Identification of Groundwater Potential Zones Using AHP and Frequency Ratio, to Devise Mitigation Measures: A GIS-Based Study

By

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DEDICATION

"Dedicated to my Family who support me in all moments of life."

and

"To teacher and friends who helped me to complete my thesis"

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Muhammad Usama

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ABSTRACT

Islamabad stands out as the sole well-organized city in Pakistan. Nevertheless, it grapples with a severe predicament of groundwater depletion by swift population escalation, inadequate water administration, urban growth, deforestation, and the influx of numerous migrants. The existing demand for water in Islamabad rests at 2200 lakh gallons for the day, whereas the Capital Development Authority (CDA) of Islamabad furnishes a mere 70 million gallons daily. The pivotal task of locating promising Groundwater Potential Zones (GWPZ) assumes vital significance in revitalizing groundwater levels to address the pressing water scarcity. The objective in this study is to identify potential sites for Groundwater Potential Zones by utilizing the analytical hierarchy process (AHP) and Frequency Ratio (FR) methods. In pursuit of the desired goal, this study has employed nine local influential variables, namely soil composition, terrain gradient, water table depth, population density, land use and land cover patterns, drainage network density, lineament density, precipitation patterns, and geological characteristics. Two distinct sets of GWPZ maps were generated using AHP & FR techniques. Subsequently, the resultant maps were categorized into five discrete classes, ranging from categorically unsuitable to highly suitable. Both techniques give satisfactory results. However, the GWPZ map from AHP yields more precise results, the Area Under Curve assessment value of 0.754, while for the FR the value was 0.64. Several mitigation measures were suggested including Rainwater harvesting, Artificial Lakes, Partial infiltration, and properly maintained sewerage system. A map depicting potential rainwater harvesting sites was also prepared using AHP. The resulting maps can be helpful for planning and implementation of hydraulic structures in this region.

Chapter 1

INTRODUCTION

1.1 Background

Water stands as a paramount and indispensable resource on our planet, serving as an essential prerequisite for all life forms. Its profound significance in shaping human society can be traced back to the earliest stages of civilization. While water is ubiquitously distributed across the Earth, its quality and quantity exhibit dynamic variations both temporally and geographically. Notably, a mere 3% of the global water inventory comprises freshwater, with most of this resource locked in frozen ice. Groundwater accounts for approximately 34% of the total water reservoir, while lakes and rivers collectively hold less than 1% of the Earth's freshwater (Gosh et al, 2022).

Groundwater stands as an invaluable resource with a pivotal role in sustaining both terrestrial and aquatic ecosystems, as well as the overall well-being of human civilizations. However, the challenges posed by burgeoning population growth and the expansion of agricultural lands have exerted escalating pressures on groundwater reserves, leading to their overexploitation and a consequential decline in water quality, (Arshad et al, 2020).

The process of groundwater recharge unfolds as water traverses beneath the Earth's surface, infiltrating saturated zones. The availability of groundwater predominantly hinges on precipitation patterns and the efficiency of recharge systems, (Sadaf et al, 2018). The depletion of groundwater resources is a complex interplay of factors incorporating swift demographic expansion, climatic variations, deforestation, urban development, as well as deficiencies within groundwater management policies., (Arshad et al, 2020).

South Asia, home to one-fifth of the global population, emerges as the most densely populated geographical region on the planet, (Haque et al, 2012).

Urbanization, a phenomenon marked by an increasing portion of the populace residing in urban centers and their peripheries, is currently undergoing unprecedented growth worldwide. Historically intertwined with industrialization, urban expansion has evolved significantly over time. Prior to 1950, only 30% of the world's population dwelled in urban areas, but since 2008, over half of the global populace has become urban residents, (Hodgson et al, 2011). Projections suggest that by 2030, this urban population is poised to approach nearly five billion individuals, with urbanization experiencing pronounced growth in Africa and Asia. Importantly, the process of urbanization bears a strong correlation with the accessibility of high-quality and sustainable water supplies, a relationship underscored by a regional comparative analysis encompassing areas beyond South Asia, (Haque et al, 2012).

In the context of South Asian megacities, the emergence of critical water-related challenges can predominantly be attributed to the rapid and spontaneous processes of urbanization and industrialization. This unchecked industrial expansion, lacking appropriate on-site wastewater and sewage treatment facilities, coupled with ineffective pollution control measures and inadequate legal oversight, constitutes the primary factors contributing to unregulated pollutant discharge. A substantial volume of untreated effluent infiltrates directly into surface water sources, resulting in contamination and the overexploitation of groundwater resources, with limited opportunities for replenishment. It is important to note that these large-scale abstractions have enduring impacts on the natural ecosystem and the aquifer environment, (Haque et al, 2012; and Onodera et al, 2011).

Groundwater resources are currently experiencing significant stress due to a confluence of factors, including population expansion, urban sprawl, intensified agricultural practices, and industrial activities. Meeting the rising demand for water with the existing groundwater reservoirs poses considerable challenges, (Gosh et al, 2022).

Specifically in Pakistan, the contribution of groundwater to the overall irrigation water supply has shown a substantial increase, rising from a mere 8% in 1960 to a significant 60% in 2010. This shift can be attributed to the continuous expansion of cultivated lands. However, this trend comes at the cost of an annual decline of 2–3 meters in the water table, primarily resulting from the continuous extraction of fresh aquifers to fulfill domestic and agricultural water requirements, (Arshad et al, 2020).

Pakistan stands out as the third-largest global consumer of groundwater and the fourth-largest extractor. The annual groundwater withdrawal in Pakistan is estimated at 65 billion cubic meters (BCM), while the sustainable annual groundwater resources in the region are assessed at estimated at 55 BCM, (Qureshi et al, 2020). This scenario is notably mirrored in Islamabad, where the population has surged from an estimated 80,000 in the 1998 census to 2 million in the most recent census, while the groundwater sources remain largely unchanged from the 1990s.

The combination of Geographic Information System (GIS) and Remote Sensing (RS) represents a swifter and more cost-effective approach to gather data and identify potential recharge sites for natural aquifers. This methodology involves the preparation of various maps that capture influential factors relevant to groundwater recharge sites, (Singh et al, 2019).

When integrated with traditional survey maps, remote sensing data proves to be an invaluable tool for pinpointing groundwater recharge zones, (Chowdhury et al, 2010). This approach not only offers extensive spatio-temporal observations but also enables the characterization of surface features, including lineaments, geomorphology, drainage patterns, and lithological properties, (Arshad et al, 2020; and Tweed et al, 2007).

1.2 Climate Change and Ground Water

Climate change introduces uncertainties into the management and availability of water resources, with the Intergovernmental Panel on Climate Change (IPCC) reporting a global mean surface temperature increase of $0.6 \pm 0.2°C$ since 1861 and projecting a potential increase of 2 to 4°C over the next century. These rising temperatures have a direct impact on the hydrologic cycle, leading to increased evaporation of surface water and transpiration from vegetation. Consequently, these changes can alter precipitation patterns, timing, intensity, and indirectly affect the movement and storage of water in various surface and subsurface reservoirs, including lakes, soil moisture, and groundwater, (Kumar et al, 2012).

The significance of the nexus between groundwater and climate change cannot be overstated. Groundwater, which constitutes a substantial portion of the Earth's freshwater resources, estimated at between 13% and 30%, plays a crucial role in mitigating the effects of droughts due to its substantial storage capacity and relative resilience to climate fluctuations compared to surface water bodies, (Dragoni and Sukhija 2023).

Groundwater, a vast subterranean reservoir of water, holds immense importance for both human needs and ecosystems. It serves as the source of over one-third of the world's water consumption, with approximately two billion people relying on groundwater for their drinking water supply. Nonetheless, the longevity and viability of global groundwater reserves encounter challenges arising from both human interventions and the less familiar repercussions of climate fluctuations. The emergence of dissolved trace elements in groundwater can be predominantly attributed to chemical weathering procedures and the introduction of anthropogenic elements., (Barberi et al, 2021).

1.3 Literature Review

The amalgamation of Geographic Information System (GIS) and Remote Sensing (RS) techniques presents an efficient and rapid approach for identifying natural aquifer recharge (NAR) sites. This process involves the creation of diverse maps encompassing influential factors relevant to groundwater recharge sites, (Singh et al, 2019). Notably, despite extensive literature reviews, it has been observed that there is a dearth of comprehensive, contemporary analysis techniques that integrate GIS, RS, and Multi-Criteria Decision Analysis (MCDA) for the investigation of suitable NAR sites, (Rahman et al, 2012).

Jamilu et al. (2018) highlight that the advent of geospatial technology has revolutionized groundwater resource management, offering a cost-effective and timely means of analysis, even in inaccessible regions.

Ahmed & Shabana (2020) exemplify the utilization of remote sensing and geospatial techniques, combined with on-ground data, for the evaluation, delineation, and validation of potential groundwater sites in Wadi El Tarfa, Egypt. They incorporate various factors, including lineaments, Stream network, population density and stream networks, to generate GIS and RS-based maps. The resulting potential maps delineate three zones of suitability, comprising 25% high, 69% moderate, and 6% low suitability for the study area. These results underscore the effectiveness of remote sensing and geospatial techniques in this context.

Hammami et al. (2019) emphasize that Multi-Criteria Decision Analysis (MCDA) methodologies have emerged as valuable tools for addressing complex decision-making challenges across diverse research domains. MCDA integrates various criteria, encompassing technological, environmental, and socioeconomic factors, to facilitate well-informed decision-making.

Rahmati et al. (2014) highlight MCDA as a valuable tool applied by numerous researchers to enhance their groundwater resource management capabilities. Particularly in data-scarce and arid regions, where groundwater resource management faces numerous complexities and challenges, MCDA provides valuable insights for planners.

In the study by Arshad et al. (2020), various datasets, including remote sensing data, conventional data from existing maps, and ground observations, were employed to create thematic layers. These thematic layers, based on expert opinions and existing literature, were developed to explore their correlation with groundwater potential recharge and vulnerability.

In their study conducted in Punjab, Pakistan, Arshad et al. (2020) employed the Analytical Hierarchy Process (AHP) and the Probability Frequency Ratio technique to identify potential recharge zones. They assigned weights to various thematic layers based on existing literature and subsequently overlayed the resulting maps. The outcomes revealed that approximately 53% of the area exhibited very low recharge potential, while 22% demonstrated moderate potential, and 25% was classified as having high recharge potential.

In a study conducted in New Zealand, Singh et al. (2019) adopted a comprehensive GIS-based approach to delineate groundwater recharge zones. Their methodology incorporated local factors such as land use/land cover, slope, lithology, soil composition, drainage patterns, and drainage density within a raster dataset to derive potential groundwater recharge sites. The resulting map indicated low recharge potential in mountainous regions and urban areas, while the highest potential was observed in lower plain areas and near large lakes.

M. Kumar et al. (2021) also harnessed GIS and RS techniques in their study and highlighted the cost-effectiveness, time efficiency, and responsiveness of GIS and RS in yielding valuable results.

In research conducted in the Korba aquifer in northeastern Tunisia, Zghibi et al. (2020) addressed groundwater decline by integrating the AHP method with Multi-Influencing Factors (MIF) to map groundwater recharge zones. The AHP analysis revealed that approximately 69% of the area exhibited good groundwater recharge potential, while the MIF findings indicated that 80.7% of the area was suitable for recharge zones.

In a study conducted by Shao et al. (2020), the Analytical Hierarchy Process (AHP) technique was employed to pinpoint suitable recharge sites. This research incorporated a range of influential factors affecting recharge, including streams, drainage, slope, elevation, land use/land cover, and geology. Subsequently, a weighted overlay analysis was conducted within the GIS environment. Identifying appropriate sites for natural aquifer recharge zones is crucial for strategically addressing groundwater crises, as the process is primarily influenced by both human activities and natural phenomena occurring on the ground and within aquifer systems, as highlighted by Zghibi et al. (2020).

Manap et al. (2012) introduced the Probabilistic-Based Frequency Ratio (FR) method for the first time in the Langat basin of Malaysia to map groundwater potential. Their approach incorporated eight groundwater-related factors and 68 groundwater data points with high potential yield values. A random split of groundwater data into 70% for model training and 30% for validation demonstrated an impressive area under the curve (AUC) of 84.78% in the frequency model, indicating its effectiveness in mapping groundwater potential.

In research by AL-Shammari et al. (2021), they utilize Multiple-Criteria Decision-Making (MCDM) methods to discern locations suitable for aquifer recharge and to determine cost-effective infrastructure for replenishing groundwater resources. This study focused on local features, including slope, geology, runoff, drainage density, water table, and land use/land cover. Weightings were assigned to thematic layers based on expert judgment. The results pinpointed six optimal sites for aquifer recharge, highlighting areas with sandy and loamy soils and barren land with slopes of less than 10% as highly suitable for recharge.

In emphasizing the scientific significance of their modeling efforts, Rahmat et al. (2015) underscored the critical importance of validation. To assess the accuracy of the Groundwater Potential Maps (GPMs) produced, the Receiver Operating Characteristics (ROC) curve was applied, with validation data drawn from groundwater well locations. This rigorous validation process ensured the reliability and precision of the generated GPMs.

1.4 Problem statement

Pakistan is poised to confront severe water stress, with projections indicating that by 2040, it will become the most water-stressed country in the region, as indicated in the study by Maddocks et al. (2015). Alarming predictions from the Pakistan Council of Research in Water Resources (PCRWR) in May 2018 foretold a grim scenario, suggesting that the nation could face a dearth of clean groundwater by 2025. Presently, access to clean drinking water is a privilege for only 20% of the population, leaving a staggering 80% reliant on contaminated water sources within Pakistan, (Alam et al, 2022).

Disturbing trends in Islamabad, as reported in a local newspaper (DAWN, 20 Dec 2018), reveal that the water table has plummeted five times over the past five years. This alarming depletion underscores the finite nature of groundwater as a resource, necessitating immediate and well-considered strategies and planning to secure a sustainable future.

1.5 Objectives

The objectives of the study are:

a) Assessment and mapping of ground water potential zones using Frequency Ratio and Analytic Hierarchy Process.

b) Devise suitable mitigation strategies for the planning and conservation of ground and surface water.

Chapter 2

MATERIALS AND METHODS

2.1 Study Area

Islamabad, the federal capital of Pakistan, is encompassing a total area of 906 square kilometers, (Pakistan bureau of statistics). Positioned on the Potohar Plateau in the northwestern region of Pakistan, Islamabad's geographical coordinates range between 33° 28′ 01″ and 33°48′36″ north latitude, and 72°48′36″ – 73°24′ 00″ east longitude, as illustrated in Figure 2.1. The city is partitioned into five primary zones, with Zone IV being the most extensive in terms of land area, and Zone I serving as the largest developed residential area.

Islamabad's elevation varies between 457 to 610 meters above mean sea level (Facts & Statistics - Islamabad, n.d.). Within Zone 1 of Islamabad, sectors play a significant role in urban planning. Each residential sector is identified by an alphanumeric code and spans approximately 2 km × 2 km. The urban area covers roughly 220 square kilometers, while the rural area extends over 466 square kilometers, with an additional 220 square kilometers designated as parkland (Sohail et al., 2019).

Nestled in the Soan River basin, Islamabad is significantly impacted by the confluence of two significant rivers, the Kurang and the Soan, in conjunction with the presence of four perennial streams: Gumrah Kas, Bedarwali Kas, Tanawala Kas, and Nala Lei. Furthermore, the hydrological dynamics of this area are further influenced by the presence of three reservoirs, namely Khanpur, Simili, and Rawal Dams.The primary surface water source is Simli Dam, with the remainder of the water demand being met through public tube wells distributed across Islamabad. Notably, the inflow to Simli Dam has been adversely affected by

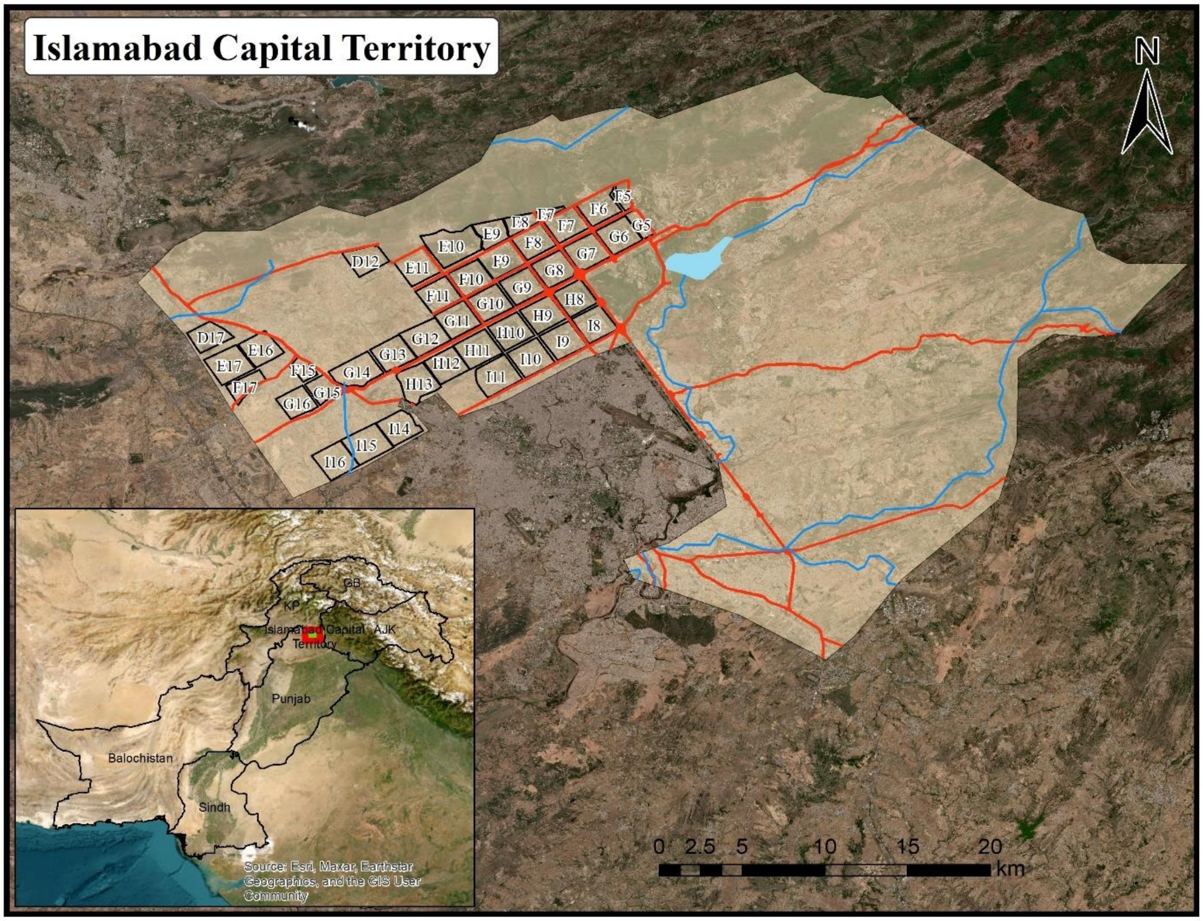

Figure 2.1. Study area map.

recent climate changes, leading to over-extraction of groundwater through tube wells and subsequently causing a decline in the groundwater table (Sohail et al., 2019).

The water supply network in Islamabad is sustained by four principal sources: streams, springs, reservoirs, and groundwater. Simli Dam serves as a crucial water supply reservoir for Islamabad city, while Rawal Lake caters to the water needs of areas beyond Islamabad's boundaries. The Capital Development Authority (CDA) has strategically installed approximately 200 tube wells to distribute water within Islamabad.

2.2 Data Sources

The identification of groundwater potential zones plays a critical role in assessing hydro resources. This decision-making process relies on multiple local factors, including topographical, environmental, technical, and economic considerations, (Xu et al, 2021). To support this evaluation, we employed a range of geospatial datasets.

The Study was initiated by procuring a Digital Elevation Model (DEM) with a spatial resolution of 30 meters through the US Geological Survey (USGS) website. This data source, recognized for its open-access nature and high-resolution imagery, served as the cornerstone for producing thematic maps that illustrate slope, drainage density, and lineament density. In parallel, we acquired Sentinel-2 imagery and subsequently conducted data processing within a Geographic Information System (GIS) environment. This imagery was purposefully employed for the examination of land use patterns and the development of a comprehensive land cover map.

In conjunction with remote sensing data, A critical ground-based component was introduced by conducting an extensive field survey. This comprehensive survey entailed the collection of groundwater table data, a process facilitated by leveraging data from Capital

Development Authority (CDA) tube wells. To augment our dataset, we accessed essential soil information from the Food and Agriculture Organization (FAO) Soil Portal, which boasted a spatial resolution of 250 x 250 meters. Additionally, we integrated population data for Islamabad, derived from the 2017 census and provided by the LandScan satellite, into our analytical framework. It is worth noting that this population data was available at a spatial resolution of 1 kilometer.

For a comprehensive overview of the data utilized in this study, please refer to Table 2.1, which succinctly outlines the various factors and data sources that underpin our investigative endeavors.

2.3 Selection of Factors

The process of factor selection plays a pivotal role in the delineation of groundwater potential zones, (Reghunath et al, 2020) and Xu et al, 2021). When deliberating upon these factors, careful consideration is given to their applicability within the research region. The choice of these factors is predicated on their substantive significance and the potential implications they may hold for the identification of recharge sites within the study area, (Buraihi and Shariff, 2015). It is important to emphasize that the selection of these factors is chiefly guided by the local context, devoid of any rigid constraints regarding the number of factors to be considered. To ensure a comprehensive and well-informed selection process, expert opinions are actively sought, and an exhaustive review of pertinent literature is undertaken.

In the present study, a meticulous approach led to the careful selection of nine local influencing factors, informed by expert input and a comprehensive examination of existing literature. These selected factors encompass slope, precipitation, land use and land cover (LULC), population density, lineament density, drainage density, soil texture, geology, and water table. It is worth noting that these factors have been recurrently employed in previous investigations pertaining to groundwater potential site assessments, (Chaudhary et al, 2016; Khudhair et al, 2020; Kumar et al, 2021; Sadaf et al, 2018; Shao et al, 2020; and Singh et al, 2019). The rationale underpinning their selection is firmly rooted in their pertinence to the local conditions prevailing within the study area, which encompasses the intricate natural terrain of Islamabad, marked by both hilly and flat landscapes. Collectively, these chosen factors encompass the physical attributes of the study area, forming the foundational basis for the identification of potential groundwater zones.

Table 2.1. Data sets used in the study.

Data	Source	Specification
Sentinel -2 4 June 2023	USGS	10 meters Spatial Resolution
Population Data	LandScan (2020) https://landscan.ornl.gov	1 Km Spatial Resolution
Water table	PCRWR, Field Survey	N/A
SRTM DEM	USGS	30 meters Spatial Resolution
Precipitation	Pakistan Meteorological Department (PMD)	Average Annual (Millimeter)
River Network	DIVA-GIS https://www.diva-gis.org/gdata	N/A
Geology Data	USGS https://certmapper.cr.usgs.gov/data/apps/world-maps/	Resolution 329*329 meter
Soil Data	FAO SOIL PORTAL www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco	Resolution 250*250 meter Depth: 30cm

2.4 Methodology

The research methodology employed in this study encompasses five integral components, which are visually represented in Figure 2.2, offering a graphical illustration of the process involved in the identification of groundwater potential zones.

In the preliminary phase, a meticulous selection process was undertaken, carefully considering nine influential factors that hold relevance to the determination of groundwater potential zones. These factors encompassed a wide spectrum, including land use and land cover (LULC), slope, drainage density, lineament density, population density, precipitation, water table depth, soil texture, and geology. The subsequent phase of the methodology centers on data preprocessing and the subsequent generation of thematic maps for each of these identified factors. This step lays the groundwork for further analysis and serves as a crucial preparatory stage in the overall research process. Moving on to the third phase, the Analytic Hierarchy Process (AHP) is employed for the assignment of weights to these factors and the subsequent normalization of these weights. The fourth stage involves the reclassification of all thematic maps into five distinct classes: "not suitable," "less suitable," "moderate," "suitable," and "most suitable." Each class is assigned specific weights based on its significance and relevance to potential zones. Following an assessment of the local factors' importance, the Frequency Ratio technique is applied to identify potential zones. Finally, in the fifth phase, an accuracy assessment is conducted using the Area Under Curve (AUC) technique. This assessment is performed on the resulting suitability maps to evaluate their accuracy and reliability.

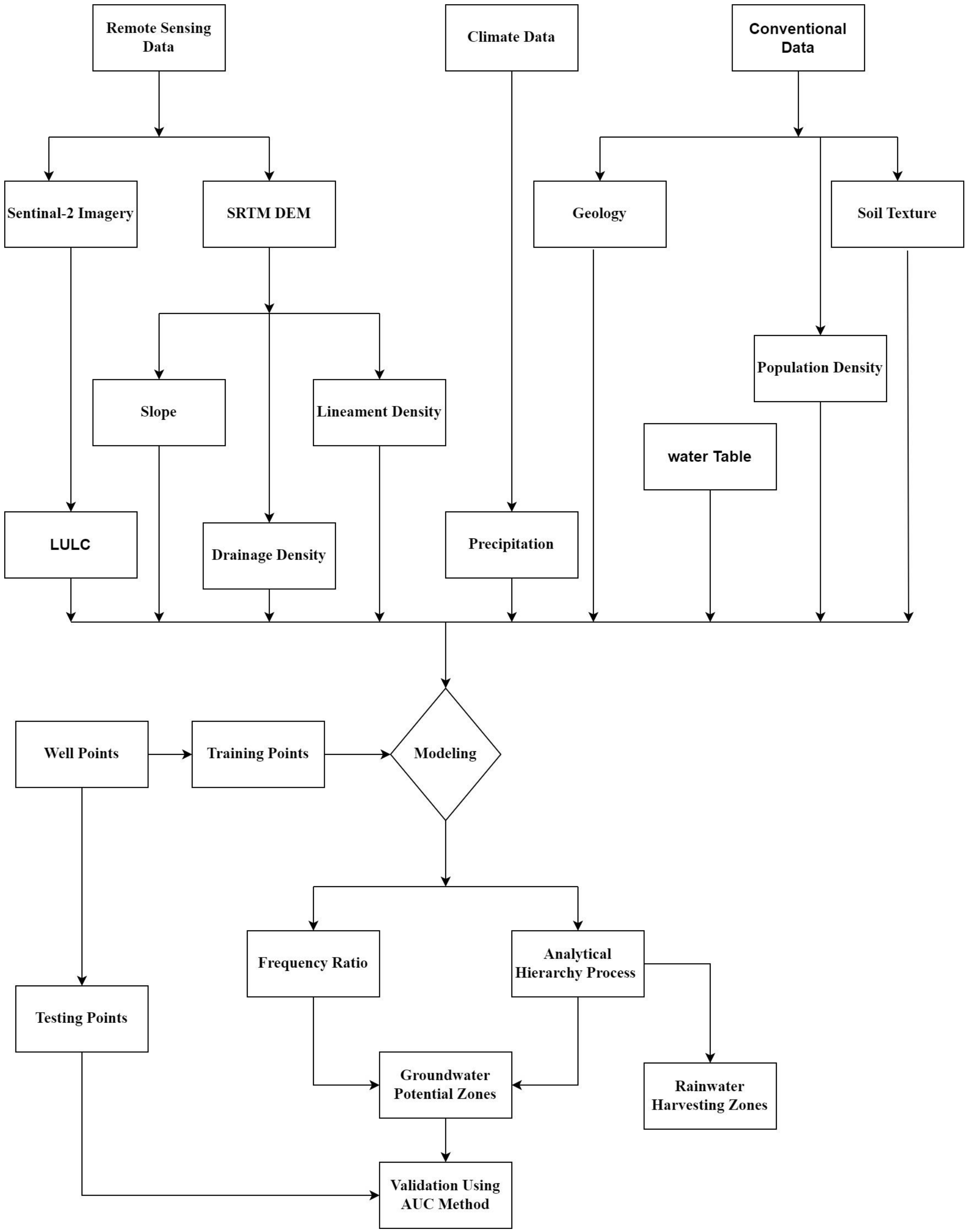

Figure 2.2. Methodology flow chart.

2.5 Preparation of Thematic Maps

Land use and land cover maps were crafted utilizing satellite imagery data, as outlined in Table 2.1. The generation of slope and lineament density maps involved the processing of Digital Elevation Model (DEM) sourced from the Shuttle Radar Topography Mission (SRTM). From the same DEM dataset, initial steps were taken to delineate streams and drainage lines, and subsequently, the drainage density was calculated.

For the creation of the soil texture map, pertinent data were collected from the Soil Portal of the Food and Agriculture Organization (FAO). This data source was instrumental in generating the soil texture map used in our study.

The soil data, with a spatial resolution of 250 x 250 meters, underwent further processing to create a thematic layer. Additionally, a thematic map for the study area was generated by utilizing population density data derived from the LandScan dataset, which encompasses census data from 2017. To construct a thematic map for potential groundwater zones, observations from tube wells were utilized. These tube wells data were transformed into a spatial map using kriging techniques.

The land use and land cover map of Islamabad was generated by applying supervised classification to Sentinel-2 imagery, which boasts a 10-meter resolution. Subsequently, these maps were reclassified, ranked, and assigned weights through the Analytical Hierarchy Process (AHP), based on their respective influences on groundwater recharge.

2.6 Specification of Selected Factors

Thematic maps representing the chosen factors were initially created. Subsequently, these maps underwent reclassification, ranking, and weight assignment through the Analytical Hierarchy Process (AHP).

Regarding the Frequency Ratio (FR) analysis, water pixels were calculated for each subclass within the layers. This computation employed a probabilistic approach and involved applying a 300-meter buffer around the tube wells.

2.6.1 Water Table

The depth at which the water in the aquifer is found, known as the water table depth (Salar et al., 2018), serves as a significant parameter. Many researchers utilize water table depth as an indicator to assess the groundwater storage capacity (Xu et al., 2021). In the case of Islamabad, the groundwater depth varies across a range from 0 meters to 130 meters.

To collect data on the water table depth, a field survey was conducted, encompassing a total of 170 CDA tube wells, along with the inclusion of data from commercial tube wells. Subsequently, the water table map was categorized into five distinct groups based on depth: (1) less than 53 meters, (2) 54-67 meters, (3) 55-79 meters, (4) 80-97 meters, and (5) 98-130 meters, as visualized in Figure 2.3. It is essential to note that areas with higher water table depths offer a greater potential for storage capacity. Conversely, in regions with shallower water table depths, soil pore spaces tend to be already saturated, resulting in limited opportunities for water percolation into the aquifer.

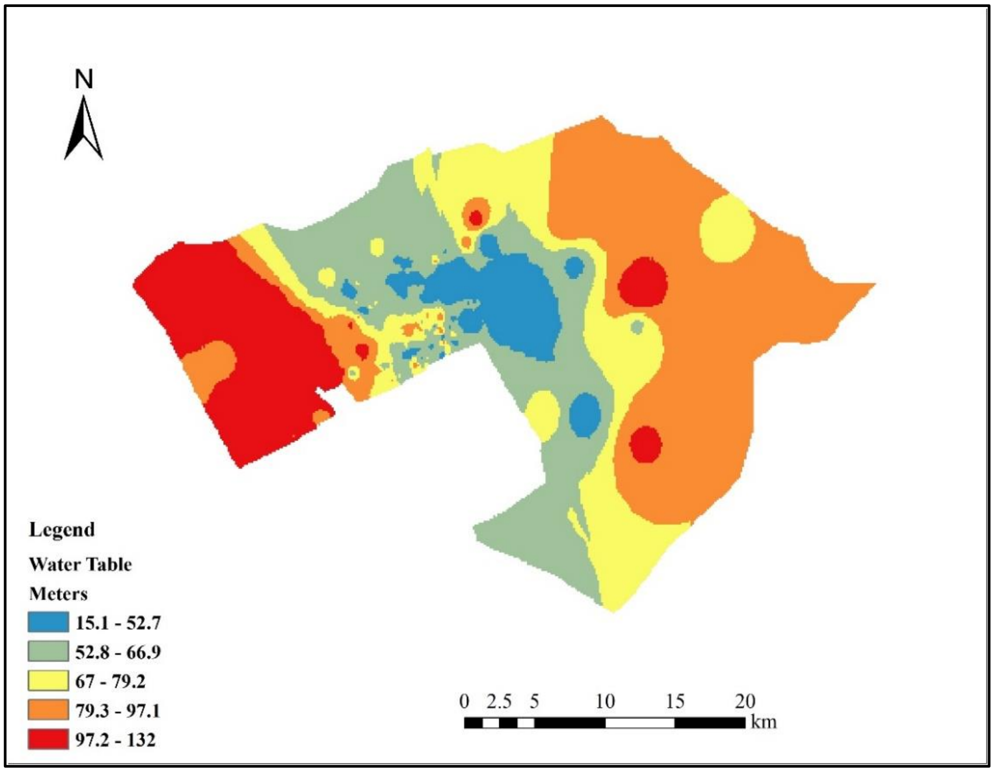

Figure 2.3. Ground water table map of Islamabad.

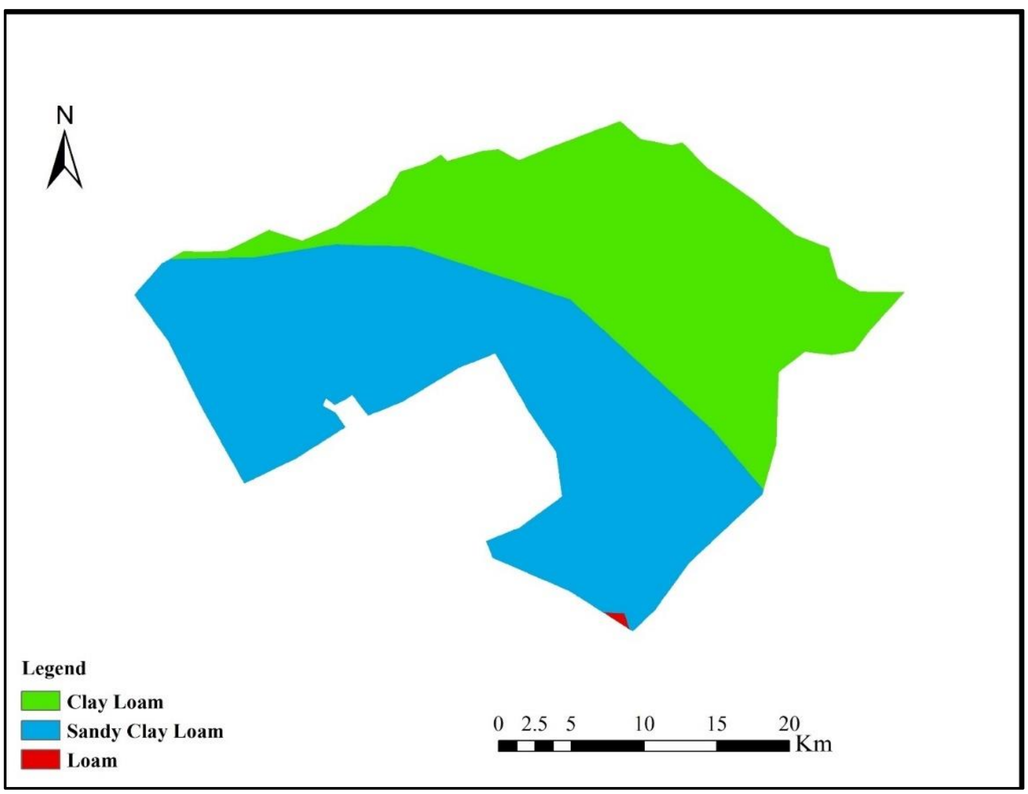

Figure 2.4. Soil Texture map.

2.6.2 Soil Types Map

Soil types significantly influence natural aquifer recharge by affecting processes like infiltration and percolation, as highlighted by Zghibi et al. (2020). In our study area, the soil map was categorized into three primary classes based on their permeability characteristics: sandy clay, loam, and clay loam, as illustrated in Figure 2.4.

Sandy clay, with its high penetration capacity, was accorded greater significance due to its substantial potential for influencing recharge. Conversely, loam and clay loam, characterized by lower infiltration rates, were assigned a comparatively lower impact on recharge in our analysis.

2.6.3 Population Density Map

As population numbers rise, there is a corresponding increase in the potential for interference with and overexploitation of groundwater resources, as emphasized by Parizi et al. (2020). Population density not only serves as a significant factor but also represents a major contributor to the depletion of groundwater resources. It's worth noting that there exists an inverse relationship between population density and groundwater recharge, whereby densely populated areas play a diminished role in aquifer recharge, as outlined by Döll (2009).

In our study, a population density map was generated using Landscan data, as depicted in Figure 2.5. This map was further categorized into five distinct classes, each representing a range of population density: (1) 0-41 persons per square kilometer, (2) 42-150 persons per square kilometer, (3) 160-410 persons per square kilometer, (4) 420-930 persons per square kilometer, and (5) 940-2000 persons per square kilometer.

2.6.4 Slope

Slopes play a direct role in shaping the dynamics of runoff and infiltration processes, as highlighted by Xu et al. (2021). In our study, a slope map was generated using Digital Elevation Model (DEM) data. Sloped terrains inherently possess the potential for groundwater recharge, with gently sloping lands being of particular significance due to their high infiltration capacity, resulting in minimal runoff. Conversely, areas with steep slopes typically exhibit lower permeability, exerting a reduced influence on recharge, as noted by Aluko & Igwe (2017). Steep sloped regions are often associated with hilly and mountainous terrains.

In our analysis, the Slope map was categorized into five classes based on weighted rankings: (1) 0°-4°, (2) 4.1°-9.5°, (3) 9.6°-18°, (4) 19°-27°, and (5) 28°-54°, as depicted in Figure 2.6.

2.6.5 Drainage Density Map

Many researchers routinely incorporate drainage density as a critical component in their investigations of potential recharge sites. Areas characterized by low drainage density are often densely vegetated, which augments permeability and porosity, leading to a higher capacity for infiltration. Conversely, regions with high drainage density tend to exhibit lower rates of recharge, as highlighted by Xu et al. (2021). Elevated drainage density contributes to increased runoff, whereas lower drainage density fosters reduced runoff, thereby enhancing the likelihood of recharge, as noted by Salar et al. (2018). The significance of drainage density lies in its pivotal role in governing water movement and recharge rates. It quantifies the portion of a watershed that is drained by the channels of streams, as described by Zghibi et al. (2020).

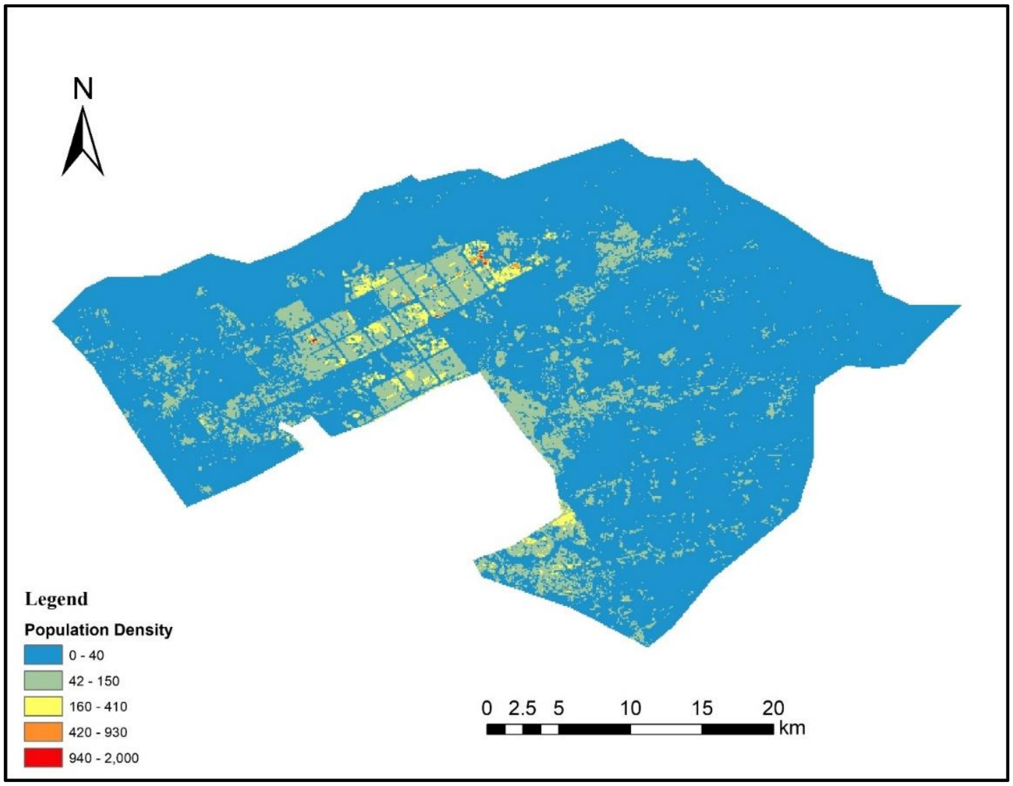

Figure 2.5. Population density map.

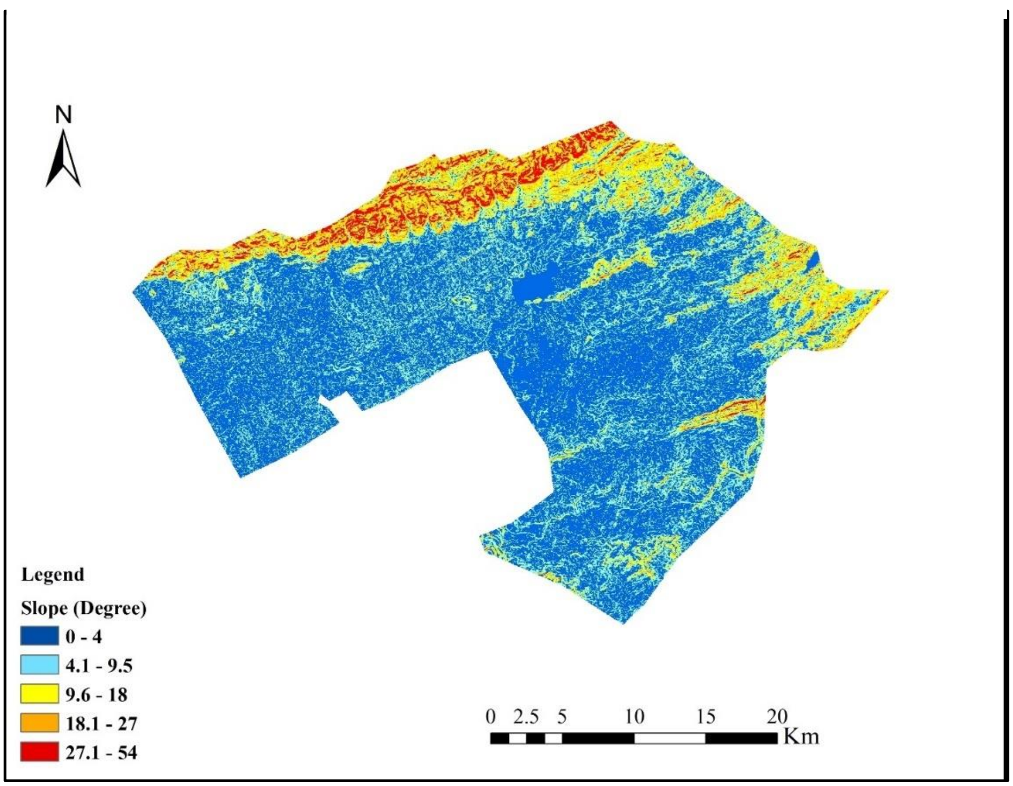

Figure 2.6. Slope map of study area.

2.6.6 Land Use Land Cover Map

The identification of groundwater potential zones is significantly influenced by Land Use and Land Cover (LULC) to a considerable extent. Land use and land cover play a substantial role in shaping the prospects for groundwater potential zones, as underscored by Ahmad et al. (2020). In this context, "land use" pertains to the various functions and activities within the study area, while "land cover" encompasses the representation of vegetation and other factors such as water bodies, terrain, soil, and paved surfaces, as described by Zaheer (2021).

In particular, the presence of vegetation and agricultural land is conducive to greater infiltration. In contrast, built-up areas tend to have a high runoff potential, rendering them unsuitable for groundwater recharge, as noted by Zghibi et al. (2020).

Our LULC map is categorized into six distinct classes, as illustrated in Figure 2.8. These classes include agricultural land, water, urban areas, dense vegetation, and light vegetation. Each of these classes has been assigned specific weights and ranked based on its influence on potential groundwater recharge zones.

2.6.7 Geology Map

The geological context of a region significantly influences surface runoff and infiltration patterns. Moreover, the presence and distribution of groundwater are notably contingent on the geological characteristics of an area, which directly impact its recharge potential.

For our study, geological data were sourced from the United States Geological Survey (USGS) portal, featuring a spatial resolution of 329 x 329 meters. The resulting geological map for the study area is visually depicted in Figure 2.9.

2.6.8 Precipitation Map

Within the research area, precipitation, primarily in the form of rainfall, stands as the predominant source of groundwater recharge and holds a pivotal role in the hydrological cycle. Rainfall serves to replenish the region's rivers while also governing the groundwater levels. It directly contributes to the potential for groundwater recharge, facilitating the storage of groundwater through the process of infiltration.

To compile our dataset, we gathered rainfall data from the Pakistan Meteorological Department (PMD).

2.6.9 Lineament Density

Lineaments play a significant role in generating both porosity and permeability, two crucial factors for groundwater recharge. In the studied area, the primary fractures align from north to south. To quantify this influence, the lineament density within the study area has been classified into five distinct categories, which are very low (0– 35 per square kilometer), low (36 - 70 per square kilometer), moderately low (71 - 100 per square kilometer), high (110 - 140 per square kilometer), and very high (150 - 170 per square kilometer), as illustrated in Figure 2.11.

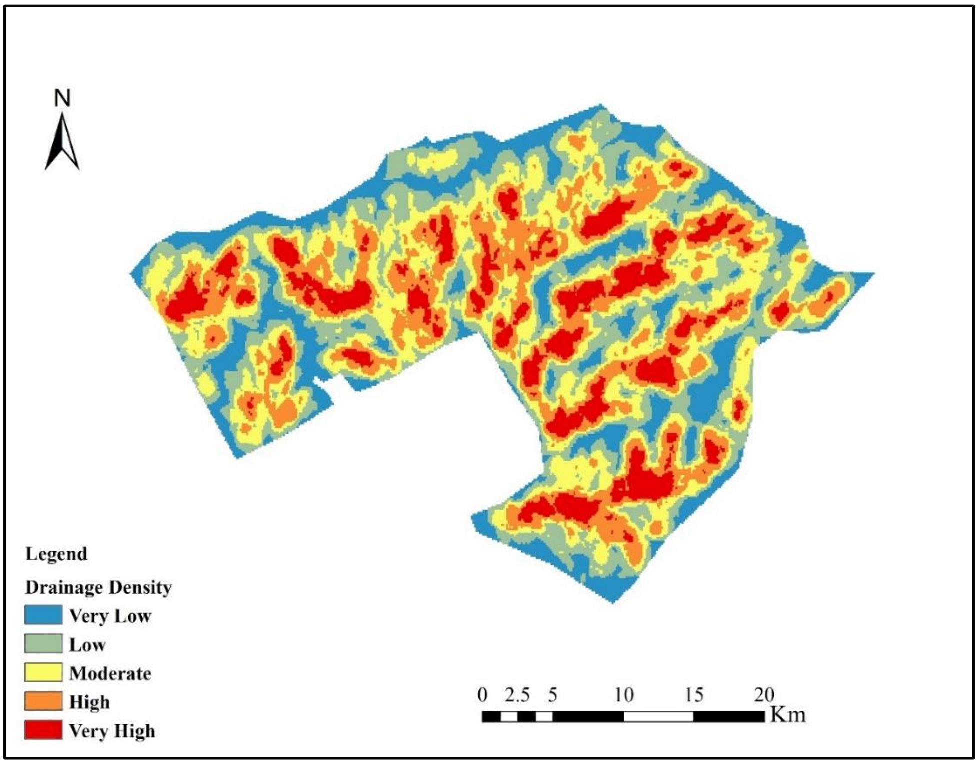

Figure 2.7. Drainage density map.

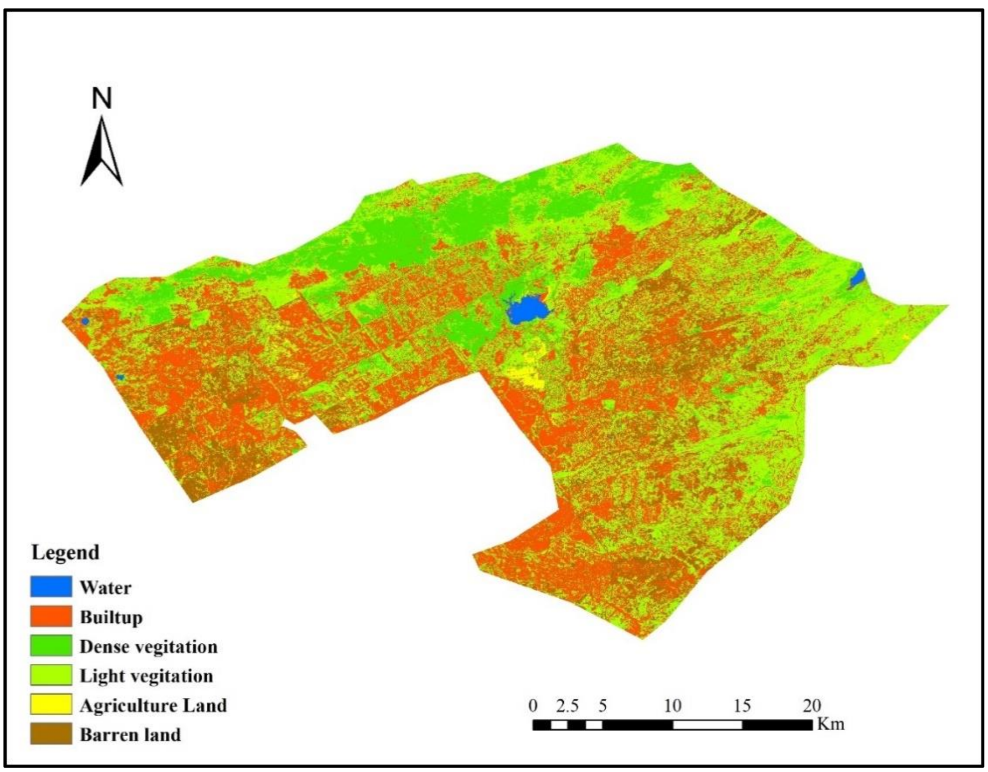

Figure 2.8.Land use landcover map.

It is noteworthy that areas characterized by high to very high lineament density exhibit substantial potential for groundwater development, signifying their suitability for this purpose.

2.7 Modelling Approach

Two most relevant and popular techniques were used to model the GWPZ namely AHP and FR.

2.7.1 Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP) has gained widespread popularity in various fields, including site selection, land use allocation, groundwater potential zone identification, and solid waste management, as highlighted by Lentswe & Molwalefhe (2020). AHP is a highly regarded decision-making technique employed for conducting pairwise comparisons among factors to assess and rank their respective levels of importance, as emphasized by Mahmoudi et al. (2021).

In our study, we have employed the AHP method, originally proposed by Saaty in 1980, to establish the weights for the selected factors used in the determination of Groundwater Potential Zones (GWPZ). In this approach, a pairwise evaluation matrix is constructed, mirroring an equal number of rows and columns to correspond with each factor under consideration. Subsequently, weights are assigned to these factors based on their perceived significance within the decision-making process.

In the context of this research, we employed a rating scale ranging from 1 to 7 to assess the relative importance of these factors and establish their prioritization. This numerical scale facilitates the assignment of values denoting the degree of importance, with 1 denoting equal importance and 7 indicating a high degree of importance. The rationale behind adopting this 1-7 scale is its alignment with the scale utilized in the weighted overlay tool as part of the ArcMap analysis, as previously highlighted by Shao et al. (2020).

To ascertain the relative weights within the normalized pairwise comparison matrix, we employed eigenvector calculations. The eigenvector was derived by dividing the values in each column by the sum of the values found in the respective column's average row. To evaluate the reliability of our comparison matrix.

The fidelity of the comparative matrix hinges upon the magnitude of the principal eigenvalue, which must meet or exceed predefined thresholds. For the sake of ensuring reliability, the consistency ratio should be equal to or less than 0.1. In this study, an Excel spreadsheet was employed for the computation of the consistency index (CI), as depicted in Equation 1, as well as the consistency ratio (CR), as demonstrated in Equation 2.

$$CI = \frac{\lambda\text{max} - \text{n}}{n - 1} \tag{1}$$

The Consistency Index (CI) is calculated using the formula provided, where 'n' signifies the count of factors under consideration, which stands at nine. The (λmax), indicating the principal eigenvector value, is determined by aggregating the cumulative weights allocated to these factors. It is of paramount importance to ascertain that the λ value surpasses or equals the number of factors encompassed in the investigation to ensure a dependable evaluation.

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

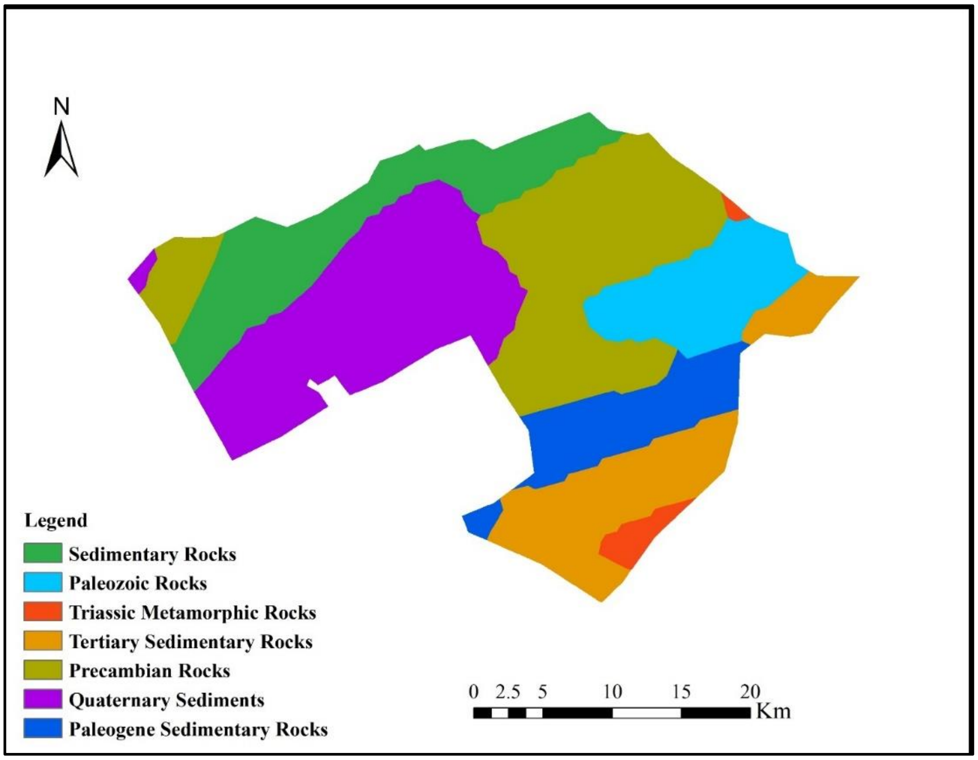

Figure 2.9. Geology map.

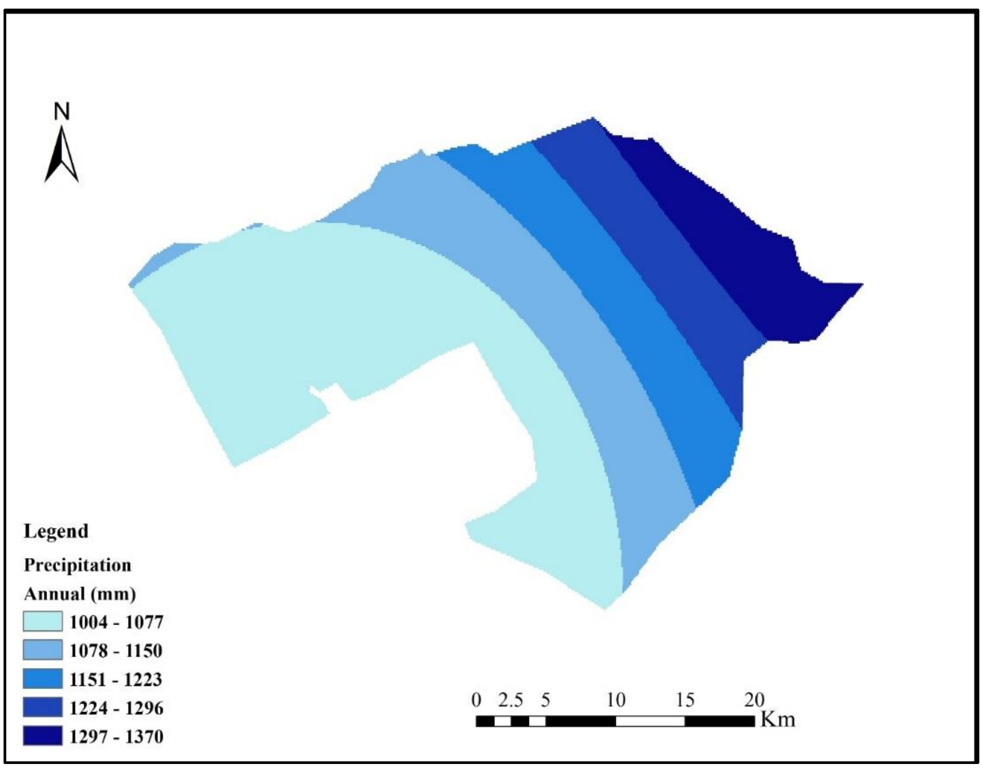

Figure 2.10. Rainfall map of study area.

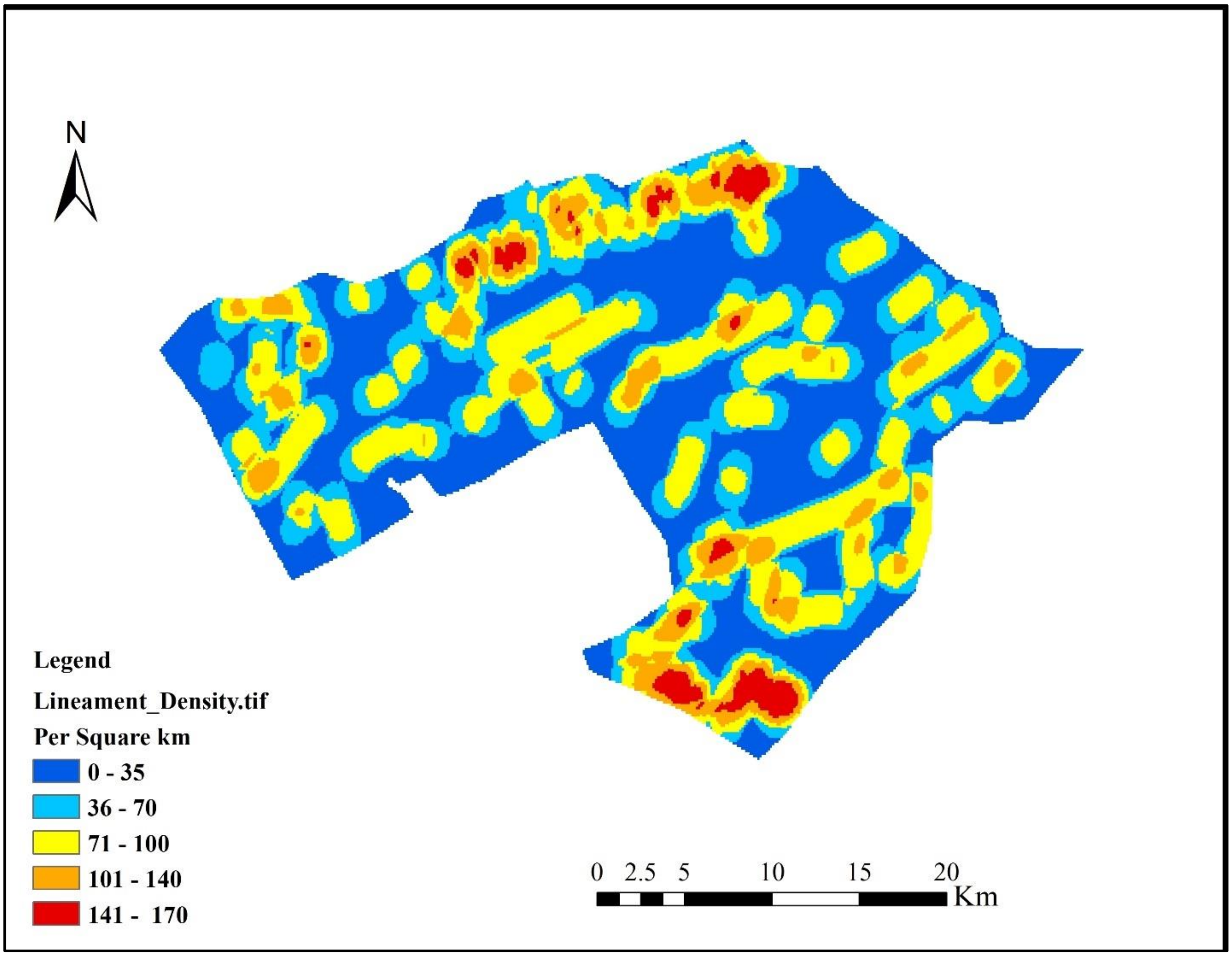

Figure 2.11. Lineament density map.

In our analysis, the Consistency Ratio (CR) plays a vital role. CR is compared against the Random Index (RI) to assess the consistency of the assigned weights. If the CR exceeds 0.10, it indicates that the assigned weights lack consistency and should be reevaluated or adjusted. Conversely, if the CR is below 0.10, it suggests a high level of consistency, affirming that the assigned weights are dependable and suitable for further analysis.

2.7.2 Frequency Ratio (FR)

The Frequency Ratio (FR) method stands as a straightforward and practical geospatial assessment tool designed to elucidate the probabilistic relationships between dependent and independent variables, including multi-classified maps, as highlighted by Rahmati et al. (2015). Its widespread use is owed to its rapid and easily computable approach, a point emphasized by Lee et al. (2012).

FR represents a bivariate statistical technique employed to assess the probability of groundwater potential zones. It operates by examining the connections between a dependent variable, such as wells, and independent variables, comprising various groundwater influencing factors, as detailed by Balamurghan et al. (2017). The FR calculation process is as follows:

$$FR = \frac{W/TW}{CP/TP} \quad (3)$$

In this Frequency Ratio (FR) model, we calculate the FR value for each class within a thematic factor. The FR value is derived using the formula provided, where:

- FR represents the frequency ratio associated with a specific class within the thematic factor.

- W signifies the number of pixels corresponding to well locations within that specific class of the thematic maps.
- TW denotes the total number of pixels representing well locations across the entire study area.
- CP represents the number of pixels within each class of the thematic layer.
- TP stands for the total number of pixels encompassing the entire study area.

2.8 Accuracy Assessment

In any modeling process, accuracy assessment constitutes a critical component, as emphasized by Bui et al. (2011). The Area Under Curve (AUC) method is a widely employed technique for accuracy assessment due to its comprehensive, logical, and easily interpretable validation approach, as highlighted by Nefeslioglu et al. (2010).

AUC values typically span a range from 0.5 to 1.0, where a value approaching 1.0 signifies the highest accuracy, whereas a value nearing 0.5 suggests a lack of accuracy in the model. To facilitate the interpretation of AUC values in terms of prediction accuracy, we categorized them into the following classes: 0.9–1.0 (excellent), 0.8–0.9 (very good), 0.7–0.8 (good), 0.6–0.7 (average), and 0.5–0.6 (poor). In our study, we assessed the success and prediction rate curves using the AUC method.

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Chapter 3

RESULTS AND DISCUSSION

3.1 Ground Water Potential Zones

Over the past four to five decades, groundwater, which is a replenishable resource, has experienced a significant reduction in recharge due to human activities and uneven development. Acquiring a comprehensive understanding of groundwater potential holds paramount importance for sound regional planning and sustainable development. This knowledge serves as a critical foundation when formulating and implementing strategies aimed at bolstering groundwater recharge mechanisms. In the context of our study, we estimated Groundwater Potential Zones (GWPZ) and subsequently categorized them into different levels, including poor, low, moderate, high, and very high groundwater potential zones.

3.1 GWPZ by AHP

The Saaty scale values, consisting of seven points, were assigned to each thematic map based on their perceived influence on groundwater potential. These values were determined through a combination of interviews, group discussions, and a review of relevant literature. A higher weight signifies a thematic layer with a greater impact on groundwater potential, whereas a lower weight indicates a lesser influence. In this Saaty scale of relative importance, a value of 7 represents an extremely significant influence, 6 represents a very strong influence, 5 represents a strong influence, 4 represents a moderately strong influence, 3 represents moderate importance, 2 represents a weak influence, and 1 represents equal importance. The assignment of scale values to each thematic layer factor was predicated upon their perceived significance within the framework of Groundwater Potential (GWP).

Our research outcomes indicate that approximately 42% of the surveyed area falls within the high to very high potential zones, while approximately 25% of the area is designated as poor to low potential, as depicted in Figure 3.2. Notably, the high to very high potential regions predominantly exist in areas characterized by gentle to moderate slopes, elevated lineament density, and reduced drainage density. Meanwhile, the moderate potential areas are in proximity to settlements, while the low to poor potential areas are found in areas with steep slopes or high population density, as depicted in Figure 3.1.

3.2 GWPZ by FR

To derive the Frequency Ratio (FR) values, we computed the number of pixels for each subclass within a parameter and determined the total number of groundwater pixels within each subclass of that parameter. Subsequently, we calculated the Prediction Rate (PR), which is a method of making informed predictions about future outcomes based on correlations between variables. The formula for the prediction rate is as follows:

$$PR = (Max\ RF - Min\ RF) MinRF \tag{4}$$

The Relative Frequency (RF) was computed by dividing the Frequency Ratio (FR) values for each class within a parameter by the sum of FR values for that particular parameter. Following this, each parameter was weighted by its respective PR (Prediction Rate) value. Subsequently, we employed this PR value to generate the groundwater potential map using the Raster Calculator within the ArcGIS environment.

Table 3.1. AHP Pairwise matrix.

Matrix		Rainfall	Geology	Slope	Drainage Density	LULC	Lineament Density	Soil	Population Density	Groundwater Table
	S. No	1	2	3	4	5	6	7	8	9
Rainfall	1	1	3	3	5	5	5	7	3	1
Geology	2	1/3	1	3	3	5	5	5	3	1
Slope	3	1/3	1/3	1	1	3	3	5	1	1
Drainage Density	4	1/5	1/3	1	1	1	2	3	2	1
LULC	5	1/5	1/5	1/3	1	1	1	3	1	1
Lineament Density	6	1/5	1/5	1/3	1/2	1	1	1	1	1
Soil	7	1/7	1/5	1/5	1/3	1/3	1	1	1	1
Population Density	8	1/3	1/3	1	1/2	1	1	1	1	1
groundwater Table	9	1	1	1	1	1	1	1	1	1

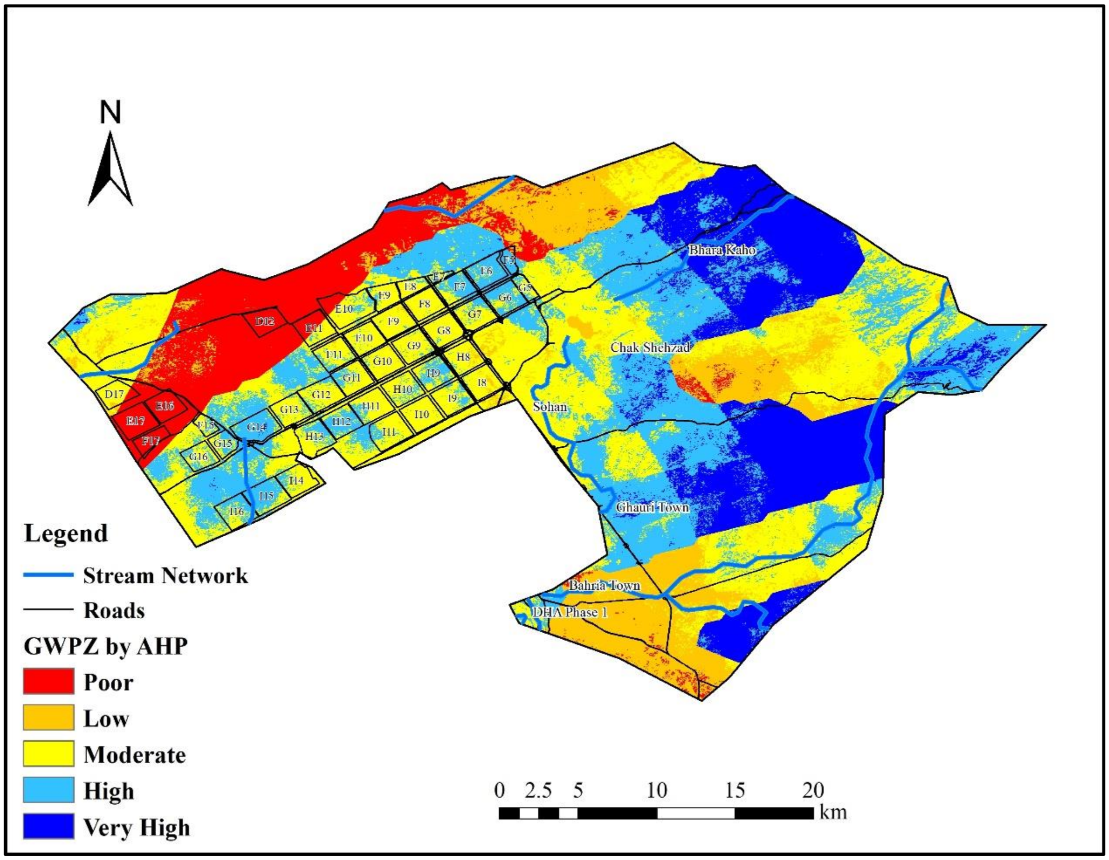

Figure 3.1.Ground water potential map by AHP.

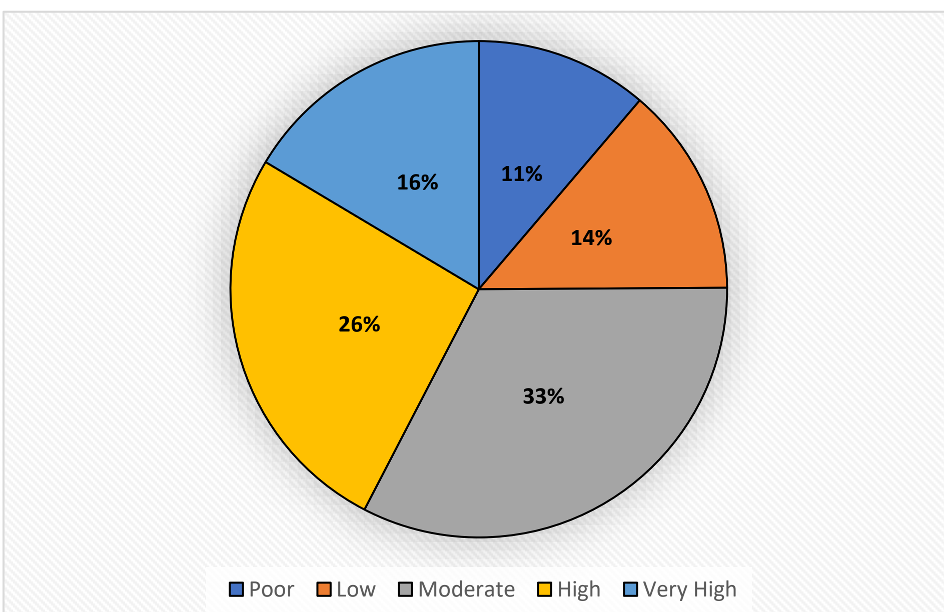

Figure 3.2. Percentage of GWPZ in study area.

values suggest a heightened probability of groundwater occurrence. Notably, slope exhibited the highest FR value at 0.69, closely followed by lineament density at 0.52, whereas soil (0.071) and population density (0.072) had the lowest FR values, as presented in Table 3.2.

Our findings indicate that 30% of the area falls within the high to very high groundwater potential zones, while 51% of the area is categorized as poor to low potential zones, as visually depicted in Figure 3.4. This distribution can be attributed to the limited presence of groundwater pixels in certain regions, which can pose challenges for the model in recognizing the presence of water.

3.3 Mitigation Strategies

For the study area, a range of strategies can be employed to enhance the recharge and preservation of surface and groundwater resources. These strategies include the implementation of a systematic rainwater harvesting system, improvement and maintenance of the sewage system, partial infiltration practices, the addition of more wells, and the construction of check dams and artificial lakes. Building small dams and artificial lakes stands out as a rapid and cost-effective approach. It not only supports long-term water recharge but also provides a stable water supply to vulnerable areas in Islamabad. This can effectively reduce groundwater extraction.

Partial infiltration, while a reliable method for groundwater recharge, faces challenges due to rapid urbanization, which reduces pervious surfaces and increases rainwater runoff instead of seepage. While regulations exist to address this issue, their enforcement is often lacking. It is crucial for the Capital Development Authority (CDA) to rigorously implement these rules during construction activities in Islamabad. This includes preserving open spaces, especially in urban areas, and promoting the maintenance of green belts and tree planting, which can facilitate infiltration.

Table 3.2. Calculations for FR model.

Sr. No	Parameter	Class	Class Pixels	Groundwater Pixels	Frequency Ratio	Prediction Rate
1	Slope (Degree)	0 - 4	265394.0	128378.0	0.5	1.9
		4.1 - 9.5	522533.0	96873.0	0.2	
		9.6 - 18	4288624.0	35516.0	0.0	
		19 - 27	2412508.0	14010.0	0.0	
		28 - 54	781530.0	5449.0	0.0	
2	Drainage Density	very low	1359897.0	15514.0	0.0	1.0
		low	1990542.0	40389.0	0.0	
		medium	2174037.0	64719.0	0.0	
		high	1806194.0	80731.0	0.0	
		very high	975367.0	78932.0	0.1	
3	Water Table (Meters)	15 - 53	586224.0	1262.0	0.0	1.6
		54 - 67	1872743.0	32046.0	0.0	
		68 - 79	1307867.0	41705.0	0.0	
		80 - 97	1593918.0	180819.0	0.1	
		98 - 130	2945285.0	24453.0	0.0	
4	Geology	Sedimentary	6164363.0	0.0	0.0	1.8
		Paleozoic	1248650.0	0.0	0.0	
		quaternary	639575.0	23590.9	0.0	
		tertiary	239963.0	0.0	0.0	
		precambin	17251.0	233.0	0.0	
5	Lineament(km^2)	0 - 35	688069.0	124310.0	0.2	1.4
		36 - 70	2241268.0	74553.0	0.0	
		71 - 100	210921.0	64408.0	0.3	
		110 - 170	5165779.0	10571.0	0.0	
6	LULC	Water	43655.0	12.0	0.0	1.4
		Built up	1164085.0	83325.6	0.1	
		Vegetation	2767643.0	23369.9	0.0	
		Fields	1201949.0	126535.8	0.1	
		Barren land	3135606.0	46925.8	0.0	

7	Population Density (/km^2)	0 - 44	525.0	0.0	0.0	1.3
		44 - 145	43061.0	0.0	0.0	
		145 - 372	28705.0	113.0	0.0	
		372 - 866	4524127.0	153698.0	0.0	
		866 - 1957	3714238.0	126407.7	0.0	
8	Precipitation (mm)	15 - 53	3632943.0	34975.0	0.0	1.1
		54 - 67	1742941.0	52771.0	0.0	
		68 - 79	905281.0	60889.0	0.1	
		80 - 97	1221363.0	41936.0	0.0	
		98 - 130	803509.0	89714.0	0.1	
9	Soil	Clay Loam	3688786.0	194369.1	0.1	2.0
		Sandy clay Loam	4613686.0	85912.6	0.0	
		Loam	7330.0	0.0	0.0	

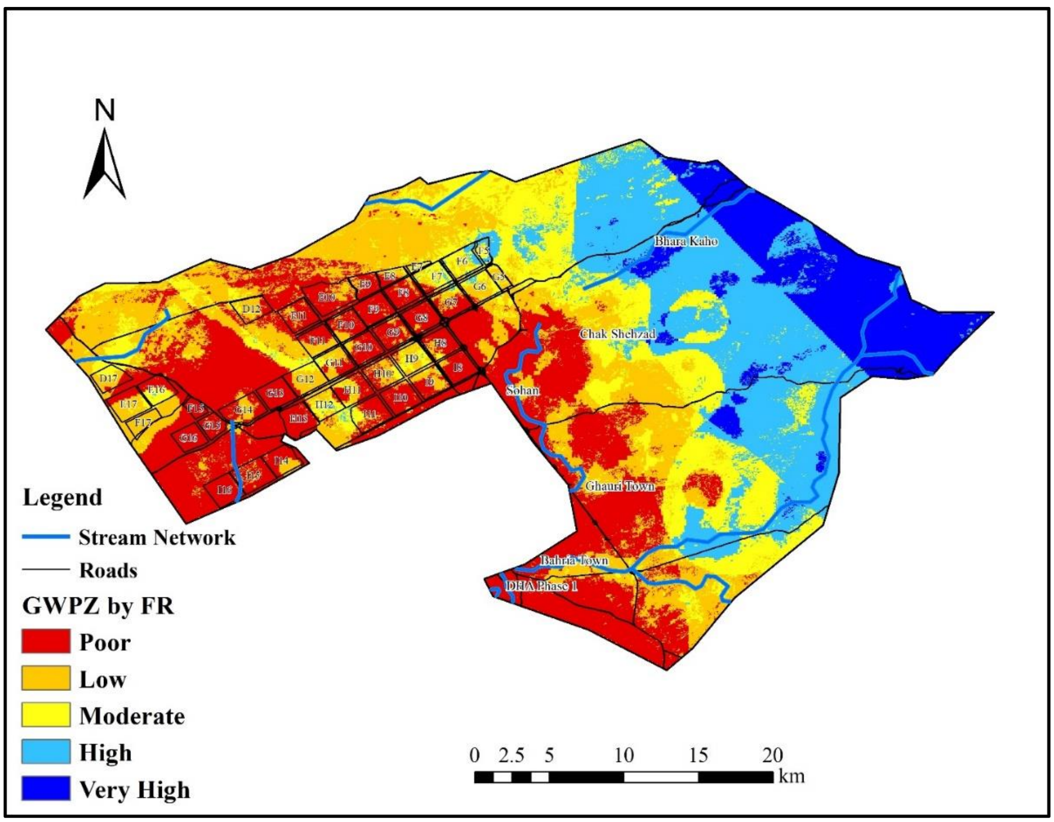

Figure 3.3. Ground water potential map based on FR model.

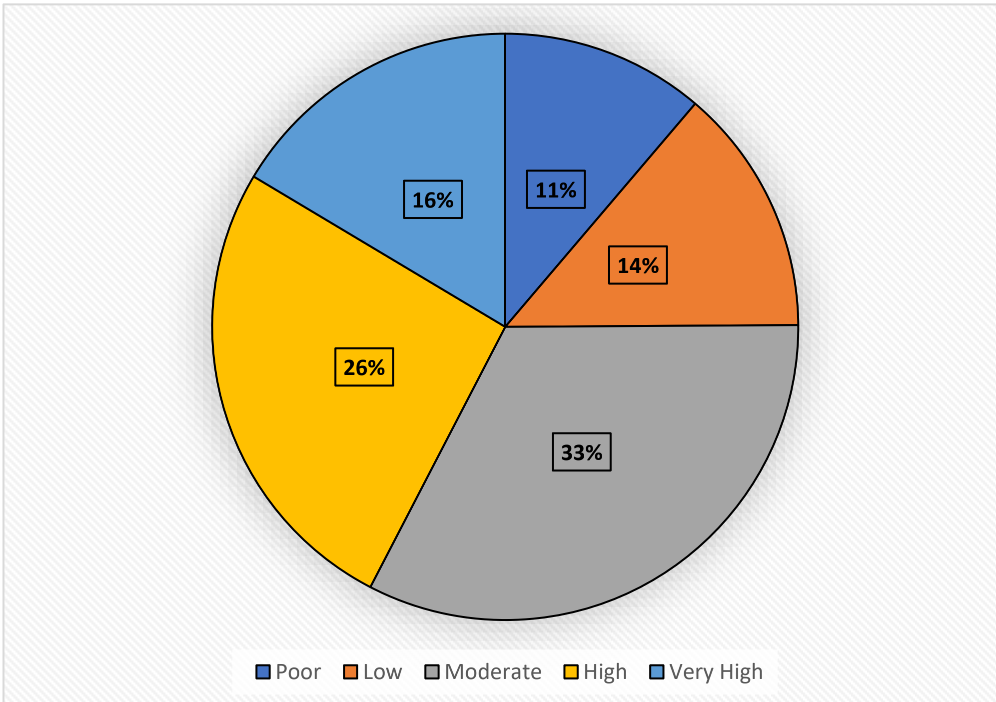

Figure 3.4. FR model based GWPZ percentage.

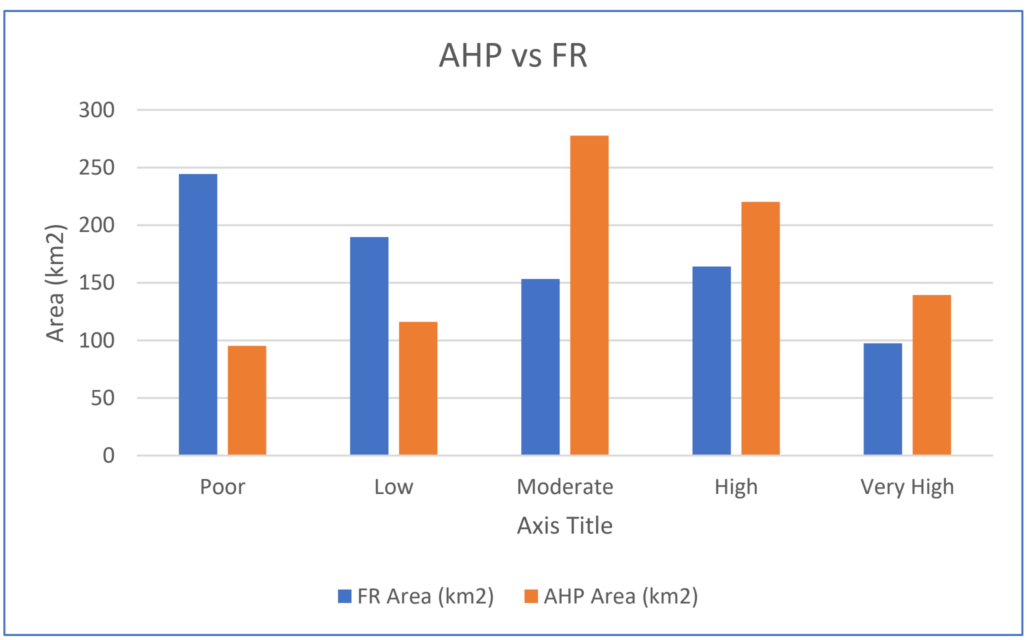

Figure 3.5. Comparison between AHP & FR outputs based GWPZ.

Rainwater harvesting is another dependable means of recharging and conserving groundwater. This strategy can be implemented both at the household and commercial levels. At the household level, small rainwater harvesting systems can be installed on rooftops to collect rainwater, which can serve as a secondary water source, reducing reliance on groundwater.

On a commercial scale, large structures can be constructed to collect rainwater, ensuring a consistent seepage for groundwater recharge. In our research, we identified potential rainwater harvesting zones using the Analytic Hierarchy Process (AHP) with six key factors affecting these zones: drainage, rainfall, slope, lineament density, soil type, and land use/land cover (LULC). Higher weightage was assigned to drainage and rainfall, while LULC received the least weight, as detailed in Table 3.3.

The resulting map was categorized into five classes, ranging from "not suitable" to "excellent." Suitable and excellent areas are typically situated near or along stream channels, which coincide with the regions of highest lineament density. In contrast, unsuitable and poor areas are often found in densely populated regions, leading to low infiltration rates and high runoff.

3.4 Accuracy Assessment

In the ArcGIS environment, the Area Under Curve (AUC) analysis was conducted using the ArcSDM toolbox, with the CDA well points data utilized for the AUC value calculations. The AUC graphs present three primary components: true positive, false positive, and the AUC curve. True positive corresponds to the ground-based data, which, in this study, comprises the well data. False positive represents the model's output, for which AUC values are being computed. The AUC graph serves as an indicator of the model's accuracy. The AUC technique generates two crucial outputs: success rates and prediction rates, contingent upon the presence of training points within each class.

The AUC values for the Analytic Hierarchy Process (AHP) and Frequency Ratio (FR) were found to be 75% and 64%, respectively, as depicted in Figures 3.7 and 3.8. These results highlight that the AHP method outperformed the FR method, with AHP achieving the highest AUC value at 0.74. This demonstrates that AHP is the most accurate and suitable approach for this study.

Table 3.3. Pairwise matrix for Rainwater Harvesting Zones.

Matrix		Drainage	Rain	Slope	Lineament Density	Soil	LULC
	S No.	1	2	3	4	5	6
Drainage	1	1	3	5	6	7	7
Rain	2	1/3	1	3	3	6	5
Slope	3	1/5	1/3	1	5	4	4
Lineament Density	4	1/6	1/3	1/5	1	1	3
Soil	5	1/7	1/6	1/4	1	1	1/3
LULC	6	1/7	1/5	1/4	1/3	3	1

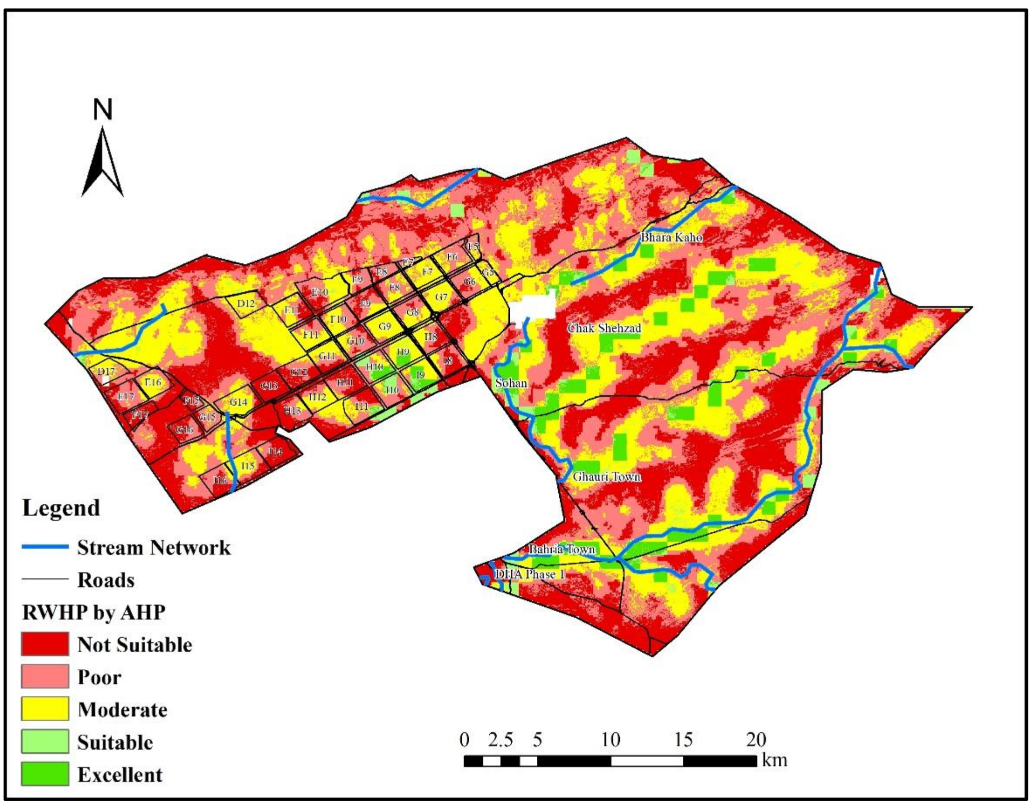

Figure 3.6. Potential rainwater harvesting zones.

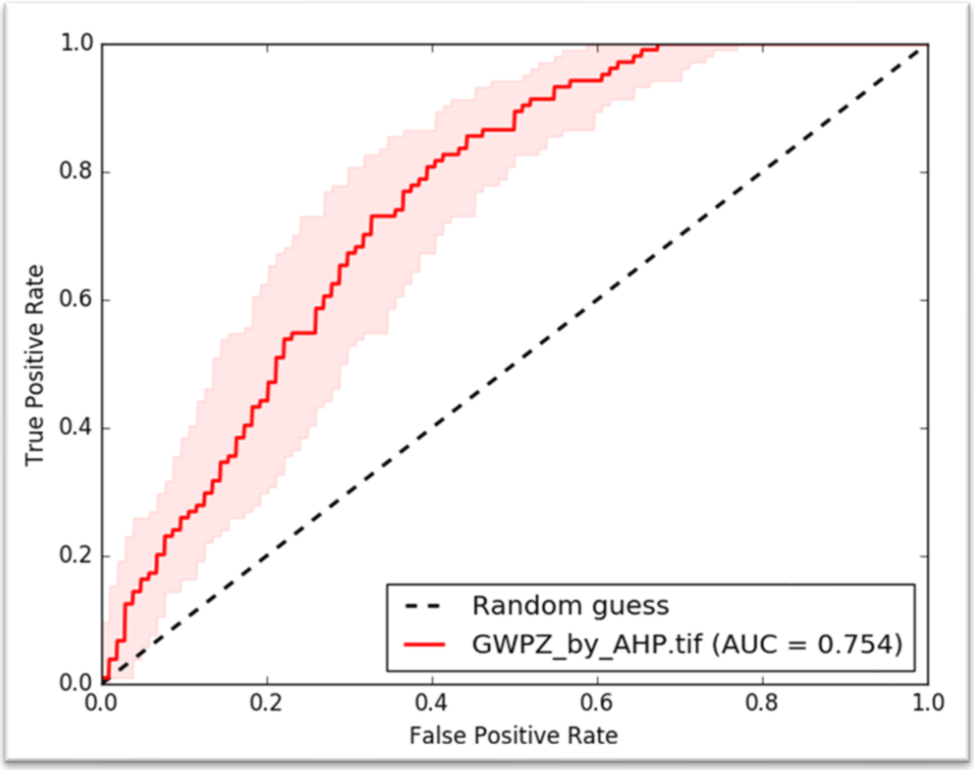

Figure 3.7. Accuracy assessment of AHP model.

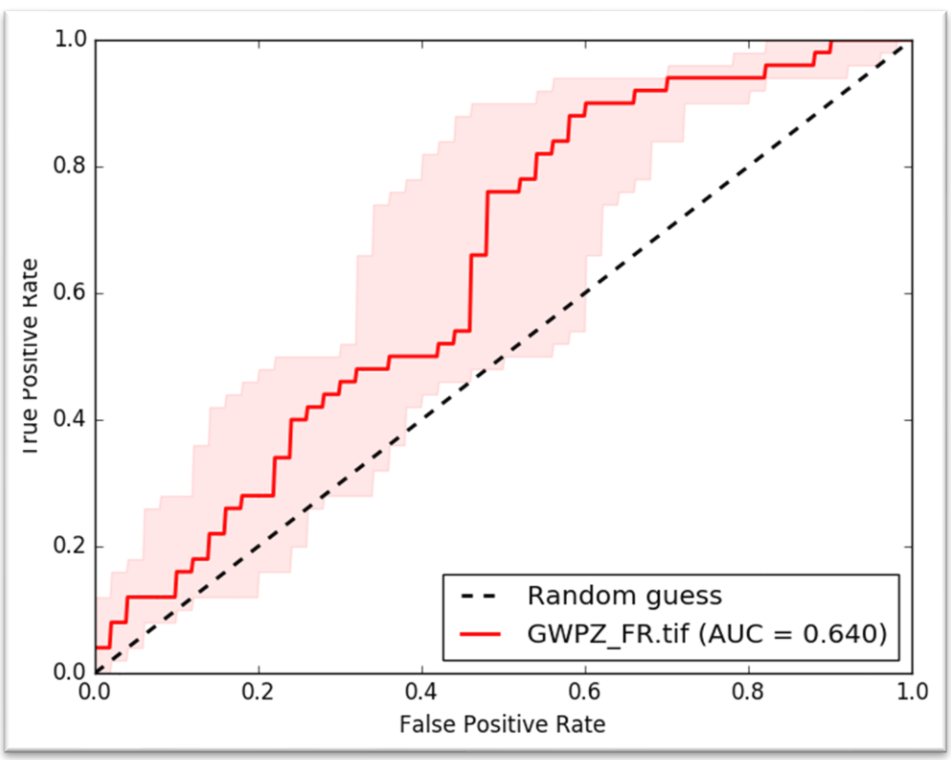

Figure 3.8. Accuracy assessment of FR model.

Chapter 4

CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

This research endeavors to tackle the urgent concern of accelerated groundwater depletion in Islamabad by employing RS and GIS techniques to pinpoint appropriate locations for groundwater recharge. The study effectively employs two established methodologies, namely the Analytic Hierarchy Process (AHP) and the Frequency Ratio (FR) methods, to identify and evaluate the potential zones for groundwater resources. Nine thematic layers, including Geology, Land Use and Land Cover (LULC), Soil, Rainfall, Lineament Density, Drainage Density, Slope, Precipitation, and Population Density, were integrated to delineate these potential zones. The resulting maps were categorized into five distinct zones: poor, low, moderate, high, and very high.

The suitability maps generated through this study highlight numerous potential sites for groundwater recharge. Specifically, the results indicate that 30% of the entire study area falls within the high to very high category when assessed using the FR model, while the AHP model designates 42% of the study area as high to very high potential zones.

In terms of model validation, it was evident that the AHP model outperformed the FR model, primarily because some inputs in the FR model were probabilistic in nature. Validation was conducted using the Area Under Curve (AUC) method, with AHP achieving an AUC value of 0.75, compared to 0.64 for FR.

Furthermore, the results indicate that the most suitable class covers a relatively small area compared to the suitable and moderate classes. This study underscores the effectiveness of RS, GIS, and Multi-Criteria Decision Making (MCDM) techniques in identifying groundwater potential zones. It also concludes that the AHP technique is a responsive, cost-effective, time-saving approach that conserves resources, including manpower, in the search for groundwater recharge locations.

Within the context of mitigating the prevailing groundwater challenges, a range of strategies warrants consideration. These encompass rainwater harvesting, partial infiltration techniques, the construction of artificial lakes and dams, enhancements to the existing sewerage infrastructure, the formulation of a wellhead protection plan, the installation of supplementary wells, and improvements to the existing development plan. In the pursuit of a sustainable and enduring solution, this study underscores the imperative of instituting a well-organized rainwater harvesting system aimed at groundwater recharge and preservation.

To facilitate the implementation of such a rainwater harvesting system, this research has generated a map delineating the zones with potential for rainwater harvesting. This map stands as a valuable resource, offering insights and aiding in the estimation and planning of the integration of rainwater harvesting practices. The insights and findings gleaned from this study provide crucial guidance to decision-makers, equipping them with the information needed to make informed decisions concerning the effective management and strategic planning of groundwater resources.

4.2 Recommendations

The primary data source for evaluating water table depth in this study was the dataset from CDA tube wells. To improve the precision of water table depth predictions across diverse locations, it is recommended to also integrate data from privately-owned tube wells and hand pumps. Furthermore, to enhance groundwater management practices, it is imperative for the Capital Development Authority (CDA) to rigorously enforce regulations that mandate the allocation of open, permeable spaces, especially within urban areas. Additionally, prioritizing the conservation of green belts and promoting tree planting initiatives should be given due importance to foster sustainable groundwater management.

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