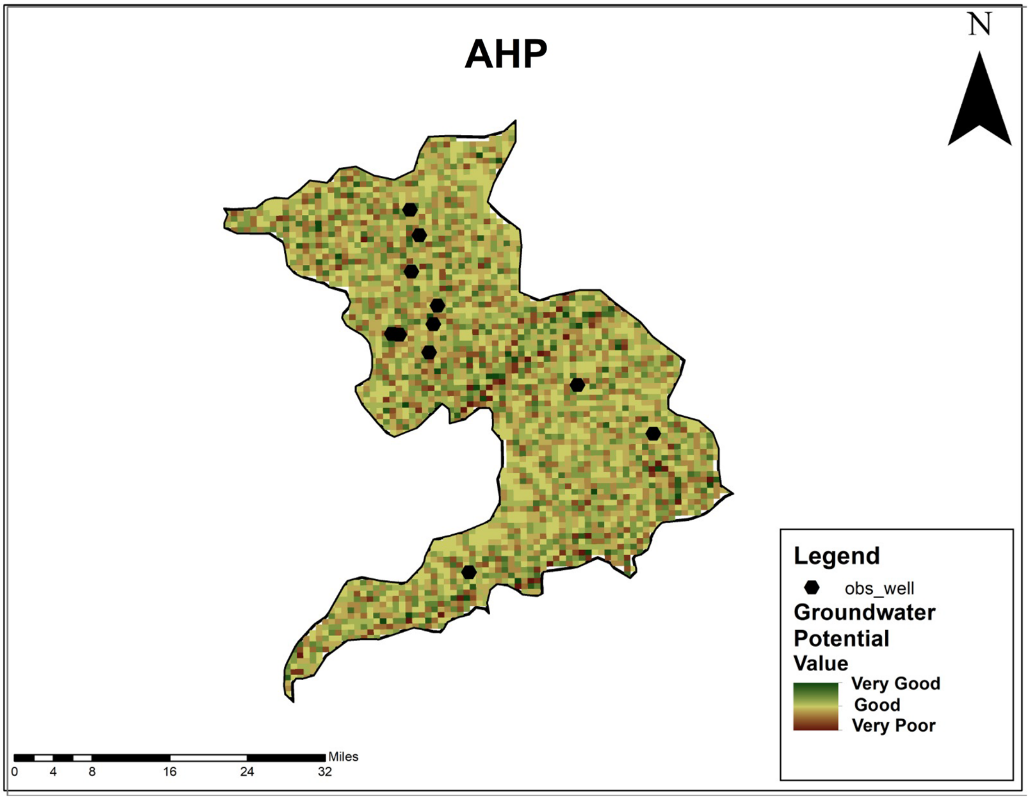
AHP and MIF could also suppress persuasive errors; therefore, this study proposes feasible plans for the entire basin with a good aquifers zone (Fig. 5). While these factors in inspection techniques and estimates affect the results, the results of the analytic hierarchy process are accurate and scientific. It will help strengthen groundwater management within the study area.

Conclusions

The study area covers a total extent of 157 square kilometers. The basin has a high probability of containing groundwater resources. The assessment indicates that MIF produced more favorable results in terms of groundwater potential compared to AHP. The paper discusses and correlates the two techniques (MIF and AHP) to determine which one is more effective in identifying potential groundwater zones in the basin. According to the cross-validation results, AHP is considered moderately effective with an accuracy of 0.5, while MIF is found to be the most accurate at 0.86 for defining potential groundwater zones. The study emphasizes the importance of managing groundwater sustainably for long-term community, economic, and ecological sustainability in the study area. It suggests that groundwater management plans should consider aspects such as rainwater harvesting, soil erosion control, and crop cultivation to ensure the responsible and efficient use of groundwater resources. The integrated approach utilizing GIS, MIF, and AHP, along with observatory well data, allows for a comprehensive assessment of groundwater potential in the basin. The study compares and evaluates the effectiveness of MIF and AHP, with MIF identified as the more accurate method for delineating potential groundwater zones. AHP and MIF approach is utilized in the study to identify possible groundwater zones in a study area. This data is useful for decision-makers and administrative employees who must manage groundwater resources in order to fulfill current and future needs. They may make educated judgments on how to regulate and allocate groundwater resources by using the results of this research. Overall, the study contributes to understanding of groundwater management strategies and emphasizes the importance of correct delineation for sustainable resource management for the future practices.



(a)



(b)

Fig. 6 **a** Groundwater maps calibrated from MIF technique, **b** groundwater maps calibrated from AHP technique

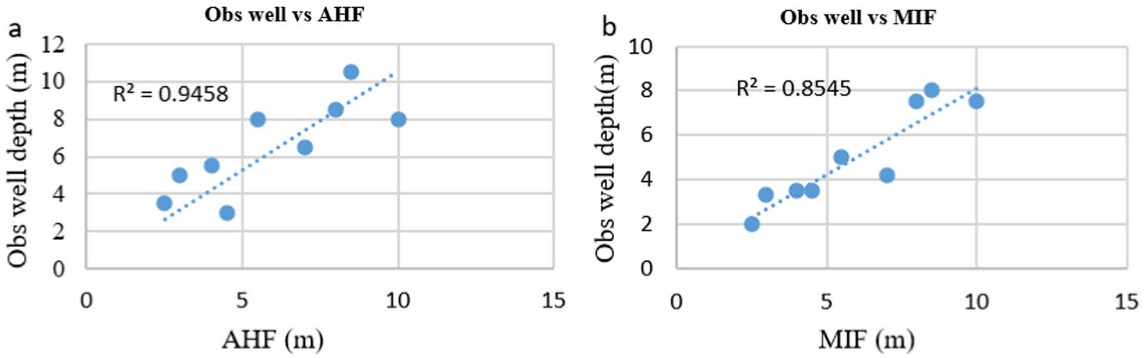


Fig. 7 Linear equation curve for validation MIF and AHP

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Authors and Affiliations

Muhsan Ehsan[1,2] · Haider Shabbir[1] · Ayad M. Fadhil Al-Quraishi[3] · Nadhir Al-Ansari[4] · Zulfiqar Ahmad[5] · Kamal Abdelrahman[6] · Muhammad Tayyab Sohail[7,8] · Zaira Manzoor[9] · Ahsan Shafi[10,11] · Ahmed Elbeltagi[12]

✉ Nadhir Al-Ansari
nadhir.alansari@ltu.se

[1] School of Geosciences and Info-Physics, Central South University, Changsha 410083, China

[2] Department of Earth and Environmental Sciences, Bahria University Islamabad, Islamabad, Pakistan

[3] Petroleum and Mining Engineering Department, Tishk International University, Erbil, Kurdistan Region 44001, Iraq

[4] Civil, Environmental and Natural Resources Engineering, Lulea University of Technology, 97187 Lulea, Sweden

[5] Director ORIC, University of Wah, Wah Cantt, Pakistan

[6] Department of Geology and Geophysics, College of Science, King Saud University, P.O. Box 2455, 11451 Riyadh, Saudi Arabia

[7] School of Public Administration, Xiangtan University, Xiangtan, Hunan, China

[8] Centre for Sustainable Energy and Economic Development, Gulf University for Science and Technology, West Mishref, Kuwait

[9] Department of Govt and Public Policy (GPP), Faculty of Contemporary Studies, National Defence University (NDU), Islamabad, Pakistan

[10] School of Public Administration, China University of Geosciences, Wuhan, Hubei Province, China

[11] School of Government, Yunnan University Kunming, Kunming 650500, China

[12] Agricultural Engineering Department, Faculty of Agriculture, Mansoura University, Mansoura 35516, Egypt