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GIS-based multi-criteria groundwater potential zone mapping using the AHP in water stressed area Chaj Doab, Pakistan

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Abstract

Groundwater is an important fresh water resource, which is readily available to humans on earth. Its depletion due to natural and anthropogenic reasons is a critical concern for regional development, prosperity and policy making particularly where an ancient civilization and major population exist. Accurate delineation of groundwater potential zones is a key factor for sustainable groundwater management, long-term conservation of aquifer resources and recharge planning. This study adopted Geographic information system (GIS), remote sensing, and field data to map Groundwater Potential (GWP) in the Chaj doab, a rapidly urbanizing and strategically important region located adjacent to Punjab's industrial triangle, making it an ideal case study for groundwater potential assessment. Groundwater occurrence and its movement is dependent on various physical and geomorphological parameters such as soil, rainfall, land use, geomorphology, drainage density, lineament density, and slope. A Multi-Criteria Decision Making (MCDM) based on Analytical Hierarchy Process (AHP) in the GIS environment was applied for weight determination of corresponding thematic layers and groundwater potential zones identification, classification and mapping. The result expressed very high potential zone comprises 8.2% (1635.17 km^2), high 24.6% (4917.7 km^2), moderate 31.8% (6351.5 km^2), low 19.9% (3982.4 km^2) and 15.2% (3049.8 km^2) very low, respectively. Furthermore, this research study findings contribute to the scientific insights on groundwater dynamics in water depleting areas. The results show the efficiency of GIS, RS and AHP in examining the groundwater prospects and provide key tools for local and regional water resource management.

Keywords: Analytical Hierarchy Process, GIS, groundwater potential, multi-criteria decision making, overlay analysis

Introduction

Groundwater is an essential part of life on earth. It is one of the sources of freshwater which is readily available to mankind (Kumar & Yaashikaa, 2019). Due to rapid population growth and agriculture expansion in this area the demand for water is increasing at an alarming rate which has exerted a pressure on groundwater which causes over exploitation and deterioration in water quality (Shan et al., 2020). In Pakistan the major demand of water for agriculture, commercial and domestic use is fulfilled by groundwater sources due to which the water table is being declined 2-3 m annually (Qureshi, 2020). Particularly, a lot of area of Punjab province, Pakistan is under cultivation and water for irrigation is extracted from groundwater commonly from the dug wells and tube wells (Rana et al., 2024). The installed tube-wells numbers have been increased from 100,000 in 1975 to 800.000 in 2014 (Razzaq et al., 2022). Moreover, the illegal drilling of bore-wells causes the unsustainability of water resources (Javed et al., 2024). The acquirers are unconfined in nature, therefore the increasing population, urbanization, climate change and other human activities are serious environmental risk put significant threats on regional development and natural resources (Davies, 2016). Therefore, a comprehensive assessment of groundwater potential is needed for its sustainable management and natural resource conservation in the area. There are multiple conventional methods to delineate the groundwater potential zones within the study area like drilling (Raza et al., 2024), geological, geophysical and other hydrogeological (Díaz-Alcaide & Martínez-Santos, 2019). The major cons of these conventional methods are the time consumption and high cost as estimated by (ullah et al., 2024). Therefore, there is a dire need to develop an approach on Groundwater potential delineation which provides valuable insights to the resource managers to ensure optimal consumption and better management plans (Díaz-Alcaide & Martínez-Santos, 2019).

In the past decades water resource managers are gaining insights to identify the groundwater recharge zones by integrating remote sensing data with conventional survey mapping (Sheffield et al., 2018). This technique enables wide-scale spatiotemporal observations and facilitates in the identification of various surface features such as lineaments, geomorphology, soil, rainfall, drainage patterns, and lithology (Roy & Chintalacheruvu, 2024) and (Haider et al., 2026). In this study the parameters were utilized to prepare the thematic layers which were subjected to weighted index overlay for developing groundwater potential mapping in the research area (Abdekareem et al., 2022). Moreover, there are many other statistical techniques integrated with RS and GIS being utilized by researchers to delineate groundwater potential zone maps like Frequency Ratio (FR) and logistic Regression (LR), Multi-Influencing Factor (MIF) techniques, Fuzzy logic approach, Evidential Belief Function (EBF) (Khan et al., 2021) and (Aslam et al., 2022). However, the incorporation of such techniques is limited to the areas which have vast databases. From the past studies such as (Aslam et al., 2021) and (Ashraf & Ahmad, 2008), it has been noticed that Multi Criteria Decision Making (MCDM) based on Analytical Hierarchy Process (AHP) is useful statistical techniques for the Groundwater Water Potential (GWP) assessment due to its assembly, pellucidity, and objectivity in decision making for regional development (Saravanan et al., 2021).

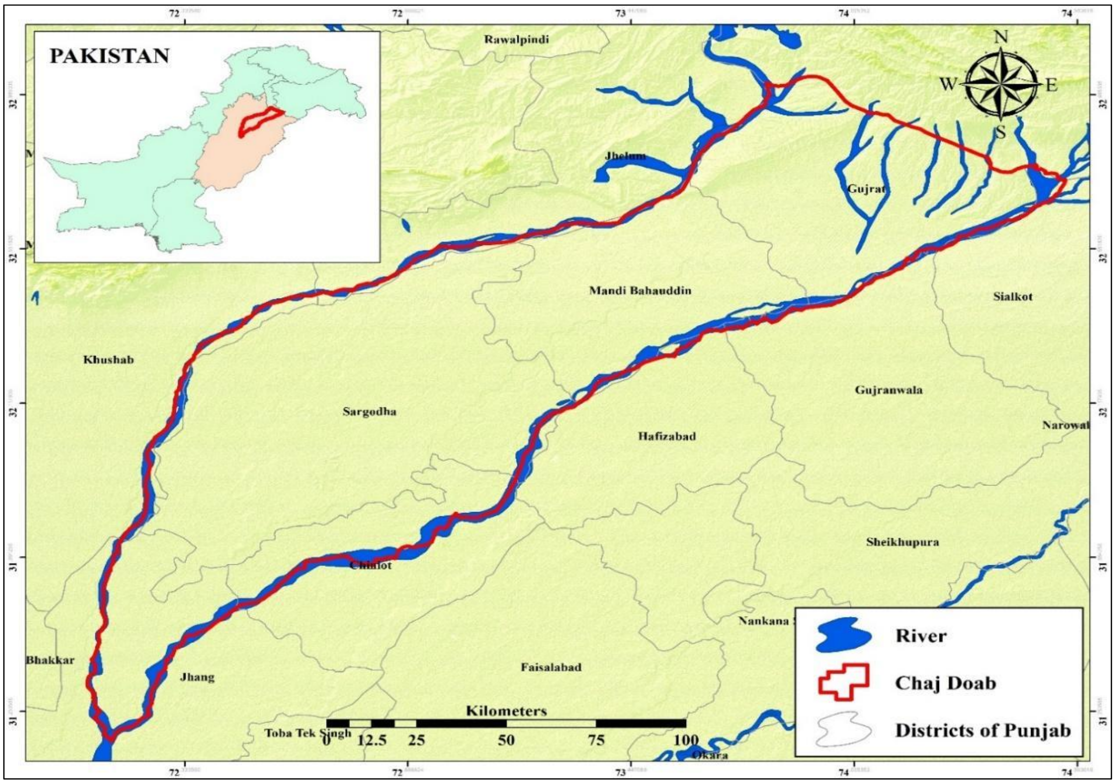
Consequently, this research provides a comprehensive approach in the area particularly where an ancient civilization exists to study the delineate groundwater potential zones by integrating the hydrogeological, geomorphological, and climatic data coupled with MCDM based AHP, GIS, and RS techniques. The most important and unique aspect of the study is use of field observations compared to the past studies, additionally, the research integrated the hydrological and geological data for ground water assessment in the region. This area is a rapidly urbanizing and strategically important region located adjacent to Punjab's industrial triangle, making it an ideal case study for groundwater potential assessment. The outcomes of this research show the geological morphology, climatic patterns, and hydrology of the study area to ensure the optimal and sustainable water management and conservation for this vital resource from nature. The outcomes will help the policy makers and water managers for agricultural zones mapping, urban water management which is a key role for regional development and prosperity.

Materials and methods

Study area

The study area Chaj Doab is located between longitudes 72°20′E and 73°30′E and latitudes 32°00′N and 33°00′N′ (Sikandar et al., 2010) with the aerial spread of 19933.78 km^2 shown in Figure 1. As an interfluvial region the region has Unconfined alluvial aquifers in extended area suitable for agriculture, whereas Semi-confined aquifers occurred locally while deep confined aquifers present in some parts of the doab, beneath thick clay horizons. Additionally, extensive use of private tubewells, insufficient canal supply, cropping intensity which exceeded the capacity of irrigation system design in the area are the major causes of groundwater abstraction. In the area the groundwater salinity is spatially variable across the region it is varied Upper and central areas to lower reaches. The major causes of salinity issues include lateral intrusion of saline groundwater, evaporation rate over the entire region in water bodies, lateral intrusion of ground water and poor irrigation system.

Chaj Doab is characterized by its proximity to the Chenab and Jhelum rivers, which form its boundaries. This doab covers Gujrat District, Bhimber District, Mirpur District, Mandi Bahauddin District, Sargodha District, Lalian Tehsil of Chiniot District and some areas of Jhang District. The area is renowned for its extensive canal network comprising distributaries and minors, providing irrigation for agricultural purposes (Aslam et al., 2022). The mean annual temperature in Chaj Doab is 24°C, with the average maximum reaching 31°C and the average minimum dropping to 18°C (Aslam et al., 2021). The major crops grown are wheat, rice, sugarcane, fodder and citrus.



Source: Adopted from Survey of Pakistan

Figure 1. Map of study area Chaj doab, Pakistan

Methodology

Multiple types of dataset are acquired to prepare the thematic layers ranging from remote sensing data, conventional data from published maps, and ground observations as shown in Table 1. The thematic layers were produced to address the GWP based on the expert opinions and previous literature.

Table 1. Groundwater assessment parameters, sources and processing

Parameter	Data source	Processing
Slope	SRTM- Digital Elevation Model (DEM) 30 × 30 M resolution	Slope extracted from DEM in degree
Soil	Food and Agriculture Organization	Extracted from the world soil database in ArcGIS 10.8.1
Lineament density	SRTM- Digital Elevation Model (DEM) 30 × 30 M resolution	Develop from line density from spatial analyst tool in ArcGIS 10.8.1
Drainage density	SRTM- Digital Elevation Model (DEM) 30 × 30 M resolution	Created stream density from spatial analyst tool in ArcGIS 10.8.1
Rainfall	Pakistan Meteorological Department	Interpolation applied on the Rainfall values using IDW technique
Geomorphology	Geological Survey of Pakistan	Georeferenced and converted to raster of 30m from the Map
Land use land cover	ESRI live Atlas	Extracted from the database by using ArcGIS 10.8.1

Thematic layers preparation relevant to GWP

Multiple parameters influence the GWP, and the selections of these parameters depend upon the research area morphological characteristics. Seven parameters namely Land use land cover (LULC), drainage density, lineament density, geomorphology, soil, rainfall, and slope were selected which were most suitable for the study area mainly based on morphological characteristics, the expert opinion, existing literature and availability of data (Mohammednur et al., 2024). LULC data was derived from the ESRI live atlas at a spatial resolution of 10m (https://livingatlas.arcgis.com/landcover/). The nine LULC classes were prepared after reclassifying the land-use classes according to the code assigned by the ESRI like 1 for water body, 2 for trees, 7 for built up area, 8 for bare ground etc. Rainfall is another important factor related to GWP (Ayalew, 2020). The annual rainfall data for 2014-2023 from four stations of study area was acquired from the different gauge stations (Earman & Dettinger, 2011) working under Pakistan Meteorology Department (PMD). After preprocessing the data, an annual rainfall map was prepared by using Inverse Distance Weightage (IDW) interpolation technique in ArcGIS (Rahman et al., 2022). Inverse Distance Weighting (IDW) methods were used for rainfall interpolation to generate a continuous rainfall surface. In ArcGIS 10.8 the data preprocessing and data checking, the Inverse Distance Weighted (IDW) interpolation method at cell size 30 of 30m, were used to generate rainfall distribution maps restricted to the study area boundary. Additionally, Cross-validation techniques were used for accuracy of the rainfall interpolation.

The second parameter of GWP, the lineament density was prepared by the processing of SRTM DEM of 30m resolution by using line density option available in spatial analyst tool in ArcGIS 10.8. (EL-Omairi et al., 2024). The map is classified into five categories as very low, low, moderate, high, and very high. The drainage density map was prepared by using a line density tool in ArcGIS on the DEM data of 30m resolution acquired from Shuttle Radar Topographic Mission (SRTM) (Oyedotun, 2022). The prepared map was reclassified using the natural break algorithm into five classes including very low, low, moderate, high, and very high (Hong et al., 2018). The slope map of Chaj doab was obtained by the processing of SRTM DEM of 30m resolution and classified into five categories as shown in figure 3e. The natural break classification enables us to identify real classes within the dataset. The soil map was developed by using data collected from the Food and Agriculture Organization (FAO) (http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/en/). There are three main classes of soil texture available for the study area namely loam, clay loam, and sandy loam. The geomorphology map was prepared from the existing map (available at https://gsp.gov.pk/gsp-publication-products/). The map was georeferenced and digitized by using ArcGIS 10.8. There are three types of landforms available namely old river terraces, recent flood plain, and sub-crecent flood plains.

Multi-Criteria Decision Making

It is a decision making process used to evaluate and choose among various alternatives (Miettinen, 2014). Multi-Criteria Decision Making (MDCM) is a technique which is applied in multiple areas such as engineering, healthcare, environmental planning, and hydrology in order to support complex decision making processes (Mardani et al., 2017). The purpose of these methods is the provision of a compromise or optimal solution which is best fitted with the problem (Tan et al., 2021).

Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP) is a MCDM technique developed by Thomas. Saaty in the 1970s. AHP is used in multiple fields like business, engineering, and project management (George et al., 2022). It offers a structured approach to assess and rank multiple criteria and alternatives in a decision-making process. AHP is generally broken down complex decision into a hierarchical order by assigning standardized weights (Albayrak & Erensal, 2004; Chaudhry et al., 2021). And enable decision makers to systematically compare and rank the decisions according to their importance.

For AHP technique the study applies standardized weights assigned to each thematic layer for various environmental and geological conditions based on the experts opinions and published data by using mixed methods approaches as done by (Qi et al., 2022). Due to local geological characteristics, climatic conditions of the study area, expert knowledge, previous studies associated with the assessment of ground water potential, and data availability seven different layers were selected. The following steps were followed to assign and standardize weigh to each thematic layer by adopting AHP technique by (Bouamrane et al., 2022) (1) defining objectives, (2) assigning weight to each variable based on past literature and expert opinion, (3) develop comparison metrics pairwise, (4) compute the geometric mean, (5) compute the normalized weights, and (6) consistency ratio calculation to validate coherence of judgment. The recommended scale values were used to develop the AHP pairwise metric (P) developed by Eq.1

$$p = \{p11 \quad p12 \ \cdots \ pn\, p21 \quad p22 \ \cdots \ p2n \ \vdots \quad \vdots \quad \ddots \quad \vdots \ p1n \quad pnn \quad \text{Eq.......1}$$

Source: Adopted from Dutta et al., 2024

The normalized weights (w_n) computed by using Eq.2.

$$w_n = \left(\frac{GM_n}{\sum_{n-1}^{Nf} \quad GM_n}\right) \qquad \text{Eq..........2}$$

Source: Adopted from Dutta et al., 2024

Geometric mean of nth row element were presented by GM where they were computed by using following Eq.3.

$$\square\square_{\square} = \sqrt{\square_{1\square}\square_{2\square} \dots\dots\dots..\square_{\square\square\square}}$$

Source: Adopted from Cogswell et al., 2018

The normalized weights were based on consistency ratio (CR) calculations by using Eq.4.

$$\square\square = \frac{\square\square}{\square\square}$$

Source: Adopted from Zhang, 2017

In the above equation CI is the consistency ratio with the value (0.132) and RI (1.32) is the random consistency index. The RI value depends on many factors and was taken from previous literature. While CI was computed by using Eq. 5.

$$CI = \frac{\gamma_{max} - n}{n}$$

Source: Adopted from Yuen, 2024

N with the value 7 is the number of thematic layers and γ_{max} (7.792) is the eigenvalue of the matrix. CR (0.10) is equal to 0.1 as this is a recommended value for mapping. Table 2. shows the normalized AHP weights for different thematic layers. To evaluate the consistency of the AHP, the Random Index (RI), Consistency Ratio (CR) and Consistency Index (CI)were used as a pairwise comparison matrix. The values calculated for each index were CI = 0.132, RI = 1.32, and CR = 0.1, whereas the principal eigenvalue (λmax) is 7.792.

a. Overlay analysis

For overlay analysis the relative weights of seven thematic layers were derived after applying the AHP as given in Table 2. The weight value of each thematic layer is corresponding to the highest or lowest weight which is applied according to their importance and field conditions (Pinto et al., 2017). Moreover, the consistency ratio for each thematic layer was computed and assigned by summarizing the normalized and assigned weights for the distinctive features of each map. These seven prepared layers were integrated by using GIS and the generated map reflected the groundwater potential map of Chaj doab. According to the boundary of the study area, the spatial extent of all raster datasets was clipped. All dataset were processed through ArcMap 10.8 with 30 m resolution after converting into raster format in layers at WGS 1984 projection system.

Validation of groundwater potential

The current status of groundwater within the study area is assessed from the groundwater depth, as there is a significant link between groundwater depth and groundwater potential zones (Ahmed et al., 2021). Both these factors are interconnected components of groundwater availability and usability. In this research the groundwater depth is utilized to validate the identified groundwater potential zones. The groundwater depth map was acquired from an online source (https://irrigation.punjab.gov.pk/). The download map was georeferenced; digitized to make it compatible for further analysis by using ArcGIS 10.8.

Results

The results of the study are diverse in nature including climatic, geological, and geomorphological and land use maps zones. Following table 2 provides a snapshot of the percentage of area occupied by groundwater potential classes in the area under examination.

Table 2. Area occupied by groundwater potential classes

GWP	Area (SqKm)	Percentage
Very low	3,049.842	15.30
Low	3,982.43	19.98
Moderate	6,351.5	31.86
High	4,914.77	24.66
Very high	1,635.18	8.20
Grand total	**19,933.79**	**100**

Afterwards the first parameter is land use and land cover (LULC). The LULC map (Figure 2a) provide the information regarding the surface water, infiltration, moisture and groundwater potential. The study area shows seven different LULC categories: crops, water, trees, rangeland, flooded vegetation, built-up area, and bare ground.

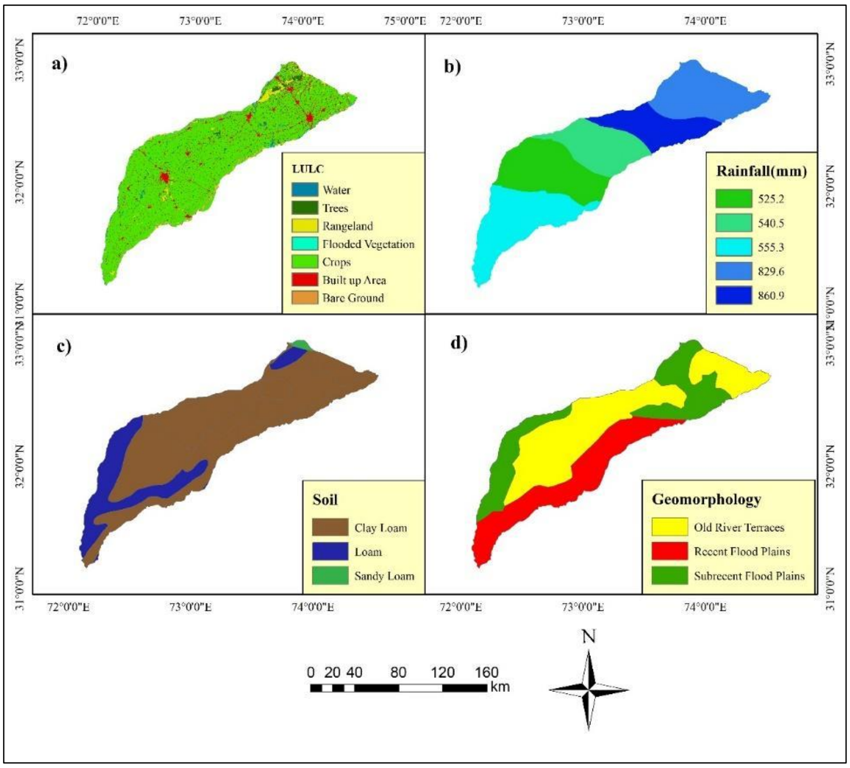


Figure 2. Map showing (a) LULC, (b) Rainfall, (c) Soil, (d) Geomorphology

Majority of the study area is covered with crops (11965.8 km^2), followed by rangeland (446.4 km^2), trees (175.6 km^2), water body (321.9 km^2), whereas builtup area 8.5% (1217.6 km^2) is covered by rural and urban settlements. The builtup area/settlements causes impervious surface, increase surface runoff, and reduces infiltration capacity of the water and prevent the water to recharge the groundwater table whereas the land covered with crops, tress/forest, and water allow the high infiltration and moderate the runoff capacity of the surface water and recharge the groundwater. Due to the high recharge capacity of the land covered with crops, trees, water bodies are given high weightage and rank as compared to the built-up area. The intensity, spatial and distribution of the rainfall parameter has a dominant influencing factor which affects the groundwater recharge potential. It controls the quantity of water which will penetrate ground and ultimately, into the groundwater system. Groundwater potential high among the areas receives high precipitation during the year. The higher the rainfall the higher the natural groundwater recharge. The average annual rainfall varies within the study area from 860.9 to 525.2 ml/year. The Gujrat district received maximum and Jhang district on the other hand received minimum rainfall within the study area. The groundwater recharge and potential are very much influenced by the intensity and the duration of the rainfall. The rainfall with high intensity and low duration has less effect on the groundwater as compared to the low intensity and long duration rainfall as shown in Figure 2b.

Soil is also a determining parameter of groundwater potential because it is directly related to the surface water infiltration rate and water retention. Different soil categories have different ability to absorb and transmit water and water potential. There are three types of soil texture (Figure 2c) in Chaj doab region namely loam, clay loam, and sandy loam. Sandy loam soil has high porosity and permeability which means it allows the surface to reach the ground water and is good for groundwater. Loam soil is also good for groundwater potential. On the other hand, the clay loam soil has low porosity and permeability. It does not readily allow the surface water to infiltrate and recharge groundwater and has low groundwater potential.

Slope is also a significant contributing parameter in the assessment of groundwater potential zones. Slopes control the movement of surface water, percolation, and the accumulation of water in an area. Slope (Figure 3e) generally measured in degrees steep slope gradient enhances the surface water runoff and does not provide enough time to water to percolate under the surface. Steep slope is linked with low groundwater recharge and poor groundwater potential. On the other hand, the gentle slope offers enough time to the water to percolate down the ground and recharge the groundwater. The areas with gentle slope are more likely to have better groundwater potential. Slope is also classified into five categories e.g. 0 to 2 degree slope is considered as gentle slope and is very good for the groundwater infiltration as shown in Figure 3c. The region where the slope is 2 to 4 degrees is considered a good class. Whereas the areas with slope more than 5 degree were considered as very poor to groundwater potential.

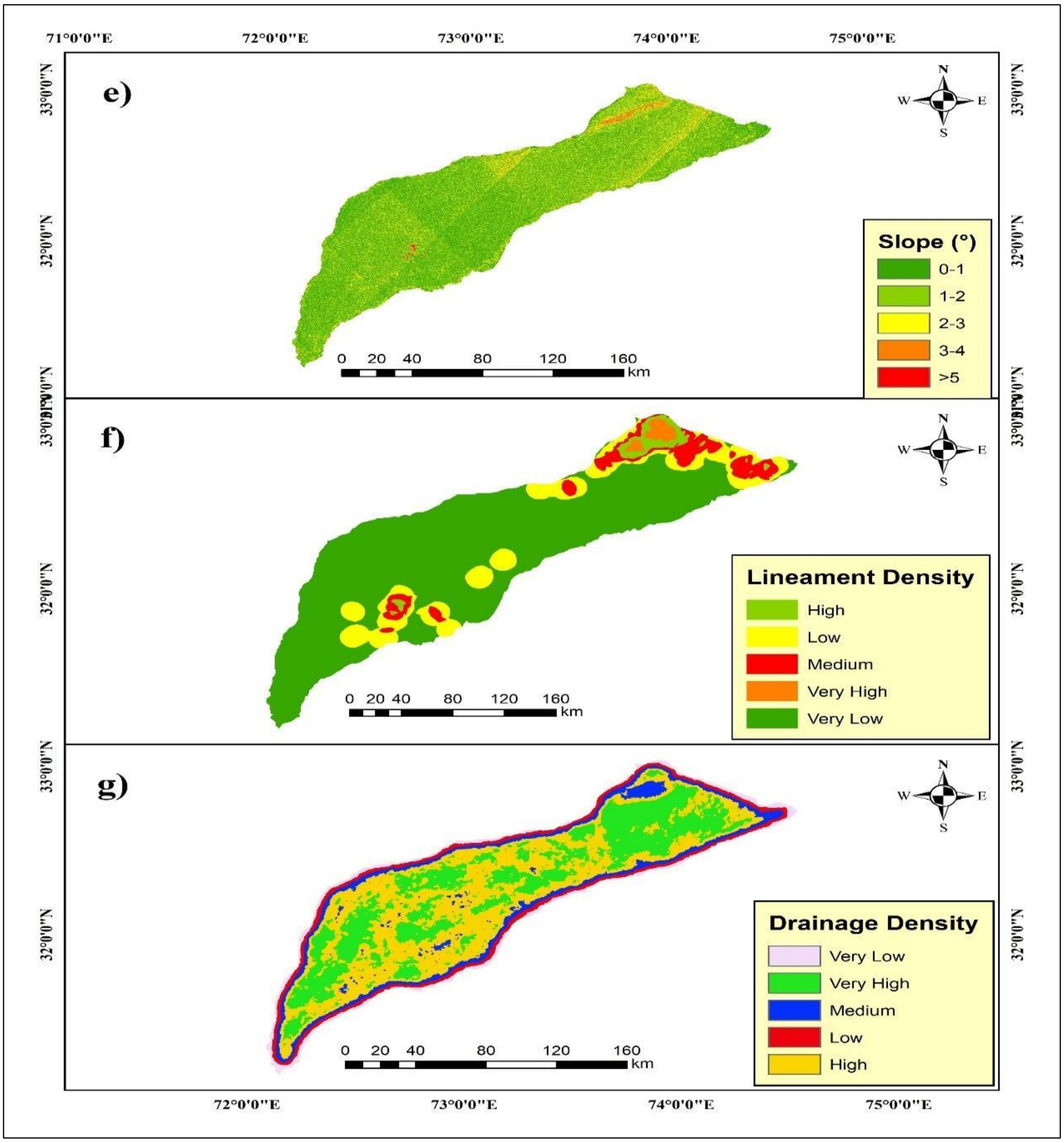


Figure 3. Map showing (e) Slope, (f) Lineament density, (g) Drainage density

Low drainage density exists around the Jhelum and Chenab rivers belts. Whereas high density is seen in plain regions of the districts. Lineament density is another important parameter which plays a significant role in the assessment of groundwater potential. Lineament density is the concentration of linear fractures and faults present within the geological structures. Lineament generally regulates the groundwater movement and storage in hard terrains or in the areas, which has limited porosity. Lineament density has a direct relationship with groundwater potential. High lineament density indicates a greater concentration of geological features like fractures and faults, which mean more groundwater flow, recharge and groundwater potential, whereas low lineament density means low groundwater flow, recharge, and low groundwater potential. The lineament density map (Figure 3f) is classified into five classes such as very low, low, moderate, high, and very high.

The drainage density is another important parameter to assess the groundwater potential zones as it shows the hydrological characteristics of the area and influences the groundwater recharge and availability. However, drainage density is inversely related with the groundwater potential. Higher drainage density results in lower infiltration and higher runoff whereas the lower drainage density increases the infiltration and lower runoff, which result in favorable groundwater zone development. Five drainage density regions were demarcated in the Chaj doab namely very low, low, moderate, high and very high as shown in Figure 3g.

The geomorphology map (Figure 2d) indicates the three distinct classes such as old river terraces, recent flood plain, and sub-recent flood plain, each class play a role in groundwater potential. The old river terraces are heighted areas generally formed by the past river activity. This area is characterized by well-consolidated sediments like permeable gravel and sand layers, which serve as aquifers. The old river terraces experience significant weathering and have moderate groundwater potential. Whereas, recent flood plains are low lying areas, which generally exist adjacent to the active river channel and face frequent flooding. The flooding covered this area with alluvial deposits like silts, sands, and clays. Due to the frequent availability of water and infiltration, this area has high groundwater potential. The sub-recent floodplain is an area, which was flooded in the recent past but now less frequently inundated. This area has relatively young sediments allowing infiltration and storage. This layer often has moderate groundwater potential.

Geomorphology is also an important parameter, which controls the groundwater potential in a study area. There are seven parameters which control the groundwater potential within the study are described in detail in table 3.

Table 3. AHP weight values of multiple factors

Parameter	Sub-Categories	Rank	Weights
Slope	Very gentle (0-2)	5	0.175
	Gentle (2-3)	3	
	Moderate (3-4)	2	
	Steep (>5)	1	
Soil	Clay loam	1	0.058
	Sandy loam	5	
	Loam	3	
Lineament density	Very low	1	0.181
	Low	2	
	Moderate	3	
	High	4	
	Very high	5	
Drainage density	Very low	5	0.098
	Low	4	
	Moderate	3	
	High	2	
	Very high	1	
Rainfall	860.9	5	0.075
	829.6	4	
	555.3	3	
	540.5	2	
	525.2	1	
Geomorphology	Old river terraces	1	0.269
	Recent flood plains	5	
	Subrecent flood plain	3	
Land use/ landcover	Crops	3	0.144
	Water	5	
	Trees	4	
	Rangeland	4	
	Flooded vegetation	2	
	Built up area	1	
	Bare ground	2	

Groundwater potential zones

The groundwater map developed by using the weighted overlay analysis on the seven thematic layers prepared as explained in methodology. The resultant map (Figure 4h) shows the spatial variation in groundwater availability across the study area, classified into five categories such very good, good, moderate, low, and very low groundwater potential zones. A careful examination of the produced map reveals notable patterns of GWP within the Chaj doab, particularly in the northeastern region.

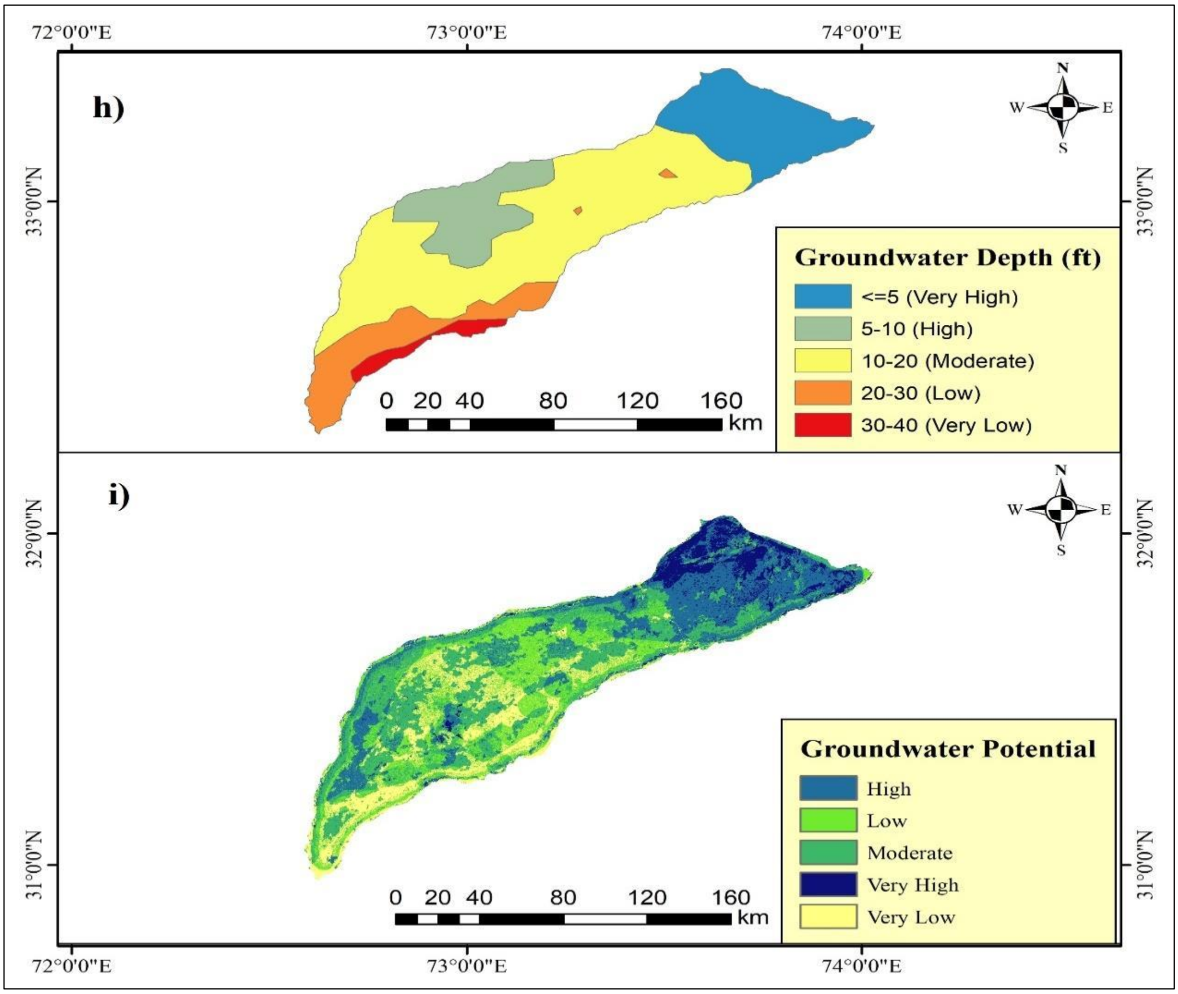


Figure 4. Groundwater (h) depth and (i) groundwater potential map

The ground water potential ranges very high and high GWP available in the northeastern part of the study covering an approximate area of 1635 (8.2%) and 4914 (24.6%) square kilometers respectively. The high GWP in this region is associated with favorable hydrogeological conditions, such as substantial rainfall, presence of forest/ trees, crops, and low built-up area, high lineament density, and presence of water bodies (Jhelum River). Moving forward to the mid-eastern and western region the moderate GWP zone dominates the region. It covers approximately 6,351 square kilometers or 31.86% of the total area as shown in Figure 4i.

This shows that a significant area of Chaj doab has reasonably accessible groundwater, providing water for agriculture, domestic, and commercial sectors. The moderate GWP is due to the existence of gentle slope, moderate rainfall, high drainage density, and presence of old river terraces geomorphology. Conversely, the southern areas of Chaj doab show very low and low GWP zones cover approximately 3049 square kilometers (15.3%) and 3982 square kilometers (19.9%), respectively. The low groundwater availability is more likely associated with the unfavorable hydrogeological conditions like average rainfall, high drainage density, low lineament density and clay loam soil texture. Such a low potential zone is very much vulnerable to water stress and sustainable management strategies to avoid resource depletion and mitigate the associated socio-economic impacts.

The spatial distribution of GWP across Chaj doab and the integrated approach of weighted overlay analysis indicate the intricate relationship exists between various parameters which influence the GWP. The high and moderate GWP show that the areas are basically well-endowed with groundwater resources. Whereas, the low and very low GWP zones demand targeted interventions like artificial techniques, water conservation measures, and sustainable water extraction techniques within the study area.

Validation of GWP

The GIS and AHP based groundwater map need actual field based data to verify the results. In this study, the computed groundwater potential zone map was validated by using groundwater depth map. There is a relationship between the groundwater depth and groundwater potential zone. The groundwater potential varies with the depth of groundwater. It is more frequent in areas where groundwater is available at low depth as compared to areas where the depth is high. The map acquired from the Punjab irrigation department shows the groundwater depth differs within the study area. The map shows correlation with the groundwater potential map as the groundwater depth is high as we move from northeast to southwest. This shows the accuracy of the map. However, there is a little uncertainty in exits with the model results commonly is western areas of the map (Figure 4h).

Discussion

Groundwater potential is one of the most important indicators of any area for human existence and urban settlement in any region. Due to the rapidly growing population not only in this region the groundwater is depleting day by day even due to different natural and manmade regions. Therefore, such studies are fundamental for regional and local development. The past studies use different methods for such assessment. However, this study is based on ground evidence and geological characteristics of the area for ground water assessment. This includes climate change, varied rainfall patterns, changing landscapes and urbanization. Very high GWP zones cover northern areas mainly due to the high rainfall and vegetation land cover. Moderate zone exists in the mid-eastern and western portion due to high drainage density and gentle slope. Whereas the regions constituting low lineament density, low rainfall, and clay loam soil, fall in low and very low potential zones.

The results of the study also highlighted the pressure of human activities on ground water resources including water sustainability. High agricultural abstraction and dense tube well networks rapidly deplete groundwater due to instability in groundwater recharge and its excess use by water extraction. The rate of rainfall to recharge the groundwater table is comparatively low as compared to water usage, which creates a disable between water recharge and water use. On the other hand, climate change has significantly altered the rainfall intensity and seasonal distribution, which ultimately reduced the groundwater potential. The impervious surfaces increased by settlement, urbanization and land-use changes further reduced the groundwater recharge.

Lastly, this research identified high and low potential water zones in highly urbanized and agricultural rich area. These results can be prioritized for future groundwater development, policy making for different water storage strategies like rainwater harvesting, artificial recharge and irrigation efficiency in the region to ensure regional development and sustainability.

Conclusion

In conclusion, this research study employs the integration of remote sensing and GIS techniques to assess the groundwater potential zones in Chaj doab, one of the most rapidly growing urban regions of Pakistan. Based on local morphological characteristics, a total seven thematic layers were produced after assigning weights, ranked according to Saaty's Analytical Hierarchy Process and weighted overlay analysis. Every area over the globe has different climatic conditions, geomorphology and geological characteristics; Therefore, it is very difficult to assign the weight to every indicator in AHP methods. However, after very careful review of the past research and experts' discussion these limitations were overcome. The results show the reliability of the integrated approach, intriguing patterns within the region. The outcomes provide valuable information for informed decision-making, sustainable resource management, and overall socioeconomic development.

This research provides an integrated approach by using different groundwater assessment related parameters like drainage density, LULC, lineament density, slope, and geomorphology, rainfall, and soil texture equipped with GIS techniques to tackle the groundwater related issues within the study area. The management strategies particularly in low potential areas involve adoption of efficient irrigation techniques, water conservation measures such as crops rotation in agriculture, Artificial groundwater recharge structures to recharge the wells and groundwater tables, and rainwater harvesting systems are important strategies to overcome the issues. The finding of this research enables the water management authorities to make sure the accessibility to safe water for achieving the United Nation Sustainable Development Goal (SDGs 6).

Competing interest

The authors declared that they have no competing interest.

Author contribution

The corresponding and first author Shajee Mehdi, was responsible for data collection, processing, and the manuscript write-up. The co-author, Muhammad Miandad, performed the data analysis for this research. Both authors contributed to the overall development and finalization of the paper.

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