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ARTICLE

Identification of Groundwater Potential Sites Using GIS and RS Techniques: Case Study of Timergara, Khyber Pakhtunkhwa, Pakistan

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ABSTRACT: Groundwater is an essential resource contributing substantially to the annual total water supply. It enables agricultural irrigation and provides billions of people with their main source of drinking water. But overuse of groundwater has decreased its supply and, in certain places, resulted in soil subsidence. In the complex hydrogeological terrain of Timergara, traditional groundwater exploration is challenging and costly, requiring more efficient mapping approaches. Groundwater recharge potential zones must be assessed in order to guarantee sustainable groundwater management. This study uses Remote Sensing (RS) and Geographic Information System (GIS) methodologies to evaluate groundwater potential sites in Timergara, Khyber Pakhtunkhwa. This research integrates eight thematic layers; rainfall, geology, slope, soil, land use/land cover (LULC), drainage density, lineament density, and lithology, using the Multi-Influencing Factor (MIF) technique to enhance mapping precision. Data from several sources were integrated to investigate groundwater occurrences through surface and subsurface investigations. Existing water bodies were identified by a GPS survey. For this study, seven important factors were taken into account: rainfall, lineament density, drainage density, geology, soil, land use/land cover, and slope. To create the final Groundwater Potential Sites (GWPS) Index map, these elements were weighted and categorized using the Multi-Influencing Factor (MIF) procedure. This was followed by a weighted overlay analysis in ArcGIS. The results reveal five distinct potential zones: very poor, poor, moderate, good, and very good. The study found that areas that fall under 'very good' and 'good' potential are primarily located in regions with low slope and high lineament density. A regression analysis between the GWPS index and well depth data was performed for validation, showing a strong positive correlation ($R^2 = 0.7126$), confirming the reliability of the GIS-based model. Finding the best locations for water extraction and supporting sustainable groundwater resource management can be facilitated by using the verified groundwater potential map.

KEYWORDS: MIF; remote sensing; groundwater potential sites; groundwater; GIS; Timergara

1 Introduction

All life on Earth depends on water, which is a crucial natural resource [1]. Water is the most abundant element on Earth and is essential for all life [2]. It can be found in different forms on the Earth's surface, including oceans, lakes, glaciers, rivers and groundwater. It is continuously flowing in the form of glaciers, rivers, streams, lakes, canals, pounds, springs, falls and underground water. Water demand has grown steadily over the past few decades, therefore assessment of the quantity and quality of water for its effective utilization has become increasingly important [3].

Pakistan, a country with abundant water resources, is facing critical water scarcity [4]. At the time of independence in 1947, each Pakistani had access to 5000 cubic meters (m^3) of water. However, this has now decreased to 1000 m^3 due to unsustainable population expansion [5]. Pakistan's total actual renewable water resources declined from 2961 cubic meters (m^3) per person in 2000 to 1420 m^3 per person in 2005, [6]. Groundwater is a vital resource in arid environments, however, excessive extraction for irrigated agriculture is causing its depletion. Climate change is also expected to increase the importance of groundwater in these areas, as extended drought periods will minimize the availability of surface water. However, on timescales relevant to human society, many groundwater reserves are not renewable, so Aquifer management is urgently needed to balance and restore previously depleted aquifers in order to adapt to climate change [7].

If groundwater is extracted at a rate that is faster than it can be replenished by natural processes, the water table will decline, which can lead to a variety of negative consequences, including spring and stream flow gradually ceasing, wetlands drying, river flow decreasing, and vegetation loss [8]. Groundwater is the largest source of freshwater on Earth, making it an essential resource for human consumption and the overall development of a region [9]. To safeguard the quality, quantity, and management of groundwater systems, it is crucial to evaluate the prospective sites of groundwater recharge. Integrated GIS and RS techniques can offer the right framework for convergent analysis of various data sets for planning and mapping groundwater resources [10].

Timergara is also facing a problem of the unavailability of limited groundwater. While groundwater is extracted and used both for domestic as well as for agriculture purposes. Increases in the production of crops and animals are often correlated with the exhaustion of the aquifer in the Timergara region. However, Gains in agricultural production brought about by using groundwater more frequently than it is replenished endanger its long-term survival.

Timergara faces juggling current water requirements with long-term needs for the future is a challenge that we must face if we want to ensure a sustainable future for all. Groundwater is used for irrigation in addition to drinking and is discharged from the aquifer with high pressure pumps. In addition, the trend of digging out tube wells and open wells by the local community is continuously increasing which may ultimately lead to a serious scarcity problem of fresh groundwater.

Moreover, the water quality is also deteriorating in Timergara. The groundwater contains a big amount of minerals and chemicals whether in the form of salts or heavy metals or in the form of pollutant organic materials due to which the quality of the water is continuously decreasing, which is harmful for both agricultural and domestic use [11].

While various numerical and geophysical methods exist for groundwater exploration, they are often data-intensive and expensive for regional-scale assessments. The integration of Remote Sensing (RS) and Geographic Information Systems (GIS) provides a cost-effective and robust alternative for identifying potential zones [12]. In this study, the Multi-Influencing Factor (MIF) technique is employed because it allows for the systematic integration of multiple thematic layers by assigning weights based on their relative impact on groundwater recharge [13,14]. This approach is particularly advantageous in data-scarce regions like Timergara, as it synthesizes diverse environmental variables—such as lineament density and lithology, into a single predictive model, overcoming the limitations of single-parameter assessments.

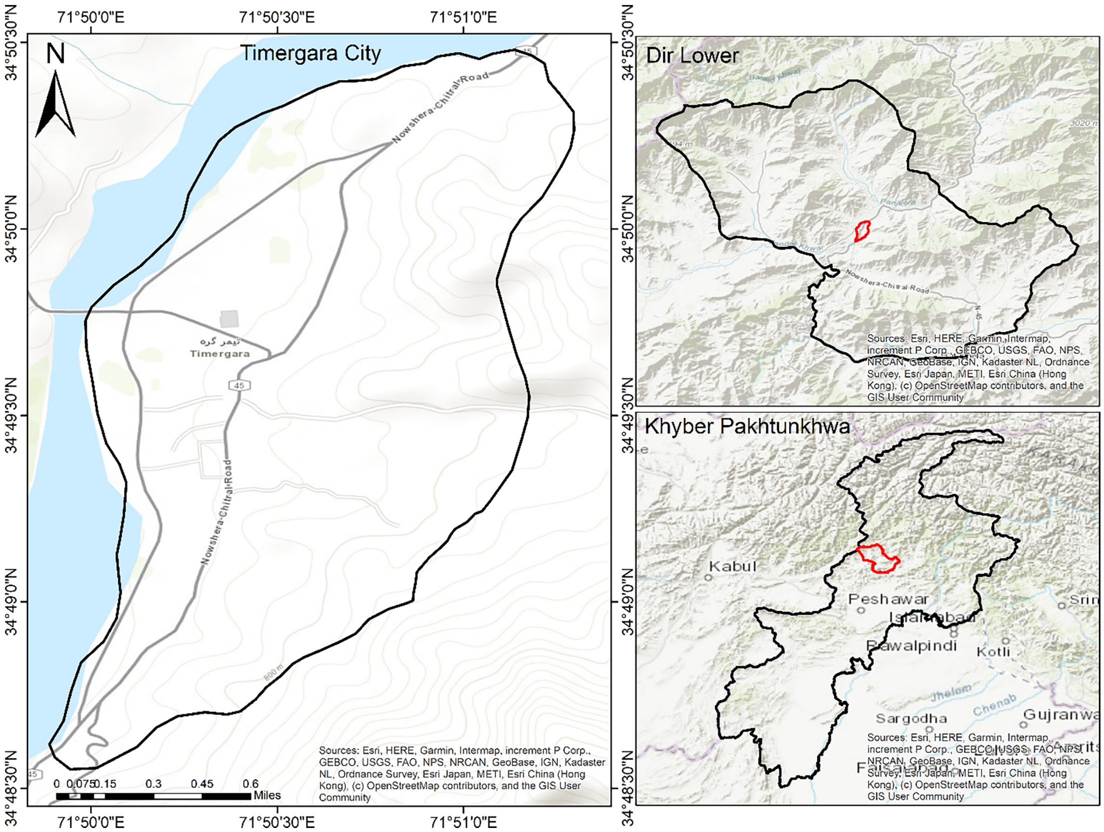
This study aims to address key challenges related to groundwater use and quality through an integrated application of the latest available techniques. The proposed study will certainly fill to better understand the groundwater resource of a study area; integrated methods can be developed and applied that combine information derived through analysis of multisource remotely sensed data in a GIS. In this research identification of favorable sites for freshwater, groundwater, and the latest GIS and RS techniques for groundwater exploration will be discussed.

The primary objective of this research is to delineate groundwater potential zones in Timergara using the Multi-Influencing Factor (MIF) geospatial approach. By identifying these zones, this study aims to provide a scientific roadmap for local planners to optimize well-site selection and implement artificial recharge structures, thereby addressing the growing water security challenges in the region.

2 Materials and Methods

2.1 Study Area

Timergara lies in Lower Dir District, Khyber Pakhtunkhwa, Pakistan, between 34°49′30″ N 71°50′30″ E, at an elevation of 823 m above sea level (Fig. 1). The area experiences a semi-arid to sub-humid climate with mean annual rainfall of ~131 mm. Hydrogeologically, groundwater occurs in fractured bedrock and alluvial deposits along the Panjkora River. The geology is dominated by igneous and metamorphic rocks of low permeability, interspersed with sedimentary formations that enhance recharge. Cambisol soils with moderate permeability are widespread, supporting agriculture. These features are further analyzed through thematic maps (Section 2.2), which provide a detailed spatial representation of rainfall, geology, soil, slope, and drainage density.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 1: Map illustrating the location of study site, Timergara.

Excavated graves of Indo-Aryans from 1500 to 600 BC are located in the town. The excavation site for Balambat is located on the western bank of the Panjkora River. 43,774 people called the town home as per the 1998 Census. Balambat and the main city are separated by the river Panjkora, which is where the majority of the main city is located. However, groundwater is being utilized by a number of people for drinking, residential use, and agriculture [15].

2.2 Methodology

Accurate, efficient, automated, near-real-time information is available everywhere on Earth, even in the most inaccessible regions is possible for remote sensing data of different spatiotemporal, radiometric, temporal, and spectral resolutions [16]. The main goal of this study was to distinguish favorable groundwater sites with the help of the multi-influencing factor (MIF) technique. With this technique, the essential information was collected from some departments and processed in ArcGIS 10.8 for groundwater potential zoning using methods, sources, and steps.

To determine groundwater potential zones, seven key input variables were chosen: drainage density (DD), land cover (LC), geology (G), lineament density (LD), soil type (ST), rainfall (R), and slope (S). Each of these variables influences and engages in complex interactions with other variables. Different influencing factors' interrelationships were determined, and relative strengths, rankings, and weights were allocated. The ArcGIS 10.8 program was used to input these values, which were then analyzed using multi-influencing factor (MIF) approaches to assign relative weightage and score. The integration of all contributing factors and their weighting values is known as weighted overlay analysis.

The primary datasets used in this study were selected based on their spatial resolution and relevance to hydrogeological modeling. The ASTER GDEM (Global Digital Elevation Model) with a 30 m spatial resolution was utilized to generate topographic indices, including slope, drainage density, and lineament density. Landsat 8 OLI (Operational Land Imager) satellite imagery (30 m resolution) was processed to delineate Land Use/Land Cover (LULC). The geological data were sourced from the United States Geological Survey (USGS) digital database, and soil characteristics were obtained from the FAO (Food and Agriculture Organization) Digital Soil Map of the World. Mean annual rainfall data were obtained from the Peshawar Meteorological Office. Additionally, field survey data from 35 existing well locations were integrated as ground-truth points for model validation. All datasets were co-registered and projected to the WGS_1984_UTM_Zone_43N coordinate system to ensure spatial consistency and accuracy in the weighted overlay analysis.

The weightage assignment for the thematic layers was conducted based on their relative importance in controlling groundwater occurrence and movement within the study area. These weights were derived through an analytical assessment of local hydrogeological conditions, where factors exhibiting a stronger influence on the subsurface storage potential, such as Land cover and Rainfall, were assigned higher weightage values compared to factors with a moderate or secondary influence. This systematic, criteria-based approach ensures that the model reflects the site-specific environmental characteristics of Timergara, rather than relying on arbitrary values (Fig. 2).

All seven criteria were given qualitative and quantitative rankings, and the resulting weights were distributed equally. Weighted overlay analysis was carried out using the tool "weighted overlay" from the overlay toolset, which is incorporated into the spatial analyst tools in Arc GIS, after assigning weights and rankings to each of the seven contributing categories and their sub-classes as shown in Table 1. The groundwater potential index for the research region was computed using Eq. (1) [17].

$$\text{GWPS Index} = \sum_{w=1}^{n}(w_i \times r_i) \tag{1}$$

The groundwater potential index (GWPI) is a composite index that is calculated using the following factors: drainage density (DD), geology (G), land cover (LC), lineament density (LD), rainfall (R), soil type (ST), Slope (S), feature rank within a layer (r), and layer weight calculated using the MIF method (w).

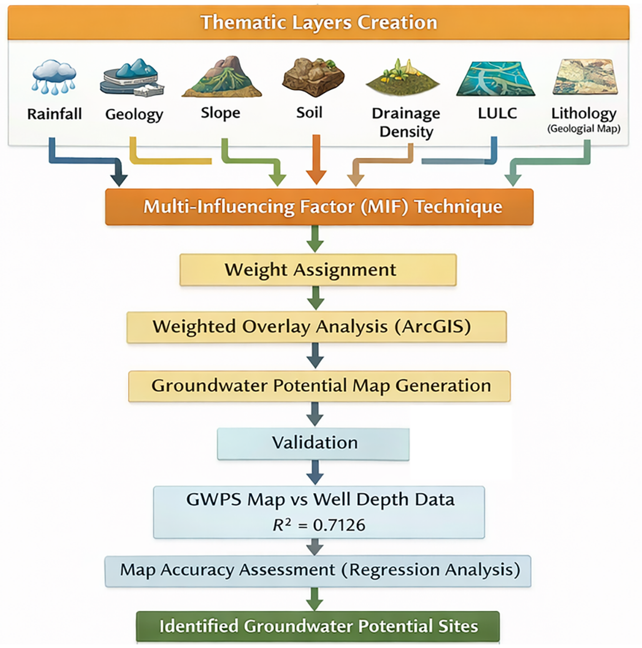


Figure 2: Methodological flow chart for the study.

Table 1: Weight and rank of each influencing parameter of groundwater recharge are assigned to thematic layers.

Selected Layers Parameters	**Sub Classes within Influencing Parameter**	**(Qualitative Rank)**	**Weight of Respectively Influencing Layers**	**Ground Water Propects (Quantitative Rank)**
Geology	Sedimentary rock	High Moderate	5	3
	Metamorphic + Igneous rocks	Low		2
				1
Drainage Density (km/km^2)	55.94–99.94	High	15	7
	32.47–55.93	Moderate		5
	11.35–32.46	Low		2
	0–11.34	Very Low		1
Rainfall (mm)	131.382	High	20	20

(Continued)

Table 1 (continued)

Selected Layers Parameters	Sub Classes within Influencing Parameter	(Qualitative Rank)	Weight of Respectively Influencing Layers	Ground Water Propects (Quantitative Rank)
Lineament Density (m/m^2)	1117.49–1446.50	High	15	7
	794.15–1117.48	Moderate		5
	487.85–794.16	Low		2
	0–487.84	Very Low		1
Land Cover	Water bodies	Very High	20	10
	Agriculture land	High		8
	Forst cover	Moderate		6
	Urban area	Low		4
	Barren land	Very Low		2
Soil Type	Cambisol	High	10	10
Slope (Degree)	15.75–27.50	High	15	1
	9.82–15.74	Moderate		2
	4.86–9.81	Low		5
	0–4.85	Very Low		7

Once the thematic layers' data were complete, it was transformed into raster datasets for weighted overlay analysis and other ArcGIS spatial analyst procedures.

The basis of a weighted overlay analysis is raster layers, thus the map for groundwater potential sites that shows the groundwater situation of the research region was created and afterward transformed into raster data for simple processing and integration [10]. As a result, if the format is vector for the, it will be converted to raster data. The ArcGIS spatial analyst tools are used to convert vector data to raster. Raster should be in geo TIFF format if it is going to be used in a weighted overlay service.

Raster ought to be a geo TIFF format if it is going to be used in a weighted overlay service. The output layer values for the weighted overlay tool range from 1 to 5. It overlays many rasters using a measuring scale and weights each one as per their significance. Zones having a value of 1 have very low groundwater potential, whereas zones having a value of 5 have very high potential. The majority of the layers were classified into four basic classes. The drainage and geological levels were categorized into 4 and 3 classes, respectively, however Landcover was given 5 classes. According to previously published literature, the qualities of each metric were examined, and weights were allocated based on how well-suited they were to the study of groundwater availability. To guarantee that all of the rasters are in the same coordinate system before doing the weighted overlay analysis, the projected coordinate system WGS_1984_UTM_Zone_43 was employed in this study.

2.2.1 Geology

Groundwater resources are distributed and zoned according to a region's geology [18]. In the present investigation, igneous and metamorphic rocks predominated in the region. The type, composition, and permeability of rock and soil considerably affect water penetration and groundwater recharge. Because metamorphic and igneous rocks, which predominate in the study area, have poor permeability, there is little water penetration where these two types of rocks are predominant. Additionally, clayey soil and shallow soil with rocky outcrop have low permeability, which restricts subsurface water percolation and aquifer recharge. Loamy soil and sedimentary rocks, on the other hand, are crucial for the replenishment of the groundwater aquifer because of their high porosity and permeability [19]. Infiltration is also possible in terrains with joints or cracks.

2.2.2 Slope

The slope has an effect on how quickly surface water infiltrates and runs off. While level surface areas can hold and drain the water inside the ground, enhancing ground water recharge, steep slopes increase runoff and restrict penetration of surface water into the ground [20]. Using ArcGIS 10.7 The maximum rate of change between each cell and its neighbors is determined by the slope function. Each cell in the output raster has a slope value. The ground is flatter when the slope value is lower; steeper when it is higher. The output slope raster can be calculated using either percent slope or degree slope [21]. The slope of the research region has been calculated in degrees using the DEM model, which was based on the ASTER data.

2.2.3 Drainage Density

Panjkora is the primary river in the research region. Rivers carry large volumes of water during the rainy season and less water during the dry season. Analyses of the drainage network are crucial for geoenvironmental and geo-hydrological investigations. High runoff and low infiltration of water into the ground are characteristics of places with high drainage density, whereas low runoff and significant penetration of surface water into the ground are characteristics of areas with low drainage density [17,22]. Data for the current study were extracted from the analysis of a DEM image in ArcGIS.

2.2.4 Rainfall

The distribution of precipitation and slope gradient determine the infiltration rate, has a substantial impact on the groundwater potential zones [23]. The Regional Meteorological Office in Peshawar provided the yearly rainfall information for the Dir meteorological stations (2005–2018). After the data were added to ArcMap 10.7 for interpolation, a rainfall map was produced using the inverse distance weighted (IDW) tool, which showed that overall rainfall in the study area is 131.342 mm annually.

2.2.5 Lineaments Density

Lineaments are signs of hidden cracks and faults that lead to the formation of groundwater reservoirs and canals. Lineament presence typically denotes permeable zones because lineament density will eventually make groundwater in a location visible [24]. The density analysis tool in the ArcGIS 10.8 environment was used to calculate lineament density, which is given as the length of the lineament per unit area (km^2).

2.2.6 Land Use and Land Cover

In geography, there are two terms that are employed: land use, which refers to how humans have utilized the land, such as for agriculture, industry, residential, transportation, commercial, irrigation, etc. [25]. Using Google Earth Pro, a map of the land use and cover of the study region was produced. Using Google Earth Pro, the supervised classification procedure has been carried out. According to the study’s findings, In the studied area, there are five primary types of habitats., including urban, agriculture, river, barren land, and water. The weight given is based on the runoff and waterlogging characteristics of land use and land cover.

2.2.7 Soil

The potential for groundwater recharge in a region is controlled by the soil texture, which also controls the soil's water-holding capacity, permeability, and water transport (both vertically and horizontally) processing, including infiltration. Water infiltration is facilitated by macropores, which are prevalent in sandy soils with a coarse texture. On the other hand, macrospores predominate in clayey soils with little water infiltration [26]. One sort of soil class, comprising Cambisol, was indicated by the thematic layer of the soil for the study region. Based on the composition and water-holding capacity of the soil, weights were assigned. assigned their limited permeability and tendency to have thin soil and clayey sand, rocky outcrops were assigned a low weighting. Due to their great porosity and permeability, loamy soils were generally given a high weight value.

3 Results and Spatial Analysis

3.1 Drainage Density Map

The drainage density map was created from DEM (Fig. 3). The areas were divided as Very Low (0–530.1), Low (530.2–1060.3), Moderate (1060.4–1590.5), and High (1590.6–2120.6) drainage density zones.

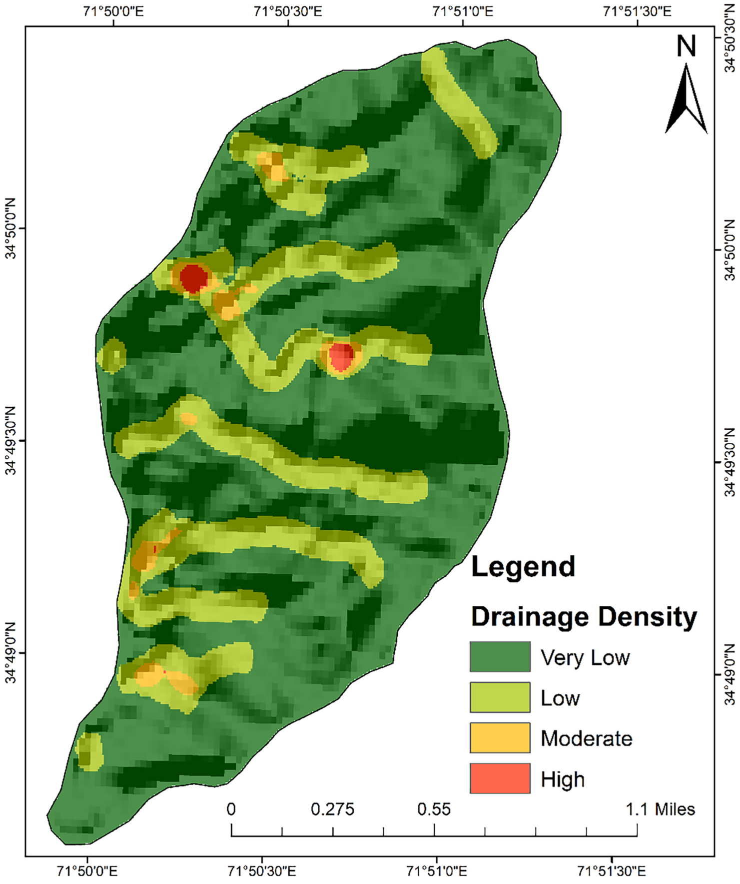


Figure 3: Drainage density map of Timergara.

3.2 Slope

The investigated area's slope was divided into four categories based on its ability to allow water infiltration. Very Low (0–4.53), low (4.54–9.27), Moderate (9.28–14.8) and High (14.9–27.5) (Fig. 4). The slope map was created by applying the surface tool on DEM data.

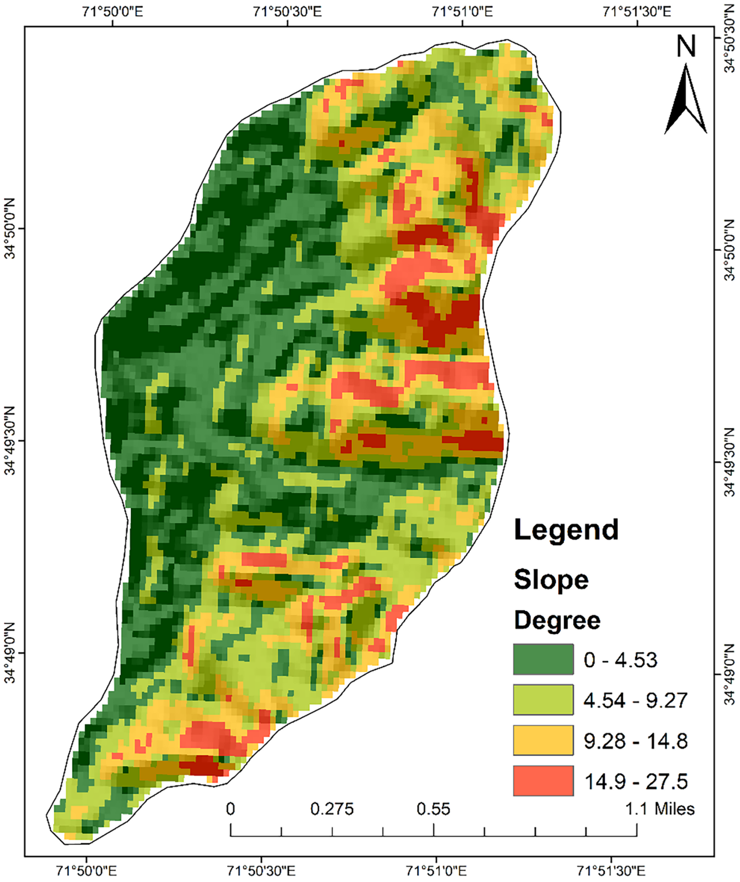


Figure 4: Slope map of Timergara.

3.3 Land Use and Land Cover LU/LC

The Land cover and Land use map of the study site (Fig. 5) is prepared from Google Earth Pro. Using Google Earth Pro, the supervised classification procedure has been carried out. afterwards dividing it into five categories, including Water, Crops, Trees, Urban and Barren, the weight assigned depending on the LU/LC's water logging and runoff characteristics.

3.4 Geology

The research area's geological map was taken from the Khyber Pakhtunkhwa geological map, digitized, and then divided into two categories: sedimentary rocks and igneous + metamorphic rocks. Depending on the infiltration capacity and potential for groundwater recharge, different grades were given (Fig. 6).

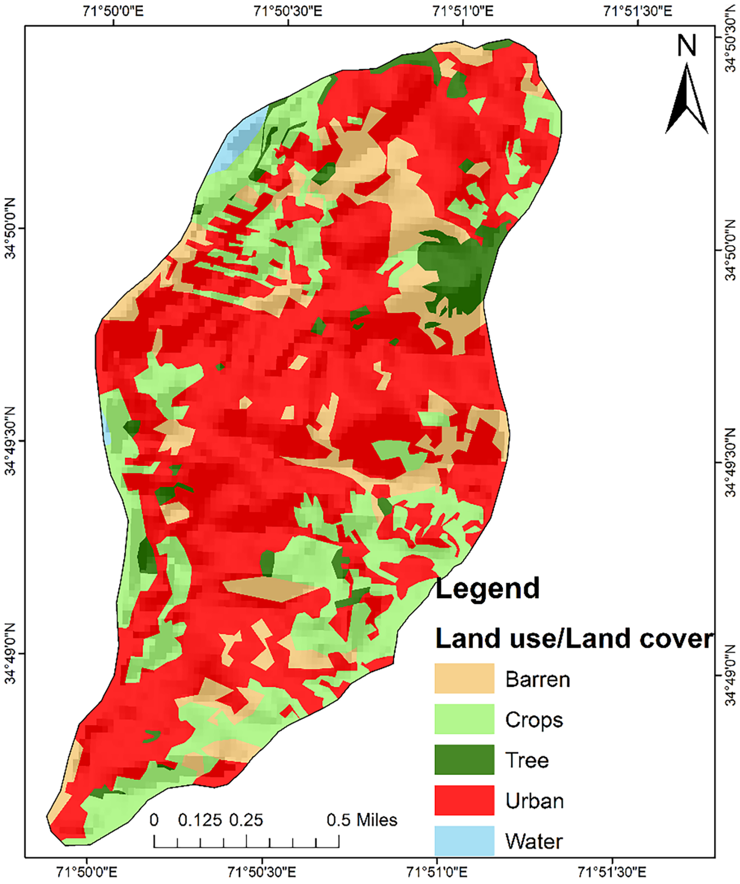


Figure 5: Land use and land cover map of Timergara.

3.5 Soil

The soil data was taken from the FAO soils portal by digitizing it into our study area which is mainly composed of Cambisol (Fig. 7).

3.6 Rainfall

The Regional Meteorological Office in Peshawar provided the annual rainfall information for the Dir meteorological stations, our rainfall data came out as 131.342 mm annually (Fig. 8).

3.7 Lineaments

Lineaments map was generated by drawing lines on the hillshade of the area. After drawing lines on fault then we applied line density tool on those lines which gave us the lineaments density map of our area (Fig. 9).

As soon as all the data for the theme layers were prepared, in order to do weighted overlay analysis and other ArcGIS spatial analyst procedures, these layers were transformed into raster datasets. Groundwater situation for the study area is shown on a map of groundwater potential sites (Fig. 10). Groundwater availability was classified as; Very Low, Low, Moderate, High and Very High, as an output of the weighted overlay analysis.

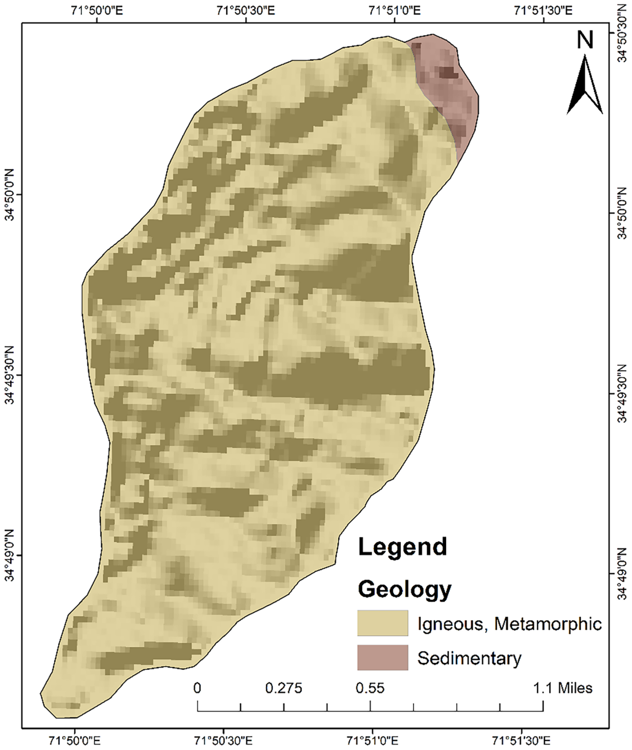


Figure 6: Geology map of Timergara.

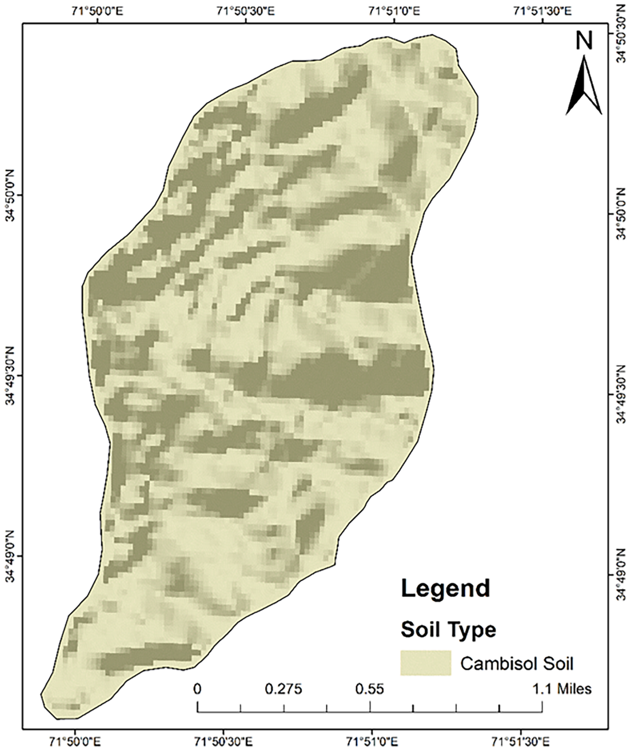


Figure 7: Soil map of Timergara.

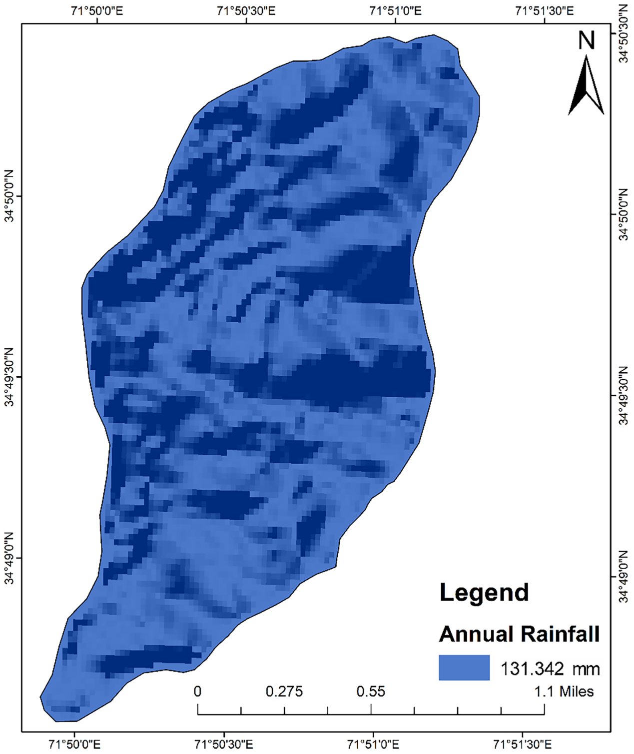


Figure 8: Rainfall data map of Timergara.

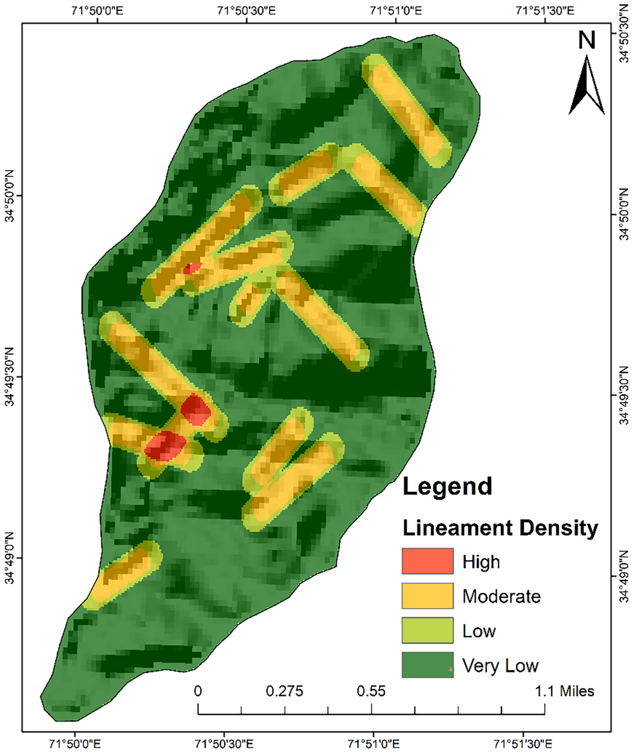


Figure 9: Lineaments map of Timergara.

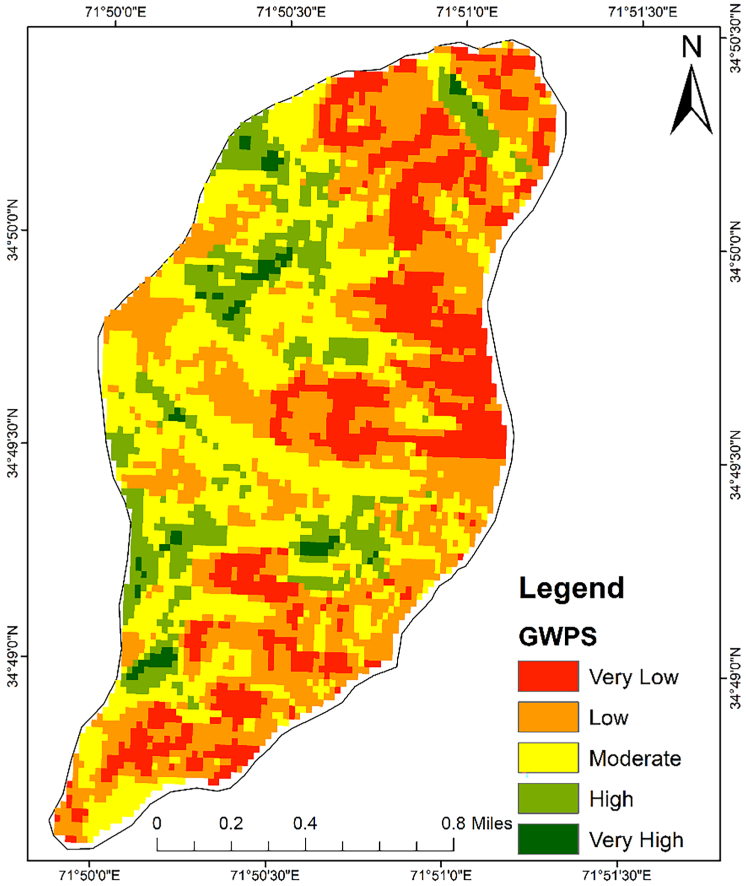


Figure 10: Map showing groundwater potential sites of Timergara.

4 Discussion

4.1 Results Verification

To ascertain the depth of the water table within the research region, a field survey was carried out. A portable GPS was used to record the locations and depth (in feet) of 35 different hand pumps, tube wells, and wells. Our survey revealed that the water's depth varied greatly, from very high (131.06 m) to very low (4.26 m). Wells were categorized into three classes based on their depth: shallow (4.26–4.57 m), intermediate (60.97–79.24 m), and deep (131.06–128.32 m). The identified groundwater potential zones layer was overlaid with the well data (Fig. 11). The accuracy of the groundwater depths was calculated utilizing the data from this well as a guide. The effectiveness of the weighted overlay results was examined using the cross-verification approach. The majority of wells with light to medium groundwater zones where groundwater potential was extremely high, according to the overlay analysis. These results are similar to those of Aykut, its contention was that GIS technology successfully confirmed the facts about the Turkish water supply and implied the potential for this technology to become a potent tool for estimating the availability of underground water, resulting in the development of plans to utilize the water resource for the improvement of local agriculture.

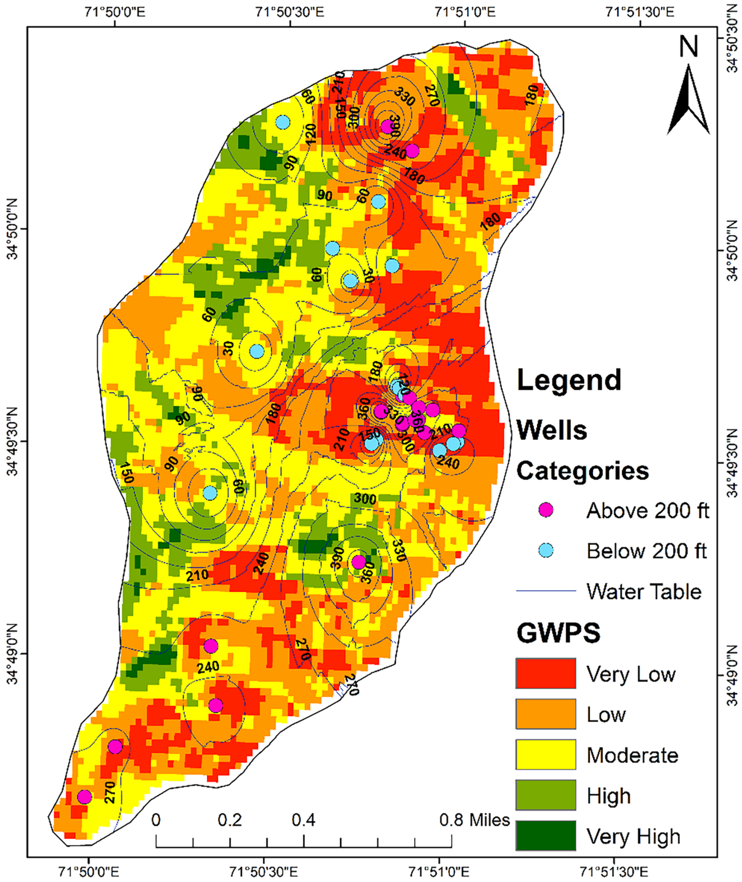


Figure 11: Water potential sites of Timergara correlate with well samples data.

A regression study between the GWPS Index values and well depth data (in feet) was carried out in order to validate the Groundwater Potential Sites (GWPS) Index map created in ArcGIS (Fig. 12). According to the results, there was a significant positive correlation, as shown by the equation y = −0.8152x + 907.37, where R^2 was 0.7126. According to this strong link, places with lower GWPS Index values show deeper groundwater levels, while areas classed with higher groundwater potential in the GIS-based model typically correspond to shallower groundwater depths. The expected relationship—that a decrease in groundwater potential is correlated with an increase in well depth, is further supported by the negative slope (−0.8152). The R^2 value indicates that the model accurately captures groundwater conditions in the real world and validates the accuracy of the GIS-based GWPS map. This validation increases the geographical analysis's legitimacy and guarantees that it can be used for managing and assessing groundwater resources.

4.2 Influence of Thematic Layers on Groundwater

In order to define groundwater potential zones in Timergara, Khyber Pakhtunkhwa, the current study shows how well Remote Sensing (RS) and Geographic Information System (GIS) approaches work when combined with the Multi-Influencing Factor (MIF) methodology. The research region was effectively divided into five groundwater potential categories, very low, low, moderate, high, and very high, by the weighted overlay analysis, demonstrating the significant spatial diversity of groundwater occurrence influenced by both natural and man-made variables [27,28].

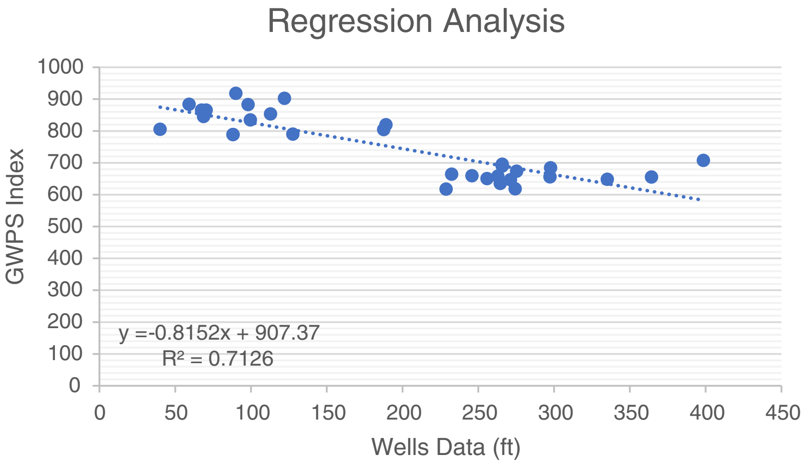


Figure 12: Regression analysis between the GWPS and well data.

Groundwater potential zones were primarily defined by thematic layers of rainfall, land use/cover, drainage density, and lineament density. High to extremely high groundwater potential zones were regularly found in areas with beneficial land use (agricultural land and water bodies), low drainage density, high lineament density, and gentle slopes. This is in line with hydrogeological principles since lineaments serve as channels for the movement and storage of groundwater, while low slopes and drainage density improve infiltration [29,30]. Previous groundwater potential studies utilizing GIS-based multi-criteria decision analysis in northern Pakistan and other semi-arid to sub-humid regions have shown similar results [17,27].

The distribution of groundwater was also greatly impacted by the research area's geological structure. In contrast to volcanic and metamorphic rocks, which typically have limited primary porosity and permeability, sedimentary formations showed greater groundwater potential. The significance of structural controls like faults and joints is highlighted by the moderate groundwater potential found in fractured zones inside hard rock terrains. This finding confirms previous research showing secondary porosity plays a crucial role in crystalline aquifers [18,24,31,32].

Another important determining element was slope; higher groundwater potential zones were found in places with extremely low to low slopes. Rapid surface runoff was encouraged by steeper slopes, which decreased infiltration and groundwater recharge. These results support the validity of the slope categorization employed in this investigation and are in line with infiltration–runoff dynamics [20,28,30].

The model's dependability is greatly increased by validating the groundwater potential map with well depth data. The GWPS score and groundwater depth showed a strong inverse association ($R^2 = 0.7126$) in the regression study, suggesting that locations with high groundwater potential typically had shallower water tables. This high statistical agreement demonstrates how well the GIS-based model captures actual groundwater conditions. The resilience of GIS-based groundwater potential mapping techniques has been further confirmed by comparable validation results reported in related works [10,17,27,29].

Notwithstanding its advantages, the study has several drawbacks. The rainfall data may not accurately reflect microclimatic differences throughout the research area because they were obtained from a small number of meteorological stations. Furthermore, seasonal variations in the water table and groundwater quality measures were not included, which could improve evaluations of groundwater suitability. Future research should integrate time-series groundwater level data, geophysical surveys, and water quality indices, as recommended in recent groundwater mapping literature [30,32].

All things considered, the study's conclusions offer insightful information for Timergara's water resource planning, well-site selection, and sustainable groundwater management. The produced map of groundwater potential can help local communities, planners, and policymakers choose appropriate groundwater extraction sites while lowering the possibility of overexploitation. The approach used in this study is affordable, reproducible, and consistent with similar RS–GIS–MIF applications in other data-scarce regions [27,28].

4.3 Comparison with Regional Studies

The findings of this study, identifying high potential zones in the low-lying southern regions, are consistent with previous geospatial assessments in Northern Pakistan [17]. However, this study enhances the regional knowledge base by integrating high-resolution lineament density with the MIF technique, providing a more granular map than earlier broader-scale surveys. This comparison confirms that the integrated GIS-RS approach is a reliable surrogate for expensive geophysical methods in hard-rock terrains.

5 Conclusions

Groundwater prospective sites can be found via remote sensing and GIS, both of which have been shown to be successful and strong tools. When compared to old groundwater inquiry techniques, at a reduced cost, precise spatial information can be provided using remote sensing data. It was an economical and stress-free method to carry out the multi parameter analysis using GIS and RS. A seven-layer groundwater potential map was prepared by overlaying eight thematic layers; Geology, soil, lineament density, drainage density, rainfall, slope, and land use and land cover. This area has been divided into a variety of groundwater potential zones, including very high, high, moderate, low, and very low. A contour map of the groundwater table and the locations of existing well fields, both received from GeoLog International, were superimposed on the groundwater potential map. There is a fairly flat groundwater table in the zones with high groundwater potentials. In this study, GIS and RS techniques are used to quickly and cost-effectively integrate surface and subsurface information, which may aid in the future location of groundwater well fields. While the current results provide a useful framework for groundwater management, they should be interpreted with caution. The study acknowledges limitations regarding the resolution of secondary data, the assumption of uniform rainfall distribution, and the lack of long-term seasonal monitoring. The regression validation ($R^2 = 0.7126$) supports the reliability of the model, but uncertainties remain due to data scale and thematic classification. Future research should incorporate deep geophysical sounding, isotope analysis, and time-series groundwater level monitoring to further validate the vertical extent and seasonal dynamics of the identified aquifers. These additions would strengthen the methodological contribution and reduce uncertainty. All things considered, the study's conclusions offer balanced and evidence-based insights for Timergara's water resource planning, well-site selection, and sustainable groundwater management. The produced map of groundwater potential can help local communities, planners, and policymakers choose appropriate groundwater extraction sites while lowering the possibility of overexploitation. The approach used in this study is affordable, reproducible, and applicable to other data-scarce regions, but its reliability depends on careful consideration of assumptions and validation.

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