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Mapping Groundwater Potential Zones in Quetta Region, Balochistan, Pakistan using Geospatial Techniques

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ABSTRACT

Groundwater is a critical natural resource with significant implications for a region's socioeconomic, ecological, and environmental sustainability. This study was conducted in the Quetta region, where groundwater serves as the primary water source. The objective was to identify groundwater potential zones using remote sensing and GIS. Various thematic maps, including drainage density, slope, soil, lineament density, land use/land cover, and rainfall maps, were created. These maps were overlaid using the weighted overlay method through the Spatial Analysis tool in ArcGIS. During the weighted overlay analysis, each parameter in the thematic maps was ranked, and weights were assigned based on their influence: drainage density (10%), slope (10%), soil (40%), lineament density (5%), land use/land cover (25%), and rainfall (10%). The resulting map categorizes groundwater potential zones into low (4.659%), moderate (39.999%), and high (55.34%). This outcome provides valuable insights for regional water resource planning, contributing to the sustainable management of groundwater resources in Quetta. Furthermore, these approaches and findings hold significance for assessing groundwater potential in other drought-prone arid regions worldwide.

KEYWORDS: Groundwater; Remote sensing; GIS

1 INTRODUCTION

Groundwater serves as a critical source of drinking water globally, particularly in regions where rainfall is scarce [1]. It is estimated that aquifers provide drinking water for more than 30% of the global population, highlighting their essential role in water security [2]. This significance is amplified in developing countries, where access to clean water is a pressing issue, further compounded by changes in hydroclimatic conditions and socioeconomic factors [3].

In Pakistan, groundwater accounts for over 70% of the drinking water supply, catering to the needs of residential, domestic, and agricultural sectors [4]. Notably, the province of Balochistan has experienced significant declines in groundwater levels, attributed to factors such as decreased precipitation, increased temperatures, extended periods of drought, and the proliferation of tube well installations. From 1980 to 2015, the number of tube wells in Balochistan escalated from approximately 5,000 to over 40,000, causing substantial reductions in groundwater levels [5]. The Quetta region, in particular, faces acute water shortages during non-monsoon periods and is entirely dependent on groundwater resources [3]. Consequently, there is an urgent need for a comprehensive groundwater potential map for the Quetta Valley to inform water resource management strategies.

Traditional methodologies for identifying, delineating, and mapping groundwater potential zones have relied heavily on extensive ground surveys, employing geophysical, geological, and hydrogeological tools. Despite their thoroughness, these approaches are often limited by high costs and significant time investments, which are particularly challenging in settings with limited resources [6][9]. In contrast, geospatial technologies, including Remote Sensing (RS) and Geographic Information Systems (GIS), offer a more efficient and cost-effective means of collecting, producing, and modeling critical data across various geoscience domains. The integration of RS and GIS facilitates rapid assessment and analysis of both surface and subsurface earth features, thereby enhancing the exploration and management of groundwater resources [7][8].

This study leverages geospatial techniques—specifically, RS and GIS—to map and delineate groundwater potential zones effectively. These advanced technologies enable the synthesis and analysis of spatial data, identifying areas with high groundwater prospects and supporting informed decisions in water resource management. The utilization of multi-source data, encompassing satellite imagery, topographical maps, and field data, provides a robust platform for spatial analysis in groundwater studies.

It addresses a crucial gap in the literature by integrating a wide array of geospatial data sources and thematic maps shown in Table 1, including drainage density, slope, soil type, and rainfall, lineament, land use land cover, to produce a detailed and context-specific map of groundwater potential zones for an arid region experiencing severe water scarcity. Through a comprehensive review of the current state of knowledge and the presentation of case studies from various geographical settings, this study highlights the critical role of geospatial techniques in improving our understanding of groundwater systems. The overarching aim is to promote the development of more efficient, sustainable, and science-based groundwater management practices capable of tackling the challenges of water scarcity, climate change, and increasing anthropogenic pressures on water resources.

2 STUDY AREA

The selected study area is Quetta city, the metropolitan city serving as the capital of the Balochistan province in Pakistan. The Quetta region is located between 30°0′ to 30°30′ N and 66°40′ to 67°15′ E [3]. The average elevation is 1,680 meters (5,510 feet) above mean sea level as shown in Figure 1.

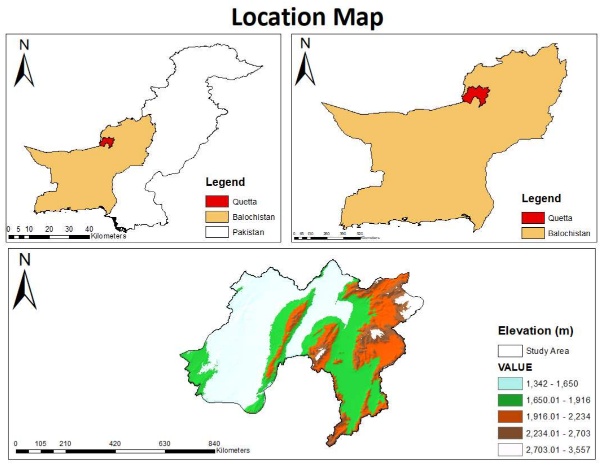

Figure 1: Location Map of the Study Area

Table 1: Database used in groundwater potential study.

Data used	Sources	Parameters	Resolution/Scale
Soil data	Geological Survey of Pakistan, Quetta	Soil Texture, Soil type	1:1,300,000
Metrological data	Regional Metrological Centre, Quetta	Rainfall	1:100,000
Landsat Sentinel -2	Esri Land Cover	Land Use Land Cover (LULC)	10 m
Geological data	USGS	Lineament density	1:100,000
Topography/Elevation data	USGS Earth Explorer: SRTM DEM	Drainage density, Slope	90 m

3 METHODOLOGY

An integrated remote sensing and GIS-based approach is a powerful tool for assessing groundwater potential zones, enabling the identification of suitable locations for groundwater withdrawals. The methodology for preparing a groundwater potential zones map in the study area is outlined below:

- Integrated thematic maps, including drainage density, slope, lithology, rainfall, soil, lineament density, and land use/land cover, are prepared from data obtained from the Geological Survey of Pakistan and satellite data respectively, by using remote sensing and GIS technique. The complete process of groundwater potential zone is in Figure 2.
- Thematic maps are created using ArcGIS software.
- Field observations are incorporated into various thematic maps.
- A multi-criterion evaluation technique is employed to assign weightages, ranks, and scores to various themes and feature classes, considering their importance in groundwater occurrence.

- After assigning weightages, ranks, and scores, all themes are converted to raster format using the 'Spatial Analysis' extension of ArcGIS software. The weights assigned to different themes are presented in Table 2.
- An integrated groundwater potential zones map is reclassified into three GIS environments using ArcGIS software. This demarcates various groundwater potential zones in the study area based on predefined decision rules. The resulting output includes classes such as good, moderate, and poor zones from a groundwater potential perspective.

In the study, the ranking system used includes very good, good, fair, moderate, and poor groundwater potential. The score of a feature class for a theme is calculated as the product of weightage and rank.

The 'Raster Calculator' option of the 'Spatial Analyst' extension in ArcInfo ArcGIS software is utilized to prepare the integrated groundwater potential zones map by adopting suitable map algebra.

The map algebra used in the 'Raster Calculator' is expressed in Eqs. (1):

$$\text{Groundwater Potential Zones} = (\text{Soil}) \times 0.40 + (\text{Land Use/Land Cover}) \times 0.25 + (\text{Lineament}) \times 0.05 + (\text{Drainage Density}) \times 0.10 + (\text{Slope}) \times 0.10 + (\text{Rainfall}) \times 0.10 \quad (1)$$

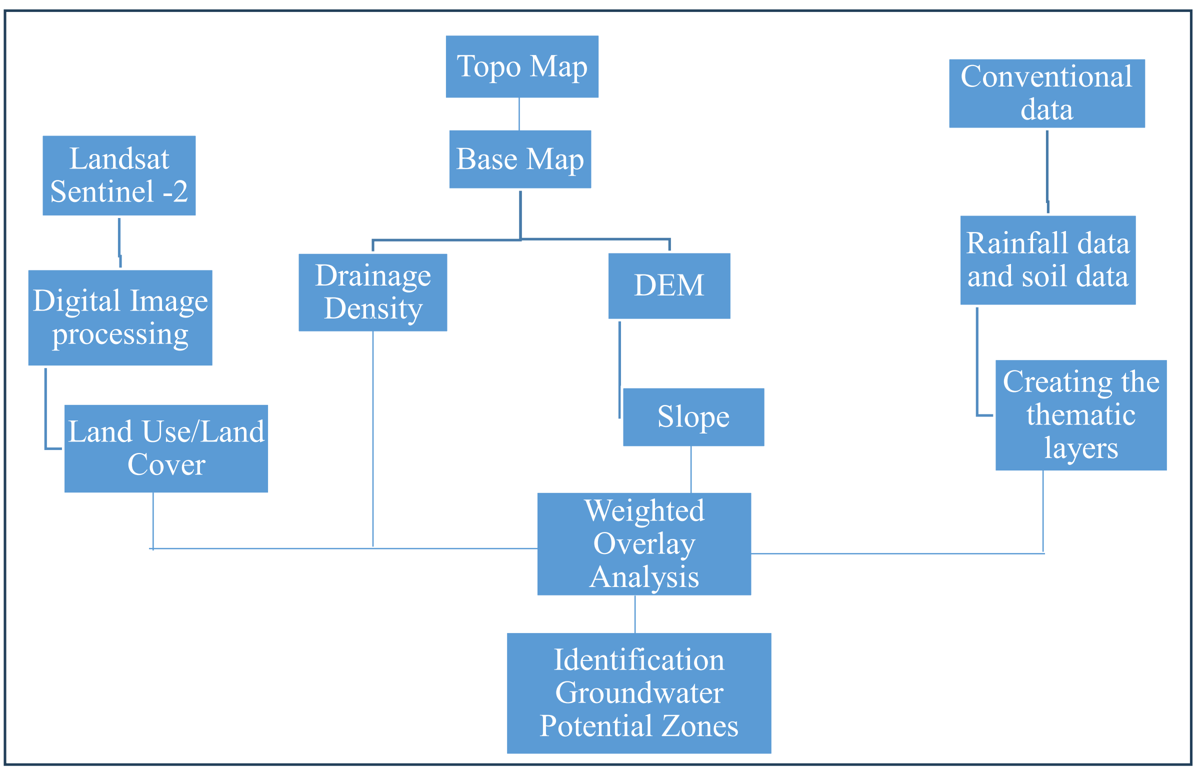

Figure 2: Flow chart for the groundwater potential zones using GIS techniques.

Table 2: Assigned and normalized for the individual features of the six different themes for ground water potential zoning.

S.No.	Themes	Weightages	Feature Class	Ranks	Score
1	Drainage Density	10	Very Low (0-2%)	4	40
			Low (2-15%)	3	30
			Moderate (15-22%)	2	20
			High (22-40%)	1	10
			Very High (>40%)	1	10
2	Slope	10	Nearly Level (0-8%)	4	40
			Gentle Slope (8-15%)	3	30
			Moderate Slope (15-45%)	2	20
			Steep Slope (>45%)	1	10
3	Soil	40	Loamy Clayey Soil	1	40
			Red sandy Soil	4	160
			Sandy Soil with coarse silt	3	120
4	Lineament Density	5	_____	_____	_____
5	Land Use and Land Cover	25	Forest	4	100
			Waste land	3	75
			Water bodies	1	25
			Agriculture	2	50
			Built Area	1	25
6	Rainfall	10	Low	1	10
			Moderate	3	30
			High	4	40

4 RESULTS AND DISCUSSIONS

Six This study employed a Geographical Information System (GIS)-based Multi-Criteria Decision Making (MCDM) approach to meticulously map and evaluate the groundwater potential zones (GPZ) within Quetta, based on six pivotal criteria influencing groundwater occurrence. These criteria included drainage density, slope, soil type, lineament density, land use/land cover, and rainfall. Each criterion was analysed through thematic maps, integrated using a weighted overlay method in ArcGIS, to delineate GPZs with varying potential.

Drainage Density: The analysis of drainage density, as depicted in the drainage density map (Figure 3), revealed a complex network of streams that are indicative of surface water flow patterns and indirectly reflect the underlying groundwater recharge capabilities. Low drainage density areas, assigned a weight of 10%, suggest higher groundwater potential due to reduced runoff and increased infiltration.

Slope: The slope map, derived from a Digital Elevation Model (DEM) and shown in Figure 4, highlighted the topographical gradients affecting surface water runoff and infiltration rates. Areas with gentler slopes were considered more favorable for groundwater recharge, thereby influencing their weight (10%) in the overall assessment.

Soil Type: Soils play a crucial role in water infiltration and retention. With four distinct soil types identified in the study area (Figure 5), those with higher permeability were deemed critical for groundwater recharge. Consequently, soil was given the highest weight (40%) in the analysis, reflecting its significant impact on groundwater potential.

Lineament Density: Lineaments, illustrated in Figure 6, represent zones of enhanced permeability due to faulting and fracturing. Although assigned a lower weight (5%), their presence is crucial for understanding groundwater flow and storage, particularly in fractured rock aquifers.

Land Use/Land Cover: The classification into six categories (Figure 7) underscores the influence of human activities and natural vegetation on groundwater recharge. Land use/land cover was assigned a weight of 25%, acknowledging areas like rangeland and forests as beneficial for groundwater potential due to their lower runoff and higher infiltration rates.

Rainfall: Rainfall patterns, mapped in Figure 8, provide direct input into the hydrological cycle, influencing recharge areas. With an average annual rainfall of 230 mm, this criterion was weighted at 10%, reflecting its role in replenishing groundwater stocks.

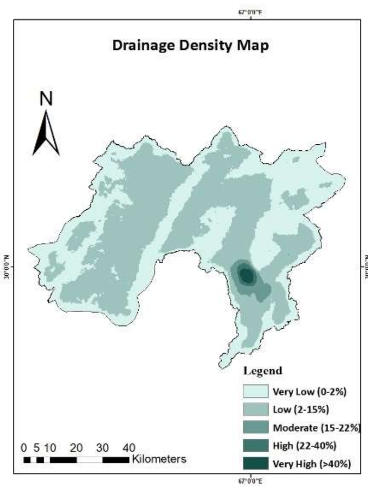

Figure 3: drainage density

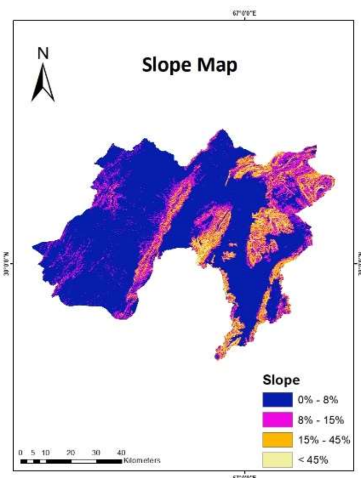

Figure 4: slope map

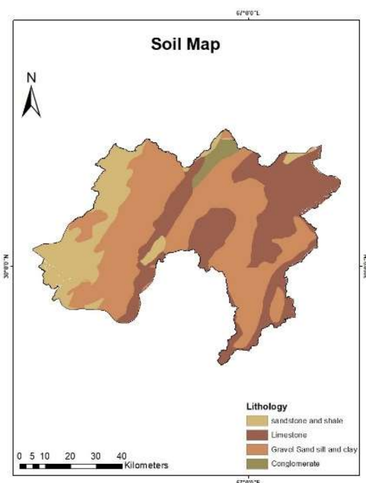

Figure 5: soil map

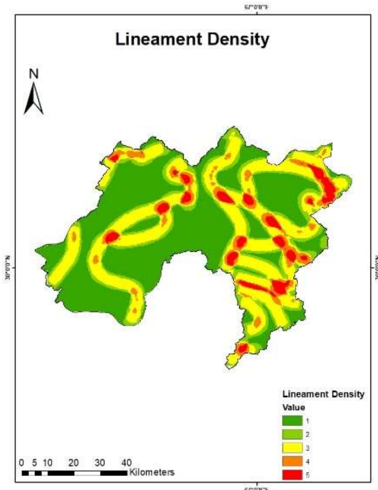

Figure 6: lineament density

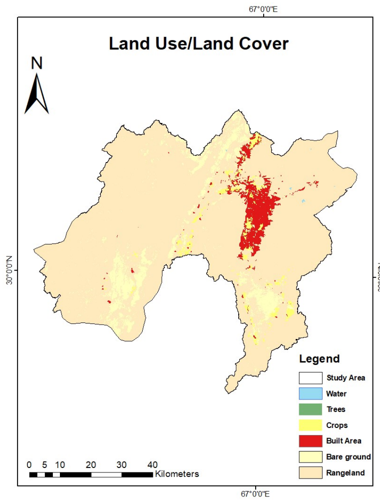

Figure 7: LULC

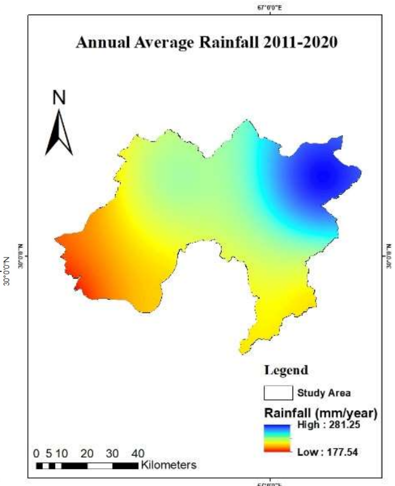

Figure 8: rainfall map

By integrating these criteria through the weighted overlay method, the study successfully delineated areas of low, moderate, and high groundwater potential, as presented in the comprehensive map (Figure 9). This nuanced mapping underscores not only the spatial variability in groundwater potential across the Quetta Valley but also the intricate balance between natural conditions and anthropogenic influences.

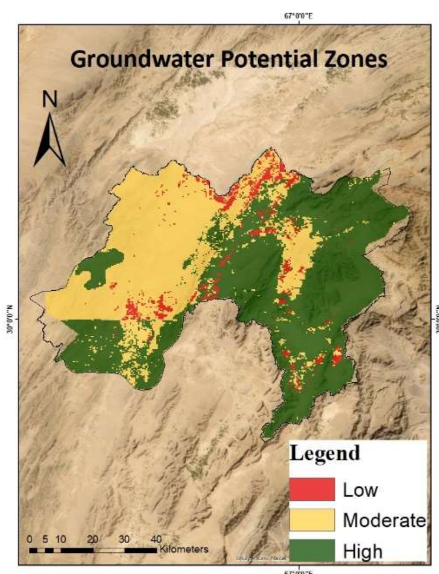

Figure 9: Groundwater potential zone map

The Groundwater Potential Zones of the area are indicated in square kilometres (km²) and as percentages in Table 3.

Table 3: Groundwater potential zones.

Groundwater Potential Zones	Area (km^2)	%
Low	211.032	4.659
Moderate	1811.474	39.999
High	2506.247	55.34

The findings reveal a nuanced understanding of groundwater potential in the Quetta area, highlighting the critical interplay of geological, hydrological, and anthropogenic factors. The application of the GIS-based MCDM approach demonstrates its efficacy in integrating diverse datasets to provide a holistic view of groundwater potential. Notably, the significant weighting towards soil type emphasizes the paramount importance of soil characteristics in groundwater recharge processes. Moreover, the study's innovative methodological framework serves as a replicable model for similar hydrogeological assessments in arid and semi-arid regions globally.

The analysis also raises important considerations for sustainable water resource management, particularly in the face of climate variability and increasing water scarcity. The delineated GPZ map offers a valuable tool for policymakers and planners in devising strategies for groundwater extraction, conservation, and recharge initiatives. Furthermore, this research underscores the importance of integrating land use planning and water resource management to enhance groundwater sustainability.

5 CONCLUSIONS

This research embarked on a comprehensive journey to delineate and evaluate groundwater potential zones within the Quetta Valley of Balochistan, Pakistan, leveraging the sophisticated integration of GIS and remote sensing technologies. Through the meticulous analysis of six thematic maps derived from satellite imagery and the application of multi-criteria decision-making techniques, this study has not only mapped but also critically assessed the spatial distribution of groundwater resources.

Our findings unveil distinct zones of groundwater potential, each characterized by varying degrees of suitability for sustainable extraction and utilization. This granular understanding underscores the vital role of geological and hydrological parameters—including aquifer characteristics, topographical slope, soil texture, drainage patterns, land use practices, lineament density, and precipitation patterns—in influencing groundwater availability. By harnessing advanced geospatial tools, this investigation has navigated the intricate interplay among these factors, offering a nuanced analysis that enhances our understanding of groundwater dynamics in arid regions.

The strategic synthesis of remote sensing data and GIS methodologies has yielded a novel groundwater potential zone map that stands as a testament to the power of integrating diverse thematic maps and analytical frameworks. This not only demonstrates the study's innovative approach but also sets a new benchmark for future research in hydrogeological assessments.

Beyond its academic contributions, this research holds profound practical implications. The generated map serves as a critical tool for policymakers, environmental planners, and water resource managers, providing them with invaluable insights for the formulation of sustainable groundwater management and extraction strategies. In light of increasing water scarcity and the pressing demands of climate change, our study offers a beacon of hope for the strategic conservation and utilization of groundwater resources in the Quetta Valley and potentially other similar arid environments worldwide.

In conclusion, this study not only advances our scientific understanding of groundwater potential zones through the prism of GIS and remote sensing but also catalyses a paradigm shift towards more informed and sustainable water resource management practices. The methodologies and findings presented herein pave the way for future explorations, promising a new era of groundwater research that is both innovative and impactful.

6 ACKNOWLEDGEMENTS

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