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Delineation of Rainwater harvesting Potential Zones using analytical hierarchy process (AHP) and GIS in District Swat

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Abstract: Water is critical to all life forms in watershed. There is intense need of water for human and animal consumption as well as for agriculture, forest, and rangeland management. Water scarcity have a tremendous stress to water-shed productivity. Water sources in form of precipitation plays a vital role in water distribution in semi-arid and arid regions. Delineation of rain-water harvesting potential zone is a basic issue for the areas where water resources are deficient or with no proper irrigation system for agriculture. The current Study deal with the identification of rainwater harvesting potentiality zones in district Swat of Khyber Pakhtunkhwa. Therefore, it is necessary to select some suitable sites based on required and essential parameter such as land-use/land-cover, geology, rainfall, soil, slope, drainage density, lineaments, geology, elevation are selected as major and minor influencing factor responsible for delineation of these zones. The weight and score of each influencing factor is derived using analytical hierarchy process (AHP). Each influencing factor were assigned a weightage based on saatys' scale table depending upon their effectiveness to the rainwater harvesting potentiality. By using the command of weighted overlay in ArcGIS spatial analyst too, all the thematic layers were integrated resulting delineation of

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rainwater harvesting potential zones. The potential zones were classified into four groups, i.e., (1) Least Suitable Site, (2) Not Suitable Site, (3) Suitable, and (4) More Suitable Site. This study revealed that zones with a More Suitable Site covered an area of 314 km^2 (6 % of the total area), Suitable Site 1720 km^2 (32 %), Not Suitable Site 1815 km^2 (34 %), and Least Suitable Site 1505 km^2 (28 %). The study concluded that the geospatial-assisted Analytical Hierarchy Process was very useful and efficient technique for the delineation of rainwater harvesting potential zones and effectively can be applied to enhance the conceptual understanding of rainwater harvesting of District Swat, Khyber Pakhtunkhwa Pakistan.

Key Words: Rainwater harvesting**,** Analytical Hierarchy Process (AHP)**,** Geographic Information System (GIS)**,** Weighted overlay analysis**,** Suitability mapping**.**

Introduction

Rainwater harvesting is critical for collecting and storing rainwater for drinking and domestic uses, especially in dry areas where it addresses water shortages, reduces groundwater extraction, enhances crop yields, promotes pasture growth, combats erosion, and conserves resources (Khastagir, A. et al., 2010; Kaposztasova, D. et al., 2014). Water is essential for human and animal existence, economic growth, and development (Haile, G. et al., 2019; Mahmood, K. et al., 2020). Irregular rainfall and insufficient precipitation contribute to global water scarcity, affecting communities with variable rainfall and resulting in livelihood insecurity (Adham, A. et al., 2018). Rainwater harvesting (RWH) offers a solution to this scarcity by providing accessible water for domestic use, benefiting flood protection, soil moisture, and soil conservation (Al-Ghobari, H. et al., 2021).

The overuse of freshwater resources due to industrialization, population growth, and agriculture has led to declining water levels, with urbanization further decreasing infiltration and groundwater recharge (Ibrahim, 2009). Thus, traditional irrigation technologies must be reconsidered as water resources may not meet future agricultural and urban demands (Prinz and Singh, 2000). Water scarcity is now one of the most significant risks to humanity (Prinz, 2000). Rainwater harvesting, rooted in traditional methods that supported ancient civilizations in arid regions (Rockstrom et al., 2007), is increasingly vital in facing climate change (Jackson, 2001). Ecological and hydrological interactions shape vegetation diversity, signaling resource use (Ludwig et al., 2005; Yu et al., 2008). By 2025, 1.8 billion people are expected to face acute water scarcity (Yannopoulos et al., 2019). Climate change and increased demand worsen water scarcity, especially in arid regions, requiring effective watershed-level management (Mahmoud and Alazba, 2015; Tiwari et al., 2018). Rainwater harvesting helps mitigate drought and floods and is a historical approach for residential water collection (EA, 2003). In agriculture, water used for irrigation often contributes minimally to the hydrological cycle.

The selection of suitable sites is crucial in rainwater harvesting (RWH) projects, involving criteria identification, weighting, and suitability mapping through the Analytical Hierarchy Process (AHP). Balkhair and Ur Rahman (2021) used eight criteria in a study, showing 40.6% of sites were excellent or good, with factors like curve number (CN), slope, rainfall, and soil being key. The study revealed a 92%

increase in excellent sites, while good and moderate categories decreased by 43% and 53%, respectively. Adham et al. (2022) analyzed seven RWH techniques through spatial analysis in ArcGIS, focusing on criteria like rainfall, runoff, and soil texture. They found that 50% of the area was moderately suitable for runoff basins, and contour ridges were highly suitable for 70%.
Mohammed and Ahmed employed a GIS-based Decision Support System (DSS) with criteria such as rainfall surplus, slope, and PRC, identifying 1.5% and 27.8% of the study area as excellent and good for in situ water harvesting (IWH). Another study by Tiwari and Rohit used GIS techniques for sustainable RWH site selection, analyzing surface elevation, soil, and runoff potential in a semi-arid region. Their method indicated two excellent, three good, and two unsuitable areas for RWH, estimating a total potential of 54.49 million cubic meters of water harvesting. Mahmoud and Tang (2023) used a DSS in the UK, identifying the northwest as well-suited for RWH, with 18.95% and 27.25% classified as excellent and good, respectively.
Other studies highlight similar GIS-based methodologies, such as Pandey et al.'s work in the Karso watershed using IRS-1C and LISS-III data for watershed improvement. Muthoni and Odera integrated GIS and remote sensing to identify suitable areas for various water harvesting structures based on potential runoff. Weighted overlay analysis and proximity analysis were key in these studies, demonstrating GIS's capability to assess large catchment areas accurately and efficiently. This approach is effective for identifying RWH sites, ensuring sustainable water management by accounting for diverse geospatial factors.

Introduction to Study Area
The present study will be conducted in the Swat district, located in the Malakand division of the Khyber Pakhtunkhwa Province in Pakistan. Until 1969, Swat district existed as a separate state before being incorporated into Pakistan. Geographically, the Swat district spans from latitude 34° 36′ 59″ to 35° 44′ 51″ N and from longitude 72° 29′ 52″ to 72° 09′ 52″ E, with an elevation of 970 meters (3182 feet). The district shares borders with Malakand district to the south, Buner to the southeast, Shangla to the east, Dir to the west, Gilgit Baltistan to the north, Kohistan to the northeast, and Chitral to the northwest. Once an independent state until 1969, Swat covers an area of approximately 10,350 square kilometers, lying within the Hindu Kush range of the Himalayas. The region's landscape showcases a unique blend of towering mountains, picturesque valleys, and fertile plains. With elevations ranging from 991 meters at Saidu Sharif to 6,257 meters at the summit of Falak Sar, Swat is renowned as the "Switzerland of Pakistan" for its breathtaking natural beauty. The district is traversed by the Swat River, whose waters support a flourishing agricultural sector, allowing for the cultivation of wheat, maize, rice, and various fruits. Swat's historical and cultural significance is highlighted by ancient Buddhist relics, rock carvings, and the literary contributions of figures like Khushal Khan Khattak, who authored "Swat Nama," leaving a lasting legacy in Pashto literature.
The region experiences a moderate climate with distinct seasons, attracting visitors year-round who seek seasonal variations in the scenic landscape. Summer temperatures are mild, while winters bring snow to the mountainous areas, and the monsoon season in July and September provides vital rainfall for agriculture. Swat's mountainous terrain is home to diverse flora, including dense

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coniferous forests, colorful alpine meadows, and orchards of apples, apricots, and cherries that contribute significantly to the local economy. This lush environment supports diverse wildlife and adds to the district's ecological and economic vitality, making Swat a prime location for both agricultural productivity and ecotourism.

According to the 2017 census, the population of Swat District was recorded at 2.309 million people, residing within a total area spanning 5337 square kilometers (GOP, 2018).

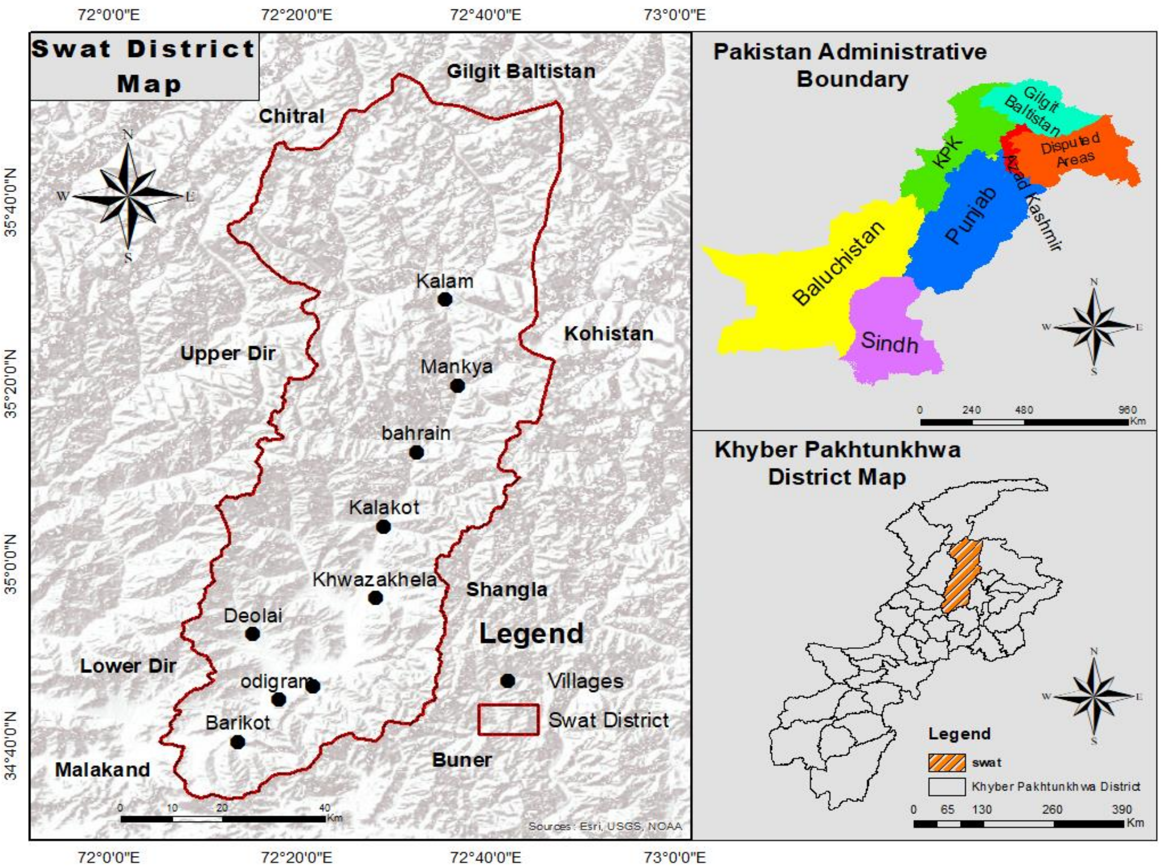

Figure1. Map showing the location of the study area, district Swat, Khyber Pakhtunkhwa, Pakistan

Research Methodology

The methodology employed in this study is weighted overlay analysis, which calculates weights of various influencing parameters using the Analytical Hierarchy Process (AHP). AHP, recognized for its effectiveness in identifying potential zones for rainwater harvesting, is a modern technique that utilizes remote sensing and GIS data. It structures decision criteria hierarchically, assesses relative importance, and ranks alternatives comprehensively, making it invaluable for addressing rainwater harvesting mapping and other natural resource issues (Saaty, 1980). As an accurate and standardized approach, AHP utilizes eigenvectors to produce precise weights .

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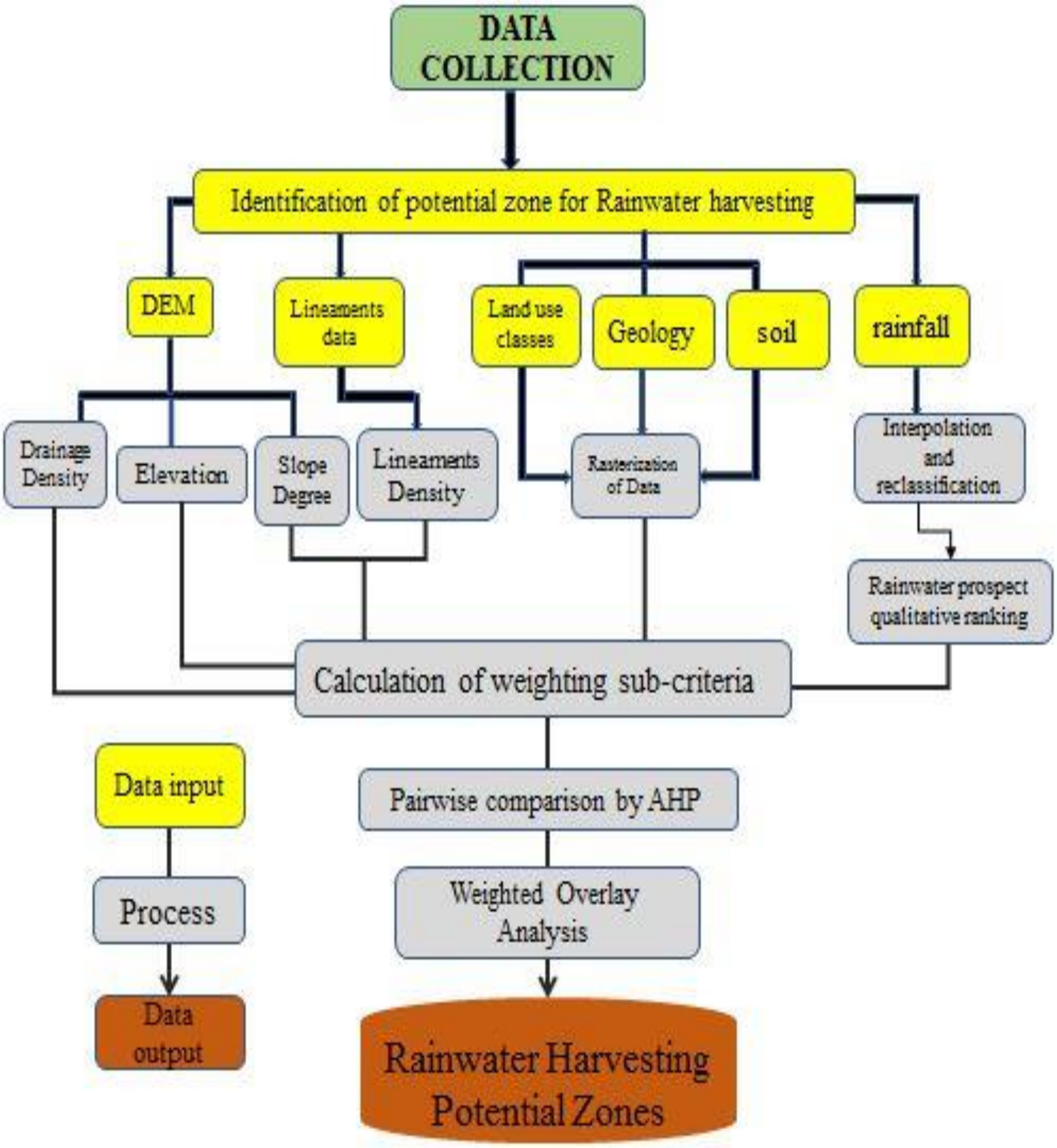

Figure2: Flowchart showing the methodology used for identification of rainwater harvesting potential zones

Both quantitative and qualitative attributes, utilizing pairwise comparisons and a ratio scale to assign weights (Sajikumar et al., 2013). The methodology is based on proven principles and has been validated through practical and decision-making problems.

By utilizing the outcomes of AHP, the potential zones for rainwater harvesting can be studied, aiding decision-makers in making informed choices. AHP employs a mathematical approach to compare and prioritize the objectives of the study area. The comparison matrix, developed by experts using Saaty's scale, is shown below. Finally, the AHP combines the criteria weights with the option scores, resulting in a global ranking for each alternative. The overall rank for each alternative is the weighted sum of the ranks based on the established criteria. The significance of the nine numbers increases as the value increases, with 1/9

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indicating minor importance and 1 representing equal importance. Each parameter was classified based on these weightage criteria (Table 1). Table 2 presents the weightage assigned to the eight factors for mapping rainwater harvesting potential zones.

Data collection

This research has been utilize data from many sources .In this study both primary and secondary data were used.

Table 1 Secondary Data Sources

S.No.	Data Acquired from Sources	Data Type	Analyzed in	Outcome
1	ALOS PALSAR	DEM 12.5m	ArcGIS	Slope/Elevation Data
2	Geological map of survey of Pakistan	Geology	ArcGIS	Geological zones
3	ALOS PALSAR	DEM 12.5m	ArcGIS	Drainage Density
4	Copernicus Open Access Hub platform	Sentinel-2 image	ArcGIS	Land cover/Land Use
5	Food and Agriculture Organization (FAO)	Soil Map of Pakistan	ArcGIS	Soil Map
6	Landsat 8 USGS	Multi Spectral Bands	PCI Geomatica	Lineaments
7	NASA Earth data GPM Satellite website	Net CDF Raster	ArcGIS	Rain Fall

Table 2 Saaty's Scale of relative importance

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored, and its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between two adjacent judgments	When compromise is needed

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Table 3 Percentage of influencing factor based on Saaty's analytical hierarchical process

Factors	Elevation	lineament	DD	Slope	geology	Soil	Rainfall	LU/LC	Weights
Elevation	9	7	6	5	4	3	2	1	0.10
Lineaments	½	1	½	1/3	3	3	5	5	0.10
Drainage Density(DD)	1/3	1/3	1	1/5	5	5	5	5	0.15
Slope	¼	1/5	1/5	1	1/2	5	3	6	0.15
Geology	1/5	¼	1/3	1/3	1	3	3	3	0.05
Soil	1/6	¼	1/5	1/5	1/5	1	2	3	0.05
Rainfall	1/7	1/7	1/7	1/7	1/7	1/7	1	2	0.20
LULC	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1	0.20
									1.00

Weighted overlay

The Rainwater Harvesting potential zones for the study area were identified by integrating the eight selected thematic layers in ArcMap 10.5. All the thematic layers were processed and converted into raster format because weighted overlay analysis support only raster format. Therefore, the vector data format was converted into raster datasets. Conversion from vector to raster is done within ArcGIS spatial analyst tool. Raster that Participates in a weighted overlay service should be in geo TIFF format. One thing must be kept in mind while performing weighted overlay analysis that is the consideration and understanding of how to handle gaps or No-Data values in raster datasets.

The weightage is just been assumed out of 100 and assigned to each parameter or layer shown in (Table 3). Each theme and its class are assigned weight and rank based on existing literature. The weights were equally divided within sub-classes and are been assigned to different influencing parameters where 9 were high rainfall for water showing the most probable location for rainwater harvesting potential zones, while 1 shows the lowest potentiality. The weights were assigned based on their characteristics in the area of rainwater availability. Before performing weighted overlay analysis it is to make sure that all the raster are in the same coordinate system, the projected coordinate system WGS 1984_UTM_Zone 42 is also used in the research work.

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Table 4: Assigned weight according to Saaty's analytical hierarchical process

Influencing Parameter	**Sub-classes of Influencing Parameter**	**Qualitative rank**	**Influence (%)**	**Quantitative score/rank**
Land use/Land cover	Waterbody Forest/Crop Builtup Area Bare Ground/Rangeland	Very High High Very Low Low	25	5 4 1 2
Rainfall in mm	820 – 840 800 – 810 780 – 790 760 – 770 720 – 750	Very High High Moderate Low VeryLow	20	5 4 3 1 1
Drainage Density in km/ sqkm	0 - 0.41 0.42 – 1 1.1 - 1.7 1.8 - 2.4 2.5 - 4.1	Very High High Moderate Low Very Low	15	5 4 3 2 1
Slope in degree	0 - 8.5 8.6 – 18 19 – 28 29 – 38 39 – 81	Very High High Moderate Low Very Low	15	5 4 3 2 1
Lineament Density	0.56 - 1.1 0.36 - 0.55 0.22 - 0.35 0.077 - 0.21 0 - 0.076	Very High High Moderate Low Very Low	15	1 2 3 4 5
Geology	Sedimentary Rock Porous sedimentary with rock mostly sand Metamorphic family rock	Very High High Moderate Low	5	5 4 3 1
Soil	Clay loam loam uwb	High Moderate Low	5	6 3 1
Elevation	673-1540 1550-2369 2370-3230 3240-4030 4040-5790	Very high High Moderate Low Very Low	10	5 4 3 2 1
			100	

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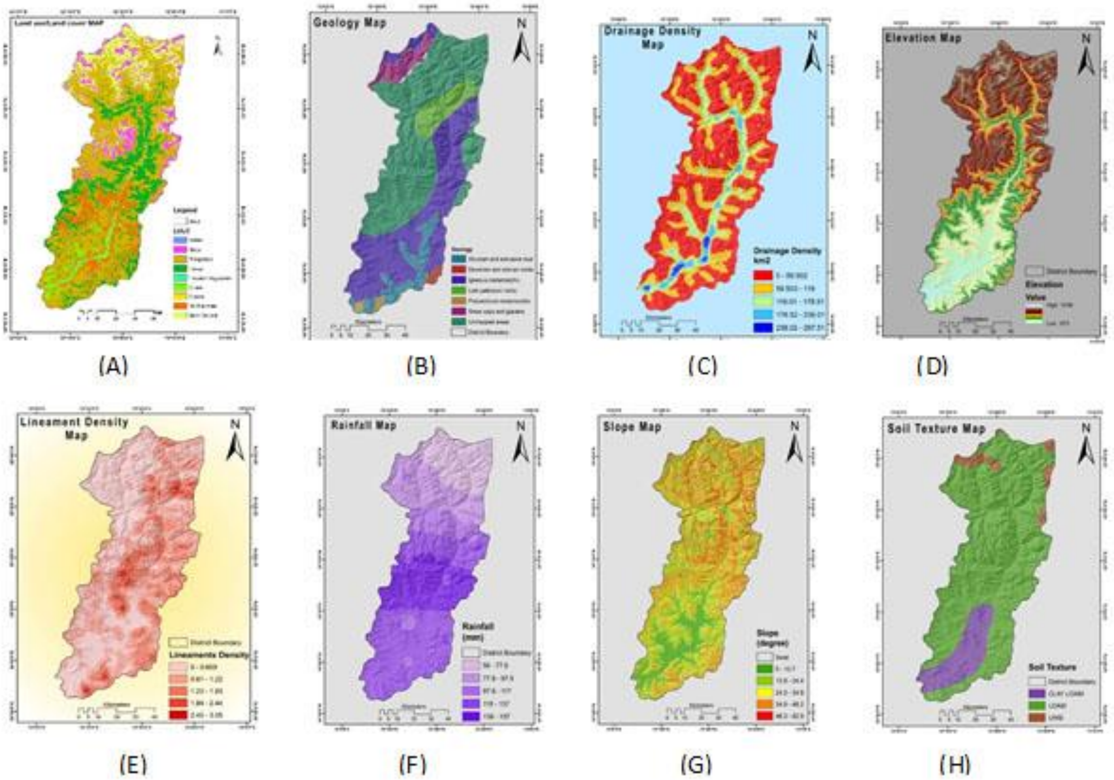

Figure 3: The thematic layers of multi influencing factors for delineation of rain water harvesting potential zones: : *(A) Land use Land cover (B)Geology (C)Drainage Density (D)Elevation (E)Lineament (F) Rainfall (G) Slope (H) Soil*

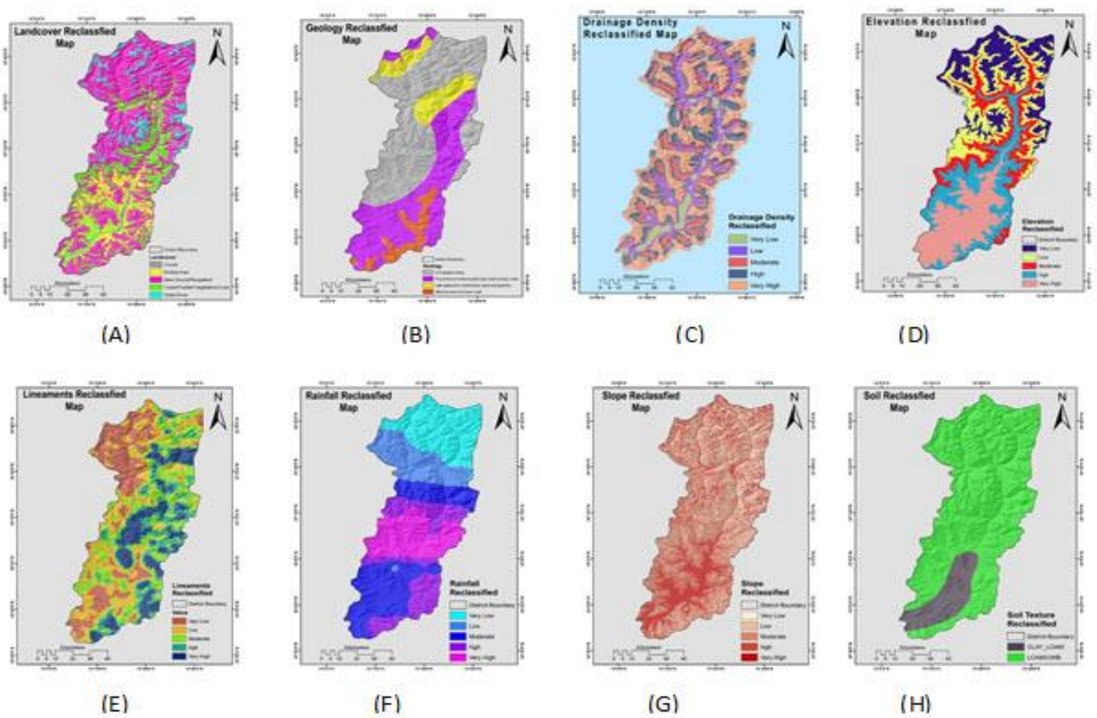

***Figure 4 Assigned weight according to Saaty's analytical hierarchical process**:(A) Land use Land cover (B)Geology (C)Drainage Density (D)Elevation (E)Lineament (F) Rainfall (G) Slope (H) Soil*

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Analysis and Discussion

To identify rainwater harvesting potential zones in District Swat, a combination of primary and secondary data was utilized, with a primary reliance on secondary sources. This chapter focuses on reclassified maps, where ranks and scores were assigned based on their influence on rainwater harvesting. The weights for each influencing parameter are summarized in Table 1 & 2. The maps in this chapter illustrate areas with varying influence on the identification of rainwater harvesting potential zones.

Influencing Parameters

1. Lineament Density

Lineaments, identified through satellite imagery, are geological features indicative of increased permeability and porosity. In this study, a multispectral image from Landsat 8 was processed using ArcGIS 10.5 and PCI Geomatica software for lineament extraction. The resulting lineament density map (Figure 3E & 4E) classified regions into five categories:

- Very Low (0-0.609)
- Low (0.61-1.22)
- Moderate (1.23-1.83)
- High (1.84-2.44)
- Very High (2.45-3.05)

High-density zones are deemed unsuitable for rainwater harvesting, while low-density zones are prioritized.

Drainage Density

Drainage density, representing the length of streams within a drainage area, indicates runoff and infiltration characteristics. Areas with low drainage density suggest better potential for rainwater harvesting. The drainage density map was generated from the ALOS PALSAR DEM using ArcGIS, categorized as follows (Figure 3C & 4C):

- Very Low (0-0.50.502)
- Low (50.503-119)
- Moderate (119.01-178.51)
- High (178.52-238.01)
- Very High (238.02-297.51)

Zones with low drainage density are favored for rainwater harvesting due to improved water storage capacity.

Slope

Slope magnitude significantly affects rainwater harvesting potential. Steeper slopes lead to increased runoff and lower infiltration. The slope map, derived from the ALOS PALSAR DEM, is classified into five categories (Figure 3G & 4G):

- Very Low (0-12.70)
- Low (12.80-24.40)
- Moderate (24.50-34.80)
- High (34.90-46.20)
- Very High (46.30-82.90)

Lower slopes are assigned higher ranks due to their favorable conditions for rainwater harvesting.

4. Elevation

Elevation influences water retention and infiltration. Lower elevations tend to retain water longer, facilitating greater infiltration, while higher elevations contribute to runoff. The elevation map (Figure 3D & 4D) ranges from 5790 to 673.

5. Land Use/Land Cover

Land use significantly impacts rainwater harvesting potential. The land use map, derived from Esri Land cover data (2020) using ArcGIS 10.5, classified various land types (Figure 3A & 4A). Rangeland was predominant, with water, forest, and crops assigned high ranks due to their positive influence on infiltration. The density of vegetation directly correlates with infiltration rates, as dense forests increase water retention (Anbazhagan et al., 2005).

Rainfall

Using the Inverse Distance Weighting method, interpolated rainfall data ranged from 58 mm to 157 mm. Areas with higher rainfall received greater weight in the analysis, enhancing their suitability for rainwater harvesting (Figure 3F& 4F).

Soil

Soil type is crucial for assessing rainwater harvesting potential, as it affects infiltration and water movement. The soil map, processed from FAO data, classified soil types into three categories (Figure 3H & 4H): clay loam, loam, and uwb. Uwb and loam soils were assigned high scores due to their water retention capabilities, while gently sloped soils received lower scores.

Geology

The geology of the study area, predominantly metamorphic rocks, influences water availability. Higher weights were assigned to sedimentary and porous rocks, which facilitate percolation and groundwater recharge. Metamorphic rocks were given lower scores due to limited percolation capacity (Figure 3B & 4B).

Rainwater Harvesting Potential Map

After assigning suitable weights to all parameters, the final rainwater harvesting potential zones map (Figure 6) was created. The potential zones are classified as follows:

1. Least Suitable Site: 1505.09 km² (28.11%)
2. Not Suitable Site: 1814.9 km² (33.90%)
3. Suitable Site: 1720.23 km² (32.13%)
4. More Suitable Site: 313.514 km² (5.86%)

Table 5: Area of district swat rainwater harvesting potential zones

Rainwater harvesting potential zones	Area Km²
More Suitable	313
Suitable Sites	1720
Not Suitable Sites	1815
Least Suitable Sites	1505

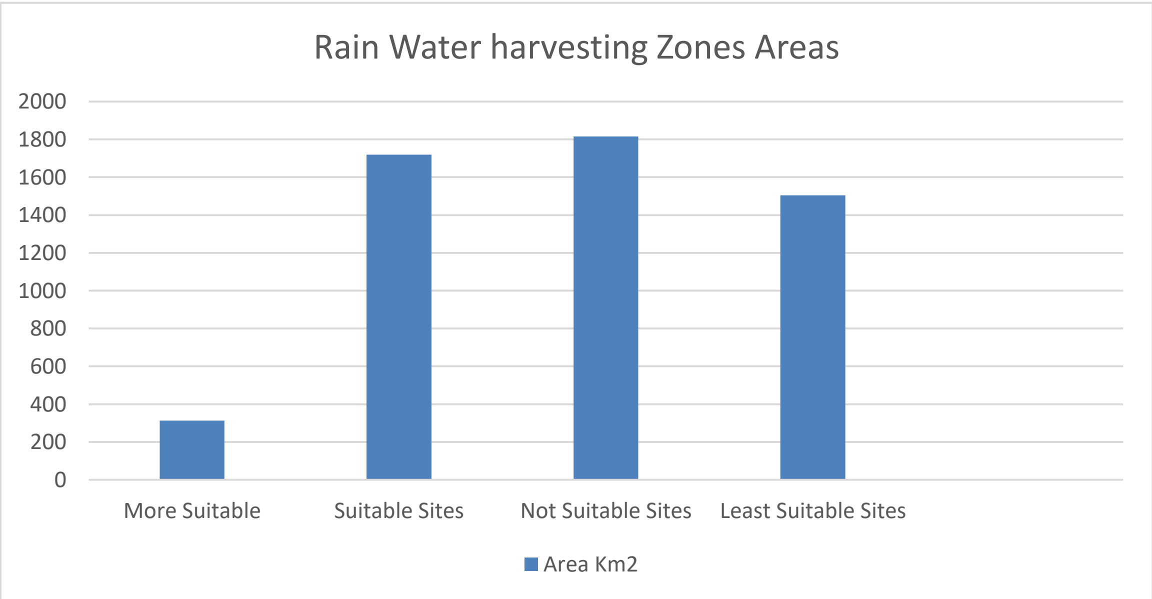

Figure 5: *Covered Area by rainwater harvesting potential zones district Swat, Khyber Pakhtunkhwa, Pakistan*

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Conclusion and Recommendation

This research aimed to identify rainwater harvesting potential zones in district Swat through the analysis of various influencing factors, including lineament density, drainage density, slope, land use/land cover, rainfall, soil, and geology. The findings obtained from the analysis provide valuable insights into the areas with high and low influence on rainwater harvesting, enabling better planning and utilization of water resources in the study area. The analysis of lineament -

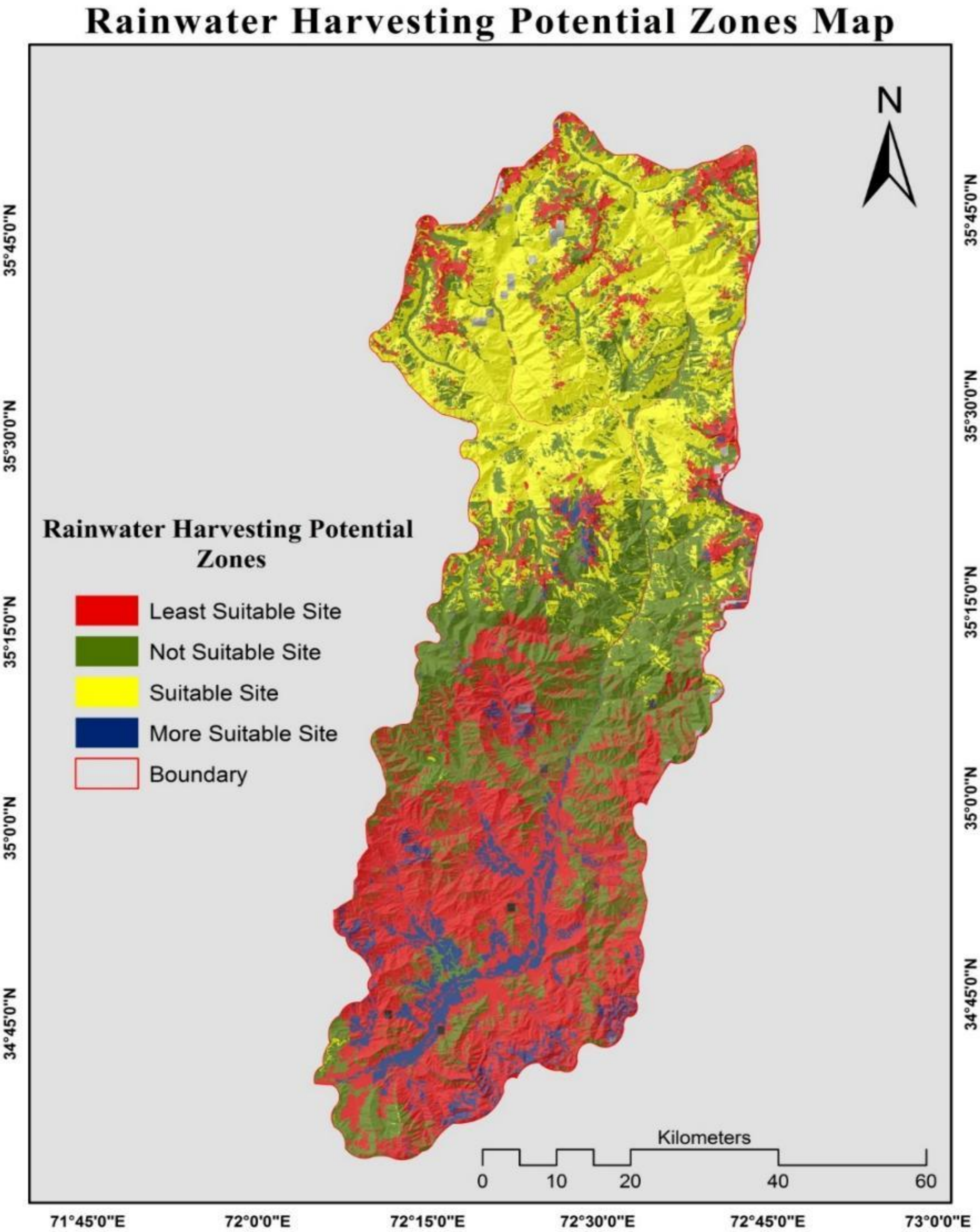

Figure 6: Map shows the delineated Rainwater Harvesting potential zones in district Swat, Khyber Pakhtunkhwa, Pakistan

-density revealed the presence of linear features indicating increased permeability and porosity, which can contribute to rainwater harvesting potential. Similarly, the assessment of drainage density helped characterize the runoff and infiltration patterns, identifying areas with good and poor rainwater harvesting prospects. The analysis of slope highlighted the importance of considering the terrain's steepness, as regions with lower slopes exhibited better rainwater harvesting potential due to lower runoff and higher infiltration rates. The examination of land use/land cover patterns revealed the significant impact of vegetation cover on recharge and runoff. Areas with dense forests and agricultural lands demonstrated higher potential for rainwater harvesting compared to rangeland and built-up areas. The consideration of rainfall patterns emphasized its direct correlation with the water table recharge, with areas experiencing higher rainfall exhibiting greater potential for rainwater harvesting. The evaluation of soil properties, particularly porosity and permeability, highlighted their crucial role in rainwater infiltration and movement. Soils with high porosity, such as tabletop soil, were identified as favorable for rainwater harvesting, while gently sloped soils demonstrated limited water percolation capacity. Furthermore, the assessment of geology indicated the influence of different rock types on rainwater percolation and recharge. Sedimentary rocks and porous formations showed higher potential for rainwater harvesting, while metamorphic rocks exhibited lower percolation rates. Based on the analysis conducted, the research provides valuable information for identifying rainwater harvesting potential zones in district Swat. These findings can aid policymakers, water resource managers, and stakeholders in implementing effective strategies for water management and rainwater harvesting in the region.

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