ASSESSMENT OF GROUNDWATER POTENTIAL USING GEOGRAPHIC INFORMATION SYSTEM BASED MULTI CRITERIA DECISION ANALYSIS METHODS: CASE STUDY OF PANJ AMU RIVER BASIN, AFGHANISTAN

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ABSTRACT

ASSESSMENT OF GROUNDWATER POTENTIAL USING GEOGRAPHIC INFORMATION SYSTEM BASED MULTI CRITERIA DECISION ANALYSIS METHODS: CASE STUDY OF PANJ AMU RIVER BASIN, AFGHANISTAN

Afghanistan, where water is the most important resource for energy production and the economy. The country still struggles with access to clean drinking water, and its main supply of drinking water comes from groundwater. Unfortunately, not much is known about the country's groundwater system.

The assessment of groundwater potential and groundwater stability is crucial for sustainable water management, agricultural development, urban and rural water supply, and disaster mitigation. It supports environmental protection, economic development, public health, and conflict prevention by ensuring reliable and sustainable access to groundwater resources. In regions such as the Panj Amu River Basin, this identification is particularly important due to the high dependence on groundwater. Therefore, the thesis focuses on water budget, groundwater potential, availability, and the impact of various parameters on groundwater recharge of the PARB using the Analytical Hierarchy Process (AHP), Frequency Ratio (FR) and Evidential Belief Function (EBF) methods. Ten thematic layers including precipitation, geology, lineament density, drainage density, soil texture, land use and land cover, topographic wetness index, curvature, normalized difference vegetation index and slope gradient were used as influencing factors along with groundwater static level data, runoff and evapotranspiration for this research work. All geographic datasets were analyzed using the ArcMap environment and the required spatial data were obtained from various approved relevant online sources.

The water balance analysis for the Panj Amu River Basin indicates that 1.887 billion cubic meters' infiltrates into the groundwater system annually. The total annual groundwater consumption by humans, livestock and agricultural activities amounts to 808.19 million cubic meters. Consequently, the annual net groundwater budget in the basin is 1.078 billion cubic meters, suggesting that the groundwater system in the PARB is currently sustainable. All three methods indicate high groundwater potential in sparsely populated mountainous regions with high rainfall and permeable geology and soil conditions. The key regions include the northeast of Takhar, the east and southeast of Baghlan and the northwest and east (some parts of the Wakhan corridor) of Badakhshan have high groundwater potential. In general, the Panj Amu River Basin has moderate groundwater potential.

Area Under the Curve (AUC) and Receiver Operating Characteristic (ROC) analysis were used to validate the study. The results show that the EBF methods has the highest efficiency with an AUC of 92.6%, followed by the FR method with 91.5% and the AHP model with 80.2%.

Keywords: Groundwater Potential, GIS, Remote Sensing, Multi-Criteria Decision Analysis, Panj Amu River Basin

ÖZET

ÇOK KRİTERLİ KARAR ANALİZİ YÖNTEMLERİNE DAYANAN COĞRAFİ BİLGİ SİSTEMLERİ KULLANILARAK YERALTI SUYU POTANSİYELİNİN DEĞERLENDİRİLMESİ: PANJ AMU NEHRİ HAVZASI ÖRNEĞİ, AFGANİSTAN

Afganistan da su, enerji üretimi ve ekonomi için en önemli kaynaktır. Ülke hâlâ temiz içme suyuna erişim konusunda zorluk yaşamaktadır. Ülkenin ana içme suyu kaynağını yeraltısuları oluşturmaktadır. Ancak, ülkenin yeraltısuyu kaynakları hakkında yeterli bilgi mevcut değildir.

Yeraltısuyu kaynakları potansiyelinin değerlendirilmesi ve sürdürülebilir su yönetimi, tarımsal kalkınma, kentsel ve kırsal su temini ve afetlerin azaltılması açısından çok önemlidir. Yeraltısuyu kaynaklarına güvenilir ve sürdürülebilir erişim sağlanmasıyla çevrenin korunması, ekonomik kalkınma, halk sağlığı ve çatışmalar önlenebilir. Panj Amu Nehri Havzası (PANH) gibi bölgelerde, yeraltısuyuna olan bağımlılığın yüksek olması nedeniyle bu kaynakların özelliklerinin bilinmesi önemlidir. Bu tez kapsamında, PANH'nın yeraltısuyu potansiyeli, kullanılabilirliği ve çeşitli parametrelerin yeraltısuyu beslenmesi üzerindeki CBS, AHP, FR ve EBF yöntemleri kullanılarak değerlendirilmiştir. Bu çalışmada, yağış, jeoloji, çizgisellik yoğunluğu, drenaj yoğunluğu, toprak dokusu, arazi kullanımı, arazi örtüsü, topografik nem indeksi, farklı bitki örtüsü indeksi ve eğim dahil olmak üzere on tematik katman ile birlikte, yeraltı suyu statik seviyeleri, akış ve buharlaşma-terleme verileri kullanılmıştır. Tüm coğrafi veri setleri ArcMap programı kullanılarak analiz edilmiştir. Tüm veriler onaylanmış çevrimiçi kaynaklardan elde edilmiştir.

Panj Amu Nehir Havzası için yapılan su bütçesi, yeraltı suyu sistemine yılda 1,887 milyar metreküp sızdığını göstermektedir. İnsani tüketim, hayvancılık ve tarımsal faaliyetler tarafından tüketilen yıllık toplam yeraltı suyu miktarı 808,19 milyon metreküptür. Sonuç olarak, havzadaki yıllık net yeraltı suyu bütçesi 1.078 milyar metreküp olup bu da PANH'deki yeraltı suyu sisteminin şu anda sürdürülebilir olduğunu göstermektedir. Her üç yöntem de yüksek yağış alan, geçirgen jeolojik ve toprak koşullarına sahip seyrek nüfuslu dağlık bölgelerde yüksek yeraltı suyu potansiyeline işaret etmektedir. Kilit bölgeler arasında Takhar'ın kuzeydoğusu, Baghlan'ın doğu ve güneydoğusu ile Badakhshan'ın kuzeybatı ve doğusu (Wakhan koridorunun bazı kısımları) yüksek yeraltı suyu potansiyeline sahiptir. Eğri Altındaki Alan ve Alıcı Operatör Eğrisi (AUC-ROC) metodlarına göre, EBF metodu 92,6 ile en yüksek doğruluğa sahip olduğu, onu %91,5 ile FR'nin ve %80,2 ile AHP takip ettiği görülmüştür.

Anahtar Kelimeler: Yeraltısuyu Potansiyeli, CBS, Uzaktan Algılama, Çok Kriterli Karar Analizi, Panj Amu Nehri Havzası

To my cherished mother and my beautiful Husnak, with all my love!

TABLE OF CONTENTS

LIST OF FIGURES

Figure **Page**

Figure **Page**

LIST OF TABLES

Table **Page**

LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
AUC	Area Under the Curve
BCM	Billion Cubic Meter
CI	Consistency Index
CR	Consistency Ratio
DACAAR	Danish Committee for Aid to Afghan Refugees
DEM	Digital Elevation Model
EBF	Evidential Belief Function
EC	Electrical Conductivity
FAO	Food and Agriculture Organization of the United Nations
FR	Frequency Ratio
GDP	Gross Domestic Product
GIS	Geographic Information System
GMW	Groundwater Monitoring Well
GWPZ	Groundwater Potential Zone
IDW	Inverse Distance Weighting
LULC	Land use/Land Cover
MCDA	Multi-Criteria Decision Analysis
MCM	Million Cubic Meter
MEW	Ministry of Energy and Water of Afghanistan
NSIA	National Statistic and Information Authority
OCHA	UN Office for the Coordination of Humanitarian Affairs
PARB	Panj Amu River Basin
ROC	Receiver Operating Characteristic
RS	Remote Sensing
USGS	United States Geological Survey

CHAPTER 1

INTRODUCTION

The first chapter contains general information, the background of the study, the transboundary waters, the problem definition, the significance of the research, the research objectives, the research questions and the framework of the work.

1.1. General Information

Urban planning is closely related to the social, economic and environmental factors that affect the city. Unplanned cities have a negative impact on the environment and the people who live in them because they are built without respecting these guidelines. Cities are home to a large number of people, so a place with a high population density inevitably affects and threatens nature. When planning residential areas, industrial facilities (waste storage, energy production, etc.) or agricultural areas, it is crucial to reduce the negative impacts that may arise. This is only possible if all data and the natural resources that already exist in the urban region are accurately identified and assessed. Groundwater resources are among the most important natural resources, but because they are not as obvious as other natural sources above ground, their importance for planning has long been overlooked. All species living nearby are either directly or indirectly affected by groundwater. As such, it has a direct influence on urban development. This connection is still relevant today, as it came up in discussions about the urban growth boom around 1900.

The main problems in the management of water resources in industrialized countries are water production, efficiency and the reuse of wastewater for domestic and productive use. However, the sustainable use of groundwater resources and their exploration remain the main concerns of developing countries. As areas with large groundwater potential have not been explored so far, the exploration of groundwater resources usually requires considerable financial resources. For this reason, many hydrogeological campaigns are carried out in unsuitable locations, leading to inadequate results and wasting time and money (Perilli, Gorelli, and Albalawneh 2021). As a result, many water infrastructures are carried out without hydrogeological survey, resulting in low-yielding, unproductive wells as well as wells with irregular yield. Similar circumstances prevail in Afghanistan and also in the Panj Amu River Basin (PARB), giving rise to this study. Boreholes and Karezs for housing, schools, health centers, public offices and in some areas for agriculture have been drilled and dug in this region by public and private entities, including foreign Non-governmental Organizations (NGOs). However, the lack of previous studies has meant that hundreds of boreholes have been unsuccessful. Many other, often productive, wells eventually dry up, either permanently or periodically. However, before embarking on exploration, Remote Sensing (RS) is another affordable and useful technique to assess the potential of groundwater (Achu, Reghunath, and Thomas 2020; Ahmad et al. 2020; Arabi Aliabad et al. 2019; Gyeltshen et al. 2020; Hamdani and Baali 2020; Karimi and Zeinivand 2021).

The purpose of this study is to accelerate research and provide a surrogate approach for accurate estimation of groundwater potential. The Panj Amu River Basin in Afghanistan was selected as the study site. This site was selected primarily because it has rich groundwater potential (GWP) but has a lack of a planned and managed groundwater system. Therefore, this study will be a window for further research and water management.

The process of determining GWP involves multiple proxies (parameters and multi-criteria), which requires the use of a multi-criteria decision-making method based on a Geographic Information System (GIS) using weighted image overlay analysis. The main problem is to determine which multi-criteria decision technique is best suited for the investigation. Next is to determine the weighting of each proxy assigned based on the impact of the analysis on the identification of GWP. Determining the accuracy and efficiency of the data generated by the activities is a critical step that should not be overlooked. Finally, it is expected that the current use of the land will be assessed in the light of the data collected and that this can be used to develop sound ideas for future projects in the Panj Amu River Basin/Afghanistan.

According to the study, the sites with high groundwater potential are located in the north and northwest of Badakhshan province near the Amu River with lithology suitable for permeability (conglomerate and sandstone) and high rainfall; the northeastern part of Takhar province near the Kokcha and Amu rivers. This area also consists of conglomerate and sandstone and has moderate rainfall. The southeastern part of Baghlan province in the Hindu Kush Mountains has very high precipitation and here too the area consists mainly of conglomerate, sandstone and siltstone, which have a high infiltration rate and hydraulic conductivity.

1.2. Study Background

The Amu River (Oxus) originates in Afghanistan's Wakhan Corridor and flows through the northern, southern and eastern borders of Afghanistan, Tajikistan and Uzbekistan, respectively (Figure 1.1). The Amu River, which is comparable in size to the Nile, is 2,540 km long, has a catchment area of 309,000 km2 and discharges about 2,000 m3/sec, with 30 % of the water coming from Afghanistan, 61 % from Tajikistan and 7 % jointly from Uzbekistan and Turkmenistan (Shroder and Ahmadzai 2016). However, the downstream countries consume around 80 percent of the total discharge, with Turkmenistan using around 33 percent and Uzbekistan around 47 percent. The upstream countries, on the other hand, use only about 18 percent of the total runoff, with Afghanistan using 7 percent and Tajikistan 11 percent (Shroder and Ahmadzai 2016).

Figure 1.1: Amu River Basin, Central Asia, (SOURCE: Jalilov, Amer, and Ward 2013)

Afghanistan is located in South and Central Asia, is a landlocked country with mountains and has an area of 647,500 km2 (Kamal 2004). According to the 2023 report of the National Statistics and Information Authority (NSIA), around 34.9 million people live in the country, of which 24.6 million (70.5 %) live in rural areas, 8.8 million (25.2 %) in urban areas and 1.5 million (4.3 %) are nomads (NSIA 2023) (NSIA, 2023). The country lies between 29° 21′ S and 38° 30′ N in latitude and 60° 31′ W and 75° 00′ E in longitude. The Himalayan-Pamir and Hindu Kush Mountains separated the north and south as well as the west and east of the country. The Suleiman and Karakoram Mountains are the main sources of water for the southeast and south of the country, as well as the majority of the country's agricultural land (Bob 2008).

About 82% of the country’s total area is bare land and pasture, 65 to 78 thousand square kilometers are arable land, which accounts for 10 - 12 percent of the total land, and less than 2% is covered by forests. About 75 percent of the country consists of mountains and hills, while the north and south are home to wetlands such as river valleys, and the southwestern region consists mostly of desert regions. The country has cold winters and hot and dry summers with temperatures between -20 °C and 50 °C, which corresponds to an arid to semi-arid climate.

Water is an essential component of life. A universal factor for human well-being is access to clean water and adequate sanitation (Potter and Darmame 2010), and sustainable development is inconceivable without human well-being (Mahmoodi 2008). As sustainable water and sanitation management and access are still a problem in many countries, especially in developing countries, the United Nations has included this issue as one of its Sustainable Development Goals (SDGs). It is difficult to solve the problem of water supply and sanitation because in developing countries, safe water supply and sanitation is directly linked to other SDGs and problems such as poverty, war and violence, urbanization, population growth, scarce financial and human resources, inadequate infrastructure and ineffective management (Potter and Darmame 2010; Forouhar and Hristovski 2012). Due to four decades of war, Afghanistan has lost academic, institutional, financial and capacity building resources and is one of the countries that lack sustainable water and sanitation services.

Afghanistan has abundant water resources, although it is a largely deserted region, mainly because of the high, snow-capped mountains of the Wakhan, Hindu Kush and Baba. Afghanistan and the surrounding countries consider the high mountain ranges as their water tower. Most of the high mountain regions have significantly more annual precipitation than the neighboring lowland areas. The snowfall that covers the snowfields and glaciers in the winter months slowly melts in the summer months, supplying rivers, streams, springs and karstified limestone aquifers with abundant fresh water. The seismotectonic province of the northern Afghan platform is home to the Northern, Panj Amu and Murghab-Kushk wa Kaskan watersheds. The freshwater aquifers are mostly confined to the region between the banks of the river valleys and the freshwater zones near the recharge zones in the mountains (United Nations -New York 1986). Each well was dug close to the river valley.

The country has sufficient water sources, although it is located in a dry area. This is mainly due to the high mountains, of which only the Hindu Kush Mountains provide 80% of the water currently available. Snow in winter and melting in summer result in natural water storage, and all rivers have a continuous flow of water in summer (ICARDA 2002). Almost 25% of Afghanistan lies more than 2500 meters above sea level. The original potential for many river basins in Afghanistan was found in the high altitudes of the Hindu Kush and the Pamirs. Afghanistan's water flow is divided into five river basins (the Panj Amu river basin, the Helmand River basin, the Kabul (Indus) river basin, the Harirod-Morghab River basin, and the Northern River basin (Blind River System)) and five non-catchment basins, as shown in (Figure 1.2).

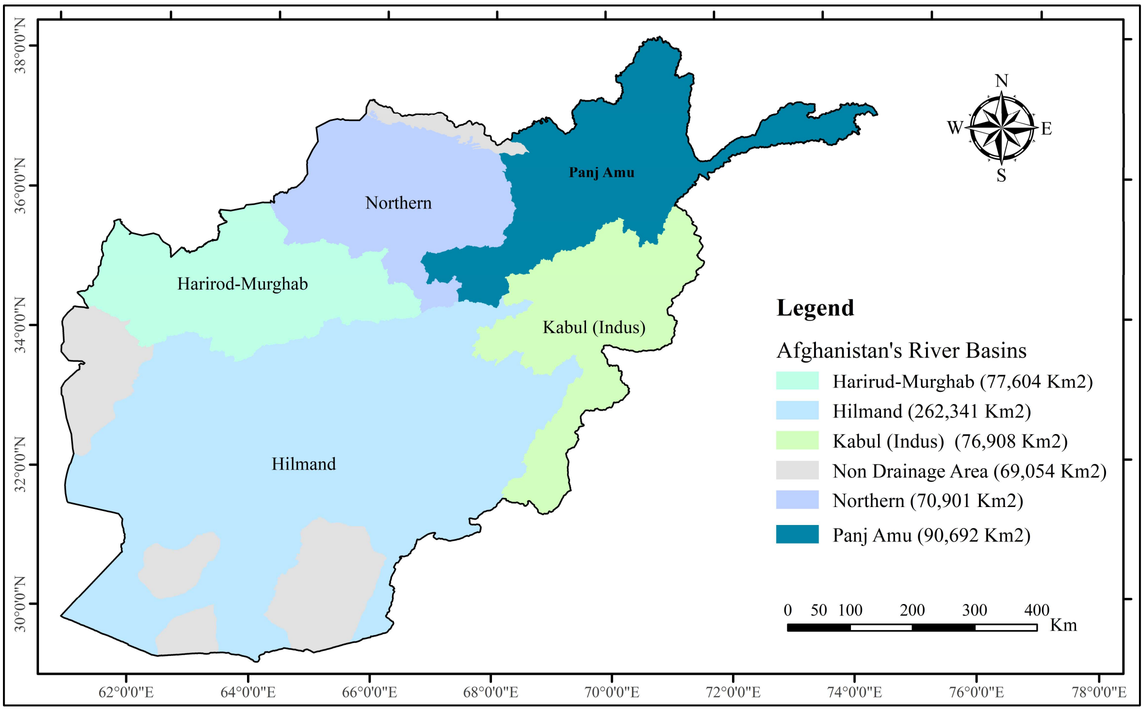

Figure 1.2: Afghanistan's River Basins and Non-drainage areas

From the report of (MEW 2016), the total annual available water resources in Afghanistan are 77 billion cubic meters (BCM) of which Panj Amu has 18.763 BCM, Kabul 15.183 BCM, Helmand about 17.136 BCM, Northern 9.825 BCM and Harirud 16.053 BCM. The country's total long-term annual precipitation is 164 BCM, evaporation is 87 BCM, which accounts for 53% of total precipitation, groundwater recharge is 16 BCM, which accounts for 10%, and surface water runoff is 61 BCM, which accounts for 37% of total precipitation (MEW 2016). However, the annual water resources in Afghanistan are estimated by (Habib 2014; JICA 2011; Ahmad and Wasiq 2004; Mahmoodi 2008) to be 75 BCM, of which 57 BCM is surface water and 18 BCM is groundwater, with a total annual abstraction of 20.3 BCM. According to (Aini 2007), the total amount of water extracted from snowfall and rainfall is 180 BCM, of which about 150 BCM is snowmelt and 30 BCM is precipitation, and only 15% of the total runoff contributes to the country's groundwater recharge.

Afghanistan receives different amounts of rainfall each year depending on location; the southwest receives 75 mm, while the northeast receives 1270 mm, with an average of 300 mm (JICA 2011). In the last three decades, especially from 1999 to 2003, there was a significant drought that led to a decrease in the number of Karezes from 6781 to 686 (Habib 2014). Water is the most valuable resource and the main source of energy production in Afghanistan and an essential factor for stable and sustainable development. As agriculture accounts for more than 50% of the country’s GDP and cannot function without water, the significance of water is widely recognized. More than 93% of the country's water is used for irrigation (Ahmad and Wasiq 2004; Ansari 2014) even claims that 99% of water is used for irrigation annually. The enormous amounts of water used for agriculture are largely wasted due to old and ineffective irrigation techniques. The Afghan government has categorized irrigation water into four groups based on the source of this water. Of these, 84.6% are streams and rivers, 7.9% are springs and karezes (an ancient irrigation technique in which water is brought to the surface from deep in the ground through a tunnel dug into the rising land at a very low gradient.

The geographical environment influences the length of the Karez wells. Karez is similar to the ancient technique of supplying water from a deep well with many vertical access shafts, called qanats, used in Persia and the Middle East) 7%, deep and shallow wells 0.5%. Afghanistan has long suffered from a lack of infrastructure for water storage and management of its water resources. Fundamentally, the country firmly believes that water resource management is key to its economic viability. Afghanistan also needs to reserve water to meet its hydropower needs. Therefore, several initiatives have been taken in recent years to strengthen the water resources sector. Although more than 2000 m3 of water per person is available annually, there is only 80 m3 of storage capacity (Saffi and Kohistani 2013).

4.55 million people live in the Panj Amu basin, of which 3.78 million (83.22 %) live in rural areas and 0.76 million (16.78 %) in urban areas (NSIA 2023). The basin is located in the northeastern part of Afghanistan between 34° 34′ S and 38° 30′ N in latitude and 66° 41′ W and 74° 53′ E in longitude, has a catchment area of 90,692 km2 (Favre and Kamal 2004; Ibrahimzada and Sharma 2012), and originates in the east and center of the Pamir and Hindu Kush mountains. According to (King and Sturtewagen 2010), the Panj Amu RB had 7230 Km2 of irrigated agricultural land in 1990, and the assumed annual water intake was 7.6 MCM. The annual survey of NSIA in 2022 shows that an area of 7,566.31 Km2 was planted in the Panj Amu River Basin (NSIA 2022).

The PARB comprises four provinces, namely Badakhshan, Takhar, Kunduz, Baghlan and some parts of Bamyan and Samangan. There is one lake (Shiva Lake) in the PARB and due to the mountainous landscape, there are many small and large rivers (Kunduz River, Taloqan (Khanabad) River, Kokcha River, Panj Amu River and Wakhan River) flowing in the PARB from east, southeast and south to north and northwest, with all these rivers eventually flowing into the Amu River.

The spatio-temporal distribution of rainfall in the PARB varies, and climate change plays a crucial role in these differences. The maximum and minimum annual rainfall 1979-2022 in the PARB was 663.65 and 103.32 mm respectively (Hayat 2022). The 2016 report of the Ministry of Energy and Water shows that a total of 39,889 BCM of annual precipitation was observed in the PARB over a long period of time, which is 24% of the total precipitation in Afghanistan (MEW 2016).

1.3. Transboundary Water and Hydro-Political Interactions

Afghanistan’s four out of five river basins are transboundary. There is an uncommon situation in the Kabul River basin where Pakistan and Afghanistan are both upstream and downstream of each other (Vick 2014). Approximately 90% of Afghanistan's surface water is transboundary, and Afghanistan is upstream country in many circumstances (Favre and Kamal 2004). For many years, the country's water flowed to its neighbors without being regulated by any formal treaties, except for the 1973 Helmand River Water Treaty (HRWT) with Iran.

In 2008 the Afghanistan National Development Strategy center of the country (ANDS 2008) has reported that, the Ministry of Energy and Water of Afghanistan has started a number of significant infrastructure projects, and some of the dams and canals have already been finished. One instance of a recently finished project is the 1.015 BCM Salma Dam project on the Harirud River (Thomas and Warner 2015), which was finished in 2016. Shah wa Arus concrete gravity dam for hydropower and irrigation is another significant project in the Kabul River Basin, situated in the Shakrdara district. Work on the project began in 2012 and has completed in 2023, according to MEW. Furthermore, feasibility studies and surveys have begun for 21 dam projects that the Afghan government had declared in 2016. Also, Afghanistan continues to advocate for the adoption of hegemonic methods through unilateral resource grab (Thomas and Warner 2015).

In overall, all water related projects in 1960s and 1970s were implemented in southeast and southern Afghanistan, but due to the Soviet Union's noncooperation, the management of water wasn't done in the PARB and northern Afghanistan. In 1964 under the reign of King Zahir Shah, Afghanistan and the Soviet Union signed an agreement to jointly evaluate the water and energy of the Panj Amu river basin. In the letter of agreement, the Afghan side also provides opportunities for Soviet experts to conduct research in their territory. It is also said that the information will be taken to Moscow for final evaluation and a full report will be prepared and shared with the Afghan side in 3.5 years. These studies did not end in favor of Afghanistan, Because the Soviet side got full information about the PARB area, and later, due to the same information and consideration of investments in the lower part of Amu river (Uzbekistan and Turkmenistan which were part of Soviet Union), in 1971 the Soviet government's planning committee stopped support of all projects in the north of Afghanistan (including Qosh Tepe Canal) and postponed them for 20 years. The reason for postponed of these projects was showed that these projects are more than the needs of Afghanistan. But the main reason was the lack of water in the lower parts of Amu River (Uzbekistan and Turkmenistan) which will be caused by these projects and the Soviet Union realized during 1964's investigations.

After the Shahi government, the new republic of Afghanistan led by President Mohammad Daoud Khan began to discuss the distribution of the water of Amu River with the Soviet Union. Two facts emerge from these works. One is the separation of the water of Aibak, Balkhab, Sarpul and Shirin Tagab rivers from the PARB, which does not flow into the Amu River. And secondly, the Soviet side had considered less (2.1 billion cubic meters) of water to Afghanistan. Because the Amo Basin (Badakhshan-Kunduz) used to consume the same amount of water. And the Soviets Union discovered this during their previous investigation. But the Afghan side wanted 9 billion cubic meters of water. That is why the negotiations failed.

Based on the same information, the Soviet Union decided on the water rights between the Central Asian republics with 566 protocol and considered the same 2.1 billion cubic meters to Afghanistan due to the membership of the river basin in the same protocols. And in response to this action of the Soviet Union, Afghanistan included the Qosh Tape Canal project in its initial development plan, but due to the communist coup in 1978 and assassination of President Mohammad Daoud Khan the project hasn't started since early 2022. To transfer water from the Amu River, the Qosh Tepe Canal is being constructed in northern Afghanistan. The total project aims to turn 5,500 Km2 of desert into agriculture land. The main canal is projected to be 285 km long, 100 m wide, and 8.5 m deep and will have a capacity of nearly 5 BCM/year of water. The construction begun in April 2022, and by September 2023, the first section of the canal which is 108 kilometers long had been dug out.

After the independence of the Central Asian countries in 1992, they confirmed the division of the 566 number protocol by signing the Almaty Agreement which Afghanistan was not part of it. Beyond this, if we look at the era of Soviet rule or the time before that, the Soviets did not invest in a single water project in the north of Afghanistan. Pul-Khumri dams were built by Germans in 1945, Khanabad dam in Kunduz was also designed by Indians in 1965 and 90 percent was implemented by Helmand Enterprise. And other agricultural projects (Gurgan, Kanal Shahi...) were also built during Zahir Shah's reign. So, in the past the Soviet Union never wanted and never gave permission to Afghan side to work on big water related projects in the PARB and northern Afghanistan. But now, neither the Afghan side has the previous situation, nor the northern sides have the previous structure and strength. Therefore, the Qosh Tepe Canal has started and will restore Afghanistan's rights in Amu River.

About the transboundary basin of Panj Amu, experts and senior officials from Tajikistan and Afghanistan conducted visits between 2005 and 2010 to talk about new areas of collaboration, including trade, energy, the environment, border security, and hydrological monitoring. Additionally, in order to promote bilateral and multilateral collaboration, delegates from both sides met at many international gatherings. With important partners like the United Nations Development Program (UNDP), the United Nations Environment Program (UNEP), the Organization for Security and Cooperation in Europe (OSCE), and the United Nations Economic Commission for Europe (UNECE), the Environment and Security (ENVSEC) Initiative assisted in 2008 in bringing Afghanistan into the Amu River Basin regional evaluation and talks. The process was aided by cooperative efforts under the United Nations Special Program for the Economies of Central Asia (UN SPECA) and UNECE Water Convention. Both governments have written and signed an international agreement on water cooperation by October 2010. The agreement's primary topics include collaboration on the Panj/Amu River, particularly in the areas of environmental protection, risk reduction and readiness for disasters, and hydrological monitoring (Omar 2013). Through UNECE-facilitated bilateral cooperation talks, the governments of Kabul and Dushanbe discussed and decided on first cooperation activities between 2012 and 2013. The Russian Federation provided the first backing, and the OSCE has also intervened. AFG-TJK Cooperation Atlas is one product of this effort. In addition to meetings, the scope of cooperation included field visits and the sharing of best practices and experiences between experts and institutions, creating a professional network, training Afghan and Tajik students, and working on communication and decision support tools. Given the sensitivity of the problem surrounding international waterways in the region, the foreign ministries of both nations are actively engaged in the process of collaboration. The majority of recent collaborative work was done during the Dushanbe International Water Conference (Omar 2013).

In conclusion, the works and strategies of Ministry of Energy and Water and as well as ANDS's water sector plan places a strong emphasis on controlling and storing water so that the nation is ready for periods of drought brought on by climate change. A draft of the Trans-Boundary Water Policy had been created by the Ministry of Energy and Water of Afghanistan and was sent to the Ministry of Foreign Affairs (MFA) (Duran 2015). To the best of our knowledge, the policy has not yet been finalized (Hayat 2022). The Afghan government also anticipates that effectively managing the nation's water resources will play a major role in reducing poverty, which is now the nation's largest concern. Last but not least, Afghanistan takes seriously the management of its water resources, be it for the development of irrigation systems, the production of hydropower, the alleviation of poverty, sustainability, future demands during droughts, or even the need for drinking water.

1.4. Problem Statement

The Panj Amu River Basin (PARB) is not exempt from the problems facing Afghanistan's water resource system, including the following issues:

1. Transboundary tensions: The Amu Darya basin, shared by Afghanistan, Tajikistan, Uzbekistan and Turkmenistan, includes the PARB. Effective cooperation is essential for the management of water resources but is often hampered by political tensions and conflicts of interest, leading to irregular water distribution and unsustainable practices.
2. Lack of water management: Due to outdated agricultural practices, deteriorating irrigation infrastructure and insufficient water conservation measures, there is considerable water wastage in the catchment area. This puts further pressure on the already scarce water resources.
3. Weakness in the face of natural disasters: The PARB records an increase in the frequency and severity of floods due to the steeper slope, heavy rainfall, rapidly melting glaciers and snowpacks, human activities, as well as drought in some parts of Bamyan. According to Pathak and Azizi the Panj Amu Basin's excessively varied river channel elevation causes the water's velocity to be high, which makes it more damaging downstream due to the burden of erosion and flooding (Pathak et al. 2022). Another study by (Ansari and Tayfur 2023) shows that the Panj Amu river basin in the northeast and the Kabul River Basin in the center and southeast of Afghanistan have a higher rate of soil loss compared to other regions.

Communities are uprooted, and infrastructures are damaged by these catastrophic occurrences.

The figures 1.3 & 1.4 shared by OCHA and European Union, show that, how the natural disasters affected Afghanistan especially the PARB.

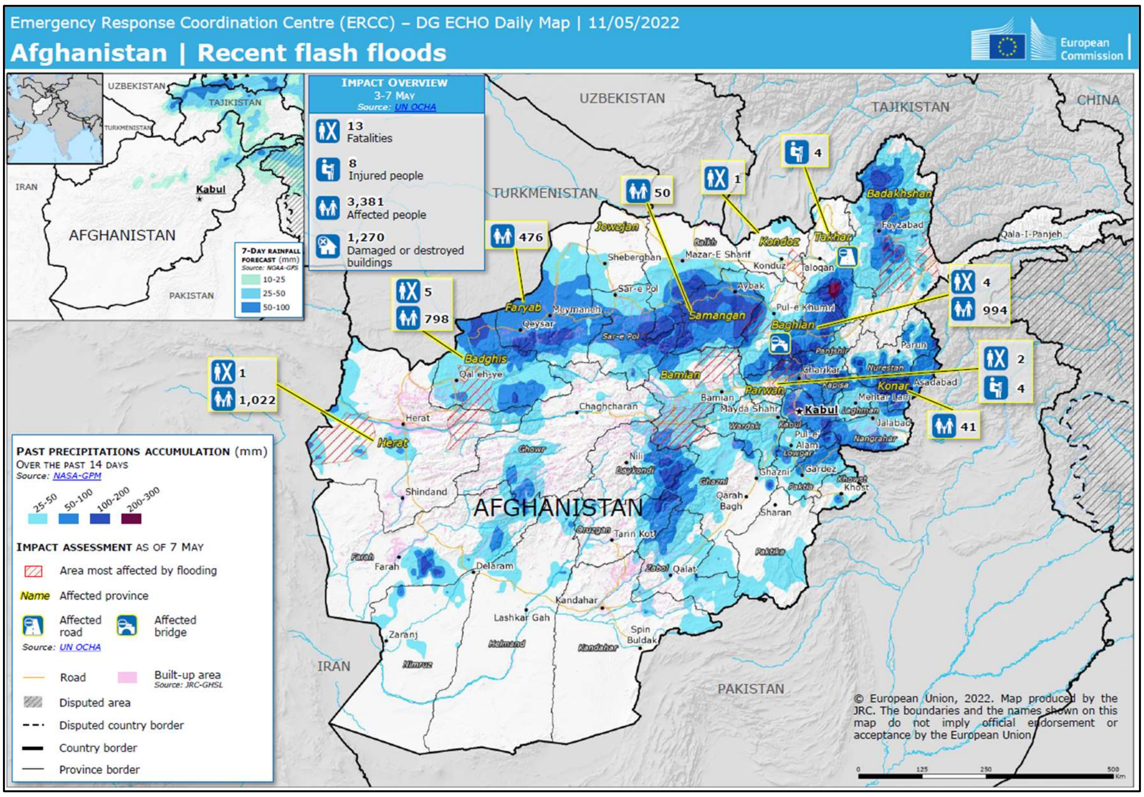

Figure 1.3: Afghanistan Flood Map, (SOURCE: EU 2022; OCHA 2022)

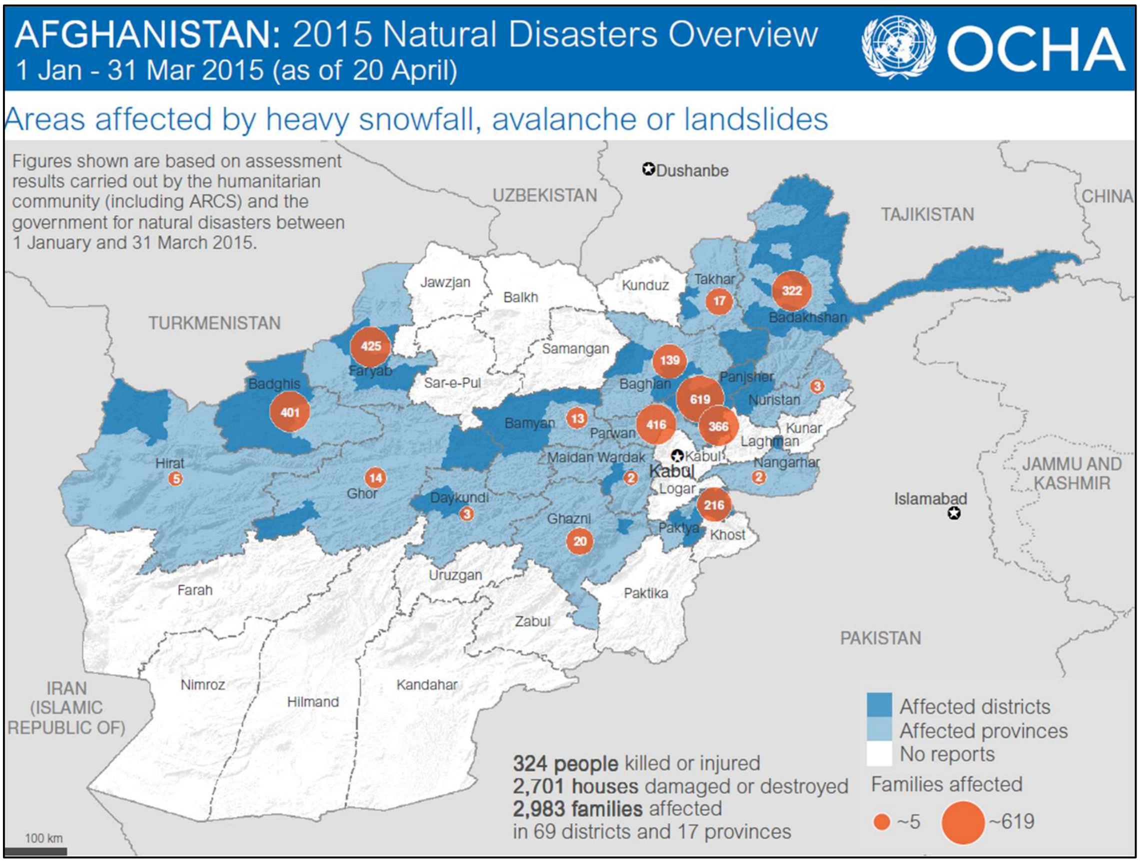

Figure 1.4: Afghanistan Natural Disasters Map, (SOURCE: OCHA 2015)

4. Impacts of climate change: The country is extremely vulnerable to the effects of climate change, such as changing rainfall patterns, rising temperatures and melting glaciers. The timing and quantity of available water is altered by these changes, jeopardising ecosystems and industries that depend on it.
5. Deteriorating water quality: Water quality is negatively impacted by pollution from industrial effluents, agricultural runoff and poor sanitation. Contaminated water threatens both ecosystems and public health.

1.5. Importance of Research

This study will help identify how groundwater potential mapping works for optimal water resources management, water supply well siting, drought management, land use planning, environmental protection, waterlogging and salinization mitigation, infrastructure planning and groundwater exploration.

The results of this study will also be useful for academics and researchers and could provide an important framework for future relevant research on the country and the region.

In addition, the groundwater potential maps will serve as a teaching tool for disaster management, spatial planning, technical protection and awareness raising for a variety of stakeholders, including the population, insurance companies and local and regional governments, as well as a source of ideas for future projects in the Panj Amu River Basin/Afghanistan.

1.6. Research Objective

The overall objective of this study is to evaluate the map of groundwater potential zones in the Panj Amu river basin by analyzing and studying the hydrological and meteorological data of last 15 years, slope, LULC, drainage density, lineament density, soil and geology of the area.

The main objectives of this study within the scope of the study are as follows:

1. To develop a watershed level approach to identify and map locations of groundwater potential in the Panj Amu River Basin, a rapidly growing catchment.

2. Improving data management and technology skills related to water, as well as information sharing and awareness raising.
3. Groundwater-related information and data should be made available to interested stakeholders.
4. Identify areas where groundwater recharge is significantly influenced by natural processes and be aware of variables that influence groundwater recharge, such as precipitation, infiltration and interactions with surface water.
5. Collect historical and current groundwater data to help improve the interpretation of groundwater monitoring well (GMW) data.
6. Identify vulnerable aquifers with subsurface geologic and hydrogeologic features worthy of protection, as well as problematic areas in terms of water quantity and quality that require further investigation.
7. Draw attention to water-related issues to assist policy and decision makers in improving plans, regulations and strategies for the development, sustainability and protection of groundwater resources.
8. Identify factors affecting groundwater potential zones.
9. Ensure that land development is consistent with the sustainability and availability of groundwater by providing useful information for land use planning and preventing the overexploitation of groundwater resources in vulnerable locations.
10. Identify regions prone to drought and water scarcity and develop plans to minimize the impact of water scarcity and measures for sustainable water management.

1.7. Research Questions

To achieve the overall objectives of the research, the following research questions will be addressed:

1. What is the best approach, information and software to find specific sites and map groundwater potential?
2. Which geographical and ecological factors are most important for groundwater quantity and recharge?
3. What is the importance of groundwater for urban planning?

CHAPTER 2

LITERATURE REVIEW

This chapter describes relevant scientific research, theories and practical techniques relating to groundwater in urban planning and the identification and mapping of groundwater potential.

2.1. Urban Planning and Groundwater

The impact of the built environment and current natural conditions on water resources should be assessed and appropriate planning guidelines should be established to ensure sustainable urban development. In urban planning, groundwater can be considered in two ways. The first is to reduce harmful impacts on people and eliminate negative impacts on groundwater resources. The second priority is to ensure the effective use of existing groundwater resources (Frans and Rijsberman 1999; Carmon, Shamir, and Meiron-Pistiner 1997).

In their study on water-sensitive urban planning, (Carmon, Shamir, and Meiron-Pistiner 1997) focused on the measures that planners can take to reduce the negative impacts of urban growth on groundwater. According to Carmon et al. aquifers are often the basis for the development of urban areas, and poor planning decisions could affect the quantity, quality and composition of aquifers as well as groundwater. They have identified two goals for water-sensitive urban planning within the context of hydrology. These include increasing the amount of water that percolates into the ground, shifting water to groundwater and reducing pollution from surface runoff, which can recharge the aquifer (Carmon, Shamir, and Meiron-Pistiner 1997). They also made a number of planning recommendations to ensure sustainable water management, including:

1. Accurately and effectively determine the quantity and quality of groundwater in regions where aquifers are elevated and serve as naturally occurring infiltration basins; conduct an assessment of potential damage in the area prior to the planning phase.
2. Establish building boundaries and avoid polluting structures in areas with high GWPZ.

3. Designate infiltration zones for urban open spaces (parks, gardens, leisure areas, etc.).
4. Ensure that parks and gardens are used to collect rainwater before it pollutes the field.

Frans and Rijsberman (1999) carried out a study in Holland to investigate the problems caused by urban expansion, but they did not take groundwater resources into account. They identified three main problems. The harmful effects on public health are the first. According to them, the dehumidification caused by the wrong structure in the Netherlands and the high groundwater table have negative effects on human health (Frans and Rijsberman 1999). Another issue is the impact of groundwater on regional hydrology. Buildings, infrastructure elements and building foundations have been damaged by the moisture and pressure of groundwater. In addition, crops have not yielded satisfactorily in locations where groundwater is absent (Frans and Rijsberman 1999). The last point is the impact on the economy. The repair expenses are a consequence of the damage to the infrastructure components, which has led to an increase in pollutants in the groundwater. The rising cost of cleaning up the polluted water has led to an increase in the cost of agricultural production. In a way, this study emphasises that planning decisions involving natural resources have been critical to the development of urban health and economy.

Another study was conducted by (Morris, Litvak, and Ahmed 2001) on groundwater protection in urban areas. They used two cities, one in Bangladesh and the other in Kyrgyzstan, to illustrate the groundwater problem, the lack of policy needed by municipal decision makers and the reasons for this lack. The lack of appropriate and up-to-date data is the first of these causes. The fact that it is not known how groundwater and sustainable development are linked is another factor. The last reason is the lack of looking at the big picture, and groundwater is also speculative in nature. It is likely that the quantity and quality of water will be affected by drilling. And this will be a challenge for planning decisions (Morris, Litvak, and Ahmed 2001). Their work aims to propose relevant strategies to protect groundwater and aquifers. Some basic steps are defined for groundwater planning in urban areas. Mapping and identifying possible pollution and hazardous activities are the most important of these. Another step is to ensure that the right information and data is collected, and the right decisions are made for regional planning. They also pointed out that a project team needs to be put together and the parties involved in groundwater need to be identified.

2.2. Assessment of Groundwater Potential

The definition of boundaries for regions with high groundwater potential is crucial. This can be achieved by combining a Geographic Information System (GIS) with Multi-Criteria Decision Analysis (MCDA) using various methods such as the Analytical Hierarchy Process (AHP), the Frequency Ratio (FR) and the Evidential Belief Function (EBF). Globally, GIS techniques using (AHP) analysis are widely used for the study of groundwater potential zones in relation to the geologic environment and are considered fast and simple. On the other hand, Frequency Ratio and Evidential Belief Function techniques are quite new and have been used in some recent research studies.

A study on the definition of GWPZ in Doddahalla watershed of Chitradurga district/India was carried out by (Ibrahim-Bathis and Ahmed 2016), which shows that the proportion of areas with abundant groundwater resources is only 15% and the proportion of areas with medium to low groundwater resources is about 70%.

2.2.1. Analytical Hierarchy Process (AHP)

AHP was chosen for weights determination of the criteria for natural resource estimate over a number of others MCDA approaches (Saaty 1988a). According to (Şener, Sener, and Karagüzel 2011) AHP is complete approach that blends pragmatic and subjective opinion of the experts to accomplish decision making via considering many factors. And (Kumar and Krishna 2018) define AHP as a strategy which speeds decision making process via identifying and weighing of distinct criteria.

Ally and his research team (Ally et al. 2023) mapped the groundwater potential zones of Mpwapwa district in central Tanzania using a GIS-based AHP analysis and according to the author, the method was successful enough to provide suggestions for Tanzania's National Development Vision 2025. (Achu, Reghunath, and Thomas 2020) processed GWPZs using the AHP model with the help of GIS and found suitable recharge mechanisms that are particularly suitable for a particular location within the context of tropical basins. (Arulbalaji, Padmalal, and Sreelash 2019) used AHP analysis for groundwater potential in the Southern Western Ghats, India, and according to the geography of the area, the result was quite reasonable. The result was that most of the catchment (59%) has medium groundwater potential, 11% high, 29% low, and the zones of very high and very low groundwater potential comprise less than 1%.

Another study was conducted by (Dinesh Kumar, Gopinath, and Seralathan 2007) to delineate groundwater potential zones by combining remote sensing and Geographical Information System (GIS) in the Muvattupuzha river basin/India. The results showed that almost 50 % of the area had very good or good groundwater potential and the remaining areas had medium to low groundwater potential. (Badhe, Choudhar, and Raut 2022) studied the groundwater potential zones of Indian Karha river basin/Maharashtra and used AHP technique which shows that groundwater potential zones occur in Baramati, Dorlewadi, Jalgaon, Loni Bhapkar and Saswad. And according to the author, GWPZs can be successfully identified using this simple and efficient method. (Ahmad et al. 2020)have used MCDA - AHP for processing and mapping GWPZ in Beshilo River basin/Ethopia in a GIS environment.

(Doke et al. 2021) have also used AHP approach for multi-criteria decision making to produce spatial mapping of groundwater potential zones in Indian hard rock basalt area. (NP and Gopinath 2018) used GIS with AHP technique to study the zonation of groundwater potential in urban and suburban areas of South India. The result shows four zones of groundwater quality as highly suitable 60%, suitable 24%, moderately suitable and unsuitable 16% areas. This study has created a unique platform for integrating geospatial and field data for sustainable urban water quality management.

AHP technique was used by (Kabeto et al. 2022) to assess groundwater potential in Ethiopia's West Arsi Zone. This shows that RS and GIS are fast, accurate and cost-effective approaches for assessing groundwater potential and recharge sectors compared to the traditional approaches of ground survey and resistivity measurement. To determine the possible suitability of rainwater harvesting in Iran's Kakareza watershed, (Karimi and Zeinivand 2021) integrated thematic layers and runoff maps of a geographically distributed model using GIS-based AHP. In Edirne-Kalkansogut (Northwest Turkey), a study was conducted by (Aykut 2021) to determine groundwater potential zones using a geographic information system and an analytical hierarchy process.

Two studies in Tamil Nadu, India were conducted by (Kanagaraj et al. 2019) and (Rajaveni and Muniappan 2023) to assess GWPZs using a multi-criteria decision-making approach - AHP analysis. The result states that the regions with good porosity and permeability have excellent groundwater potential, while the regions with hard rock and hills have low groundwater potential. (Ifediegwu 2022) analyzed the groundwater potential zones in Nigerian Latifia district/Nasarawa state, and (Melese and Belay 2022) investigated the mapping of GWPZs in Ethiopian Muga watershed/Abay basin using AHP and GIS methods.

An academic work by (Silwal et al. 2023) in eastern Nepal, Kankal River Basin, was conducted to find groundwater potential zones using GIS-based AHP method. The result was that 15% of the area is in the high potential zone and about 50% of the area is in the low potential zone, indicating that the area is facing a shortage of groundwater resources. (Bhadran et al. 2022) assessed the groundwater potential of the Karuvannur River Basin in South India using the GIS Fuzzy Analytical Hierarchy Process (F-AHP). The study shows that the F-AHP method achieves an accuracy of 80.9% in this area. (Tani and Tayfur 2021) identified GWPZs in Kabul River Basin/Afghanistan using AHP method and as a result of the study, the authors claim that Kabul River Basin has sufficient groundwater potential to be utilized for drinking water and irrigation development in the future.

A work in a semi-arid Mediterranean coastal aquifer (Korba unconfined aquifer / Northeast Tunisia) was done by (Zghibi et al. 2020) to map groundwater recharge zones by using an analytical hierarchy process and several influencing factors, and as a result, they found that the GWRZs as very high 16%, high 53%, medium 11.5%, low 15.8% and very low 2.9%. In this study, they found that the accuracy of the AHP method was 75.6%, while the MIF method achieved an accuracy of 70.4%. GWPZs were evaluated in southwestern Ethiopia, Kaffa zone, using GIS and MCDA – AHP by (Woldegebriel, Amibo, and Bayu 2021), where the accuracy of the estimation was checked based on the borehole yield data in the selected area and found to be 68.42% accuracy, proving that the AHP approach provides results that are remarkably accurate and reliable.

2.2.2. Frequency Ratio (FR)

Bonham defined frequency ratio as a probability of a particular factor, or likelihood that a particular factor will occur (Bonham-Carter 1994). Oh and Razandi, defined frequency ratio as a bivariate statistical model that is used as a crucial tool for geospatial assessment to ascertain the probabilistic link between dependent and independent variables or multi-classified thematic layers (Razandi et al. 2015; Oh et al. 2011).

The AHP and FR, GIS-based models were used by (Ahmadi et al. 2020) to map the groundwater potential in the center of Antalya, Turkey. The results showed that about 24 of the areas were classified as high potential zones for the AHP model and 4.04% for the FR model. The authors used the areas under the ROC curve (AUC) to test the accuracy of the above models. The AUC shows that the FR model is 65% accurate, while the AHP model is 56% accurate, making the FR model the most accurate.

In Maharashtra, India, a study was conducted by (Das 2019) to delineate groundwater potential zones in the Vaitarna basin and compare the frequency ratio technique with the analytical hierarchy process technique. Nine layers with different factors in a GIS environment were used. To ensure the accuracy of the study, 302 wells and a threefold validation were performed. The validation shows that the FR model has an accuracy of 75%, while the AHP technique achieves an accuracy of 70%. The author pointed out that the groundwater potential maps produced with the FR model can be used for groundwater management and effective planning in the Vaitarna Basin. Another study on groundwater potential mapping was conducted by (Guru, Seshan, and Bera 2017) in the cold desert of India. They used 86 wells for the FR model, which had an accuracy of 77.23%. They found that the area of very high potential is 3.19%, high is 4.59%, moderate is 8.51%, low is 12.05% and very low is 71.66%. The region's water budget was also calculated and shows that there is a huge demand for water supply from May to September (tourist season).

Yousef Razandi and his research team (Razandi et al. 2015) worked with three models (Analytical Hierarchy Process, Frequency Ratio and Certainty Factor) to create a groundwater potential map for the Varamin Plain in Tehran, Iran. The research group used 71 groundwater wells for analysis, of which 50 wells were used as training dataset and 21 wells were used for validation. FR model was the most accurate model among them with 77.55% accuracy, AHP achieved 73.47% accuracy and CF model achieved 65.08. The author suggests that his work can be used for associated organizations in Iran to conduct a thorough assessment of water resources management evaluation and groundwater exploration for possible planning.

Based on the findings of (Thanh et al. 2022) which conducted a study in Kanchanaburi province of Thailand on groundwater potential zoning and used the analytic hierarchy process, frequency ratio and random forest models, the AUC value of AHP is 72%, FR is 74% and RF is 76%, which shows that the random forest model is more accurate than the other two models. The study found that the eastern area of

Kanchanaburi province has high groundwater potential, and the western area of this province has low groundwater potential. A group of researchers (Elvis et al. 2022) worked on a project to identify the groundwater potential zones of the Yoyo River Basin in the M´eiganga region, Adamawa, Cameroon. In addition to geographical and hydrological data, they used 195 wells as a training dataset. For the validation of this study, 84 wells were used, which shows that the AHP model was 76.21% accurate (better than the others), and the FR model was 73.62% accurate.

2.2.3. Evidential Belief Function (EBF)

Evidence belief function is a comprehensive framework for reasoning with uncertainty, or a potent instrument for integrating, interpreting, and exploiting varied information and viewpoints in decision-making, risk assessment, resource allocation, uncertainty analysis, performance evaluation procedures, and policy development.

In West Bengal, India, Biman (Ghosh 2021) studied the groundwater potential and applied the Evidential Belief Function and Analytic Hierarchy Process models. The author found that the EBF model is 83.28% more accurate than the AHP model 76.33%. According to the EBF model, five different potential zones were found with 12.43% very low, 29.47% low, 30.47% moderate, 21.06% high and 6.58% very high potential of groundwater. The study will educate decision makers on land use planning of lower Dwarkeswar basin and sustainable management of groundwater resources.

Another study using AHP and EBF models was conducted by (Saranya and Saravanan 2023) in India to investigate the vulnerability of groundwater in Cuddalore district near the coast of Tamil Nadu. The study suggests that the EBF model is 86.6% more accurate than the AHP model with 74.4% accuracy, so the map generated using the EBF model should be used for future planning and water management.

Recently, a study was conducted by (Li, Abdelkareem, and Al-Arifi 2023) to investigate the potential of water resources of the lower sections of the Yellow River in Shandong Province, China. They used GIS-based FR and EBF models and found that the FR model is more accurate at 70.7% than the EBF model at 66.5%. The map shows 23.67% very low, 40.6% low, 26.44% medium, 8.9% high and 0.39% very high groundwater potential. Another study in Iran was conducted by (Pourghasemi and Beheshtirad 2015) to investigate the groundwater potential of the Koohrang watershed.

CHAPTER 3

GROUNDWATER

The third chapter of this study considers the overall information about groundwater, groundwater’s hydrogeology, groundwater recharge and usage and as well as groundwater monitoring system in the Panj Amu River Basin.

Groundwater is one of the most important natural resources, stored beneath the earth's surface by infiltration through various layers of rock. The world's freshwater resources come from groundwater potential, which accounts for over 30% of the total. About 65 of groundwater is used for agricultural irrigation, 25% for drinking water supply and 10% for industry. Groundwater is defined as an important freshwater supply due to its affordability, constant chemical composition, freshness and lower detectability of contaminants (Jha, Chowdary, and Chowdhury 2010; Patra, Mishra, and Mahapatra 2018). It is essential for human well-being and ecological balance (Magesh, Chandrasekar, and Soundranayagam 2012; Shekhar and Pandey 2015) as well as for economic growth (Houghton et al. 2001). The United Nations World Water Development Report indicates that approximately 2.5 billion people rely solely on groundwater resources to meet their basic water needs, with 43% of the world's agricultural water coming from these sources (Connor 2015). Groundwater supplies are said to be under extreme stress worldwide, particularly in developing countries (Das et al. 2019). Due to factors such as climate change, ongoing urbanization, low rainfall and rapid population growth, dependence on this resource has increased significantly in recent years (Ibrahim-Bathis and Ahmed 2016). As a result, excessive groundwater consumption is widespread, contributing to a significant decline in groundwater levels (El Rahman 2001; Konkul, Rojborwornwittaya, and Chotpantarat 2014). Conversely, irrigation using groundwater is said to improve food security and is crucial for overall economic growth (Ali et al. 2012). In Afghanistan, agriculture is the most important sector, accounting for 50% of the total gross domestic product (Hayat and Baba 2017). In Afghanistan, groundwater resources are traditionally utilized through karez, springs and shallow, hand-dug open wells for both domestic and agricultural purposes. Both the Danish Committee for Aid to Afghan Refugees (DACAAR) and the United States Geological Survey (USGS) have conducted studies on the quality of groundwater in Afghanistan. DACAAR has been working in

Afghanistan for more than 20 years to supply the rural population with drinking water by means of drilled wells that are pumped by hand. The Afghan Ministry of Rural Rehabilitation and Development (MRRD) is also a key player in providing drinking water to the rural population through the National Solidarity Program (NSP) (DACAAR 2019).

3.1. Hydrogeology/Natural Groundwater System

In Afghanistan, groundwater is found in a variety of rocks ranging in age from Precambrian metamorphic basement to Quaternary sediments (Figure 3.1). Five hydrogeological divisions (crystalline rocks, Triassic and Lower Cretaceous pressurised thermal waters, Upper Cretaceous and Paleogene (Cr-Pg) karst aquifers, Neogene (Pliocene and Miocene) aquifers, and Quaternary aquifers) define the natural groundwater system in Afghanistan (DACAAR 2019).

The crystalline rocks consist of Precambrian, metamorphic basement rocks containing fractured water. Due to weathering and faulting, these rocks may have a secondary fracture permeability that could make them potentially significant water-bearing systems. The crystalline rocks act as a barrier to groundwater flow when no original fracture is present. Precambrian hard rocks, which make up the majority of crystalline rocks, are sedimentary and metamorphic rocks with exposed igneous rocks (granites and granodiorites). These rocks exhibit folds, fractures and deformations. Groundwater moves through faults, joints and fractures in crystalline formations that separate layers with different hydraulic properties. In certain cases, groundwater moves through fracture, fault, weathering and contact zones from high areas (the central, eastern and southeastern mountain ranges) to low areas (the northern plains, southern and western lowlands). The hydraulic characteristics and hydrogeological conditions are linked to the natural groundwater system. Most drainage systems are determined by structure and enter crystalline formations through fractures, joints and faults. Groundwater rises to the surface as springs along streams and small valleys with different hydraulic properties.

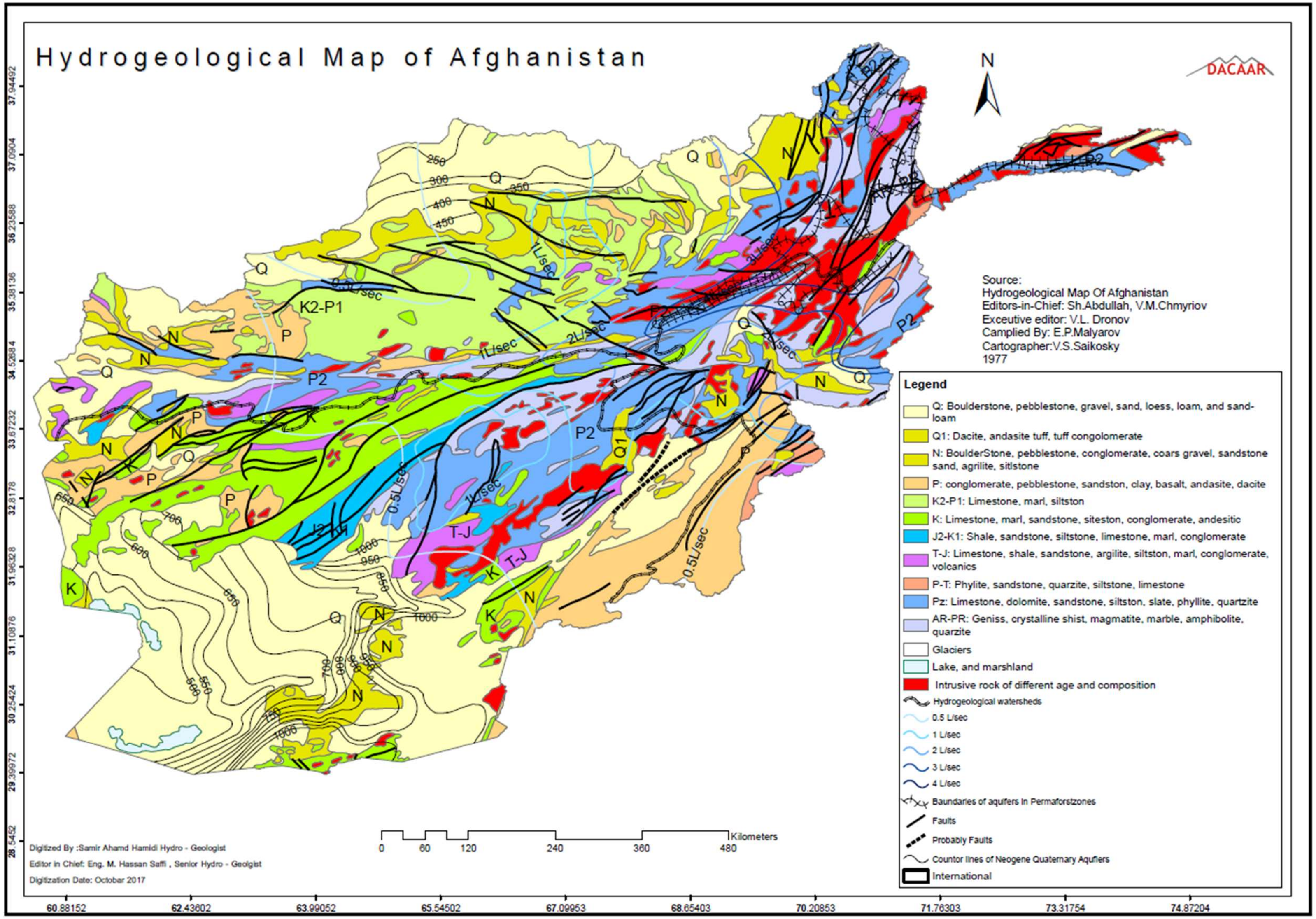

Figure 3.1: Hydrogeological Map of Afghanistan, (SOURCE: DACAAR 2019)

The majority of Afghanistan's Upper Cretaceous-Paleogene (Cr-Pg) fracture-karst aquifers are located in the south, southwest, center, north and northeast regions of the country, which are the most important aquifers in the country (DACAAR 2019). The carbonate rocks (limestone, dolomite, limestone, marl and marble) of different ages are the places where the fractured karst aquifers are formed. The faults, contact zones, karst development cracks, channels and cavities with different thicknesses and hydraulic properties create the natural aquifers. The properties of the aquifer and its surface springs in the foothills control the flow of groundwater (on the slopes of low elevations).

Karst springs, which emerge from fractured karst aquifers, are essential for both drinking water supply and irrigation of agricultural land. The discharge of the springs ranges from 2 liters per second in the Badghis province Ghormach region to 3,332 liters per second upstream in the Balkh River in the Sholgara region. The water quality is good and suitable for agriculture and as drinking water (DACAAR 2019). The largest sources of water for irrigation and water supply appear to be the karst springs with different discharges originating from different aquifers of the karst development. Therefore, these sources in the northern part of the country, where the shallow and deep groundwater is highly mineralized, should be given top priority in water supply programming and planning. The most important aquifers in Afghanistan for socio-economic growth and environmental security are the fractured karst aquifers, which therefore need to be studied in detail.

Aquifers and aquifer-aquitard systems from the Neogene (Pliocene and Miocene) are supported by an auratic bedrock consisting mostly of silt, clay, sand and gravel, sandstones, siltstone and conglomerate. These aquifer systems, which vary in thickness and hydraulic properties, are widespread throughout Afghanistan. In the east, southeast and south of Afghanistan, Pliocene and Miocene sediments alternate with aquifer systems that offer fairly good prospects for water quality and quantity. These sediments are less abundant in the southwest, west, northwest, north and lowlands of the northeast of the country. These aquifer systems, which include brackish and saline groundwater, are described as successive layers of sandstones, siltstones, conglomerates and clay with gypsum and salt deposits (Saffi 2007).

The Quaternary aquifers, which consist of alluvial deposits (sand, pebbles, silt, clay, gravel, conglomerate and breccias), are widely distributed in eastern, southern, western, northern and central Afghanistan along river valleys and mountain foothills. The main hydrogeological units of the artesian basins in northern Afghanistan (Amu-Darya, Kulab-Kukcha, Kunduz, Sheberghan and Kushka) are as follows:

1. Pressurised thermal water is found in Jurassic-Cretaceous aquifers of carbonate-bearing sandstone and siltstone sediments.
2. Several alternating aquifers from the Pliocene to the upper Eocene consist of limestone, siltstone and sandstone with thin layers of gypsum and saturated brackish water.
3. The alluvial deposits (silt, clay, sand, gravel, pebbles and boulders) that make up the Quaternary aquifers vary in thickness, hydraulic properties and water quality. Most of the fresh water in these aquifers is found in the middle and narrow sections of valleys that run alongside rivers.
4. In Dasht-e-Lily (Joz Jan province) and Dorahi Heratan (Balkh province), thermal pressure groundwater rises to the surface with varying discharge and temperature (Oil and Gas Exploration Department dug tube well) (Saffi and Kohistani 2013).

The Neogene and Quaternary aquifers that make up the natural groundwater system of the Amu Dariya artesian basin (I-1) alternate in many layers that differ in thickness, hydraulic properties and water quality. These regions, which are separated from the Sheberghan Artesian Basin by the Mazar-e-Sharif Fault and from the Kunduz Artesian Basin by the Kunduz Fault, are Kaldar, Kholm, Mazar-e-Sharif, Balkh, Chemtal, Daulatabad, Shortepa, Hairatan, Aqcha, Karqin and Mingajik. As a result of increased groundwater discharge (from the Quaternary formation) from Marmul Mountain into the Amu River, groundwater mineralization has also increased. The groundwater level varies between 40 m (near Marmul Mountain) and 2 m (near the Amu River). The mineralization of the water varies from 0.8 mg/l at the foothills of the Marmul Mountains to 3.7 mg/l in the right channel of the Amu River. The discharge rates of the drilled wells at a drawdown of 4.8–5 m vary between 2 l/s (Dasht-e-Shadian) and 100 l/s (Balkh district) (Saffi and Kohistani 2013). This alluvial aquifer, which is composed of conglomerate deposits, sand, gravel and boulders, lies between 65 and 95 meters below the surface (Dorahi Hairatan to Balkh District). The discharge from the tube well at a gradient of 4.8–6 m is between 5 ml/s (Dorahi Hairatan) and 80 l/s (Balkh District). The water in this area has a mineralization of less than 1 mg/l. The groundwater in the region on the border with Uzbekistan is highly mineralized. The local groundwater system, which flows from the mountains into the lowlands and along the rivers, is favored by the aquifers (Saffi 2007). Although most areas of Balkh province (Khulm, Dawlatabad, Chimtal, Fayz Abad, Aqcha and Minga Jiek districts) lack fresh drinking water, the deep and shallow groundwater are highly mineralized, so tapping the groundwater through tube wells for drinking water is a waste of time and money. There are two ways to build a regional piped water supply system:

1. On the Balkh River, where two sizable karst springs are located. The left spring discharges 3,332 liters per second, while the right spring discharges 1,522 liters per second. Both springs' water is clean enough to drink and use in the home.
2. Chashma Hayat, a sizable Karst spring, is located 12 kilometers upstream from the Kulm district. The spring has a 1,600 l/s discharge. The water is perfectly safe to drink and use (Saffi 2007).

The natural groundwater system of the Kunduz artesian basin (I - 2) consists of many alternating layers of Quaternary and Neogene aquifers with different water qualities, hydraulic properties and thicknesses. Char Dara, Imam Sahib, Khanabad, Aliabad, Archi, Qala Zal, Sher Khan Bandar and the city center of Kunduz are some of these places. The Neogene and Quaternary sediments are widely distributed. The Quaternary sediments consist of clay, silt, sandy loam and sand. The water table is between 8 and 42 meters, the Quaternary alluvial aquifer is between 15 and 85 meters thick with a mineralization of 0.8 and 4.3 mg/l, the discharge is between 6 and 17 meters with a gradient of 2.3 to 4.8 meters. The groundwater in the region bordering Tajikistan is extremely mineralized (Saffi 2007).

The Amu River forms the northern border of Takhar province, and the artesian basin of the Kulab Kokcha region (I-3) stretches along both banks of the river. Yangi Qala, Rustaq, Warsaj, Kalafghan, Chah Ab, Khowaja Ghar and Taluqan are located on the Afghan side of the region. The groundwater in this region is replenished by the Kukcha and Farkhar rivers. The sandstone, siltstone and shale that make up the Neogene formation are quite thick. The aquifer of the Quaternary Formation consists of sand, sandstone, gravel and conglomerate (DACAAR 2019).

The regions of Andkhoy, Pashtun Kot, Sare-Pol, Khowaja Dokoh, part of Sherintagab, Sheberghan, Qaramqule, Maymona, Bala Murghab, Qaisar, Khwaja Sabz Posh, Almar, Dashte Laily, Dowlatabad and Ghormach are all included in the Sheberghan Artesian Basin (I–4). The Quaternary aquifers consist of alluvial medium and coarse sediments (gravel, boulders, pebbles and cobbles) with different thicknesses and hydraulic properties. The Quaternary sediments in the upstream areas contain fresh groundwater, while the Quaternary sediments in the downstream areas mostly contain brackish and saline groundwater. The Pliocene and Miocene sediments are overlain by Quaternary deposits characterized by the successive layering of siltstone, sandstone, clay and conglomerate with the presence of salt and gypsum as well as brackish and saline water. According to the DACAAR report (2019), the electrical conductivity of groundwater in this region ranged from 840 µS/cm (Shu BAakhtu village in Khwaja Sabz district) to 52430 µS/cm (Atenkhwaja village in Shirin Tagab district), and the groundwater table ranged from 3.2 m in the river course to 45 m in the foot hills of the mountains, with a discharge of 2 l/s in the foot hills to 8 l/s in the river valley with a drawdown of 15 to 4 m (DACAAR 2019). Most of Faryab province (Qaram Qule, Sherintagab, Andkhoi, Maymona and Dowlatabad districts) suffers from severe freshwater shortages. Deep and shallow groundwater is highly reclaimable, so tapping groundwater through tube wells for drinking water supply is a waste of time and money (Banks, 2013-2014).

Two options exist for establishing a local piped water supply system:

1. In the village of Jug Ha, in the Dawlat Abad area, there is a spring with a discharge of around 450 liters per second on the right bank of the Shirin Tagab river. This spring’s water is clean and suitable for drinking and domestic usage.
2. Yanga Qala village in the Maymona district is home to a spring, which has a 40 l/s discharge rate. The water is perfectly safe to drink and use around the house.

The districts of Kushke Kohna, Kushke Naw and Gulran in the province of Herate are all part of the Koshka artesian basin (I–6). The Quaternary aquifer contains predominantly fresh groundwater and consists of coarse sediments (boulders, pebbles and gravel) and alluvium with different thicknesses and hydraulic properties. The Pliocene and Miocene deposits, which consist of conglomerate, sandstones, clay and siltstone with salt and gypsum deposits and contain brackish and salty groundwater, are layered over the Quaternary layers (Saffi 2007). The EC of groundwater varies from 1345µS/cm in Chil Dokhtaran district in Kushk-e-Naw to 8400µS/cm in Toraghondi, with the water table ranging from 3 m in Qala-i-Safedak to 39.6 m in Toraghondi. In addition, the groundwater discharge changes from 1 l/s in the foothills to 4 l/s in the river valley, which corresponds to a drawdown of 20–4 m. Mineralization increases from the upper to the lower section of the Pliocene and Miocene aquifer. Since the lower part of the Quaternary aquifer consists of red clay, which is highly mineralized, drilling tube wells for drinking water is a waste of time and money. Many of the tube wells in the area contain saline water (Saffi and Kohistani 2013).

Dolomite, marble, marl, dolomitic limestone and Cretaceous limestone (K) form the fracture-karst rock water basins of Murghab, Maimana and Shashan. The faults, channels, interaction zones, cavities and karst growth cracks with hydraulic properties and different thickness form the natural aquifers. On the slopes of the low elevations, the properties of the aquifer and its surface springs in the foothills of the mountains regulate the flow of groundwater. The springs release 2 liters per second in Ghormach district of Badghise province and 3332 liters per second upstream of the Balkh River. The karst springs in these regions are very important for drinking water supply and irrigation. The best water sources for agriculture and water supply seem to be the karst springs, which originate from different karst aquifers, each with a different discharge. Therefore, these sources should be given top priority in water supply planning and programming in the northern region of Afghanistan, where both deep and shallow groundwater have high mineral content. The Firoz Koh, Band-e-Turkistan and Parapamisus mountain ranges, which have high topographic elevations and precipitation in the form of snowfall and rainfall, are the locations of the Hydrological Massif (Band-e-Turkistan and Surkhab). Rainfall and snowmelt provide enough water for the hydrological basins or rivers of the northern Afghan platform to pump groundwater. Due to the exposure of igneous rocks of different ages, there are several geological layers, including those from the Cainozoic, Mesozoic and Palaeozoic ages. Due to the many fractures, layers, weathering, faults and contact zones, the hydrogeological situation is complicated, and the hydraulic properties and hydrogeological conditions are linked to the natural groundwater system. The small river channel runs through narrow valleys where springs emerge from the groundwater system (Saffi 2007).

3.2. Groundwater Recharge and Usage

Groundwater is a naturally occurring resource that meets the water needs of communities for irrigation, drinking and environmental conservation. Aquifers are the accumulation of water in porous rock (Bear 2012). Morris defined aquifers as layers of rock where groundwater is stored in the earth's crust. Aquifers fill with surface water that has been absorbed from the Earth’s surface (Morris, Litvak, and Ahmed 2001). The properties of the material through which the groundwater moves determine how much and how fast it moves (which is the potential of the water) (Bear 2012). Aquifers in urban areas serve three main purposes: they are one of the main sources of groundwater, they can also be used as disposal points for sewage, and they can contain underground infrastructure such as foundations, underpasses, tunnels and warehouses (Morris, Litvak, and Ahmed 2001).

Danish Committee for Aid to Afghan Refugees (DACAAR) has conducted studies on the quality of groundwater and has pursued two important objectives by installing several shallow wells across the country: to have and maintain a database of wells in the country and to provide drinking water to the people. An analysis of the DACAAR database has shown that aquifers have been severely depleted since 1999 and groundwater levels have dropped significantly due to drought and excessive groundwater use for a number of reasons, including industry, environmental security, irrigation and water supply. As a result, many of the traditional water supply systems for irrigation, such as karezes and shallow wells, have dried up. This has raised questions about the sustainability and reliability of groundwater resources in the future. To ensure that groundwater resources are utilized effectively and efficiently, a number of key stakeholders and collaborators in the water sector, including the Milinda Moragoda Institute (MMI), Kabul University, Polytechnic University, the German Agro Action (GAA), the Ministry of Energy and Water of Afghanistan (MEW), the Oxford Committee for Famine Relief - Oxfam Australia (OXFAM), the Swedish Committee for Afghanistan (SCA), the Swiss Agency for Development and Cooperation (SDC), the United State Embassy, the USGS, the United State Agency for International Development (USAID), the Agency for Technical Cooperation and Development (ACTED), the Action Contre La Faim (ACF), the Afghanistan Geological Survey (AGS) and the World Food Program (WFP)ags have committed to help establish a national groundwater monitoring and management system.

The results of data management, assessment, and mapping by the national GMW network show that Afghanistan's groundwater resources are gradually being depleted and the quality of water in the country is declining every year. The "early warning" of potential threats to groundwater is the depletion of groundwater and the deterioration of its water quality. Overexploitation and wasteful use of precious groundwater resources are the result of a lack of understanding of the relationship between groundwater discharge and recharge and the effectiveness of water conservation measures.

According to the GMW network in DACAAR, the steady decline in groundwater levels in Afghanistan's river basins has resulted in groundwater being demanded and used more than it is recharging (DACAAR 2019).

The country's annual water resources amount to 75 BCM, of which groundwater accounts for about 18 BCM (Ahmad and Wasiq 2004) (see Table 3.1). However, the Ministry of Energy and Water's estimate shows that the country has 77 BCM of potential annual water resources, of which the PARB contributes 18,763 BCM (MEW 2016). The amount of water resources required annually for irrigation is about 20 BCM, which is 99% of the total water consumption, of which 3 BCM is groundwater. According to Vincent W. Uhl, the annual groundwater recharge for the Panj Amu River Basin is estimated at 2.97 billion m3/year (Uhl and Tahiri 2003). Rivers and streams supplied over 85% of the water used annually, while alluvial aquifers supplied about 15% of the total (Saffi and Kohistani 2013).

Table 3.1: Estimated and projected groundwater & surface water resources BCM/year (SOURCE: Mahmoodi 2008; Ahmad and Wasiq 2004).

Water Resource	Potential / Available Water	Present Usage & unused			
		Used	Balance unused	Future Use	Balance unused
Surface water	57	20	37	40	17
Groundwater	18	3	15	10	8
Total	75	23	52	50	25

The Afghanistan Water Resources Development Technical Assistance Project (AWARD-TISC and Limited 2013) has pointed out that Afghanistan has considerable water resources, with an estimated 84 billion liters per year or an average of more than 2000 liters per person, and that the Panj-e-Amu River Basin produces about 48 billion cubic meters of renewable surface water annually, with the Kabul Basin coming second with 21.6 BCM, Helmand with 9.3 BCM, the Hari Rod Murghab Basin with 3.1 BCM and the Northern Basin with 1.9 BCM.

The average annual recharge of aquifers was estimated by the FAO in 1996 to be 14.9 BCM; however, this number has dropped to 10.8 BCM (Uhl and Tahiri 2003), of which 2.8 BCM of water is used for different purposes. Unfortunately, it is unclear how much of these potential resources can be used without impacting ecosystems and socio-economic growth.

According to the DACAAR report, groundwater supplies were significantly affected by the prolonged drought that began in 1998 and lasted until 2002, coinciding with the dry year of 2004. The decline in groundwater levels caused by scientifically unjustified overexploitation, drought, high evaporation, low rainfall, and poor management has resulted in most karezes, shallow wells and springs drying up in most areas of the country. Modern drilling techniques are being used to tap deeper confined and unconfined aquifers for irrigation, domestic, industrial, and other purposes. A deeper understanding of future groundwater is essential, as are laws, policies and regulations to support current uses and meet future needs (Saffi and Kohistani 2013).

3.3. Monitoring of Groundwater

Assessing the relationships between long-term fluctuations of groundwater with climate variability and anthropogenic parameters, estimating the rate of depletion and understanding the dynamics of freshwater depend critically on monitoring the state of aquifers and fluctuations in groundwater storage in both spatial and temporal scales (Yeh and Famiglietti 2009). Bierkens and Wada classify large-scale monitoring methods for groundwater alteration and depletion into three main categories, including:

1. Water balance method: The difference between groundwater abstraction and groundwater recharge forms the basis of the water balance method. It is assumed that groundwater depletion occurs when and where the abstraction rate exceeds the recharge rate. Limitations of this method include the lack of understanding of water bodies, streamflow recharge and the impact of evapotranspiration on the estimation process (Konikow and Leake 2014). Large-scale hydrological models

use the water balance technique because measuring groundwater recharge and abstraction is a lengthy process (Bierkens and Wada 2019).

2. Indirect geodetic method: By using remote sensing methods and data, including GPS, lidar observations and radar, or by using traditional geodetic surveys, the indirect geodetic approach can be performed (Bierkens and Wada 2019; Minderhoud et al. 2017). As land surface deformations are often a sign of groundwater depletion, this technique uses data from land subsidence events to assess groundwater changes for regional studies (Galloway and Burbey 2011).
3. Volume-based method: Assessing the variability of water storage in aquifers is of paramount importance for effective water resources management (Reddy and Syme 2014). Volume-based techniques estimate depletion rates by directly measuring changes in groundwater storage over time. By taking water withdrawals into account, these methods provide more accurate estimates compared to alternative approaches (Bierkens and Wada 2019). Two volume-based methods can be used to assess and track fluctuations in groundwater levels:

    i. Remote sensing data: Based on volume estimates, however, remote sensing techniques offer an additional way to assess groundwater changes. Within this method, groundwater levels and storage coefficients modeled in hydrological models enable large-scale spatio-temporal estimates of groundwater depletion (Bierkens and Wada 2019). The precision of the simulations has a significant influence on the accuracy of the hydrological models. In addition, the uncertainty of the estimates increases as more simulated groundwater abstraction and recharge data are needed to obtain accurate estimates of the volume of storage loss (De Graaf et al. 2014; Sutanudjaja et al. 2018). A relatively new satellite project that can be used to derive large-scale variations in groundwater storage is the GRACE mission. The next part takes a closer look at this strategy.
    ii. In situ observations: The conventional method for estimating groundwater fluctuations uses in-situ measurements from groundwater piezometers. By analyzing actual records from monitoring wells, this approach provides the clearest and most accurate estimates of hydraulic head or water table fluctuations (Bierkens and Wada 2019). Equation (3.1) is used to estimate

storage fluctuations on a regional scale by using the specific yield of the aquifer and groundwater level changes (Leblanc et al. 2009).

$$\Delta GWS = \Delta H \times Sy \tag{3.1}$$

Where ΔGWS is groundwater storage fluctuations, ΔH is groundwater level changes, and Sy is specific yield.

Point observations have a high degree of precision, but their appropriate use is limited by the small network of observation wells and incomplete data. Furthermore, the interpolated surface of the point data is needed for regional analysis, which introduces additional uncertainties into the results (MacDonald et al. 2016; Scanlon, Longuevergne, and Long 2012).

CHAPTER 4

METHODOLOGY AND MATERIALS

This section addresses the study area (Panj Amu River Basin), available data, and the use of Geographic Information Systems (GIS) for Multi-Criteria Decision Analysis (MCDA) using methods such as Analytical Hierarchy Process (AHP), Frequency Ratio (FR), and Evidential Belief Function (EBF) for hydrologic geospatial analysis and modeling. The chapter outlines the successive stages in creating a model for a research area and examines the mapping of groundwater potential in the Panj Amu River Basin.

4.1. Study Area: The Panj Amu River Basin (PARB)

The PARB is located in northeastern Afghanistan and lies between 34° 34′ S and 38° 30′ N in latitude and 66° 41′ W and 74° 53′ E in longitude (Figure 4.1). The basin has a catchment area of 90,692 km2 and originates in the east and center of the Pamir and Hindu Kush Mountains (Ibrahimzada and Sharma 2012; Favre and Kamal 2004). The Amu (Oxus) River rises in the PARB (Wakhan Corridor) and flows through the northern, southern and eastern borders of Afghanistan, Tajikistan and Uzbekistan respectively.

The PARB comprises four provinces, namely Badakhshan, Takhar, Kunduz, Baghlan and some parts of Bamyan and Samangan. The PARB has one lake (Shiva Lake) and due to the mountainous terrain, there are many small and large rivers (Kunduz River, Taloqan (Khanabad) River, Kokcha River, Panj Amu River and Wakhan River) flowing into the PARB from east, southeast and south to north and northwest, and all these rivers eventually flowing into the Amu River. The PARB has six watersheds: Kokcha, Upper Panj, Lower Panj, Upper Kunduz, Lower Kunduz and Taloqan Sub-Basins (Figure 4.2).

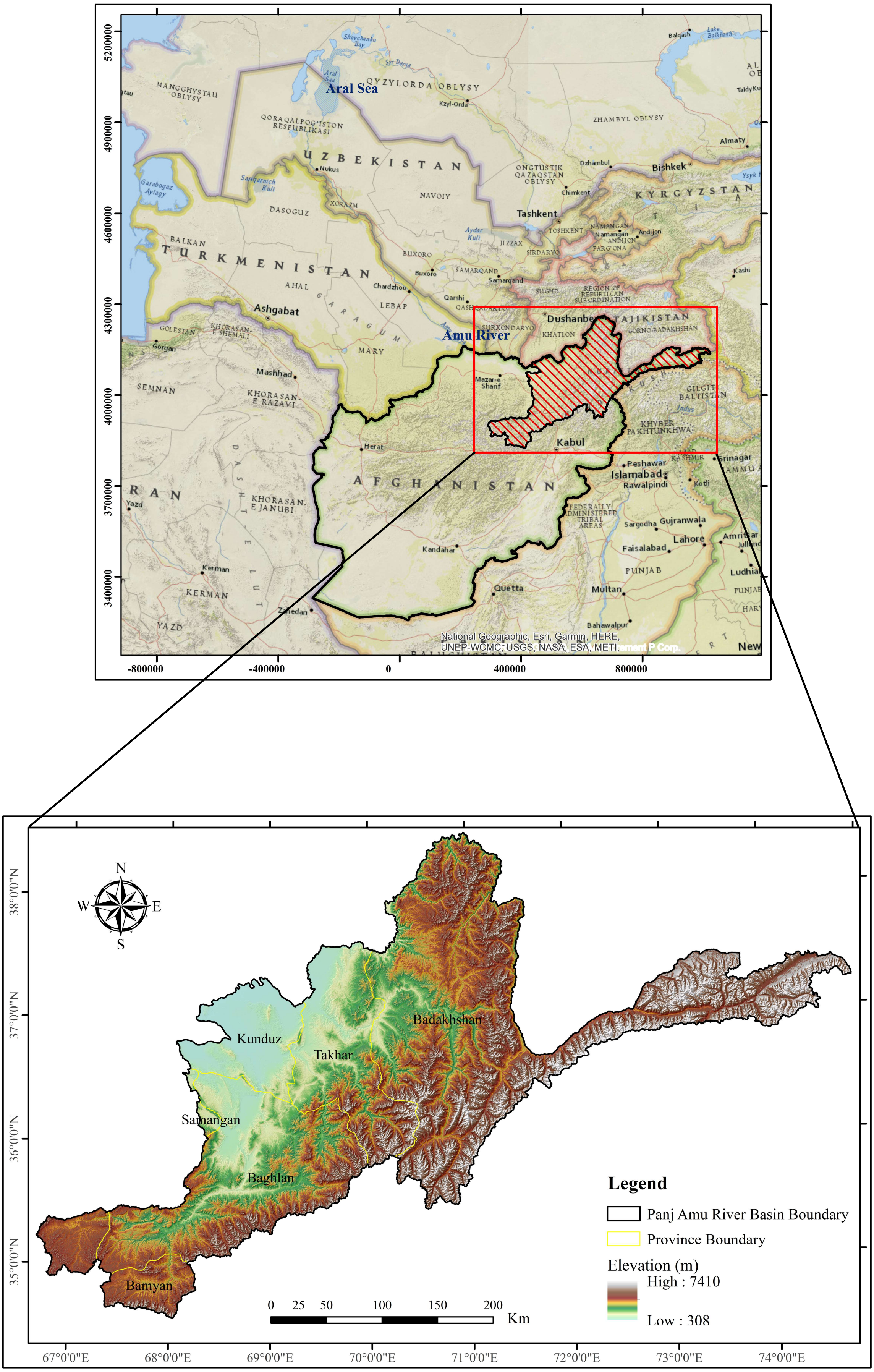

Figure 4.1: The PARB's Study Area Map

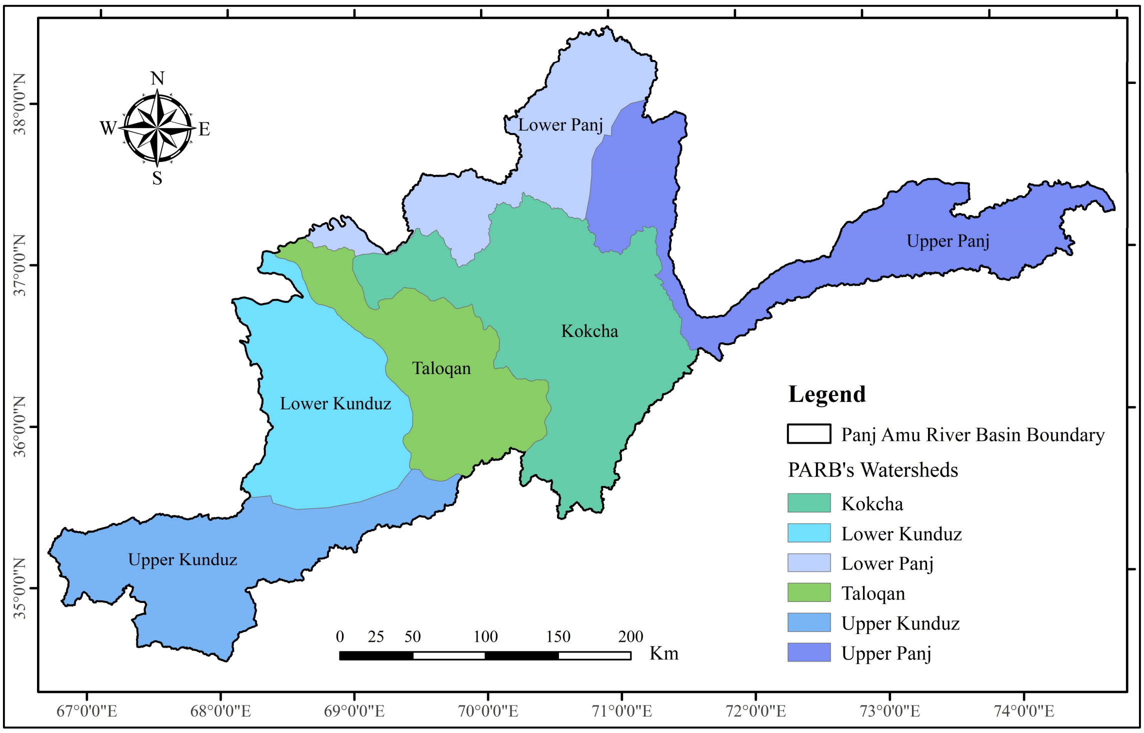

Figure 4.2: Sub-Basins (Watersheds) Map of the PARB

The PARB originates in the central highlands of the Pamir and Hindu Kush Mountains, 7500 meters above sea level, and reaches an average altitude of 300 meters above sea level in the northwestern part (Kunduz province near the Amu River). The mountainous topography of the PARB basin has steeper slopes and valleys in the upper reaches and barren land in the lower reaches. Due to the steeper slopes, heavy rainfall, glacial and snowmelt, human activities and drought in some parts of Bamyan, the frequency and severity of flooding in the PARB is increasing. The reports and disaster maps of OCHA and the European Union (Figures 1.3 and 1.4) (EU 2022; OCHA 2015, 2022) show that the PARB is the most affected region in Afghanistan. According to (Ansari and Tayfur 2023), the Panj Amu River basin in the northeast and the Kabul River basin in central and southeast Afghanistan show higher soil losses compared to other regions. Communities are uprooted and infrastructure is damaged by these catastrophic events.

There are 4.55 million people living in the Panj Amu catchment area, of which 3.78 million (83.22 %) live in rural areas and 0.76 million (16.78 %) in urban areas (NSIA 2023). According to (King and Sturtewagen 2010), the PARB had 7230 Km2 of irrigated agricultural land in 1990, which is about 11% of the current agricultural land of the whole country, and the assumed annual water intake was 7.6 MCM. The annual survey of NSIA in 2022 shows that 7,566.31 Km2 area was planted in the Panj Amu River Basin. The spatio-temporal distribution of rainfall in the PARB varies and climate change plays an important role in these differences. The maximum and minimum annual rainfall 1979-2022 in the PARB were 663.65 and 103.32 mm, respectively (Hayat 2022). The decade-long precipitation history in the PARB shows a decrease and due to the low precipitation, the average temperature has increased in the last four decades. The decadal average temperatures in 1979-1988, 1989-1998, 1999-2008 and 2009-2018 are 12.17, 12.28, 13.42 and 14.39 °C respectively. The 2016 report of the Ministry of Energy and Water shows that a total of 39,889 BCM of annual precipitation was observed in the PARB over a long period of time, which is 24% of the total precipitation in Afghanistan (MEW 2016).

Despite having a lot of hydropower potential, this basin has not yet been developed. Currently the basin is home to four hydroelectric and irrigation dams.

1. Puli Khumri Dams: Two hydropower plants and irrigation dams in the city of Puli Khumri in Baghlan province, which were built in 1943 with German assistance. The dams have a capacity of 9 MW and 4.5 MW of electricity. However, due to the depreciation of the system and the flash floods of 2011 and 2012, the large dam can only generate less than 6 megawatts of electricity, while irrigation thirty thousand hectares of agricultural land. The dams currently supply electricity to the Baghlan-i-Markazi district and the Dandi Ghori sugar mill in Puli Khumri, as well as occasionally to a textile factory.
2. Nahr Gawkush Dam: Nahr Gawkush Dam is a hydroelectric power plant and an irrigation dam with two wide channels for irrigation, built in 1968 with the help of the World Bank on the Khanabad-Takhar River in the Khanabad district of Kunduz province. The dam has a capacity of 10 MW of electricity and an irrigation area of 186 km2.
3. Shorabak Dam: Shorabak was built in 2021 on the Kokcha River in Fayzabad district of Badakhshan province. It is a hydropower dam with a capacity of 7.5 MW of electricity.

According to Ministry of Energy and Water of Afghanistan, the Panj Amu River Basin has seen a number of proposed irrigation and hydroelectric projects in an effort to further explore its enormous potential (MEW 2013), and one of these projects which completed in 2021 was Shorabak dam.

4.2. Available Data

The data used for mapping groundwater potential using GIS-based MCDA methods were obtained from some open sources providing satellite imagery, Non-Governmental Organizations (NGOs), land and water management departments and local authorities.

The Afghan Ministry of Urban Development and Housing provided data on land use and land cover, and the Ministry of Energy and Water provided annual rainfall and runoff data for the Panj Amu River Basin. The description and corresponding sources of these data are summarized in (Table 4.1).

Table 4.1: Sources of spatial layer data used to determine groundwater potential map.

No	Data	Details	Source
1	Wells Data	Groundwater's Static Level	DACAAR
2	Population and Husbandry Data	Excel Files and Annual Reports	National Statistics and Information Authority (NSIA)
3	DEM	Aster DEM	ALOS World 3D - 30m
4	Evapotranspiration	Excel File of 500 m and 8-day resolution data (Jan 2000 - Dec 2022)	NASA's EARTHDATA-AppEEARS
5	Streamflow	Excel File of 35 Gaging Stations (2009-2017)	Ministry of Energy and Water of Afghanistan
6	Precipitation	Excel File of 36 Hydrometeorological Stations (1979-2022)	Ministry of Energy and Water of Afghanistan
7	Lithology	Lithology Map	U.S Department of Interior/U.S. Geological Survey (Lithology of Afghanistan)
8	Drainage Density	Topographical Factor	Obtained from DEM
9	Lineament Density	Topographical Factor	Obtained from DEM
10	TWI	Topographical Factor	Obtained from DEM
11	LULC	Shapefile with 30 m resolution	Minister of Urban Development and Housing
12	Soil	Soil Texture map	FAO World's Soil Map
13	Curvature	Topographical Factor	Obtained from DEM
14	NDVI	Environment Factor, 30 m resolution	Google Earth Engine
15	Slope	Topographical Factor	Obtained from DEM

4.3. Assessment of Groundwater Potential Areas

One of the most important sources of water for people in arid and semi-arid regions is groundwater. Sustainable development planning can benefit greatly from an understanding of the spatial distribution of groundwater, basic extraction techniques and associated flows, particularly in arid and semi-arid regions. In this case, groundwater potential mapping (GWPM) is useful as a method for predicting the spatial distribution of groundwater (Arabameri et al. 2019). In the past, time-consuming, expensive and incompletely covered methods such as geophysical, hydrogeological, geological, drilling and geoelectrical analysis were used to collect information about the possible potential of groundwater (Boitt, Khayasi, and Wambua 2023). However, nowadays several research studies propose GIS-based MCDA methods that are low-cost, efficient and effective.

The selection of baseline parameters for groundwater potential is categorized into five main groups based on some common characteristics and effectiveness: morphological factors (e.g. slope, landforms, topographic ruggedness index and curvature); hydrological criteria (e.g, river network density, rainfall amount and SPI); permeability factors (e.g. TWI, soil type and geology); LULC factors (e.g. LULC, soil-adjusted vegetation index (SAVI) and NDVI); anthropogenic criteria (e.g. population density, settlement areas, distance from roads) (Swain, Singha, and Nayak 2020). Based on the research, study area and literature review, ten, eight and eight essential criteria were selected for the AHP, FR and EBF methods, respectively.

The AHP approach is used for weighing each criterion, the Fr model is used to determine the frequency ratio of each criterion with respect to the well data, and the EBF method is used to evaluate the evidence confidence of each criterion considering the well data. The criteria were ranked based on suggestions from hydrologists, hydrogeologists, water resources and soil management experts. Each criterion or indicator was categorized into five groups according to how likely the trend is to groundwater potential: 5 = very high, 4 = high, 3 = moderate, 2 = low and 1 = extremely low. Version 10.8.2 of the ArcMap software was used to analyze and investigate the most important factors and to create the groundwater potential map. The flow chart of the methodology used to determine the groundwater potential in the PARB is explained in (Figure 4.3).

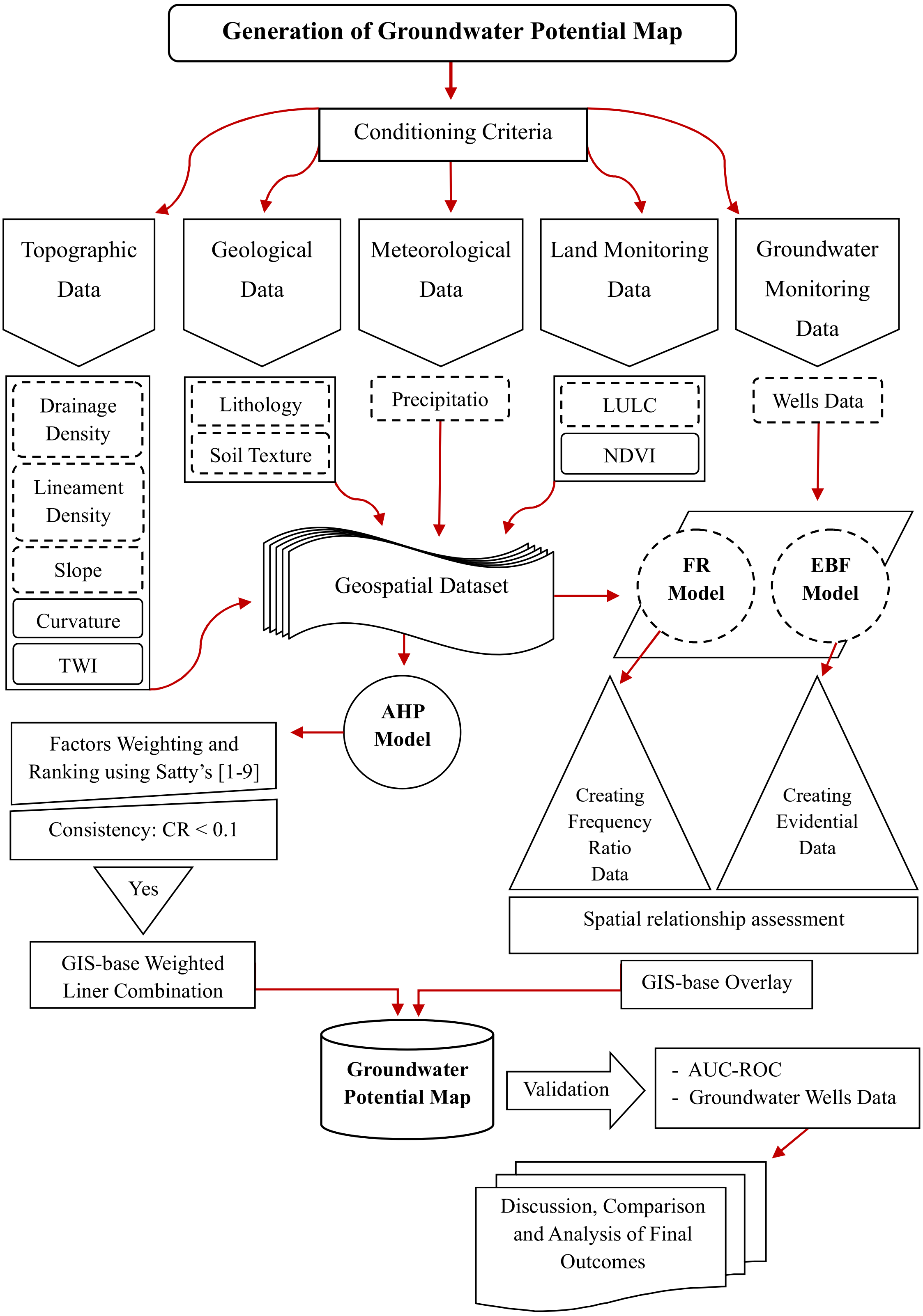

Figure 4.3: Flow Diagram for Identifying Groundwater Potential Areas

CHAPTER 5

WATER BUDGET AND MCDA MODELS CALCULATIONS

The fifth section of this study discusses the water budget of the basin, Multi-Criteria Decision Analysis (MCDA), groundwater potential influencing factors, and the Panj Amu River Basin groundwater monitoring wells data.

5.1. Water Budget

A mass of water that moves through the fractures or pores under the earth's surface is called a groundwater system. This mass of water is in motion, and precipitation continuously replenishes the system with water, while evapotranspiration and discharge to surface waters continuously removes water from the system. Owen notes that the source and amount of water in a groundwater system depends on external variables such as precipitation rate, location of rivers and other surface waters, and evapotranspiration rate, so that each groundwater system is different from the others (Owen 1995). However, all groundwater systems have one thing in common: they all need to maintain the total amount of water entering, leaving and being stored in the system. According to Huilin, the water budget is an accounting system that takes into account all inflows, outflows and storage changes (Gao et al. 2010). According to Richard, water budgets provide a way to assess the sustainability and accessibility of a water supply. A water budget essentially states that the rate at which water enters and leaves a region, such as a watershed, balances the rate of change in the amount of water stored there. Effective planning and management of water resources and the environment requires an understanding of the water balance and the underlying hydrological processes (Healy et al. 2007).

$$P + Qin = ET + Qout + \Delta S \qquad (5.1)$$

Where P is precipitation, Qin is water flow into the system, ET is evapotranspiration (The sum of surface water, soil, and plants' evaporation), ΔS is change in water storage, and Qout is water flow out of the system.

Natural flow patterns are altered by human activities such as irrigation and groundwater abstraction, and these adjustments must be taken into account when calculating the water balance. Since all water must come from somewhere, human activities affect the amount and rate at which water enters, flows through and leaves the system.

The water budget of the Panj Amu river basin has also been determined by the inflow, outflow and consideration of floating population, agriculture and livestock along with water consumption, demand and supply.

5.1.1. Precipitation

The hydrological and meteorological networks in Afghanistan were quite effective in recording temperature, precipitation, and river flows. In 1943, German engineers constructed the first dam station in Puli khumri, and in 1950, the Afghan government began compiling primary data to estimate water runoff in the PARB by establishing a hydrological station (MEW 2014). The United States Geological Survey (USGS) established hydrological stations throughout the country in the early 1950s, which remained in operation until the late 1970s. Then, in 1964 and 1965, 22 hydrological stations were established in the PARB. However, the Soviet invasion of 1979 damaged these networks and data collection was discontinued until after 2001. Subsequently, the USGS assisted the MEW in reinstalling some stations (Kamal 2004). Later, in 2008, the MEW began collecting hydro-meteorological data. Although this data is not currently publicly available, you can obtain it by applying for it (Hayat 2022). So, we applied to the Ministry of Energy and Water for precipitation and runoff data and received the precipitation data from 1979 to 2022.

Table 5.1: Annual Average Precipitation (mm) of the PARB (1979-2022)

Station Name	X	Y	River	1979-2022	2008-2022
Baghlan	470487.76	3996067.95	Kunduz	319.88	252.51
Keshem	593489.91	4087978.3	Keshem	379.55	342.21
Nazdik Taluqan	565922.92	4054675.84	Farkhar	421.02	387.98
Puli Kundasang	462050.76	3938910.33	Kunduz	270.20	268.53
Doab	410019.98	3902797.74	Bamyan	340.24	277.30
Dasht Safid	400517.14	3908708.56	Kahmard	374.20	280.04
Baharak	668269.75	4096775.45	Zardiw	377.69	347.44
Sumdara	651245.22	4103273.27	Sumdara	372.49	424.55
Shash Pul	662788.91	4097981.43	Wardoj	412.47	347.96
Nazdik Jurm	665451.49	4088254.73	Kokcha	398.48	346.77
Bamyan	392554.5	3854096.55	Bamyan	265.26	179.90
Puli Bangi	518584.5	4064982.86	Bangi	302.46	317.70
Puli Alchin	487759.55	4073159.89	Taluqan	250.01	241.02
Chahar Dara	484477.3	4062105.82	Kunduz	253.22	231.22
Tang Nahrin	514482.92	3990378.97	Nahrin	361.56	351.75
Gerdab	487748.14	4023995.72	Kunduz	257.88	254.87
Doshi	472022.75	3940076.83	Andarab	274.86	260.02
Balay Kelagai	477859.92	3955206.01	Kunduz	338.29	276.39
Sheghnan	721139.77	4156368.5	Panj	463.56	363.18
Eshkashem	731653.19	4068197.39	Panj	389.91	228.08
Kofab	629405.75	4211117.61	Kofab	721.88	578.40
Puli Mastan	587934.3	4020721.27	Farkhar	313.36	274.42
Taq Archa	668722.68	4134013.07	Shiwa	571.21	555.23
Tangshiw	698937.48	4207305.22	Shiwa	412.92	396.79
Anjuman	651176.84	3987399.44	Badakhshan	596.94	498.33
Khwajaghar	543267.78	4102601.2	Takhar	306.08	277.83
Faizabad	638352.35	4108213.26	Kokcha	479.88	439.63
Ahangran	406947.24	3855033.63	Bamyan	255.10	167.80
Ai Khanum	537390.25	4116038.66	Panj	393.03	223.43
Taqcha Khana	563398.99	4043376.39	Namakab	402.00	355.85
Khenjan	492518.18	3934343.44	Salang_Shamali	2512.17	2489.63
Worsaj	592637.58	3986515.65	Takhar	283.21	242.85
Khash	653982.72	4078118.7	Badakhshan	396.10	366.83
Tapa Farhat	472286.98	4004867.26	Baghlan	301.20	264.75
Rustaq	570367.58	4110933.62	Takhar	442.74	409.94
Sust	301400.89	4095640.47	Wakhan	290.12	221.56

The spatio-temporal distribution of precipitation in the PARB varies, and climate change plays a vital role in these differences. The maximum and minimum annual precipitation and snowfall recorded from 1979 to 2022 based on 36 hydrometeorological stations were 2532.17 and 92.82 mm, respectively, and the average precipitation calculated by the formula (5.2) for areal precipitation is 430.59 mm. But in the last 15 years (2008 – 2022), the average value has decreased to 381.74 mm/year due to drought. According to the above 15-year average, the total annual precipitation in the Panj Amu river basin is about 34.62 BCM.

$$P_{av} = \frac{P_1 + P_2 + P_3 + \ldots + P_n}{n} = \frac{\sum_i^n P_i}{n} \quad (5.2)$$

A report by the Ministry of Energy and Water from 2016 shows that the total annual precipitation in the PARB amounts to 39,889 BCM in the long term (MEW 2016). The data for the last 22 years has been plotted as shown in (Figure 5.1) and shows the drought from 1999 to 2001 and 2017 to 2018 where the average annual precipitation in the PARB was below 300 mm. The catchment also experiences some wet years such as 2015 and 2021. According to current meteorological forecasts, there will be heavy snowfall in winter and high precipitation in summer in 2024.

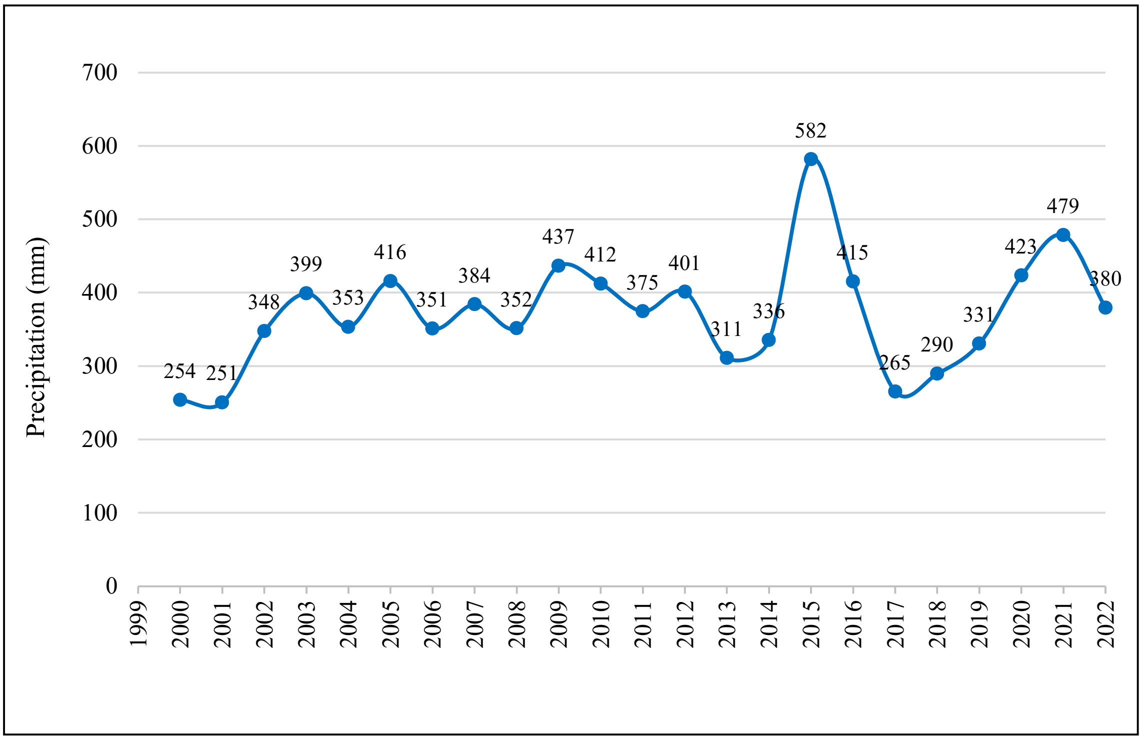

Figure 5.1: The PARB's Average Annual Precipitation 2000-2022

5.1.2. Evapotranspiration (ET)

Evapotranspiration is the sum of the evaporation of surface water, soil and plants, which is an essential factor for the water balance. The evapotranspiration data was downloaded from the NASA EARTHDATA-AppEEARS with a resolution of 500 m and 8 days from the beginning of January 2000 to the end of December 2022. According to this data, the average actual evapotranspiration (ET) is 154.05 mm/Km^2/year and potential evapotranspiration (PET) is 924 mm/year in the Panj Amu River Basin, and the total actual evapotranspiration for the entire region was calculated to be 13.97 BCM/year. Figures 5.2 and 5.3 show the average monthly actual and potential evapotranspiration.

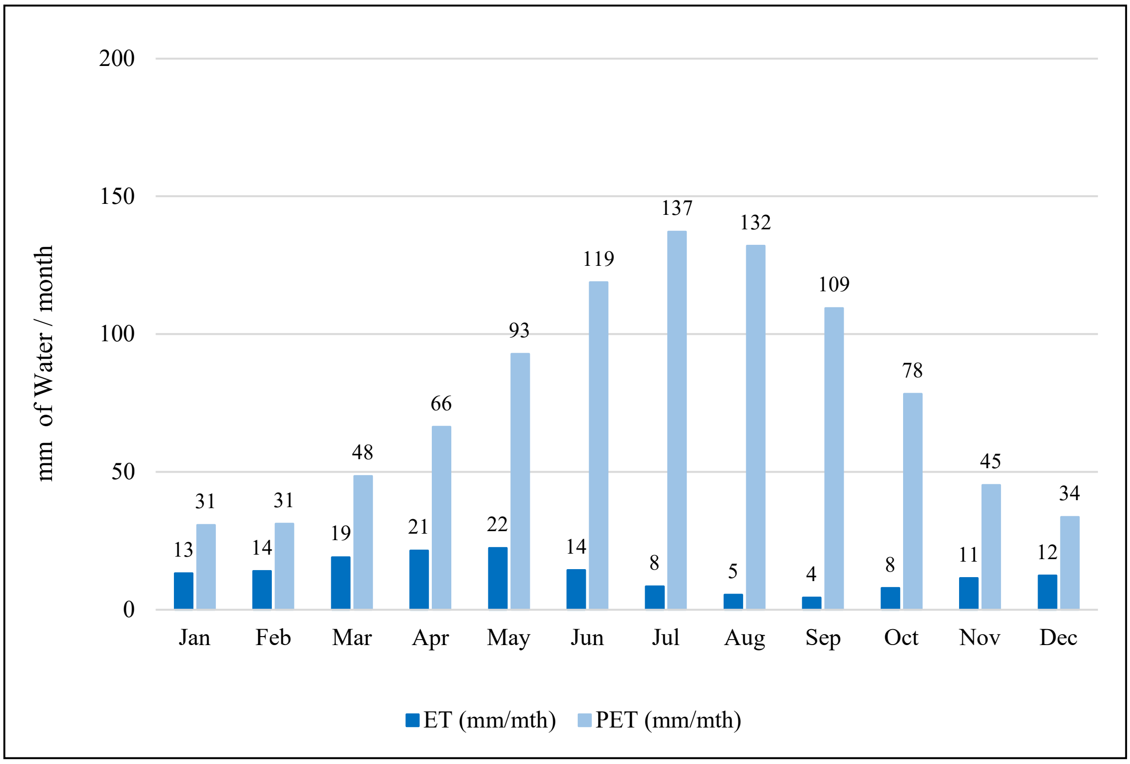

Figure 5.2: The PARB's Average Actual & Potential Evapotranspiration 2000-2022

Actual and potential evapotranspiration behave in opposite ways throughout the year. In general, actual evapotranspiration is high in spring and low in summer, while potential evapotranspiration is very high in summer.

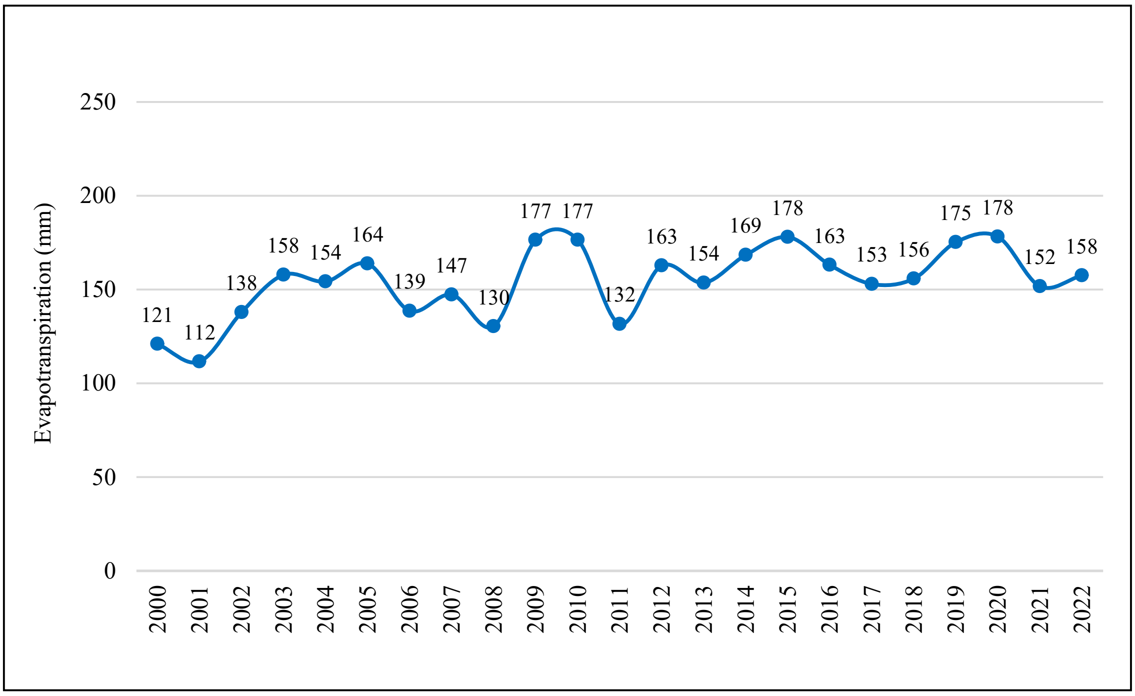

Figure 5.3: The PARB's Annual Actual Evapotranspiration 2000-2022

The annual actual evapotranspiration in the PARB has been shown in (Figure 5.3). The actual evapotranspiration has decline in 2000 to 2001, which was probably caused by 1998 to 2000 drought years, also some peak years namely: 2009, 2010, 2015, 20119, and 2020.

5.1.3. Stream Flow

In 1982, Rallison and Miller explained the occurrence of surface runoff as a condition in which the moisture content of the soil exceeds the field capacity of the soil and precipitation completely fills the pore space of the soil (Rallison and Miller 1982). This means that surface runoff has a direct impact on the groundwater system. And surface runoff is one of the most important parameters of the water balance.

Afghanistan has a potential of 57.03 billion cubic meters (BCM) of surface water resources (Table 5.2). Over 47% of Afghanistan's surface water (27 BCM) flows out of the country and 57% of the country's total river water flows within the country. Since most of the water flows into the Amu River and is shared with Afghanistan's northern neighbors, the PARB has the capacity to produce 22 billion cubic meters of surface water annually, making it the richest river basin in Afghanistan (Favre and Kamal 2004).

However, Shorder and Ahmadzai claim that the total annual runoff in the PARB is 45.4 to 48.1 BCM, which is 57% of the runoff of the entire country (80.3-87.93 BCM) (Shroder and Ahmadzai 2016).

Table 5.2: Catchment areas of the river basins of Afghanistan, modified from (Ibrahimzada and Sharma 2012; Hayat and Baba 2017; Kamal 2004)

River Basins	Catchment Area (Km2)	Drainage Area %	Flow Potential (BCM)
Panj Amu	90,692	14	22
Kabul	76,908	11.88	20.79
Helmand	262,341	40.52	9.3
Harirod & Murghab	77,604	11.99	3.06
Northern	70,901	10.95	1.88
Non-Drainage	69,054	10.66	0
Total	647,500		57.03

According to (Saffi and Kohistani 2013) three main watersheds of the PARB namely; Panj (upper and lower), Kokcha, and Kunduz (upper and lower) have annual potential of 48.12 billion cubic meters water resources, which includes both surface and groundwater.

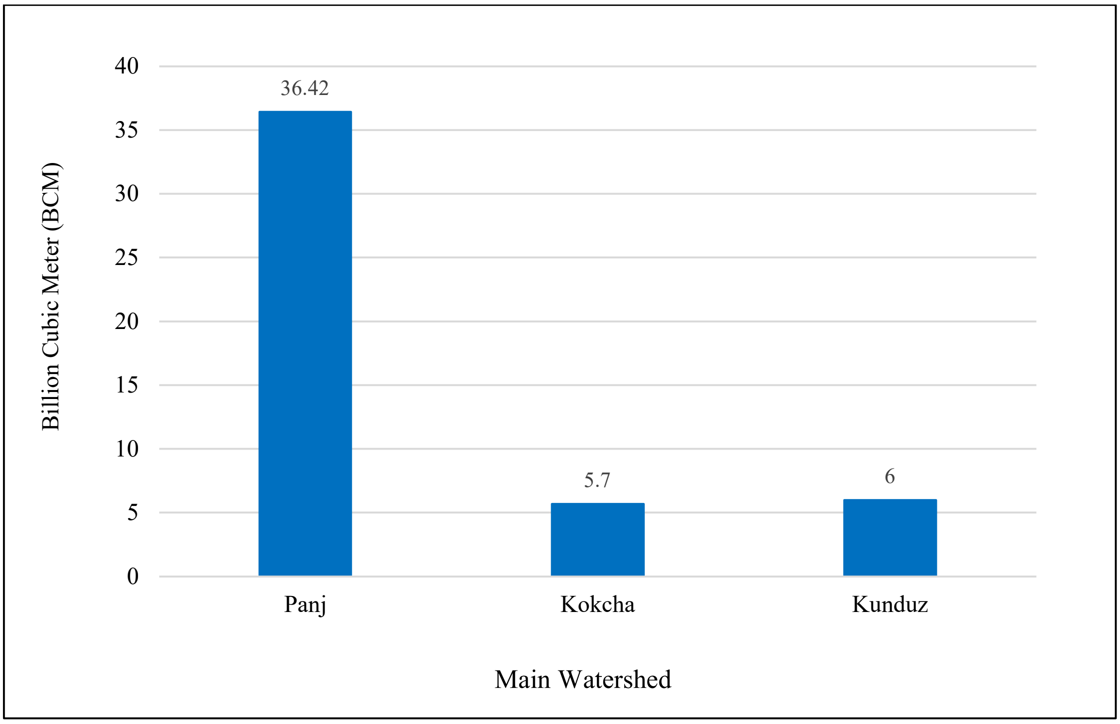

Figure 5.4: Annual Potential of Main Watersheds of the PARB (SOURCE: Saffi and Kohistani 2013)

According to the 2013 report on cooperation between the Islamic Republic of Afghanistan and the Republic of Tajikistan in the field of hydrology and environment in the upper Amu River basin, Afghanistan has withdrawn only 5 Km^3 ~ 5 BCM of water from the Amu River in the last 20 years, Tajikistan 7.5 – 8.5 BCM, Turkmenistan 23 – 28 BCM, Uzbekistan 26 – 40 BCM and Kyrgyzstan 0.1– 0.5 BCM (Omar 2013).

This study used discharge data provided by the Afghan Ministry of Energy and Water (MEW), which includes 35 monitoring stations in the Panj Amu catchment area (Figure 5.5). No nationwide runoff measurements are available before 2008. And the Afghan Ministry of Energy and Water only provided us with runoff data between 2009 and 2017.

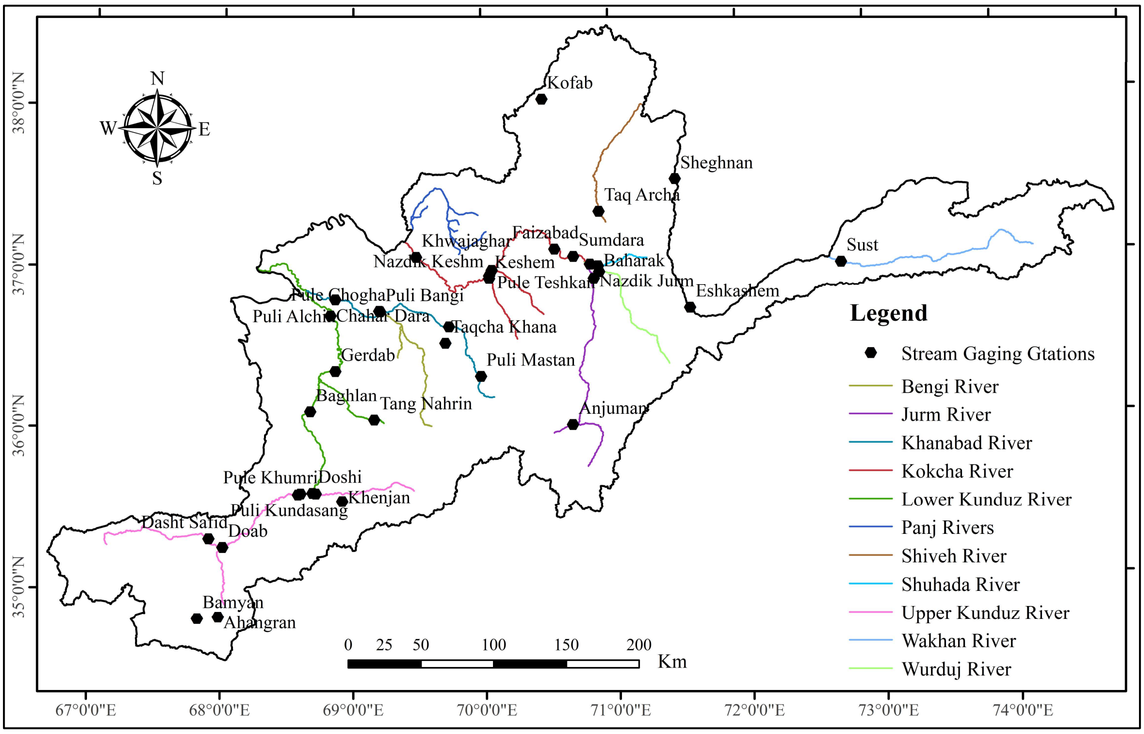

Figure 5.5: Rivers and Stream Gaging Stations Map of the PARB

Table 5.3: Runoff (MCM) in the Panj Amu River Basin from 2009-2017

Station Name	X	Y	Drainage Area (Km^2)	MCM
Baghlan	470487.76	3996067.95	19740	1821.01
Keshem	593489.91	4087978.3	2145	477.28
Nazdik Taluqan	565922.92	4054675.84	4110	1546.69
Puli Kundasang	462050.76	3938910.33	12620	2837.74
Doab	410019.98	3902797.74	5005	509.38
Dasht Safid	400517.14	3908708.56	3795	307.58
Baharak	668269.75	4096775.45	1035	557.13
Sumdara	651245.22	4103273.27	219	199.9
Shash Pul	662788.91	4097981.43	4485	1675.36
Nazdik Jurm	665451.49	4088254.73	7670	2357.11
Bamyan	392554.5	3854096.55	945	90.36
Puli Bangi	518584.5	4064982.86	4200	785.32
Puli Alchin	487759.55	4073159.89	10385	770.87
Chahar Dara	484477.3	4062105.82	24820	1456.18
Tang Nahrin	514482.92	3990378.97	672	163.41
Gerdab	487748.14	4023995.72	22930	1895.14
Doshi	472022.75	3940076.83	3724	1005.7
Sheghnan	721139.77	4156368.5	29945	13057.1
Eshkashem	731653.19	4068197.39	13904	5994.61
Kofab	629405.75	4211117.61	1099	791.34
Puli Mastan	587934.3	4020721.27	3190	642.23
Taq Archa	668722.68	4134013.07	1839	765.1
Anjuman	651176.84	3987399.44	1411	375.46
Khwajaghar	543267.78	4102601.2	20645	6093.71
Faizabad	638352.35	4108213.26	12709	4140.52
Ahangran	406947.24	3855033.63	1660	161.53
Puli Khumri	474335.505	3939621.026	17410	2415.32
Puli Kundasang	463767.682	3939657.711	12610	1146.85
Nazdik Keshm	593487.473	4089840.696	16765	4966.61
Nazdik Baharak	669136.955	4092861.423	3350	1103.43
Khenjan	492518.18	3934343.44	251	141.18
Taqcha Khana	563398.99	4043376.39	265	448.67
Pule Teshkan	595228.17	4093690.34	811	283.28
Pule Chogha	517857.175	4065309.439	9760	1817.16
Sust	301400.89	4095640.47	4636	3205
	Total			66005.26

There is varying information about Afghanistan's groundwater and surface water and in particular about the Panj Amu River Basin. According to the 2008 Afghanistan Water Sector Strategy reports, the amount of surface water in the PARB is 22 BCM/year. However, the Ministry of Energy and Water's estimation shows that the PARB contributes 18.763 BCM/year of water resources (MEW 2016). And according to

(Shroder and Ahmadzai 2016), the Amu River has a discharge of about 45.4 – 48.1 BCM/year, of which 24 BCM/year comes from the Afghanistan PARB. The calculated long-term total runoff from Pul Alchin, Chahar Dara, Khwajaghar, Sheghnan and Kofab gaging stations installed at the ends of the main rivers and covering almost the entire catchment area of Panj Amu is 22.169 BCM/year contributing to the Amu River. Since the Sheghnan gaging station also receives some water from Tajikistan, the total annual runoff should be less than 22 BCM. The total annual outflow (18.763 BCM) reported by the Ministry of Energy and Water in 2016 is more reasonable and has been used in this study.

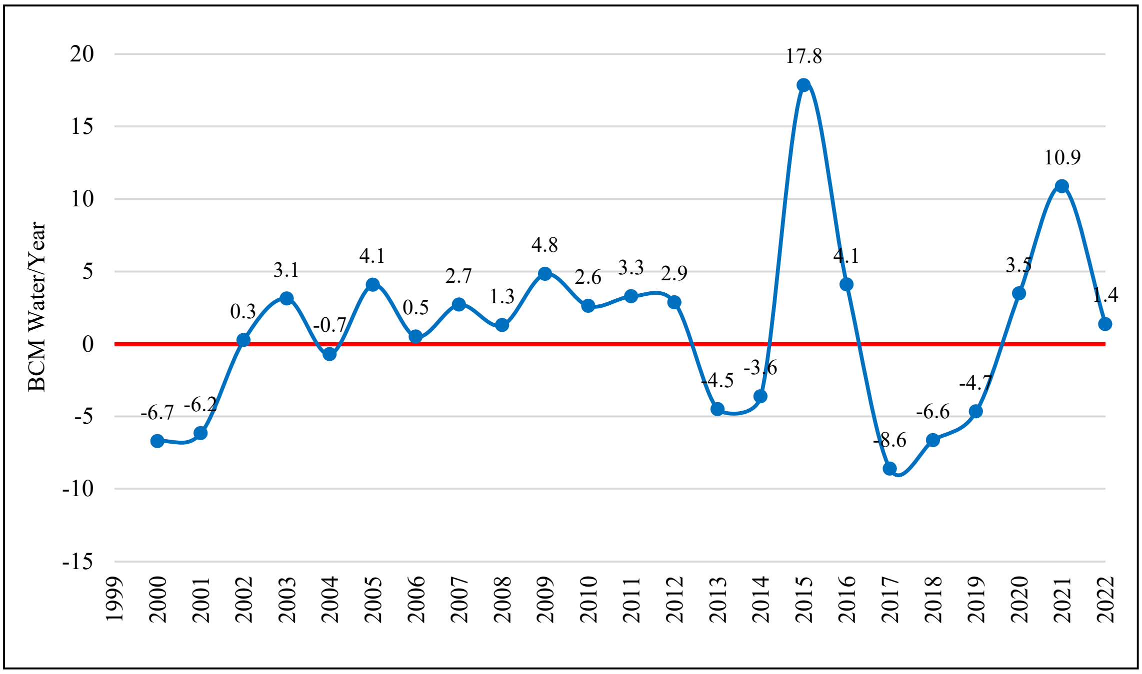

Figure 5.6: The PARB's Annual Water Balance with Constant Runoff 2000-2023

The average runoff of the PARB by MEW, 2016 was estimated 18.763 BCM so here it was used as constant runoff from 2000 to 2023. According to this estimation as shown in (Figure 5.6), in 2000, 2001, 2013, 2014, 2017, 2018 and 2019 years the recharge to groundwater system in the PARB is lower than zero. The reason for the decline was the drought from 1998 to 2000, and as well as the drought again in 2013 and 2017 respectively. (Figure 5.6) also shows some peak years like 2015 and 2021 which are the best years for recharging groundwater.

$$P = Q + ET + \Delta S \quad (5.3)$$

$$\Delta S = P - ET - Q \tag{5.4}$$

The water balance is estimated by the (5.4) equation, where P is precipitation, Q is streamflow, ET is Evapotranspiration and ΔS stands for change in storage.

According to the calculation, the annual water balance is 1.887 billion cubic meters. The water balance reflects a favorable situation for water resources in the basin and shows that currently the region doesn't have water scarcity. It indicates that there is enough water in the basin for a variety of purposes, including agricultural irrigation, municipal water supply, industrial processes, and ecological requirements.

5.1.4. Human Water Consumption

Numerous human activities have an impact on the natural water cycle. The soil is modified for agriculture through the construction of irrigation and drainage systems, which alters the transpiration, evaporation, runoff, and infiltration rates of plants. In urban environments, there is a tendency for buildings, roads and parking lots to increase runoff and decrease infiltration (Healy et al. 2007). The direct consumption of water by humans for various purposes also changes the water balance. Water budgets serve as a basis for evaluating the potential impact of changes made by humans or nature to one component of the water cycle on other components of the cycle, so it is important to consider population when studying the water balance.

Data on the population of the provinces in the Panj Amu River Basin, the agricultural products of the basin and the number of animals living in the PARB was obtained from the National Statistics and Information Authority of Afghanistan (NSIA), which is presented below.

Table 5.4: Estimated Population of Provinces in the PARB, modified from (NSIA 2023)

Provinces	Rural	Urban	Total
Baghlan	846242	226705	1,072,947
Badakhshan	1064938	46069	1,111,007
Takhar	994698	159580	1,154,278
Kunduz	877724	330665	1,208,389
Total	3,783,602	763,019	4,546,621
Percentage	83.22 %	16.78 %	

A field study conducted from 2011 to 2012 in 10 districts of Kandahar city shows that the average water consumption in this city is 59 liters per person per day (Haziq and Panezai 2017).

Panj Amu River Basin has 4,546,621 inhabitants who consume 97,911,483.24 m3 of water per year. As shown in (Table 5.4), the majority of people in the PARB living in rural areas, accounting for 83.22 percent of the total population of the basin, and it is evident that water consumption in rural areas is lower than in urban areas, so the average water consumption of 59 liters per capita per day is used for this study.

5.1.5. Agricultural Water Consumption

Afghanistan is an agricultural country, and this sector accounts for more than 50% of the country's total GDP. It is a landlocked country with mountains, where about 65 to 78 thousand square kilometers of land is arable, which accounts for ten to twelve percent of the total land area. According to (King and Sturtewagen 2010), the PARB had 7230 Km2 of irrigated agricultural land in 1990, which is about 11% of the current agricultural land of the whole country, and the adopted annual water intake was 7.6 MCM. From the annual survey and report of NSIA published in May 2022, it was found that 7,566.31 Km2 area was planted with various agricultural products in PARB.

Table 5.5: Predicted of Irrigated Farming and Assumed water intake in three river basins of Afghanistan revised from (King and Sturtewagen 2010).

Basin	Predicted Development of Irrigated Farming (Km2)			Assumed Water Intake (MCM)		
	1990	2000	2020	1990	2000	2020
Panj Amu	7230	12500	15800	7.6	12.4	16
Helmand	8000	4000	5000	3	4	5
Kabul	1100	1460	1460	1.1	1.5	1.5
Total	16330	17960	22460	11.7	17.9	22.5

Table 5.6: Agricultural product's Area (Km2) by Province (SOURCE: NSIA 2022)

No	Agricultural Products		Baghlan	Badakhshan	Takhar	Kunduz	Total
1	Wheat	Irrigated	543	208	630	1189	2570
		Rain-fed	438	747	956	317	2458
2	Barley		35.09	13.81	43.57	10.89	103.36
3	Rice		186.69	21.57	222.96	491.52	922.74
4	Maize		42	0.35	4.75	22.9	70
5	Cotton		20	0	31.3	61.5	112.8
6	Bean		22	6.89	3.38	6.2	38.47
7	Pea		36.8	53	10.6	12.5	112.9
8	Mung bean		16	0.65	21.9	9.5	48.05
9	Soya bean		0	1.5	10.3	0	11.8
10	Potato		22.36	15.5	41.78	3.09	82.73
11	Onion		21.5	3	19.9	9.5	53.9
12	Tomato		17.6	1.8	11.95	14.85	46.2
13	Eggplant		2.74	0.04	1.33	0.31	4.42
14	Carrot		7	0.31	3.55	3	13.86
15	Cucumber		0.44	0.34	0.55	0.59	1.92
16	Okra		1.6	0.21	1.1	3.78	6.69
17	Green bean		1.83	0.35	0.45	0.35	2.98
18	Cauliflower		1.25	0	1	0.54	2.79
19	Pumpkin		1	0.08	0.1	1	2.18
20	Courgetti		1.95	0	0.8	0.54	3.29
21	Lettuce		0.7	0.09	0.6	0.62	2.01
22	Garlic		0.55	0.1	0.2	0.62	1.47
23	Melon		113.5	52.14	49.4	29.5	244.54
24	Watermelon		47.2	11.8	27.7	44.64	131.34
25	Flaxseed		45.5	0.83	44.3	17	107.63
26	Sesame		39.6	129.66	8.5	19	196.76
27	Saffron		0.01	0.07	0.06	0.18	0.32
28	Peach		6.75	7.85	4.38	3.8	22.78
29	Pear		7.28	2	2.68	0.98	12.94
30	Pomegranate		0.49	0.21	0.13	0	0.83
31	Apple		10.04	19.7	5.79	0.88	36.41
32	Grapes		2.05	0.34	1.05	2.88	6.32
33	Apricot		7.76	16.33	3.68	1.82	29.59
34	Plum		2.78	0.5	4.24	1.9	9.42
35	Cherry		4.67	3.06	2.32	0	10.05
36	Berry		6.59	15.08	0.2	0.15	22.02
37	Almond		8.21	9.59	6.95	8.78	33.53
38	Walnut		3.27	24.18	1.82	0	29.27
	Total		1,725.8	1,367.93	2,181.27	2,291.31	7,566.31

Table 5.7: Water requirement ML/ha for different agricultural products

Crop Types	Million L/ha	m3/km2	Source
Wheat	2.99	299,000	(Tadesse and Bekelle 2007)
Tomato	2.87	287,000	(Tadesse and Bekelle 2007)
Rice	8-10	800,000-1,000,000	(Michael, Kuznetsov, and Mirau 2014)
Cotton	1.83	1,830,440	(Aydogdu et al. 2018)
Maize	3.27	333,000	(Tadesse and Bekelle 2007)
Potato	2.94	294,000	(Tadesse and Bekelle 2007)
Onion	2.14	214,000	(Tadesse and Bekelle 2007)
Barley	2.93	293,000	(Tadesse and Bekelle 2007)
Peas	1.527	152,700	(Kaur, Sidhu, and Vatta 2010)
Garlic	4.5	450,000	(Kaur, Sidhu, and Vatta 2010)
Carrot	2.175	217,500	(Kaur, Sidhu, and Vatta 2010)
Cucumber	2.78	278,000	(Garcia-Caparros et al. 2017)
Green bean	1.68	168,000	(Garcia-Caparros et al. 2017)
Watermelon	2,12	212,000	(Garcia-Caparros et al. 2017)
Melon	2,52	252,000	(Garcia-Caparros et al. 2017)
Eggplant	4.19	419,000	(Garcia-Caparros et al. 2017)
Bean	1.6 - 4	160,000	-
Soybean	5.98 – 6.9	598000	(Chibarabada, Modi, and Mabhaudhi 2017)
Mung bean	1.9243	192,430	(Sosiawan, Adi, and Yusuf 2021)
Okra	4 - 6	500,000	(Konar and Dey 2015)
Cauliflower	2 - 4.6	360,000	(Konar and Dey 2015)
Pumpkin	3.212	321,200	(Reinesch et al. 2022)
Courgetti	2.78	278,000	(Garcia-Caparros et al. 2017)
Lettuce	2 - 3	250,000	-
Flaxseed	2.516	251,600	-
Sesame	2.516	251,600	(Mohamoud et al. 2020)
Saffron	5	500,000	(Sepaskhah and Kamgar 2009)
Peach	2.8	280,000	-
Pear	2.8	280,000	(Nagy et al. 2010)
Pomegranate	2.8 - 6	280,000	(Ayars et al. 2017)
Apple	2.8	280,000	-
Grapes	2.8	280,000	-
Apricot	2	200,000	-
Plum	2.5	250,000	-
Cherry	1.3	130,000	-
Berry	2	200,000	-
Almond	1.5	150,000	-
Walnut	1.5	150,000	-

The agricultural land area, quantified at 7,566.31 square kilometers as delineated in (Table 5.6), necessitates an annual water demand totaling 2,571,528,174 cubic meters, or 2.572 BCM based on the consumption data of different agricultural products which presented in (Table 5.7).

5.1.6. Husbandry Water Consumption

Water consumption in husbandry, including water used for livestock, is an important factor which should be taken into consideration.

Consistent with estimates (Table 5.8), the animals living in the four provinces (Baghlan, Badakhshan, Takhar and Kunduz) of the Panj Amu River Basin will drink 70957392.48 m3 of water per year. According to the Afghan Ministry of Agriculture, Irrigation and Livestock, the consumption of groundwater in the Panj Amu River Basin is distributed as follows: 99.5% for human consumption, 27.4% for irrigation purposes and 10.2% for agricultural activities (MAIL 2020).

Considering the MAIL report, consumption of groundwater in the PARB by human, livestock and agricultural products is 97.42 MCM/year, 7.24 MCM/year and 704.18 MCM/year respectively, while consumption from rivers and surface water is 0.49 MCM/year, 63.72 MCM/year and 1.87 BCM/year respectively. In total, 808.84 MCM/year of water is withdrawn from groundwater in the PARB. Thus, according to equation (5.1), the water budget in the Panj Amu RB is 1.078 BCM/year.

Table 5.8: Number of Animals by province (SOURCE: NSIA 2022)

Province	Baghlan	Badakhshan	Takhar	Kunduz	Total
Camels	267	620	160	2730	3777
mules	191	13	41	67	312
Donkeys	52035	133387	79000	47500	311922
Horses	6900	5331	9000	7100	28331
Goats	380137	717753	505000	109000	1711890
Sheeps	555600	998634	610000	1220000	3384234
Cows & Cattles	250136	433248	410000	590000	1683384

Table 5.9: Drinking water requirements (Liter/day), modified from (Naqvi et al. 2015)

Species	Physiological condition	Average weight (kg)	Drinking Water
Cattle	Large breed, dry cow	680	73.2
Goat	Lactating − 0.2 l milk/day	27	9.6
Sheep	Lactating − 0.4 l milk/day	36	12.9
Camel	Mid lactation − 4.5 l milk/day	350	41.8
Chicken	Adult broilers (100 animal)	-	33.1
Mules	-	-	50 L/day
Donkeys	-	-	30 L/day
Horses	-	-	55 L/day

In the Panj Amu River Basin, the water balance plays a crucial role in maintaining hydrological equilibrium. The annual water balance, which is estimated at 1.887 billion cubic meters, indicates the total water inflows and outflows within the catchment area. Of this, approximately 1.078 BCM is attributed to groundwater recharge, which illustrates the recharge of the groundwater system. At the same time, 808.84 MCM/year are withdrawn from the groundwater reservoirs in the catchment area (Figure 5.7).

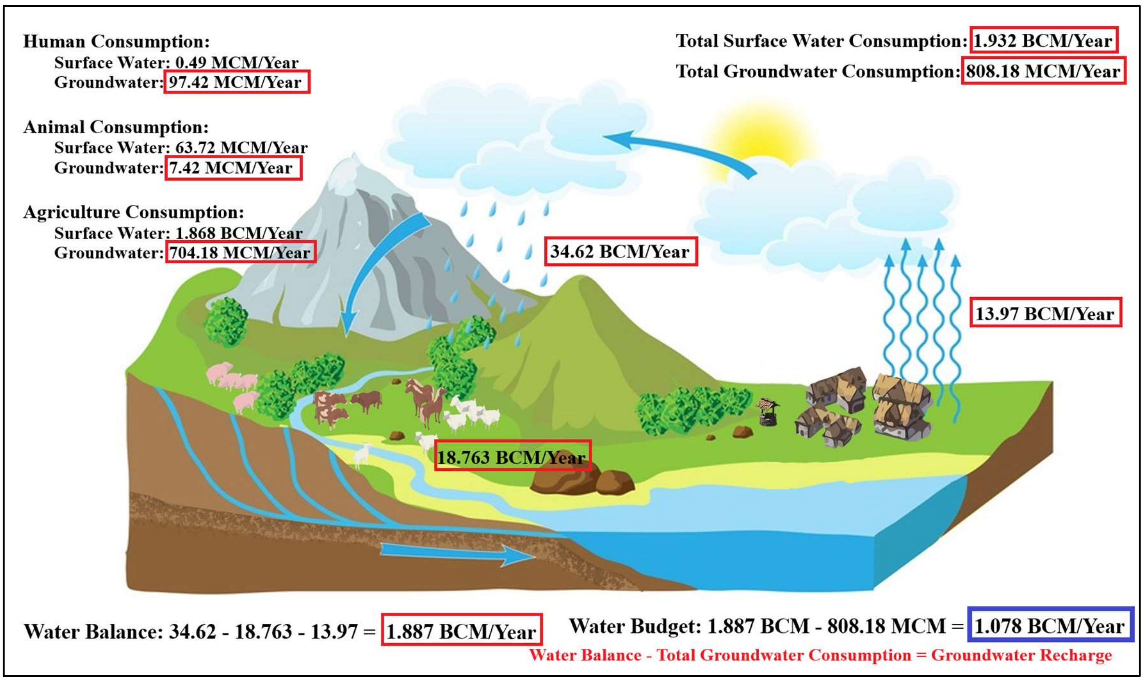

Figure 5.7: Diagram of Water Budget for the PARB (2008-2022)

5.2. Multi Criteria Decision Analysis (MCDA)

In this study, three multi-criteria decisions (AHP, FR and EBF) were used to evaluate the groundwater potential of the PARB. It is important to note that all factors affecting groundwater quantity have the same cell size and appropriate resolution.

According to Malczewski, the Analytical Hierarchy Process is a multi-criteria decision technique that describes a problem and prioritizes possible solutions based on user evaluation and judgment (Malczewski 2006). The AHP was developed in the 1970s by Dr. Thomas Saaty and is a multi-criteria approach to decision analysis. By decomposing a problem into a hierarchy of structures and more manageable sub-problems and then evaluating the relative importance of each sub-problem, the AHP helps people or groups make decisions about complex situations (Saaty 1980).

The frequency ratio model is a statistical approach developed in the 1970s by R.B. Singh that simulates environmental conditions. It is an essential tool for risk assessment, strategic planning and decision making in a variety of fields as it provides a mathematical framework for the study of probabilities and frequencies. Many researchers (Ahmadi et al. 2020; Das 2019; Elvis et al. 2022; Guru, Seshan, and Bera 2017; Razandi et al. 2015; Thanh et al. 2022; Li, Abdelkareem, and Al-Arifi 2023) have used the frequency ratio method for various studies and topics; flood investigation, landslide, groundwater investigation, groundwater vulnerability, groundwater potential mapping and risk management.

A comprehensive framework for dealing with uncertainty, the theory of belief functions, also known as evidence theory or Dempster-Shafer theory (DST), has clear links to other frameworks, including probability theory, imprecise probability theory, and possibility theory. Glenn Shafer has extended the idea, first introduced by Arthur P. Dempster in the context of statistical inference, into a general framework for modeling epistemic uncertainty, or a mathematical theory of evidence. Using this theory, it is possible to summarize data from many sources and determine a level of belief that considers all available data. The Evidence Belief Function (EBF) is a powerful tool for integrating, interpreting, and utilizing diverse information and viewpoints in decision making, risk assessment, resource allocation, uncertainty analysis, performance evaluation procedures and policy development.

5.2.1. Analytic Hierarchy Process Method (AHP)

Planners can use their scientific expertise and experience to break down a problem into a hierarchical structure and solve it using the Analytic Hierarchy Process method. Areas of application for the AHP include project management, product development, investment analysis and strategic planning. It is advantageous when several factors need to be considered and a group of people with different backgrounds are involved in the decision-making process.

To determine the weighting of the criteria and elements, the AHP was chosen as an application for natural resource estimation over a number of other MCDA approaches

(Saaty 1988b). According to (Şener, Sener, and Karagüzel 2011), the AHP is a comprehensive approach that combines pragmatic and subjective expert opinions to achieve decision making considering many factors. And (Kumar and Krishna 2018) define AHP as a strategy that accelerates the decision-making process by identifying and weighting different criteria.

According to (Saaty 1980), the AHP technique includes the following steps:

1. Determining the problem and taking appropriate action.
2. Enumerating the elements involved in the issue to create a hierarchical system.
3. Examining each criterion and sub-criterion in relation to each other.
4. Determination of priorities: Determining the relative weighting or priority of each element or sub-criterion based on the results of the pairwise comparisons. A mathematical procedure is used to determine the weights, considering the values of the pairwise comparison matrix.
5. Analyze the sensitivity: Use the consistency ratio (CR) to examine the consistency of the pairwise matrix of the factor. To be acceptable, the (CR) value must be less than 0.1.
6. Evaluate and make decision: Make your choice based on the weights obtained.

Farhad and Ali Asghar (Hosseinali and Alesheikh 2008) also give six main steps for AHP methodology:

- Description of the objectives and the unstructured problem.
- Using the eigenvalue method to evaluate the relative weights of the decision criteria.
- Identification of specific factors and alternatives.
- Creation of comparison matrices through pairwise comparisons.
- Integration of the weighted decision criteria to obtain the evaluation of the alternatives.
- Calculation of the consistency index.

To determine the importance of each factor within each section, a pairwise comparison of each component set is performed for each factor that fits into the higher section. For the importance and weight of each factor, a comparative rating questionnaire was developed by (Saaty 1980) based on a ranking scale from 1– to 9 as shown in (Table 5.10). Based on this scale, a pairwise comparison matrix was created using the AHP calculator to evaluate the normalized weights of the influential factors/criteria using the eigenvector approach. The relative weights of the factors were the results of the AHP approach, while the pairwise comparisons of the individual parameters served as inputs.

Table 5.10: Pairwise comparison scale of the AHP technique (SOURCE: Saaty 1980)

Ranking	Importance Level
1	Equal Importance
2	Equally to moderately
3	Moderately important
4	Moderately to strongly
5	Strongly preferred
6	Strongly to very strongly
7	Very much strongly
8	Very strongly to extremely
9	Extremely important

In the first step of the AHP, a pairwise comparison matrix was created, with each entry in the matrix indicating how each element compares to the others. In this comparison, the impact of each aspect affecting groundwater potential is assessed independently. The rows in the pairwise comparison matrix correspond to the inverse value of each parameter and its relevance in relation to another parameter (Rezaei-Moghaddam and Karami 2008). To obtain the weighting coefficients of the parameters, the per-pair comparison approach is used. The relative relevance of each factor was determined using a numerical scale matrix from 1 to 9 (Table 5.10) created by (Saaty 1980). Equation 5.5 was then used to create the matrix for the pairwise comparison. The evaluation criteria are used to evaluate each option in the decision analysis matrix. If the problem has n factors and m choices, the decision analysis matrix is as follows:
An $m * n$ pairwise comparison matrix is represented by PC.

$$PC = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ d_{m1} & d_{m2} & \cdots & d_{mn} \end{bmatrix} \tag{5.5}$$

Additionally, each criterion's weighting factor was calculated in equation (5.6), and the element's normalized pair-wise matrix was produced; see (Table 5.12).

$$Wj = \frac{\sum_{i=1}^{n} d_{ij}}{n} \tag{5.6}$$

Where [dij] is the normalized performance of the [ith] alternative in the [jth] criteria.

Table 5.11: The AHP model's pairwise comparison matrix

Factors	RF	G	LD	DD	ST	LULC	TWI	CUR	NDVI	S
RF	1	2	4	3	3	3	3	3	4	7
G	1/2	1	3	3	3	3	4	5	5	7
LD	1/4	1/3	1	2	3	3	3	4	5	6
DD	1/3	1/3	1/2	1	2	2	2	3	3	3
ST	1/3	1/3	1/3	1/2	1	2	3	3	2	6
LULC	1/3	1/3	1/3	1/2	1/2	1	2	3	2	7
TWI	1/3	1/4	1/3	1/2	1/3	1/2	1	2	3	6
CUR	1/3	1/5	1/4	1/3	1/3	1/3	1/2	1	4	4
NDVI	1/4	1/5	1/5	1/3	1/2	1/2	1/3	1/4	1	6
S	1/7	1/7	1/6	1/3	1/6	1/7	1/6	1/4	1/6	1

RF: Rainfall, G: Geology, LD: Lineament density, DD: Drainage density, ST: Soil Texture, LULC, TWI: Topographic Wetness Index, CUR: Curvature, NDVI: Normalized Difference Vegetation Index, S: Slope.

Normalized weights are created for each component by averaging the rows, and the normalized pairwise comparison matrix is prepared by dividing each cell by the total of each column.

Table 5.12: Normalized pairwise comparison matrix and factors weights.

Factor	RF	G	LD	DD	ST	LULC	TWI	CUR	NDVI	S
RF	0.26	0.39	0.40	0.26	0.22	0.19	0.16	0.12	0.14	0.13
G	0.13	0.20	0.30	0.26	0.22	0.19	0.21	0.20	0.17	0.13
LD	0.07	0.07	0.10	0.17	0.22	0.19	0.16	0.16	0.17	0.11
DD	0.09	0.07	0.05	0.09	0.14	0.13	0.11	0.12	0.10	0.06
ST	0.09	0.07	0.03	0.04	0.07	0.13	0.16	0.12	0.07	0.11
LULC	0.09	0.07	0.03	0.04	0.04	0.06	0.11	0.12	0.07	0.13
TWI	0.09	0.05	0.03	0.04	0.02	0.03	0.05	0.08	0.10	0.11
CUR	0.09	0.04	0.02	0.03	0.02	0.02	0.03	0.04	0.14	0.08
NDVI	0.07	0.04	0.02	0.03	0.04	0.03	0.02	0.01	0.03	0.11
S	0.04	0.03	0.02	0.03	0.01	0.01	0.01	0.01	0.01	0.02

The consistency index (CI) equation (5.8), and consistency ratio (CR) equation (5.7) must be regularly used to verify the consistency-based comparison analysis conducted throughout the AHP approach. According to (Saaty 1980, 1988a; Malczewski 1999) the comparisons cannot be considered legitimate until the (CR) is less than 0.1, and for this study the obtain (CR = 0.083 < 0.1) which is less than 0.1 which judges the consistency of the matrix. To assess the consistency of the pairwise comparison matrix, a numerical index known as (CR) or consistency ratio is used.

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{5.7}$$

Where (CI) is the consistency index and (RI) is the random index which is equivalent to (RI = 1.49) in this study and is dependent upon the number of criteria, and the value of (RI) is determined by the matrix order. The method for calculating (RI) is the Saaty scale (Saaty 1980).

$$\mathrm{CI} = \frac{\lambda - \mathrm{n}}{\mathrm{n} - 1} \tag{5.8}$$

Where (λ) is the matrix's eigenvalue which equal to (λ = 11.116) for this study, and n is the number of criteria. As such, a pairwise comparison matrix is used to compare each criterion against all others.

The criteria/alternatives with the highest weighting coefficient are those that have the greatest influence on the quantity and dimensions of groundwater potential. Each aspect impacting groundwater quantity was first categorized into one of five uniform standard scales, ranging from 1 (very low sensitivity to groundwater) to 5 (very high openness to groundwater). The criteria were created in a grid format. Each element was subdivided into smaller groups and ranked according to its influence on groundwater activity. The ranks of each subclass were then normalized by dividing each rank value by the sum of all ranks. The higher-ranking category values in (Table 5.13) correspond to locations that are more vulnerable to groundwater, while lower values are associated with areas that are less vulnerable.

Table 5.13: Assigned normalized rates and weights for all thematic layers and classes.

Influencing Factors	Classes	Area (Km^2)	Potentiality of Groundwater	Rating	Normalized Rates	Wi %
Rainfall	< 270 mm	3683.31	Very Low	1	0.07	23.2
	270 – 350	31289.07	Low	2	0.13	
	350 – 450	47860.93	Medium	3	0.2	
	450 – 750	5569.44	High	4	0.27	
	> 750	1604.21	Very High	5	0.33	
Geology	Conglomerate and Sandstone	19607.72	Very High	5	0.05	20.7
	Granite	3871.83	Very Low	1	0.01	
	Gneiss	11462.33	Very Low	1	0.01	
	Sandstone and Siltstone	10988.20	High	4	0.04	
	Volcanic and Sedimentary Rocks	860.26	Medium	3	0.03	
	Basalt	644.73	Medium	3	0.03	
	Basaltic Andesite and Basalt	49.02	Medium	3	0.03	
	Schist and Phyllite	439.32	Very Low	1	0.01	
	Granite and Granodiorite	4733.39	Very Low	1	0.01	
	Limestone and Dolomite	6900.04	Medium	3	0.03	
	Clay and Siltstone	2699.45	Very Low	1	0.01	
	Rhyolite	1790.00	Low	2	0.02	
	Eolian Deposits	685.07	High	4	0.04	
	Loess	2786.19	Medium	3	0.03	
	Marble and Gneiss	1265.83	Very Low	1	0.01	
	Diorite and Granodiorite	1013.74	Very Low	1	0.01	
	Diorite and Plagiogranite	2667.65	Very Low	1	0.01	
	Limestone and Chert	301.62	Medium	3	0.03	
	Siltstone and Shale	1499.60	Very Low	1	0.01	
	Granodiorite and Granosyenite	4954.10	Very Low	1	0.01	

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Table 5.13 (Cont.).

Influencing Factors	Classes	Area (Km^2)	Potentiality of Groundwater	Rating	Normalized Rates	Wi %
	Limestone	1259.73	Medium	3	0.03	
	Limestone and Sandstone	702.54	High	4	0.04	
	Metavolcanic Andesitic Lava	73.09	Low	2	0.02	
	Alkaline Lava	36.61	Medium	3	0.03	
	Andesite	1041.40	Medium	3	0.03	
	Lava	1489.55	Medium	3	0.03	
	Gneiss and Granite	85.80	Very Low	1	0.01	
	Clay and Shale	625.57	Very Low	1	0.01	
	Basalt and Sandstone	1989.48	Medium	3	0.03	
	Ultramafic Intrusions	85.98	Very Low	1	0.01	
	Gabbro and Diorite	625.40	Very Low	1	0.01	
	Fan Alluvium and Colluvium	224.01	Very High	5	0.05	
	Till	1151.60	Low	2	0.02	
	Granite Porphyry	36.94	Very Low	1	0.01	
	Andesitic Lava	48.22	Low	2	0.02	
	Gabbro and Mafic Metavolcanics	8.85	Very Low	1	0.01	
	Rhyolite and Sandstone	21.34	Medium	3	0.03	
	Granite and Granosyenite	385.05	Very Low	1	0.01	
	Andesite and Granite Porphyry	22.98	Low	2	0.02	
	Rhyolite to Andesite	16.48	Medium	3	0.03	
	Metamorphic Rocks--Undivided	31.99	Very Low	1	0.01	
	Gabbro and Monzonite	55.18	Very Low	1	0.01	

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Table 5.13 (Cont.).

Influencing Factors	Classes	Area (Km^2)	Potentiality of Groundwater	Rating	Normalized Rates	Wi %
	Andesitic Tuff	17.04	Medium	3	0.03	
	Granodiorite	30.07	Very Low	1	0.01	
	Metavolcanic Rhyolite and Ande	2.06	Medium	3	0.03	
	Basalt Tuff	72.86	Medium	3	0.03	
Lineament Density	< 0.1 Km/Km^2	1556.47	Very Low	1	0.07	14.4
	0.1 – 0.5	7533.87	Low	2	0.13	
	0.5 – 1	20010.92	Medium	3	0.2	
	1 – 1.5	53807.28	High	4	0.27	
	> 1.5	7098.48	Very High	5	0.33	
Drainage Density	< 0.05 Km/Km^2	3795.80	Very High	5	0.33	9.5
	0.05 – 0.1	25376.48	High	4	0.27	
	0.1 – 0.15	37286.85	Medium	3	0.2	
	0.15 – 0.2	19964.69	Low	2	0.13	
	> 0.2	3583.20	Very Low	1	0.07	
Soil Texture	Calcic Xerosols-2b	3067.55	High	4	0.17	8.8
	Lithosols, Cambisols and Rankers-2c	25439.12	Very Low	1	0.04	
	Lithosols and Xerosols-c	39584.41	Medium	3	0.13	
	Haplic Yermosols-2ab	8372.33	Medium	3	0.13	
	Lithosols, Humic Cambisols and Rankers-c	1022.23	Medium	3	0.13	
	Lithosols and Xerosols-2c	3624.89	Low	2	0.08	
	Lithosols and Vertisols-2c	4472.73	Low	2	0.08	
	Calcaric Fluvisols-2a	342.12	Medium	3	0.13	
	Gleysols	4646.21	Medium	3	0.13	
LULC	Rangeland and Bare Areas	10057.25	Medium	3	0.04	7.3
	Bare Areas	7549.86	Low	2	0.02	

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Table 5.13 (Cont.).

Influencing Factors	Classes	Area (Km^2)	Potentiality of Groundwater	Rating	Normalized Rates	Wi %
	Waterbody & Marshland	2025.68	Very High	5	0.06	
	Snow covered	4276.44	Very High	5	0.06	
	Irrigated Agr. Land	4010.21	High	4	0.05	
	Rainfed Agr. Land	9769.53	High	4	0.05	
	Rangeland	47667.93	Medium	3	0.04	
	Fruit Trees	136.09	Medium	3	0.04	
	Rangeland and Built-up	0.00	Low	2	0.02	
	Irrigated Agr. Land and Fruit Trees	130.04	High	4	0.05	
	Forests & Shrubs	1244.67	High	4	0.05	
	Rainfed Agr. Land and Rangeland	760.24	Medium	3	0.04	
	Built-up and Fruit Trees	3.83	Medium	3	0.04	
	Vineyards	3.07	High	4	0.05	
	Irrigated Agr. Land and Built-up	3.28	Medium	3	0.04	
	Forests, Shrubs and Rangeland	6.26	High	4	0.05	
	Sand Cover and Rangeland	1032.71	High	4	0.05	
	Sand Cover	881.59	High	4	0.05	
	Waterbody, Marshland and Bare Areas	0.44	High	4	0.05	
	Rangeland, Waterbody and Marshland	33.08	High	4	0.05	
	Waterbody, Marshland and Irrigated Agr. Land	1.98	High	4	0.05	
	Irrigated Agr. Land and Vineyards	0.40	High	4	0.05	

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Table 5.13 (Cont.).

Influencing Factors	Classes	Area (Km^2)	Potentiality of Groundwater	Rating	Normalized Rates	Wi %
	Rainfed Agr. Land, Forests and Shrubs	10.03	Medium	3	0.04	
	Built-up	402.30	Very Low	1	0.01	
TWI	< 6.5	933.86	Very Low	1	0.07	5.9
	6.5 – 7	57619.07	Low	2	0.13	
	7 – 8	21530.06	Medium	3	0.2	
	8 – 11	6089.12	High	4	0.27	
	> 11	3766.48	Very High	5	0.33	
CUR	Concave (< -0.5)	25969.32	Medium	3	0.33	4.8
	Flat (-0.5 – 0.5)	38766.55	Very High	5	0.56	
	Convex (> 0.5)	25257	Very Low	1	0.11	
NDVI	< -0.05	1372.27	Very Low	1	0.07	3.7
	-0.05 – 0.05	30153.97	Low	2	0.13	
	0.05 – 0.15	43891.86	Medium	3	0.2	
	0.15 – 0.3	13802.6	High	4	0.27	
	> 0.3	1364.93	Very High	5	0.33	
Slope	0 – 5 Degree	11630.39	Very High	5	0.33	1.7
	5 – 10	9198.19	High	4	0.27	
	10 – 20	30980.82	Medium	3	0.2	
	20 – 40	33554.63	Low	2	0.13	
	40 – 82.15	4579.62	Very Low	1	0.07	

Using the raster calculator in ArcGIS, the following equation (5.10) was applied to determine the groundwater potential zones (GPZ).

$$GPZ = \sum_{i=1}^{n} AHP_i \tag{5.9}$$

Equation (5.9) can be re-written in basic form as:

$$\begin{aligned} GPZ = {} & RF_w RF_R + G_w G_R + LD_w LD_R + DD_w DD_R + ST_w ST_R \\ & + LULC_w LULC_R + TWI_w TWI_R + CUR_w CUR_R \\ & + NDVI_w NDVI_R + S_w S_R \end{aligned} \tag{5.10}$$

Where RF: Rainfall, G: Geology, LD: Lineament density, DD: Drainage density, ST: Soil Texture, LULC, TWI: Topographic Wetness Index, CUR: Curvature, NDVI: Normalized Difference Vegetation Index, S: Slope, $_W$ is weighting, and $_R$ is rating.

5.2.2. Frequency Ratio Method (FR)

Bonham defined the frequency ratio as the probability of a particular factor or the probability of a particular factor occurring (Bonham-Carter 1994). Oh and Razandi defined the frequency ratio as a bivariate statistical model used as a crucial tool for spatial assessment to determine the probabilistic association between dependent and independent variables or multi-classified thematic strata (Oh et al. 2011; Razandi et al. 2015). According to Das, groundwater potential mapping is conducted based on the correlation between the location of observation wells and factors affecting groundwater potential (Das 2019).

In this study, the link between the groundwater potential-related parameters and the distribution of observation wells forms the basis for the frequency ratio. The frequency ratio is determined using the following additional formula:

$$\mathrm{FR} = \frac{\frac{\mathrm{Pgw}}{\mathrm{Tgw}}}{\frac{\mathrm{Pf}}{\mathrm{Tf}}} = \frac{\%\text{ of Wells}}{\%\text{ of Pixels}} \tag{5.11}$$

Where Pf is the number of pixels in each sub-class of a factor, and Tf is the total number of pixels of a factor, Pgw is the number of pixels having groundwater wells for each sub-class of a factor, and Tgw is the total number of wells.

The FR was calculated according to equation (5.11) with 461 observational wells, and the result has been shown in (Table 5.14).

Table 5.14: The spatial relationship between factors and wells with an assigned FR.

Factors	Classes	No of Pixels	Percentage of Sub-Class	No of Wells	Percentage of Wells	FR
Rainfall	< 270 mm	4092565	4.092	29	6.291	1.54
	270 – 350	34765635	34.763	180	39.046	1.12
	350 – 450	53178814	53.175	226	49.024	0.92
	450 – 750	6188270	6.188	22	4.772	0.77
	750 mm <	1782453	1.782	4	0.868	0.49
Geology	Conglomerate and Sandstone	21786355	21.930	226	49.237	2.245
	Granite	4302035	4.330	12	2.614	0.604

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Table 5.14 (Cont.).

Factors	Classes	No of Pixels	Percentage of Sub-Class	No of Wells	Percentage of Wells	FR
	Gneiss	12735918	12.820	70	15.251	1.190
	Sandstone and Siltstone	12209116	12.289	30	6.536	0.532
	Volcanic and Sedimentary Rocks	955836	0.962	5	1.089	1.132
	Basalt	716370	0.721	4	0.871	1.209
	Basaltic Andesite and Basalt	54468	0.055	0	0.000	0.000
	Schist and Phyllite	488136	0.491	0	0.000	0.000
	Granite and Granodiorite	5259323	5.294	10	2.179	0.412
	Limestone and Dolomite	7666722	7.717	13	2.832	0.367
	Clay and Siltstone	2999385	3.019	7	1.525	0.505
	Rhyolite	1988893	2.002	5	1.089	0.544
	Eolian Deposits	761190	0.766	0	0.000	0.000
	Loess	3095762	3.116	11	2.397	0.769
	Marble and Gneiss	1406475	1.416	5	1.089	0.769
	Diorite and Granodiorite	1126373	1.134	3	0.654	0.576
	Diorite and Plagiogranite	2964058	2.984	5	1.089	0.365
	Limestone and Chert	335134	0.337	5	1.089	3.229
	Granite and Granodiorite	5259323	5.294	10	2.179	0.412
	Siltstone and Shale	1666219	1.677	4	0.871	0.520
	Granodiorite and Granosyenite	5504558	5.541	11	2.397	0.433
	Limestone	1399704	1.409	3	0.654	0.464
	Limestone and Sandstone	780599	0.786	1	0.218	0.277
	Metavolcanic Andesitic Lava	81206	0.082	0	0.000	0.000
	Alkaline Lava	40678	0.041	0	0.000	0.000
	Andesite	1157115	1.165	2	0.436	0.374
	Lava	1655061	1.666	3	0.654	0.392

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Table 5.14 (Cont.).

Factors	Classes	No of Pixels	Percentage of Sub-Class	No of Wells	Percentage of Wells	FR
	Gneiss and Granite	95330	0.096	3	0.654	6.811
	Clay and Shale	695073	0.700	2	0.436	0.623
	Basalt and Sandstone	2210528	2.225	8	1.743	0.783
	Ultramafic Intrusions	95014	0.096	1	0.218	2.278
	Gabbro and Diorite	694893	0.699	5	1.089	1.557
	Fan Alluvium and Colluvium	248896	0.251	1	0.218	0.870
	Till	1279536	1.288	2	0.436	0.338
	Granite Porphyry	41041	0.041	0	0.000	0.000
	Andesitic Lava	53580	0.054	0	0.000	0.000
	Gabbro and Mafic Metavolcanics	9829	0.010	0	0.000	0.000
	Rhyolite and Sandstone	23719	0.024	0	0.000	0.000
	Granite and Granosyenite	427831	0.431	2	0.436	1.012
	Andesite and Granite Porphyry	25536	0.026	0	0.000	0.000
	Rhyolite to Andesite	18313	0.018	0	0.000	0.000
	Metamorphic Rocks--Undivided	35541	0.036	0	0.000	0.000
	Gabbro and Monzonite	61301	0.062	0	0.000	0.000
	Andesitic Tuff	18936	0.019	0	0.000	0.000
	Granodiorite	33396	0.034	0	0.000	0.000
	Metavolcanic Rhyolite and Ande	2284	0.002	0	0.000	0.000
	Basalt Tuff	80950	0.081	0	0.000	0.000
Lineament Density	$< 0.1\ ^{Km}/_{Km^2}$	1729415	1.729	3	0.651	0.376
	0.1 - 0.5	8370965	8.370	36	7.809	0.933
	0.5 - 1	22234356	22.233	95	20.607	0.927
	1 – 1.5	59785864	59.781	277	60.087	1.005
	1.5 Km/Km^2 <	7887200	7.887	50	10.846	1.375
Drainage Density	$< 0.05\ ^{Km}/_{Km^2}$	4217550	4.217	17	3.688	0.874
	0.05 – 0.1	28196091	28.194	78	16.920	0.600
	0.1 – 0.15	41429838	41.427	195	42.299	1.021

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Table 5.14 (Cont.).

Factors	Classes	No of Pixels	Percentage of Sub-Class	No of Wells	Percentage of Wells	FR
	0.15 – 0.2	22182989	22.181	136	29.501	1.330
	$0.2\ {}^{Km}/_{Km^2} <$	3981332	3.981	35	7.592	1.907
Soil Texture	Calcic Xerosols-2b	852098	3.387	16	3.471	0.976
	Lithosols, Cambisols and Rankers-2c	7066421	28.087	85	18.438	1.523
	Lithosols and Xerosols-c	10995670	43.705	272	59.002	0.741
	Haplic Yermosols-2ab	2325647	9.244	58	12.581	0.735
	Lithosols, Humic Cambisols and Rankers-c	283953	1.129	4	0.868	1.301
	Lithosols and Xerosols-2c	1006913	4.002	18	3.905	1.025
	Lithosols and Vertisols-2c	1242426	4.938	3	0.651	7.589
	Calcaric Fluvisols-2a	95032	0.378	1	0.217	1.741
	Gleysols	1290614	5.130	4	0.868	5.912
LULC	Rangeland and Bare Areas	11174723	11.174	12	2.603	0.233
	Bare Areas	8388730	8.388	1	0.217	0.026
	Waterbody & Marshland	2250750	2.251	22	4.772	2.120
	Snow covered	4751602	4.751	0	0.000	0.000
	Irrigated Agr. Land	4455787	4.455	86	18.655	4.187
	Rainfed Agr. Land	10855034	10.854	33	7.158	0.660
	Rangeland	52964362	52.960	120	26.030	0.492
	Fruit Trees	151210	0.151	10	2.169	14.347
	Rangeland and Built-up	1	0.000	0	0.000	0.000
	Irrigated Agr. Land and Fruit Trees	144485	0.144	12	2.603	18.017
	Forests & Shrubs	1382965	1.383	2	0.434	0.314
	Rainfed Agr. Land and Rangeland	844708	0.845	4	0.868	1.027
	Built-up and Fruit Trees	4255	0.004	3	0.651	152.952
	Vineyards	3406	0.003	0	0.000	0.000

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Table 5.14 (Cont.).

Factors	Classes	No of Pixels	Percentage of Sub-Class	No of Wells	Percentage of Wells	FR
	Irrigated Agr. Land and Built-up	3642	0.004	1	0.217	59.565
	Forests, Shrubs and Rangeland	6959	0.007	0	0.000	0.000
	Sand Cover and Rangeland	1147454	1.147	2	0.434	0.378
	Sand Cover	979539	0.979	0	0.000	0.000
	Waterbody, Marshland and Bare Areas	493	0.000	0	0.000	0.000
	Rangeland, Waterbody and Marshland	36758	0.037	0	0.000	0.000
	Waterbody, Marshland and Irrigated Agr. Land	2205	0.002	0	0.000	0.000
	Irrigated Agr. Land and Vineyards	443	0.000	0	0.000	0.000
	Rainfed Agr. Land, Forests and Shrubs	11142	0.011	0	0.000	0.000
	Built-up	446998	0.447	153	33.189	74.254
Slope	0 – 5	12922661	12.931	138	29.935	2.315
	5 – 10	10220210	10.227	126	27.332	2.673
	10 – 20	34423130	34.445	182	39.479	1.146
	20 – 40	37282920	37.306	15	3.254	0.087
	40 – 82.15	5088470	5.092	0	0.000	0.000

The following formula (5.13) was used to integrate the FR of each sub-class of variables in ArcGIS.

$$GPZ = \sum_{i=1}^{n} FR_i \quad (5.12)$$

$$GPZ = RF_{FR} + G_{FR} + LD_{FR} + DD_{FR} + ST_{FR} + LULC_{FR} + S_{FR} \quad (5.13)$$

Where RF: Rainfall, G: Geology, LD: Lineament density, DD: Drainage density, ST: Soil Texture, LULC, S: Slope, GPZ: Groundwater Potential Zones, and $_{FR}$ is stand for Frequency Ratio.

5.2.3. Evidence Belief Function Method (EBF)

The Evidence Belief Function is a comprehensive framework for dealing with uncertainty, or a powerful tool for integrating, interpreting and utilizing diverse information and viewpoints in decision making, risk assessment, resource allocation, uncertainty analysis, performance evaluation procedures and policy development. The method is used by many researchers (Carranza, Woldai, and Chikambwe 2005; Ghorbani Nejad et al. 2017; Ghosh 2021; Li, Abdelkareem, and Al-Arifi 2023; Park 2011; Pourghasemi and Beheshtirad 2015; Saranya and Saravanan 2023) for groundwater investigations.

According to Carranza, an EBF is an educational and spatial combination model (Carranza, Woldai, and Chikambwe 2005), and Bui states that the evidentiary data layers in this model were created by transforming the thematic layers of groundwater treatment factors (Tien Bui et al. 2019). The predictive groundwater potential map was created by applying the spatial linkage between the influencing factors and the groundwater well data to integrate the layers of evidential data. There are four stages in the EBF model: Belief (Bel), Disbelief (Dis), Uncertainty (Unc) and Plausibility (Pls), and according to (Ghosh & Carranza, 2010) the sum of Bel, Dis and Unc is always equal to 1.

Unc determines the interaction between belief and disbelief. The sum of the values for Belief and Disbelief is equal to 1, indicating their binary association when the value of Uncertainty is 0 (complete understanding of the phenomenon). In contrast, the value of uncertainty should be 1, which is called an uncertain state. In reality, the connection cannot be binary because every natural event is associated with some degree of uncertainty. Thus, to fully understand each event, it is important to evaluate not only belief, but also disbelief and uncertainty.

The four stages of EBF model are calculated with respect to the following equations (5.14) – (5.19).

$$\lambda(\mathrm{Tp})\mathrm{E_{ij}} = \frac{\mathrm{N}}{\mathrm{D}} = \frac{\dfrac{\mathrm{N(L} \cap \mathrm{E_{ij})}}{\mathrm{N(L)}}}{\dfrac{\mathrm{N(E_{ij})} - \mathrm{N(L} \cap \mathrm{E_{ij})}}{\mathrm{N(A)} - \mathrm{N(L)}}} \tag{5.14}$$

$$\mathrm{Bel} = \frac{\lambda(\mathrm{Tp})\mathrm{E_{ij}}}{\sum \lambda\,(\mathrm{Tp})\mathrm{E_{ij}}} \tag{5.15}$$

$$\lambda(Tp^{-})E_{ij} = \frac{\frac{N(L) - N(L \cap E_{ij})}{N(L)}}{\frac{N(A) - N(L) - N(E_{ij}) + N(L \cap E_{ij})}{N(A) - N(L)}} \quad (5.16)$$

$$Dis = \frac{\lambda(Tp^{-})E_{ij}}{\sum \lambda(Tp^{-})E_{ij}} \quad (5.17)$$

$$Unc = 1 - Dis - Bel \quad (5.18)$$

$$Pls = 1 - Dis \quad (5.19)$$

Where L: Geospatial data layers number, Eij: Evidence, i is number of layers, and j stand for class attributes, N: Proportion of areas with groundwater wells, D: Proportion of areas without groundwater wells, N(L∩Eij): Groundwater well pixels per class, N(L): Total number of groundwater wells, N(Eij): Number of pixels per class for each factor, and N(A): Total number of pixels in the area.

The spatial relationship between conditioning factors and groundwater occurrence were found with the above formulas and have been shown in (Table 5.15).

Table 5.15: Spatial relationship between factors and groundwater occurrence using EBF model.

Factors	Classes	No of Pixels	No of Wells	Bel	Dis	Unc	Pls
Rainfall	< 270 mm	4092565	29	0.32	0.19	0.49	0.81
	270 – 350	34765635	180	0.23	0.19	0.58	0.81
	350 – 450	53178814	226	0.19	0.22	0.59	0.78
	450 – 750	6188270	22	0.16	0.20	0.64	0.80
	750 mm <	1782453	4	0.10	0.20	0.70	0.80
Geology	Conglomerate and Sandstone	21786355	226	0.07	0.01	0.91	0.99
	Granite	4302035	12	0.02	0.02	0.96	0.98
	Gneiss	12735918	70	0.04	0.02	0.94	0.98
	Sandstone and Siltstone	12209116	30	0.02	0.02	0.96	0.98
	Volcanic and Sedimentary Rocks	955836	5	0.04	0.02	0.94	0.98
	Basalt	716370	4	0.04	0.02	0.94	0.98
	Basaltic Andesite and Basalt	54468	0	0.00	0.02	0.98	0.98
	Schist and Phyllite	488136	0	0.00	0.02	0.98	0.98

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Table 5.15 (Cont.).

Factors	Classes	No of Pixels	No of Wells	Bel	Dis	Unc	Pls
	Granite and Granodiorite	5259323	10	0.01	0.02	0.96	0.98
	Limestone and Dolomite	7666722	13	0.01	0.02	0.97	0.98
	Clay and Siltstone	2999385	7	0.02	0.02	0.96	0.98
	Rhyolite	1988893	5	0.02	0.02	0.96	0.98
	Eolian Deposits	761190	0	0.00	0.02	0.98	0.98
	Loess	3095762	11	0.02	0.02	0.95	0.98
	Marble and Gneiss	1406475	5	0.02	0.02	0.95	0.98
	Diorite and Granodiorite	1126373	3	0.02	0.02	0.96	0.98
	Diorite and Plagiogranite	2964058	5	0.01	0.02	0.97	0.98
	Limestone and Chert	335134	5	0.10	0.02	0.88	0.98
	Siltstone and Shale	1666219	4	0.02	0.02	0.96	0.98
	Granodiorite and Granosyenite	5504558	11	0.01	0.02	0.96	0.98
	Limestone	1399704	3	0.01	0.02	0.96	0.98
	Limestone and Sandstone	780599	1	0.01	0.02	0.97	0.98
	Metavolcanic Andesitic Lava	81206	0	0.00	0.02	0.98	0.98
	Alkaline Lava	40678	0	0.00	0.02	0.98	0.98
	Andesite	1157115	2	0.01	0.02	0.97	0.98
	Lava	1655061	3	0.01	0.02	0.97	0.98
	Gneiss and Granite	95330	3	0.22	0.02	0.76	0.98
	Clay and Shale	695073	2	0.02	0.02	0.96	0.98
	Basalt and Sandstone	2210528	8	0.03	0.02	0.95	0.98
	Ultramafic Intrusions	95014	1	0.07	0.02	0.91	0.98
	Gabbro and Diorite	694893	5	0.05	0.02	0.93	0.98
	Fan Alluvium and Colluvium	248896	1	0.03	0.02	0.95	0.98
	Till	1279536	2	0.01	0.02	0.97	0.98
	Granite Porphyry	41041	0	0.00	0.02	0.98	0.98
	Andesitive Lava	53580	0	0.00	0.02	0.98	0.98
	Gabbro and Mafic Metavolcanics	9829	0	0.00	0.02	0.98	0.98
	Rhyolite and Sandstone	23719	0	0.00	0.02	0.98	0.98
	Granite and Granosyenite	427831	2	0.03	0.02	0.95	0.98

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Table 5.15 (Cont.).

Factors	Classes	No of Pixels	No of Wells	Bel	Dis	Unc	Pls
	Andesite and Granite Porphyry	25536	0	0.00	0.02	0.98	0.98
	Rhyolite to Andesite	18313	0	0.00	0.02	0.98	0.98
	Metamorphic Rocks--Undivided	35541	0	0.00	0.02	0.98	0.98
	Gabbro and Monzonite	61301	0	0.00	0.02	0.98	0.98
	Andesitic Tuff	18936	0	0.00	0.02	0.98	0.98
	Granodiorite	33396	0	0.00	0.02	0.98	0.98
		58930	0	0.00	0.02	0.98	0.98
	Metavolcanic Rhyolite and Ande	2284	0	0.00	0.02	0.98	0.98
	Basalt Tuff	80950	0	0.00	0.02	0.98	0.98
Lineament Density	$< 0.1\ ^{Km}/_{Km^2}$	1729415	3	0.08	0.20	0.72	0.80
	0.1 - 0.5	8370965	36	0.20	0.20	0.60	0.80
	0.5 – 1	22234356	95	0.20	0.20	0.59	0.80
	1 – 1.5	59785864	277	0.22	0.20	0.58	0.80
	$1.5\ ^{Km}/_{Km^2} <$	7887200	50	0.30	0.19	0.51	0.81
Drainage Density	$< 0.05\ ^{Km}/_{Km^2}$	4217550	17	0.15	0.20	0.65	0.80
	0.05 – 0.1	28196091	78	0.10	0.23	0.66	0.77
	0.1 – 0.15	41429838	195	0.18	0.20	0.63	0.80
	0.15 – 0.2	22182989	136	0.23	0.18	0.59	0.82
	$0.2\ ^{Km}/_{Km^2} <$	3981332	35	0.33	0.19	0.48	0.81
Soil Texture	Calcic Xerosols-2b	852098	16	0.05	0.11	0.84	0.89
	Lithosols, Cambisols and Rankers-2c	7066421	85	0.07	0.13	0.80	0.87
	Lithosols and Xerosols-c	10995670	272	0.03	0.08	0.88	0.92
	Haplic Yermosols-2ab	2325647	58	0.03	0.11	0.86	0.89
	Lithosols, Humic Cambisols and Rankers-c	283953	4	0.06	0.11	0.83	0.89
	Lithosols and Xerosols-2c	1006913	18	0.05	0.11	0.84	0.89
	Lithosols and Vertisols-2c	1242426	3	0.35	0.12	0.53	0.88
	Calcaric Fluvisols-2a	95032	1	0.08	0.11	0.81	0.89
	Gleysols	1290614	4	0.27	0.12	0.61	0.88
LULC	Rangeland and Bare Areas	11174723	12	0.00	0.05	0.95	0.95

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Table 5.15 (Cont.).

Factors	Classes	No of Pixels	No of Wells	Bel	Dis	Unc	Pls
	Bare Areas	8388730	1	0.00	0.04	0.96	0.96
	Waterbody & Marshland	2250750	22	0.01	0.04	0.95	0.96
	Snow covered	4751602	0	0.00	0.04	0.96	0.96
	Irrigated Agr. Land	4455787	86	0.01	0.04	0.95	0.96
	Rainfed Agr. Land	10855034	33	0.00	0.04	0.96	0.96
	Rangeland	52964362	120	0.00	0.06	0.93	0.94
	Fruit Trees	151210	10	0.04	0.04	0.92	0.96
	Rangeland and Built-up	1	0	0.00	0.04	0.96	0.96
	Irrigated Agr. Land and Fruit Trees	144485	12	0.05	0.04	0.91	0.96
	Forests & Shrubs	1382965	2	0.00	0.04	0.96	0.96
	Rainfed Agr. Land and Rangeland	844708	4	0.00	0.04	0.96	0.96
	Built-up and Fruit Trees	4255	3	0.47	0.04	0.49	0.96
	Vineyards	3406	0	0.00	0.04	0.96	0.96
	Irrigated Agr. Land and Built-up	3642	1	0.18	0.04	0.78	0.96
	Forests, Shrubs and Rangeland	6959	0	0.00	0.04	0.96	0.96
	Sand Cover and Rangeland	1147454	2	0.00	0.04	0.96	0.96
	Sand Cover	979539	0	0.00	0.04	0.96	0.96
	Waterbody, Marshland and Bare Areas	493	0	0.00	0.04	0.96	0.96
	Rangeland, Waterbody and Marshland	36758	0	0.00	0.04	0.96	0.96
	Waterbody, Marshland and Irrigated Agr. Land	2205	0	0.00	0.04	0.96	0.96
	Irrigated Agr. Land and Vineyards	443	0	0.00	0.04	0.96	0.96
	Rainfed Agr. Land, Forests and Shrubs	11142	0	0.00	0.04	0.96	0.96
	Built-up	446998	153	0.23	0.03	0.75	0.97
Slope	0 – 5	12922661	138	0.37	0.16	0.47	0.84
	5 – 10	10220210	126	0.43	0.16	0.41	0.84
	10 – 20	34423130	182	0.18	0.18	0.64	0.82
	20 – 40	37282920	15	0.01	0.30	0.69	0.70
	40 – 82.15	5088470	0	0.00	0.21	0.79	0.79

Belief (Bel), Disbelief (Dis), Uncertainty (Unc), and Plausibility (Pls).

When the four stages of EBF model for all factors have been found, then the intersection of all factors was calculated by Raster Calculator in ArcMap with respect to (5.20) – (5.23) equations. As a result, the groundwater potential zones map will be generated.

$$\mathrm{Bel_X} = \frac{(\mathrm{Bel_A} * \mathrm{Bel_B}) + (\mathrm{Bel_A} * \mathrm{Unc_B}) + (\mathrm{Bel_B} * \mathrm{Unc_A})}{1 - (\mathrm{Bel_A} * \mathrm{Dis_B}) - (\mathrm{Bel_B} * \mathrm{Dis_A})} \tag{5.20}$$

$$\mathrm{Dis_X} = \frac{(\mathrm{Dis_A} * \mathrm{Dis_B}) + (\mathrm{Dis_A} * \mathrm{Unc_B}) + (\mathrm{Dis_B} * \mathrm{Unc_A})}{1 - (\mathrm{Bel_A} * \mathrm{Dis_B}) - (\mathrm{Bel_B} * \mathrm{Dis_A})} \tag{5.21}$$

$$\mathrm{Unc_X} = \frac{\mathrm{Unc_A} * \mathrm{Unc_B}}{1 - (\mathrm{Bel_A} * \mathrm{Dis_B}) - (\mathrm{Bel_B} * \mathrm{Dis_A})} \tag{5.22}$$

$$\mathrm{Pls_X} = \mathrm{Bel_X} + \mathrm{Unc_X} \tag{5.23}$$

5.3. Influencing Factors of Groundwater Recharging

The groundwater static level data and the valuable criteria for groundwater potential were selected on the basis of an extensive review of the literature. These include precipitation, which is the main source of water, geology, which controls infiltration, movement and storage of water, lineament density, which increases hydrolase conductivity, drainage density, which controls the distribution of runoff and infiltration rates, soil type, which determines infiltration rates, land use and land cover, which influence the recharge process, topographic wetness index, curvature, normalized difference vegetation index, and slope, which determines water flow energy.

The static water table and spatial maps of all other factors were created and converted to a raster file with a cell size of 30-30 m to apply three different MCDA techniques: AHP, FR and EBF models to find the vulnerable areas for groundwater and create the groundwater potential map of PARB.

5.3.1. Rainfall (RF)

Precipitation is an essential part of the water cycle and an important source of groundwater. Therefore, it is an essential component for aquifer recharge and groundwater recharge, taking into account the geology, lineament density, soil characteristics and slope of the area. For the development of groundwater management strategies, it is important to understand how precipitation affects groundwater.

The spatio-temporal distribution of precipitation in the PARB varies, and climate change plays a crucial role in these differences. The maximum and minimum annual precipitation and snowfall recorded from 1979 to 2022 based on 36 hydrometeorological stations were 2532.17 and 92.82 mm, respectively, and the average precipitation is 430.59 mm/year. The average annual precipitation data from 36 precipitation observation stations (Figure 5.8) in the PARB were interpolated using the inverse distance weighting (IDW) technique in ArcGIS to analyze them and create a spatial map of the average annual precipitation of the PARB (Figure 5.9). The created raster map was divided into five groups and graded from 1 for the lowest to 5 for the highest amount of precipitation (Table 5.13).

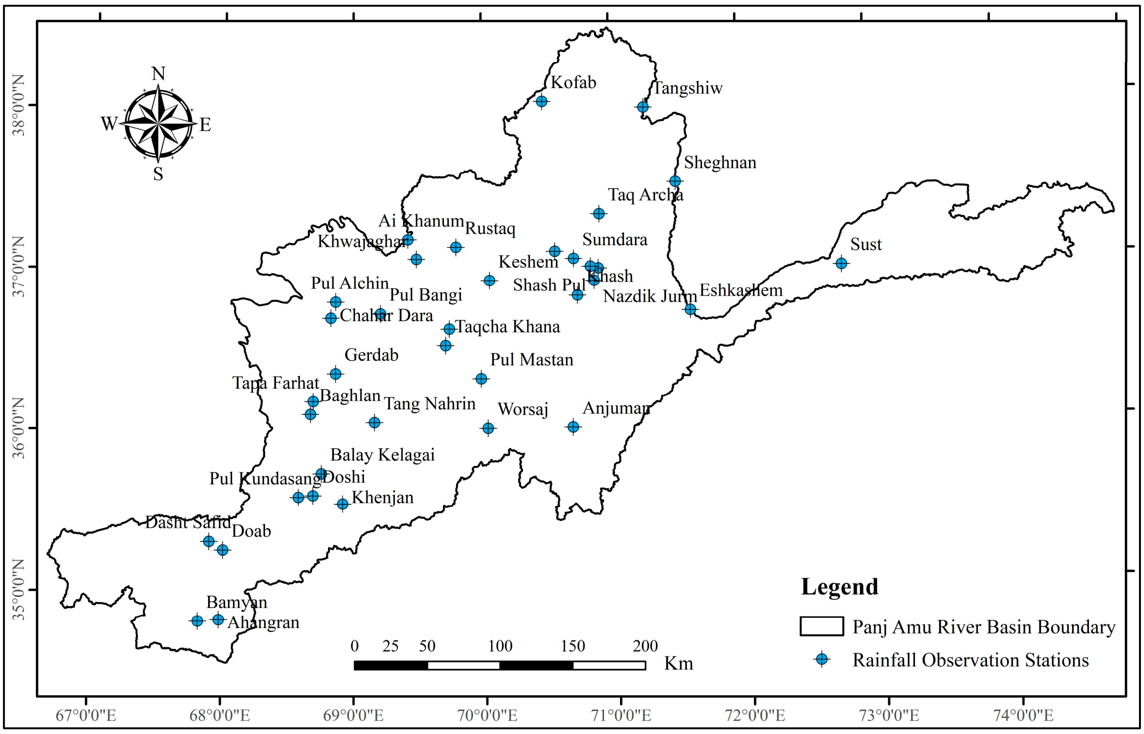


Figure 5.8: Map of Meteorological Stations in the PARB

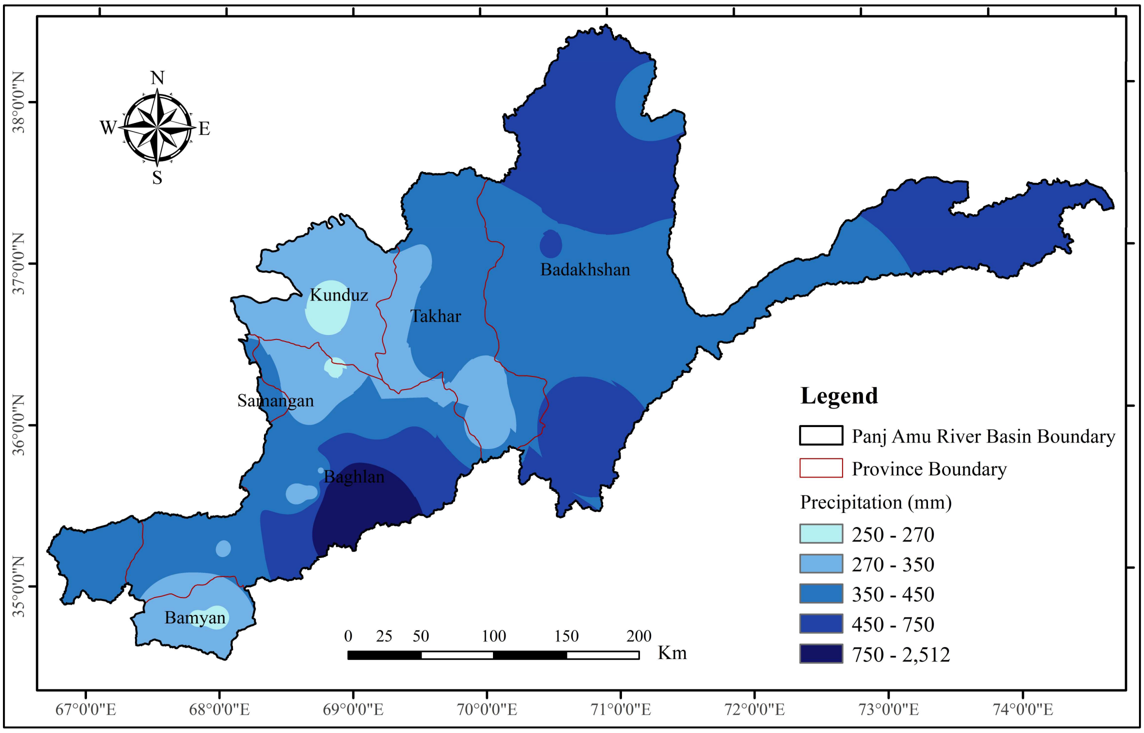


Figure 5.9: Mean Annual Precipitation map of the PARB.

5.3.2. Geology (G)

The geological characteristics of a site can directly or indirectly influence the recharge of groundwater through infiltration and runoff, depending on the conductivity and porosity of the formation. The porosity and permeability of an aquifer are directly influenced by the geologic formation; therefore, a thorough study of the lithology can provide insight into the source and state of the groundwater (Doke et al. 2021; Rahmati et al. 2015). And according to Tolche, lithology alters the distribution, quantity and flow of groundwater (Tolche 2021). Geology is the key factor in assessing groundwater potential, as the varying lithological strata are sensitive to active hydrological processes. Lithology is thought to have a major influence on the temporal and spatial variability of watershed hydrology (Miller, Ritter, and Kochel 1990).

The permeability of the lithology influences the circulation of water in the soil. Sand and gravel allow water to pass through more easily than others, so that less surface water can accumulate, and the chance of groundwater recharge is high. Clay and shale, on the other hand, are less permeable rocks and sediments that can prevent water infiltration, increasing surface water flow and reducing groundwater recharge. The surface characteristics of the lithology can also influence surface water flow. Certain types of limestone are examples of smooth, impermeable rocks and sediments that can increase surface runoff and decrease groundwater recharge.

The map of the geologic age and lithology of Afghanistan serves as the basis for the geologic map of the PARB (Figure 5.10), which was taken from the US Geological Survey (Doebrich 2006). The PARB consists of different geological formations: Conglomerate and sandstone 22%, gneiss 13%, sandstone and siltstone 12%, limestone and dolomite 8%, granodiorite and granosyenite 5.5%, granite and granodiorite 5%, granite 4%, loess 3%, clay and siltstone 3%, diorite and plagiogranite 3%, basalt and sandstone 2%, rhyolite 2%, lava 1.5%, siltstone and shale 1.5%, marble and gneiss 1.5%, limestone 1.5%, volcanic and sedimentary deposits 1%, basalt 1%, eolian deposits 1%, diorite and granodiorite 1%, limestone and sandstone 1%, andesite 1%, till 1%, etc. The geological classes were divided into classes 1 to 5 according to their infiltration and permeability rate.

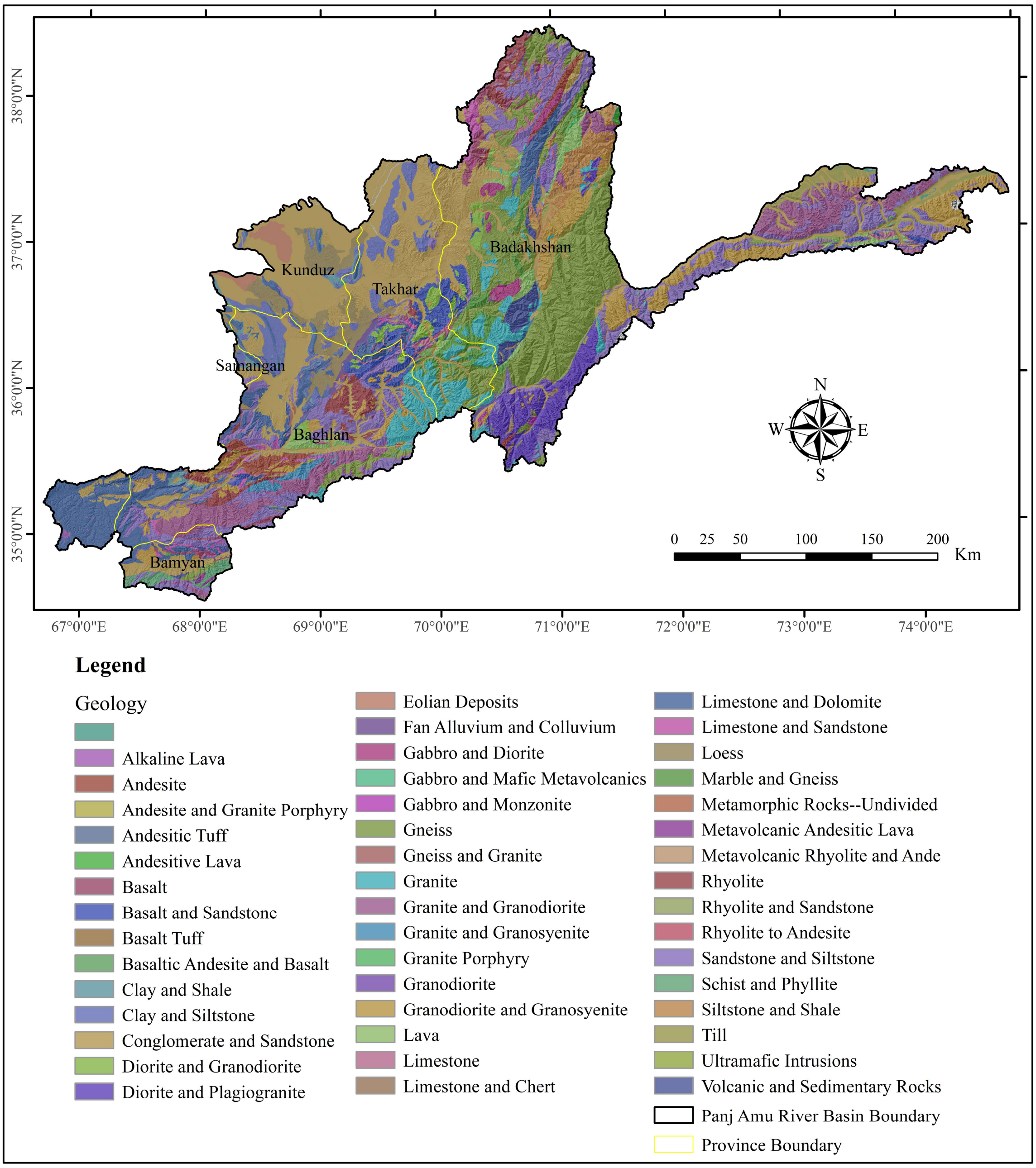


Figure 5.10: Geological Map of the PARB

5.3.3. Lineament Density (LD)

One of the most important parameters for groundwater recharge is the density of the lineaments. Mahalingam claims that areas of groundwater potential occur where there is a high density of lineaments (Mahalingam and Vinay 2015). The generally linear alignments of lineaments, which are structurally regulated linear or curved structures, are seen from the satellite. The surface topography of the underlying structures is expressed by these features. According to Surajit, the fault and fracture zones that lead to an increase in secondary porosity and permeability are represented by lineaments. As they are the pathways for groundwater transmission, these elements are crucial from a hydrogeological perspective (Murasingh and Jha 2013). Ndatuwong explained that lineaments are ideal sites for groundwater movement due to their high permeability and porosity (Ndatuwong and Yadav 2014).

The lineament density map was created from the fault lines visible on the satellite images. Using ArcGIS, lines were drawn on the fractures in the map with the different shading angles and then the line density option in the spatial analysis tools was used to generate the lineament density. Most of the Panj Amu catchment is covered by the Pamir and Hindu Kush Mountains, which is an earthquake area in Afghanistan and has some fault lines, so the lineament density in the catchment is higher than other river basins in the country.

The lineament density in the west of Badakhshan, southeast of Baghlan and northeast of Bamyan is higher than in the other areas, reaching 1.77 Km/Km^2. Hardis and Bhuvaneswaran explain that areas with higher lineament density offer great potential for groundwater development as they allow groundwater infiltration and recharge (Bhuvaneswaran, Ganesh, and Nevedita 2015; Haridas, Aravindan, and Girish 1998), groundwater recharge is good in these areas. On the other hand, the density in the north and west of Kunduz and in the north of Takhar, which are almost flat lands, is low at 1m to 10 over km^2 (Figure 5.11).

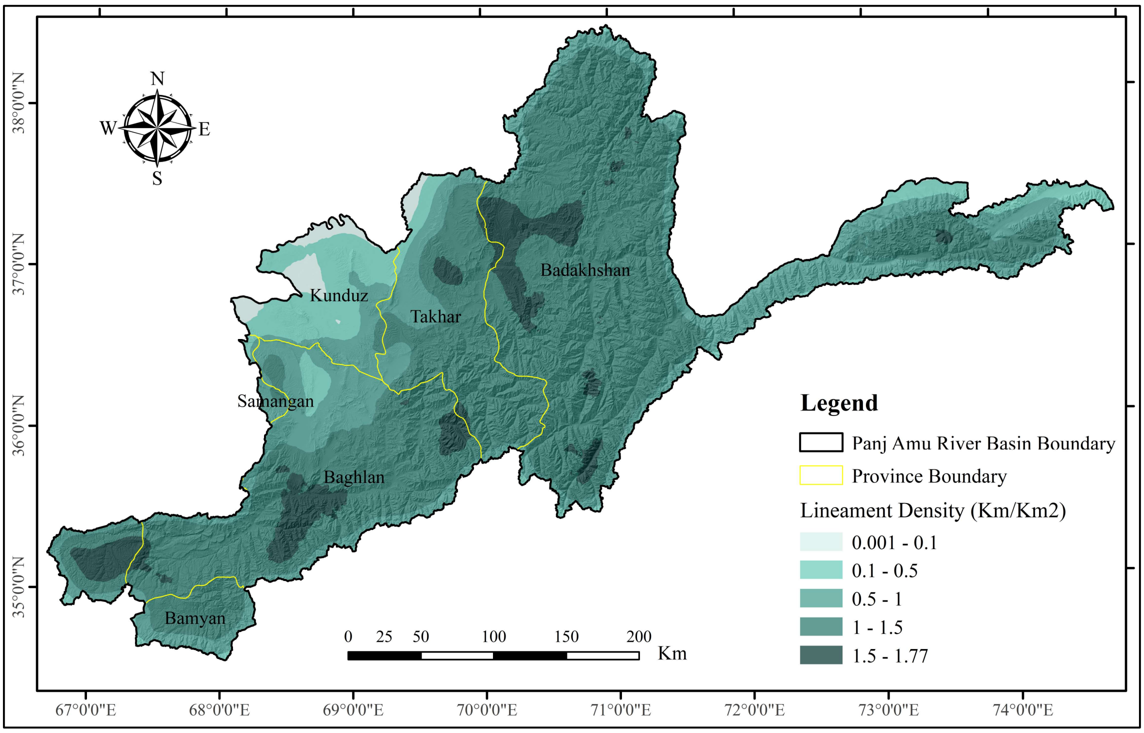


Figure 5.11: Lineament Density Map of the PARB

5.3.4. Drainage Density (DD)

Drainage density is defined by Horton in 1945 as the total stream length per drainage area (Horton 1945), equation (5.24). Runoff density is a quantifiable measure that expresses the length of watercourses in the catchment (Singh, Gupta, and Singh 2014). Drainage density depends on the precipitation, vegetation cover, lithology, infiltration, and permeability rate of the area. Drainage density is inversely related to groundwater recharge. The higher the drainage density, the lower the infiltration into the groundwater.

$$D_d = \frac{L}{A} \tag{5.24}$$

Where D_d is drainage density, L is the total stream length, and A is the area of basin.

To create the drainage density map from the Arc Hydro tools, the terrain-preprocessing tool's is used, and a filling sink was performed to remove the highest and lowest elevations that attract water. Then the flow direction tools were used to analyze the fill sink map and create a flow direction map of the area. Then the flow accumulation tools were used to analyze the map of flow direction and create a map of flow accumulation for the area. The raster calculator was used to create the stream definition map from the flow accumulation map, and the streams were ordered according to the Strahler method (Karami et al. 2021; Strahler 1957, 1964) (Figure 5.12), which was directly applied by ArcGIS. The stream network was then analyzed using the line density option of the Spatial Analyst tools to create a map of the PARB's drainage density (Figure 5.13). The map was divided into 5 categories in terms of its suitability for groundwater potential and recharge.

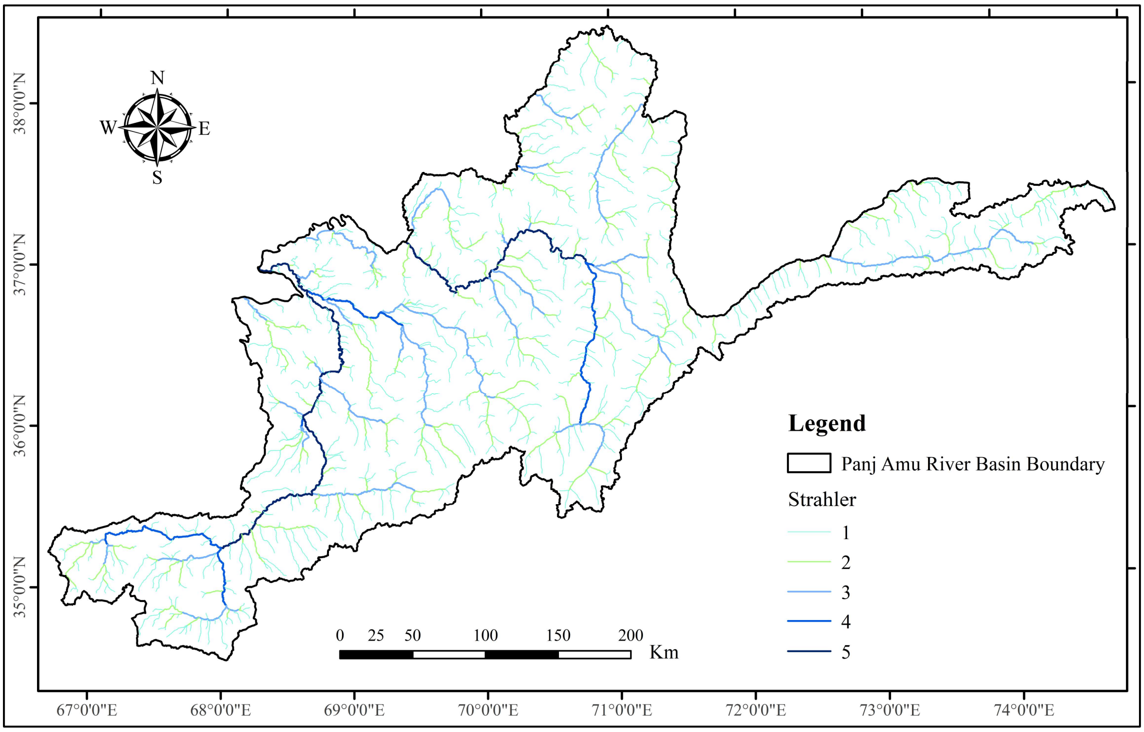


Figure 5.12: Strahler Map of the PARB

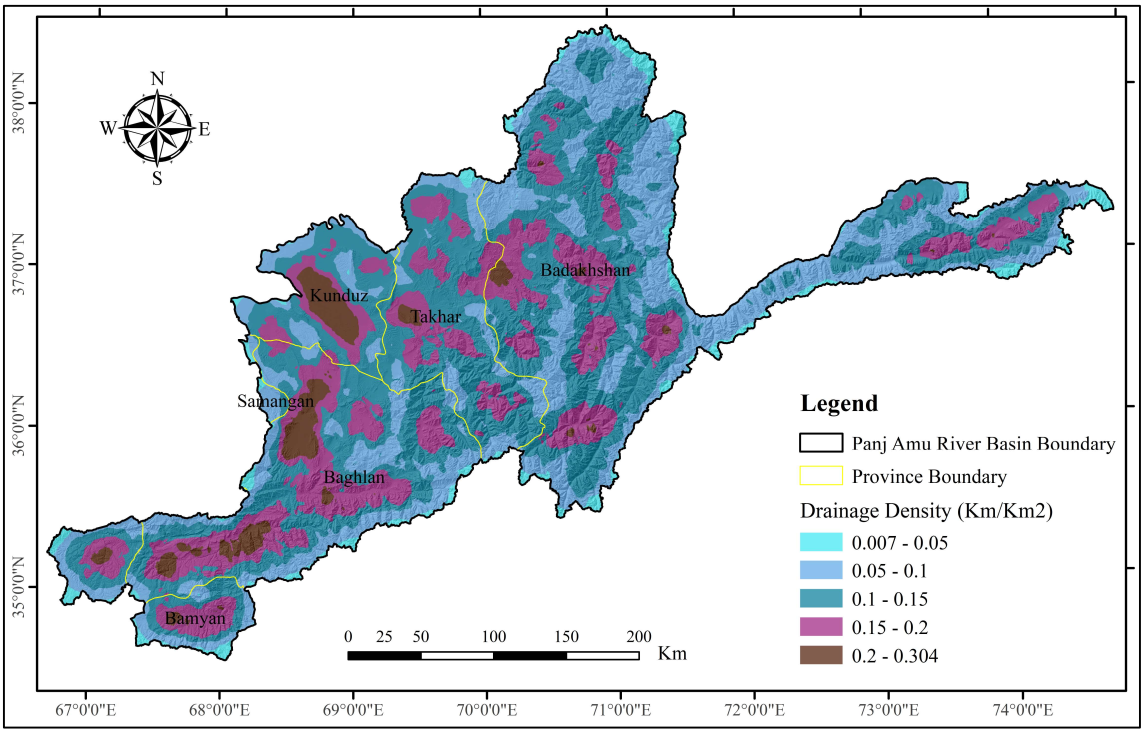


Figure 5.13: Drainage Density Map of the PARB

5.3.5. Soil Texture (ST)

This study uses data from the Food and Agriculture Organization's (FAO) Digital Soil Map of the World. The soil map comes from the website of the Food and Agriculture Organization of the United Nations (FAO) (http://www.fao.org/geonetwork/srv/en/metadata.show%3Fid=14116) and has a scale of 1:5.000.000.

According to (Mehra, Oinam, and Singh 2016), soil properties such as type and texture have a major influence on the spatial variance of groundwater recharge. The proportion of sand, silt and clay in the soil can be used to create texture triangles that represent the ability of the soil to store and infiltrate water. Runoff, soil porosity, thickness and water holding capacity are among the factors that influence groundwater recharge. The behavior of eight different soil textures in relation to groundwater recharge was investigated by (Zomlot et al. 2015). They found that loamy soils have a strong positive correlation with groundwater recharge, while clay soils have a negative correlation.

Table 5.16: Soil Types and Texture in the Panj Amu River Basin modified from (Nachtergaele 2001; Regassa et al. 2023)

Soil Code	Soil Type (FAO)	Soil Texture
Xk4-2b	Calcic Xerosols [2b]	Sandy loam
I-B-U-2c	Lithosols, Cambisols, Rankers [2c]	Shallow soils with rocks and gravel, sandy and loamy, sandy to clay
I-X-c	Lithosols, Xerosols [c]	Shallow soils with rocks and gravel, sandy to loamy or even clay
Yh23-2ab	Haplic Yermosols [2ab]	Sandy, loamy, or clay
I-Bh-U-c	Lithosols, Humic Cambisols, Rankers [c]	Shallow soils with rocks and gravel, sandy to clay
I-X-2c	Lithosols, Xerosols [2c]	Shallow soils with rocks and gravel, sandy to loamy or even clay
I-Y-2c	Lithosols, Vertisols [2c]	Shallow soils with rocks and gravel, clay to clay loam
Jc53-2a	Calcaric Fluvisols [2a]	Loamy or silty
GL	Gleysols	Waterlogged or saturated - sandy to clay

Loamy soils have higher porosity and permeability than clay soils, so loamy soils should be ranked higher than clay soils (Das and Pal 2020). Loam and sand with rocks are the main soil textures in the PARB. These soil types dominate almost everywhere in the catchment (Figure 5.14).

Infiltration is the penetration of water into the soil and subsurface layer by rainfall or snowfall, and the soil texture determines the infiltration rate. It is one of the most important hydraulic properties of soil for agricultural irrigation, groundwater recharge, land surface and subsurface hydrology (Shaban, Khawlie, and Abdallah 2006; Souissi et al. 2018). Dry soil infiltrates faster and eventually reach a steady rate when all air voids in the soil layer are filled with water. Quantitative measurement of soil infiltration rate in a watershed is difficult as it depends on many factors such as soil texture, surface topography, rainfall intensity and vegetation cover, etc. Infiltration characteristics are also directly related to groundwater resources, as groundwater resources are better utilized as infiltration increases. The dry clay soil has more cracks and has high infiltration, but the wet clay soil holds more water than infiltration (Regassa et al. 2023; Shaban, Khawlie, and Abdallah 2006; Souissi et al. 2018). In this study the soil textures are ranked with respect to (Table 5.17).

Table 5.17: Rate and Potential of Soil according to its Texture revised from (Berhanu, Melesse, and Seleshi 2013)

No	Soil Texture	Infiltration Rate mm/h	Infiltration Potential
1	Sand	210.1	Very High
2	Loamy sand	61.2	High
3	Sandy loam	25.9	High
4	Loam	13.2	Medium
5	Silt loam	6.9	Medium
6	Sandy clay loam	4.3	Medium
7	Clay loam	2.3	Low
8	Silt clay loam	1.5	Low
9	Sandy clay	1.3	Low
10	Silt clay	1	Very Low
11	Clay	0.5	Very Low

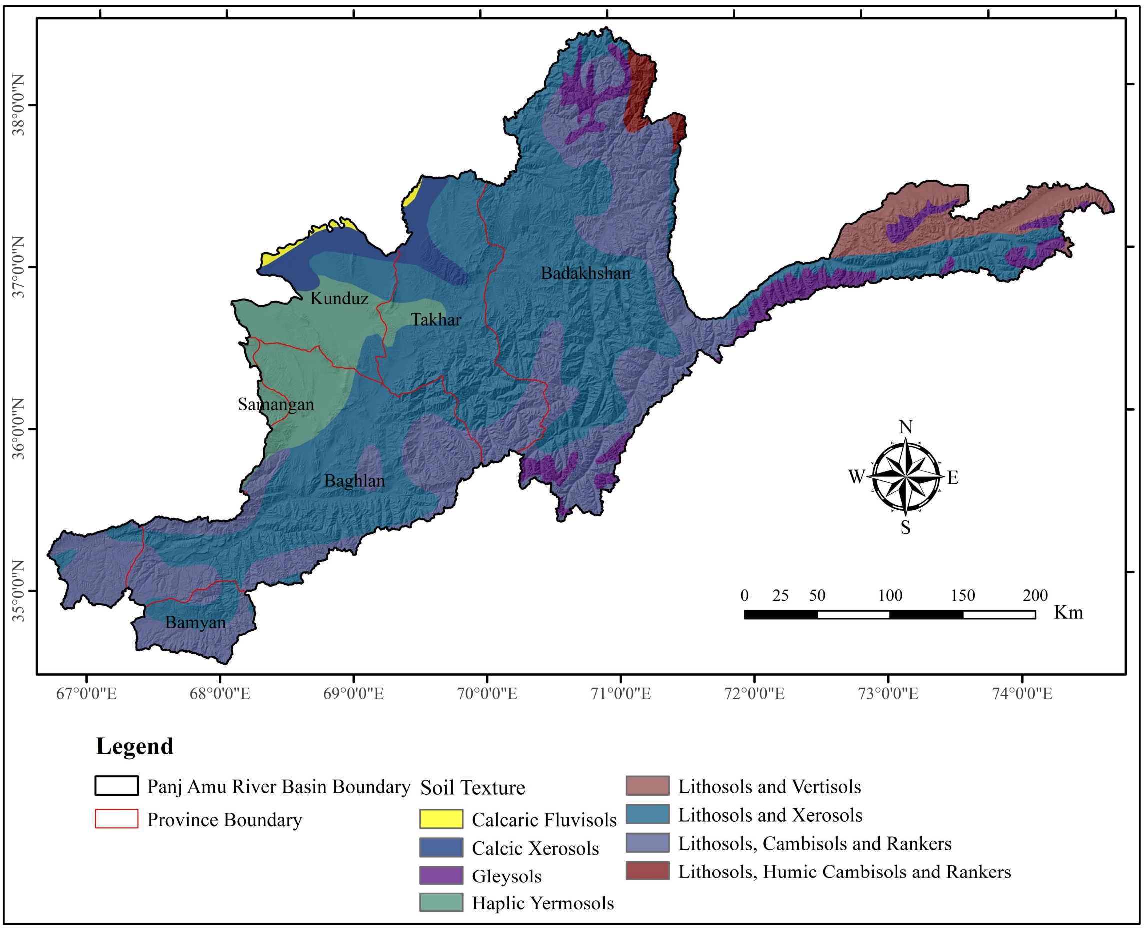


Figure 5.14: Soil Texture Map of the PARB

5.3.6. Land Use and Land Cover (LULC)

Land use and land cover studies provide crucial information on the amount of groundwater needed and used and are also a crucial factor in the selection of sites for artificial groundwater recharge (Singh, Bhardwaj, and Kumar 2011). According to Mandal, the different land uses such as residential areas and existing towns, forests and agricultural land affect the surface texture, soil permeability and water permeability of the area, so land use provides information about groundwater potential (Mandal et al. 2016). Evapotranspiration, infiltration, groundwater recharge and groundwater interaction are significantly influenced by LULC. Conversely, impermeable surfaces such as roads and residential areas as well as unvegetated terrain accelerate runoff. Rainfall lag times are often shortened by urbanization, while runoff peaks and cumulative runoff are often increased (Murck, Skinner, and Porter 1996).

The LULC is categorized in the study as follows: Pastureland, bare land, water bodies and marshland, snow-covered land, irrigated agricultural land, rainfed agricultural land, fruit trees, forests and shrubs, vineyards, sand cover, and cultivated land. Water and wetlands, snow-covered land and irrigated agricultural land are extremely important and have a positive impact on groundwater recharge, while bare land, residential and built-up areas and pastures have a negative impact. The LULC data comes from the Afghan Ministry of Agriculture, Irrigation and Livestock (MAIL) and the LULC map of PARB was created using ArcMap (Figure 5.15).

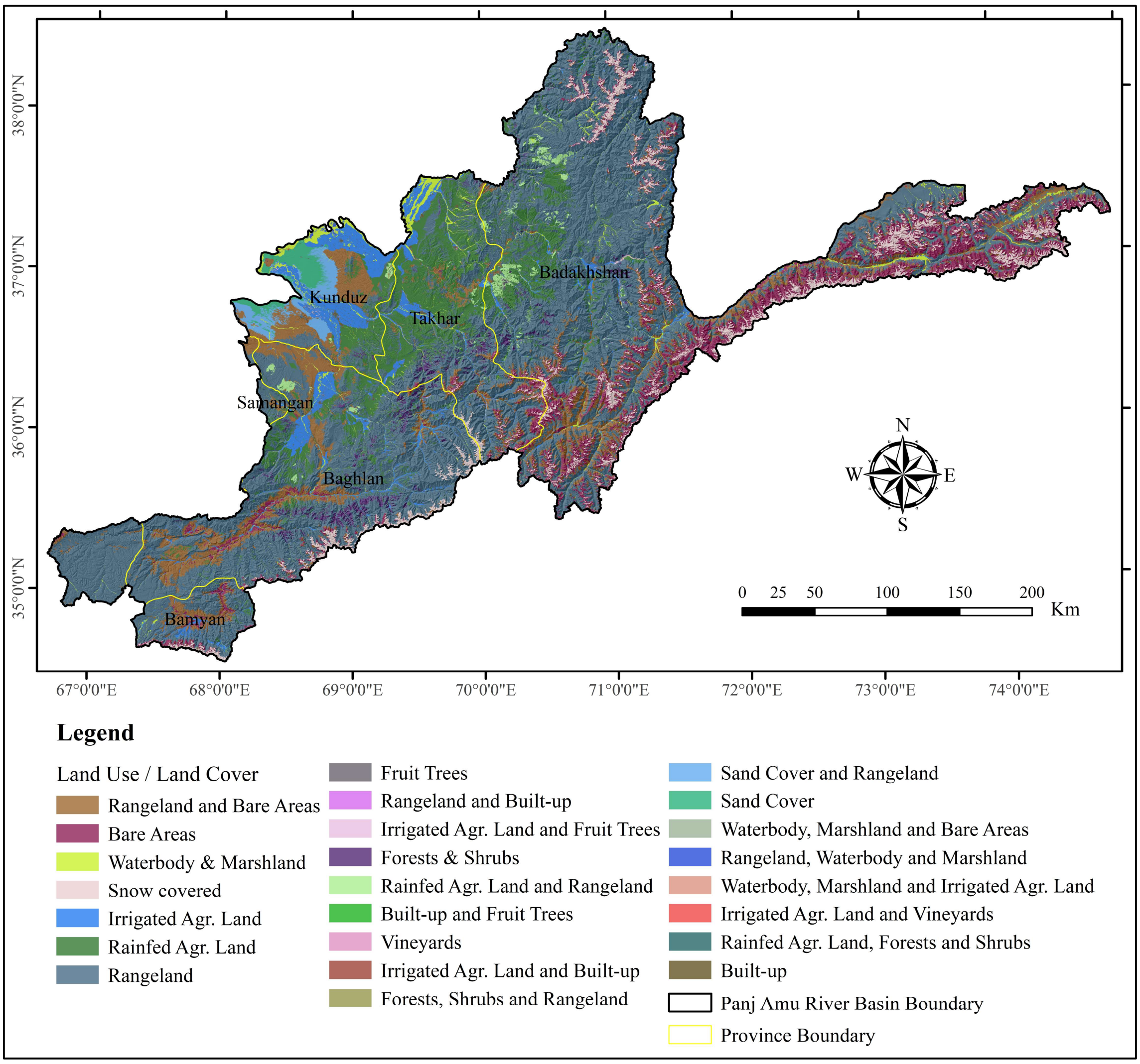


Figure 5.15: Land Use and Land Cover Map of the PARB

5.3.7. Topographic Wetness Index (TWI)

A steady state moisture index, the topographic wetness index (TWI), is sometimes referred to as the composite topographic index (CTI) (Sørensen, Zinko, and Seibert 2005). The index quantifies the influence of topography on hydrological processes (Moore, Lewis, and Gallant 1993). The influence of topographic factors on the location and quantity of saturated sources of surface runoff formation can be explained by the TWI (Razandi et al. 2015). TWI and the runoff model were developed together (Beven and Kirkby 1979) and are therefore an important factor to consider when investigating groundwater recharge. TWI has been used as a criterion for defining groundwater potential zones in several studies (e.g. (Al-Abadi et al. 2017; Arulbalaji, Padmalal, and Sreelash 2019; Moore and Burch 1986; Moore, Grayson, and Ladson 1991; Naghibi, Pourghasemi, and Dixon 2016; Rajaveni and Muniappan 2023).

TWI evaluates the effects of local terrain on the runoff process and determines the size and dimensions of saturated regions prone to runoff (Wilson and Gallant 2000). And according to (Pourali et al. 2016), the TWI describes the accumulation of water at a specific location in relation to a specific watershed. The index is determined by the upstream contributing area per unit width orthogonal to the flow direction and the slope. The topographic wetness index is defined by the equation (5.25).

$$\mathrm{TWI} = \mathrm{Ln}\left(\frac{\mathrm{Am}}{\tan\beta}\right) \tag{5.25}$$

Where Am represents the upslope draining area, and $\tan\beta$ stands for the local slope.

The TWI is a topographically based indicator of a landscape's capacity for water accumulation. Due to increased water availability from surface runoff and infiltration, regions with higher TWI values may have a greater potential for groundwater recharge. The surface properties determine the accuracy of the TWI. A raster model of the TWI is created using the 30*30 m DEM and areas vulnerable to groundwater recharge are identified based on this index (Figure 5.16).

Different slope values and flow routing techniques were used to determine and create an acceptable TWI. Subsequently, the TWI models created were verified through observations of satellite photos and remote sensing methods, as well as the use of pre-existing watercourses such as a wetland region. Larger TWI values are associated with higher potential, while smaller TWI values are associated with lower potential for groundwater recharge (Table 5.13).

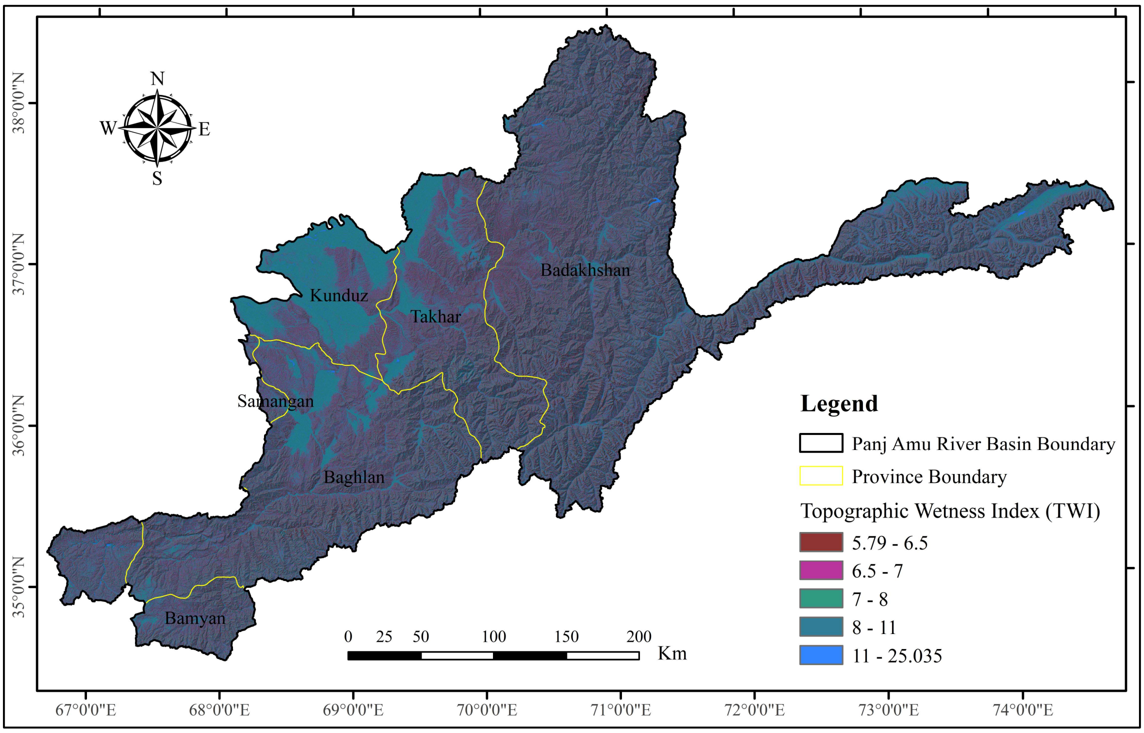


Figure 5.16: Topographic Wetness Index (TWI) Map of the PARB

5.3.8. Curvature (CUR)

The curvature illustrates the degree of distortion of the slope surface and represents the morphology of the soil at a particular location (Wang et al. 2020). Curvature, which symbolizes the morphology of topography, consists of three elements: Profile, Plan and Total, the latter combining Profile and Plan (Benjmel et al. 2020). Groundwater recharge can be strongly influenced by the curvature of the terrain. In areas with strong curvature (convex), water drains faster than in areas with relatively flat terrain, so that convex land has a low recharge potential, while flat land has a high recharge potential. The curvature of the land can also affect the flow of water through drainage systems and underground aquifers. According to Mojaddadi, convex, concave and flat surfaces are the three general forms of curvature (Mojaddadi et al. 2017). The curvature of a landscape serves as an indicator of changes in slope. It can influence the distribution of water across a landscape and the flow paths of surface water. While convex sites (ridges) may have lower rates of groundwater recharge because water drains rather than infiltrates, concave areas (valleys) can promote groundwater recharge by collecting and diverting water to the subsurface. Abadi has stated that the curvature of the plane affects the divergence and convergence of the flow, while the curvature of the profile mainly affects the flow velocity at the surface and coincides with the direction of the maximum slope gradient (Al-Abadi, Al-Temmeme, and Al-Ghanimy 2016).

In this study, the curvature of the PARB terrain was calculated using the digital elevation model (DEM) in ArcMap. First, the profile and plan of the area were created, then they were combined, and the curvature map was created, which was then categorized into three groups (positive slope cells mean convex areas, negative slope cells mean concave areas and flat regions) (Figure 5.17).

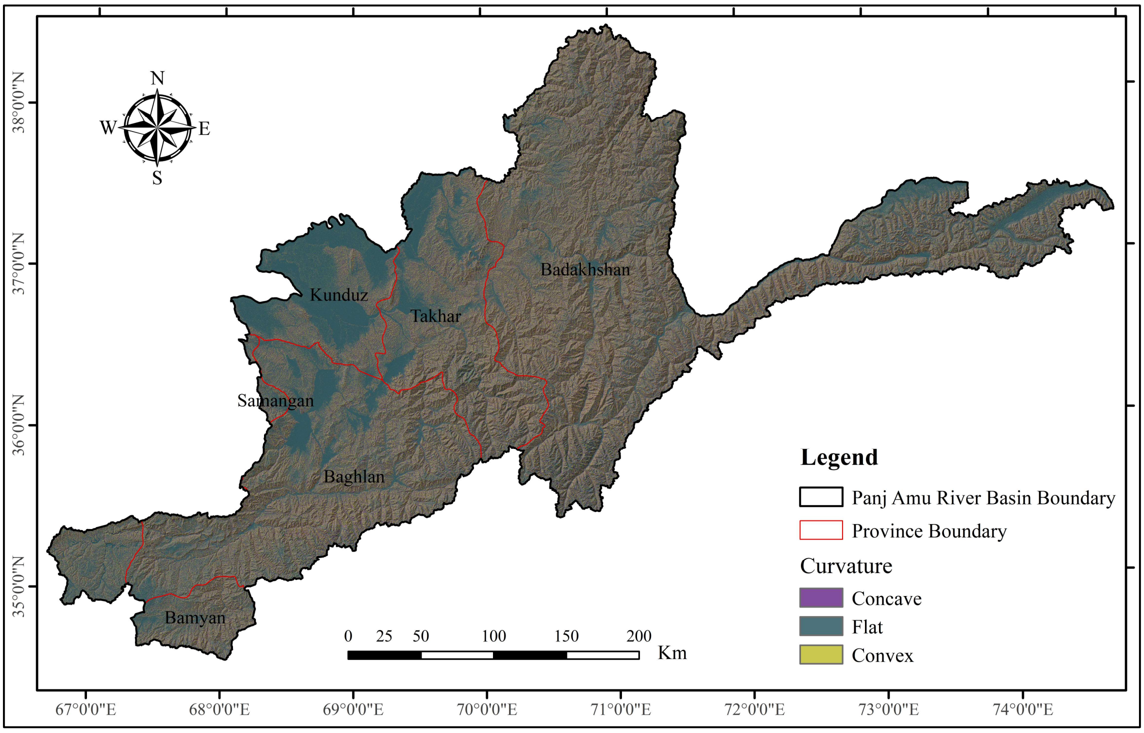


Figure 5.17: Curvature Map of the PARB

5.3.9. Normalized Difference Vegetation Index (NDVI)

A remote sensing-based conditioning factor that measures the condition and density of green vegetation is called Normalized difference vegetation index. The spectral reflectance values of the red and near infrared bands of the remote sensing data are used to calculate the NDVI. It indicates how much of the vegetation in an area is photosynthetically active. Higher NDVI values are often associated with stronger plant cover, which can add organic matter to the soil to store water and improve groundwater recharge by reducing surface runoff and promoting infiltration. NDVI values range from -1 to 1, and higher values indicate a denser vegetation area (Han et al. 2021). According to Wang, vegetation cover increases infiltration and decreases surface runoff, so it can influence groundwater recharge (Wang et al. 2023). Dense and healthy vegetation has a significantly higher capacity to absorb precipitation, which reduces runoff and increases the infiltration of water into the soil. It also helps to increase the likelihood of groundwater recharging. It is therefore an important factor to consider when investigating groundwater potential.

The LANDSAT image with 30 m resolution for NDVI was obtained from Google Earth Engine by applying the code below:

```
var dataset = ee.ImageCollection('LANDSAT/LC08/C01/T1_32DAY_NDVI')
              .filterDate('2020-10-01', '2021-10-01')
              .map(function(image){return image.clip(PanjAmu)});;
var colorized = dataset.select('NDVI').mean();
var colorizedVis = {
  min: -1,
  max: 1,
  palette: [
    'ffffff', 'ce7e45', 'df923d', 'f1b555', 'fcd163', '99b718', '74a901',
    '66a000', '529400', '3e8601', '207401', '056201', '004c00', '023b01',
    '012e01', '011d01', '011301'
  ],
};
//Map.setCenter(6.746, 46.529, 6);
Map.centerObject(PanjAmu,7)
Map.addLayer(colorized, colorizedVis, 'Colorized');

// Export the image
Export.image.toDrive({
  image: colorized,
  description: 'NDVI',
  scale: 30,
  fileFormat: 'GeoTiff',
  region: PanjAmu,
});
```

Then the (5.25) equation is used by ArcMap to generate the NDVI, which measures the plant density and greenness as a ratio between the red (R) and near infrared (NIR) values of Landsat 8 images. To assess the NDVI for Panj Amu RB, Landsat 8 data for the year 2023 was downloaded. The NDVI map of PARB, which ranges from -0.5 to 0.78, is shown in (Figure 5.18). The procedure for calculating the normalized difference vegetation index is shown in the formula (5.26).

$$NDVI = \frac{Band5 - Band4}{Band5 + Band4} \tag{5.26}$$

These watersheds which indicate greater greenery and dense vegetation and have high NDVI values are susceptible to groundwater recharge, so they were assigned scores of 5, 4, and 3, however, the ones with lower NDVI values which indicate less greenery and dense vegetation are assigned ratings of 2 and 1 respectively (Table 5.13).

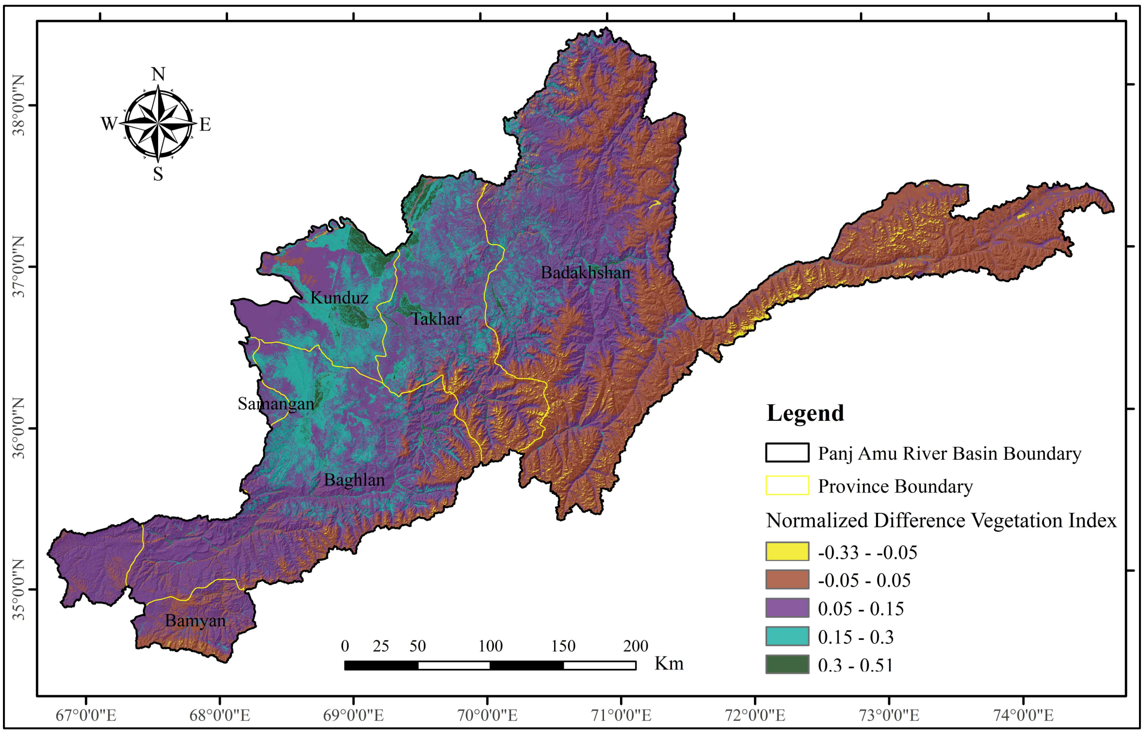


Figure 5.18: Normalized Difference Vegetation Index (NDVI) Map of the PARB

5.3.10. Slope (S)

The slope is a notable topographical factor for groundwater recharge. It has a direct effect on the infiltration of surface water. A lower slope angle refers to flatter terrain, while a higher slope angle is associated with steeper terrain. Steep slopes have a limited potential for recharge as water drains quickly and precipitation does not have enough time to infiltrate. On moderate slopes, however, water can remain longer, and precipitation can recharge underground. For this reason, groundwater recharge occurs more frequently on moderate slopes than on steeper ones (Badhe, Choudhar, and Raut 2022). According to Das, the surface runoff, and infiltration rate in a given region are directly influenced by the slope (Das 2021). Due to the higher recharge rate, regions with a medium slope have a higher groundwater potential (Magesh, Chandrasekar, and Soundranayagam 2012). The zones with groundwater potential are influenced differently by the thematic slope factor classes (Misi, Gumindoga, and Hoko 2018; Serele, Pérez-Hoyos, and Kayitakire 2020; Simmers 1990). According to Fernández and Lutz, the processes of water collection and drainage in all geomorphic areas are determined by the ground slope (Fernández and Lutz 2010). Since a steep slope promotes runoff and rapid drainage of meteoric water, sites with low slopes have low surface runoff and high infiltration rates. Thus, slope is crucial in finding locations that are best suited for water infiltration into the soil (Mogaji, Lim, and Abdullah 2015).

The digital elevation model (DEM) of Panj Amu RB was processed in ArcMap environment and a map of slope was generated. Then, the slope density map was categorized into five classes (Figure 5.19). Various studies have made different classifications of slope for mountainous regions and water recharge. In this study, the classification was selected based on these studies (Berihun et al. 2020; Chen et al. 2016; Devkota et al. 2013; Kanwal, Atif, and Shafiq 2017). High slopes are associated with more runoff, erosion and lower permeability, while lower slopes are associated with lower runoff and higher infiltration (Hatefi and Ekhtesasi 2016; Prasad et al. 2008; Razandi et al. 2015). Therefore, the higher slope classes were categorised as 2 and 1, while the lower slope classes were categorised as 5, 4 and 3, respectively (Figure 5.19).

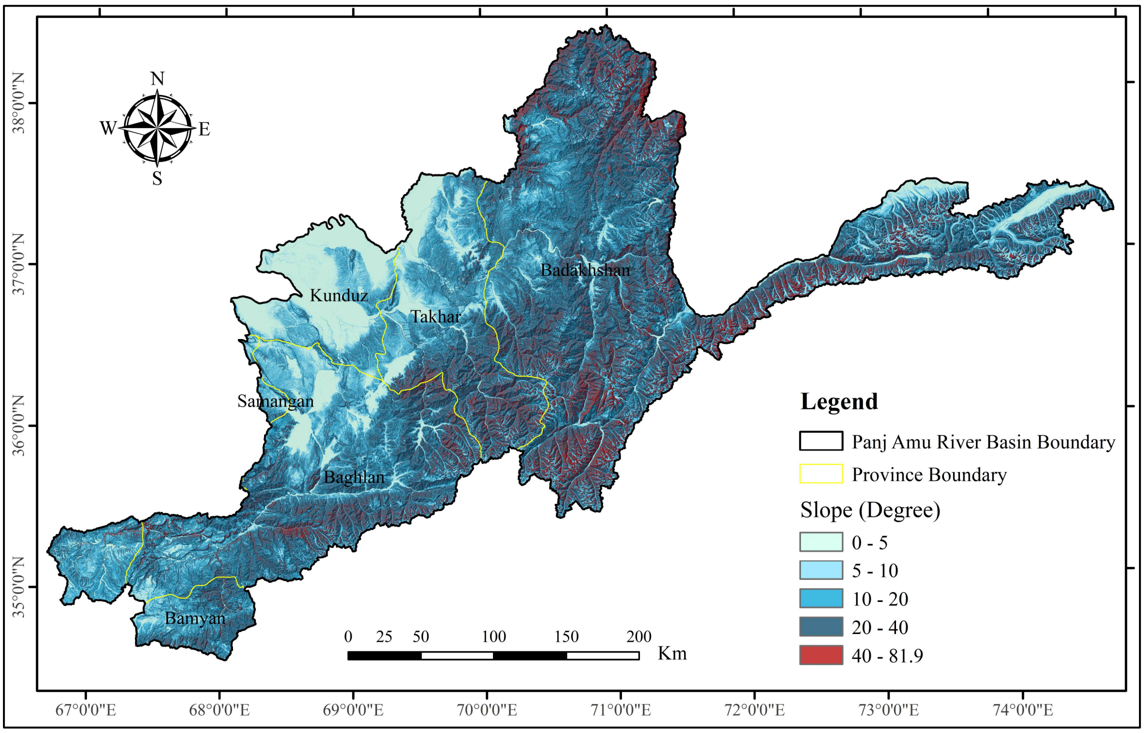


Figure 5.19: Slope Map of the PARB

5.4. Wells Data Analysis

In this study, the wells data for the PARB was sourced from the Danish Committee for Aid to Afghan Refugees (DACAAR). The Danish Committee (DACAAR) dug these wells mainly in villages or near to residential areas to fulfill the needs of the local population and at the same time monitor the groundwater system (Figure 5.20).

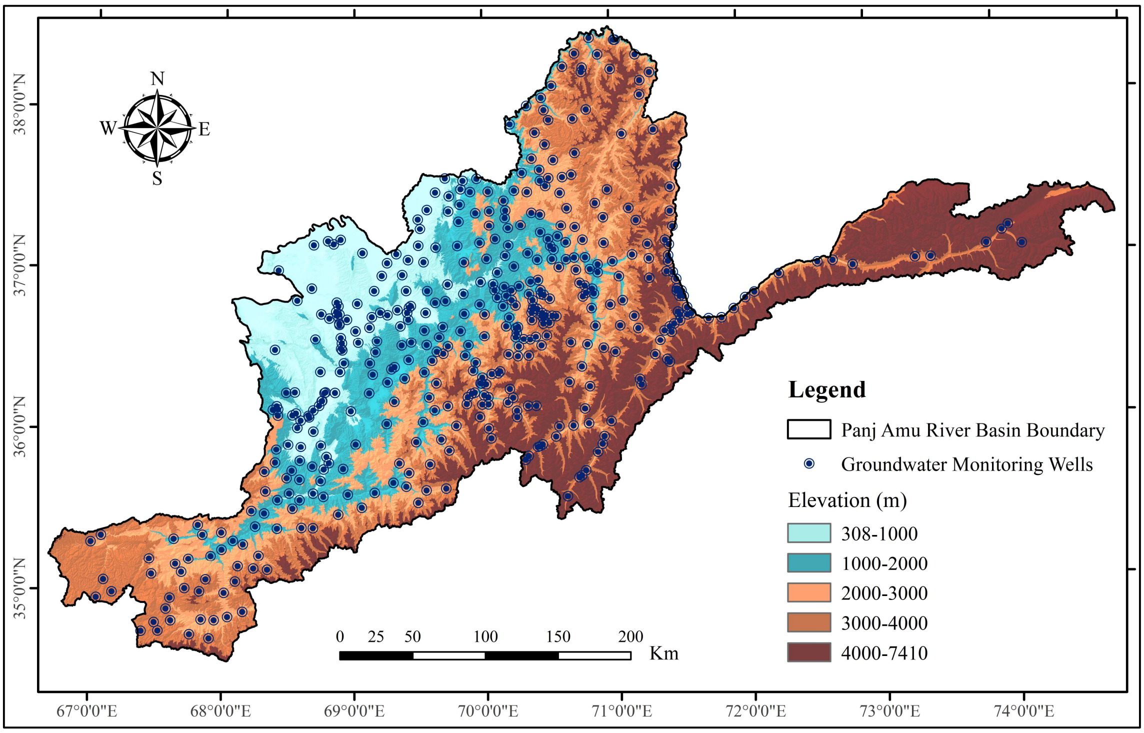


Figure 5.20: Groundwater Monitoring Wells Map

The data set covered different time periods for different regions. To ensure consistency and relevance, a specific six-year period from 2017 to 2022 was chosen for the analysis. This time frame was chosen in order to obtain an up-to-date and comprehensive overview of the groundwater situation in the catchment area and thus enable a targeted and meaningful assessment of the static groundwater level and trends.

The data on the static groundwater level was interpolated and then graphically displayed in ArcGIS using the IDW (Inverse Distance Weighted) technique. This process facilitated the creation of a map of the static groundwater level (Figure 5.21).

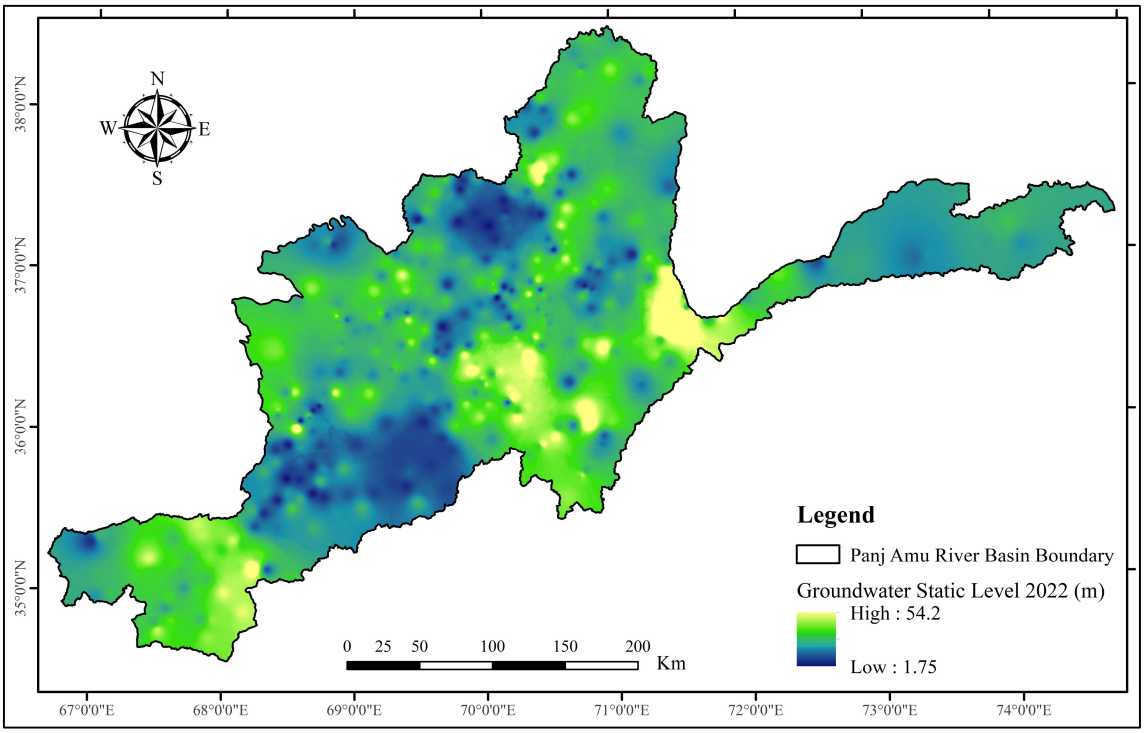


Figure 5.21: Groundwater Static Level Map of the PARB

Subsequently, the groundwater static level map was subtracted from the Panj Amu River Basin (PARB) elevation map within ArcGIS. The process was achieved through the utilization of Spatial Analyst Tools → Map Algebra → Raster Calculator function, resulting in the generation of the groundwater table map (Figure 5.22). Then the kilometric contour lines on the groundwater table map in the PARB were generated using the Spatial Analyst Tools within the ArcMap software. Specifically, the contours were created through the Spatial Analyst Tools → Surface → Contours sequence (Figure 5.22). These contour lines served as the basis for determining the direction of groundwater flow. To ascertain this flow direction, the Spatial Statistics Tools were used, specifically the functionality under Measuring Geographic Distribution → Linear Directional Mean in ArcMap (Figure 5.22).

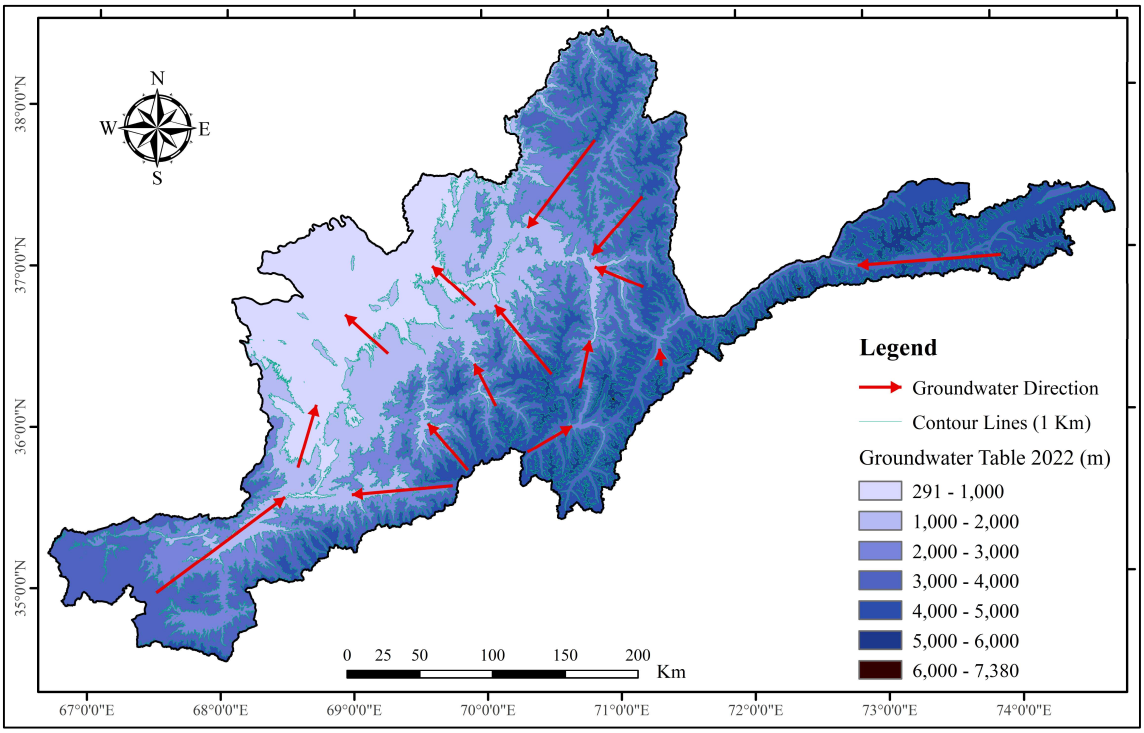


Figure 5.22: Groundwater Table Map with Contour Lines of the PARB

First, the six-year water level difference was analyzed to learn how the water level has decreased annually in the different areas of the catchment, and as shown in (Figure 5.23). Over the entire period from 2017 to 2022, the data shows that some of the wells have a high yield and commendable performance, while others show inadequate performance. Of the 461 groundwater monitoring wells analyzed, 109 wells are characterized by optimal performance, 224 wells show moderate performance, and 121 wells show the most unfavorable performance (Figure 5.23). The data set of groundwater monitoring wells has been integral to the generating of groundwater potential zone maps through the application of Frequency Ratio (FR) and Evidence Belief Function (EBF) models. Thirty percent, or 139 high-yield wells, were selected to evaluate the effectiveness and accuracy of the Multi-Criteria Decision Analysis (MCDA) methods using Area Under the Curve and Receiver Operating Characteristic (AUC-ROC) analysis.

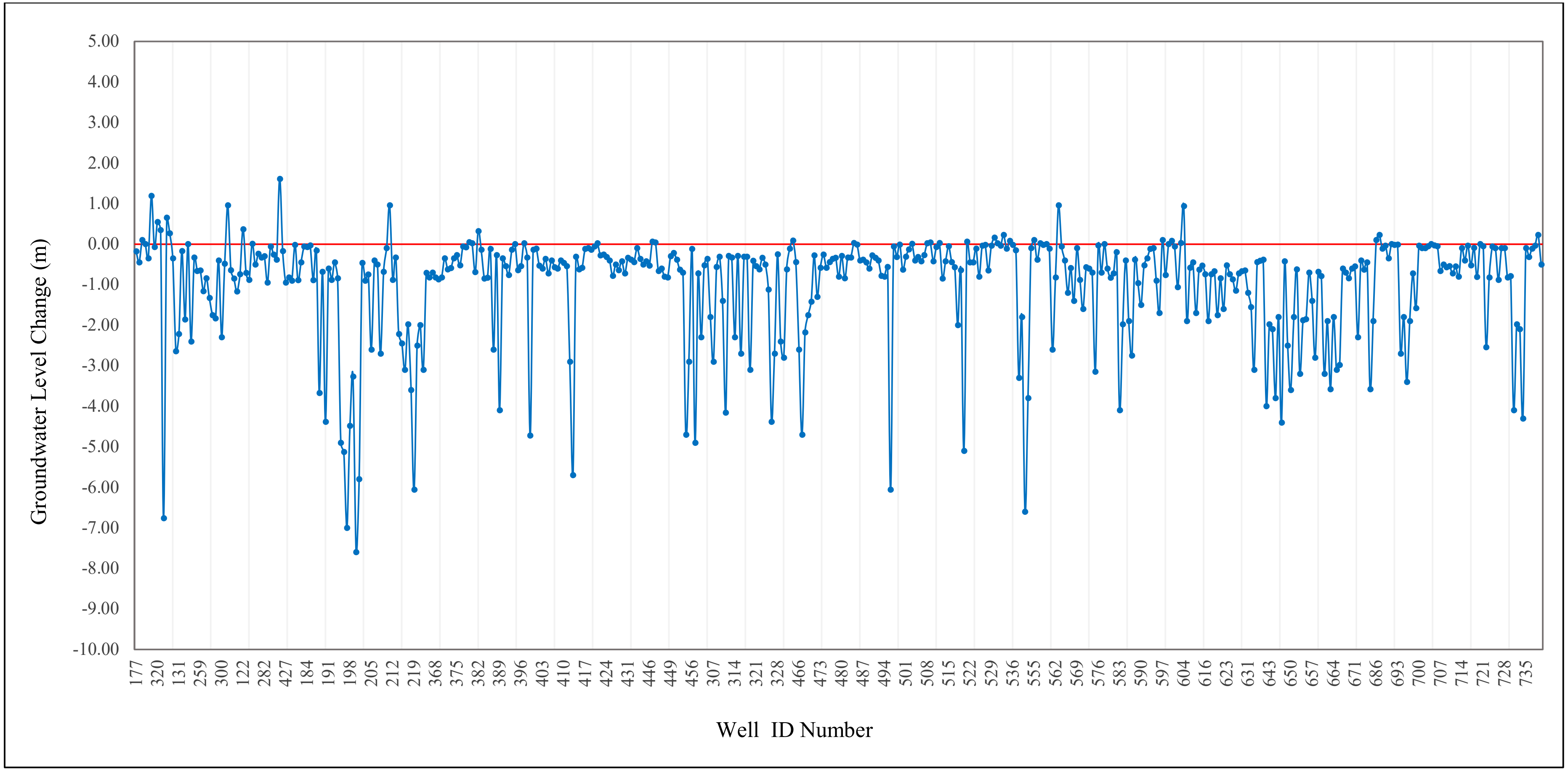


Figure 5.23: Groundwater Level Change from 2017 to 2022 in the Panj Amu River Basin

Some maximum and minimum peak point wells water level change from 2017 to 2022 in Panj Amu River Basin were illustrated in (Figure 5.24).

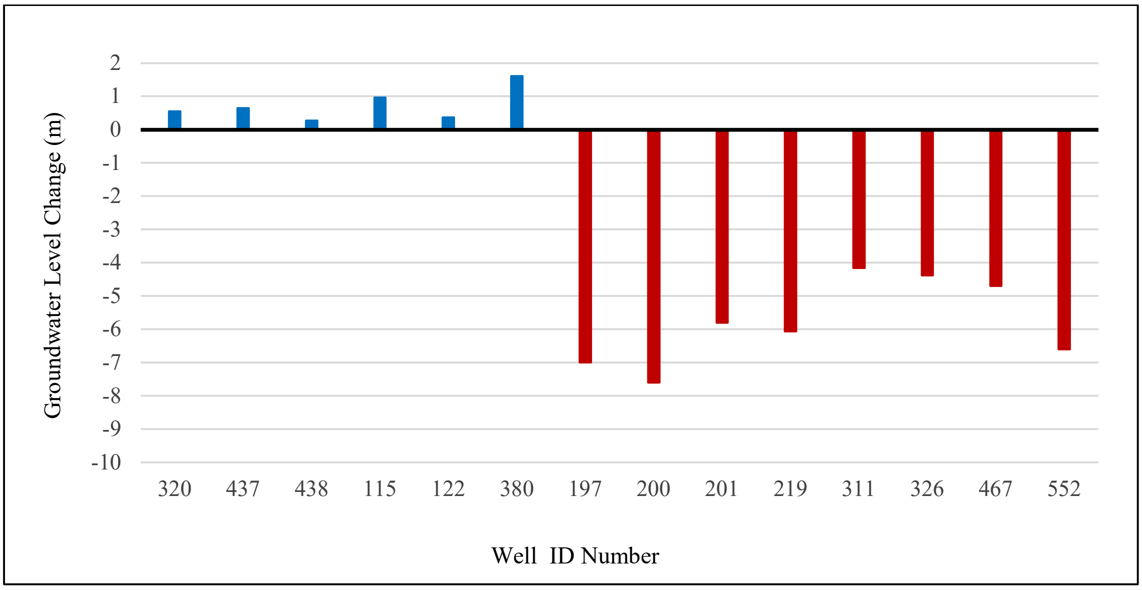


Figure 5.24: Some Peak Points Wells Water Level Change from 2017 to 2022

The maximum peak points were shown in (Figures 5.25, and 5.26) with respect to the related region's precipitation, to display how and why the ground water level is stable or increased.

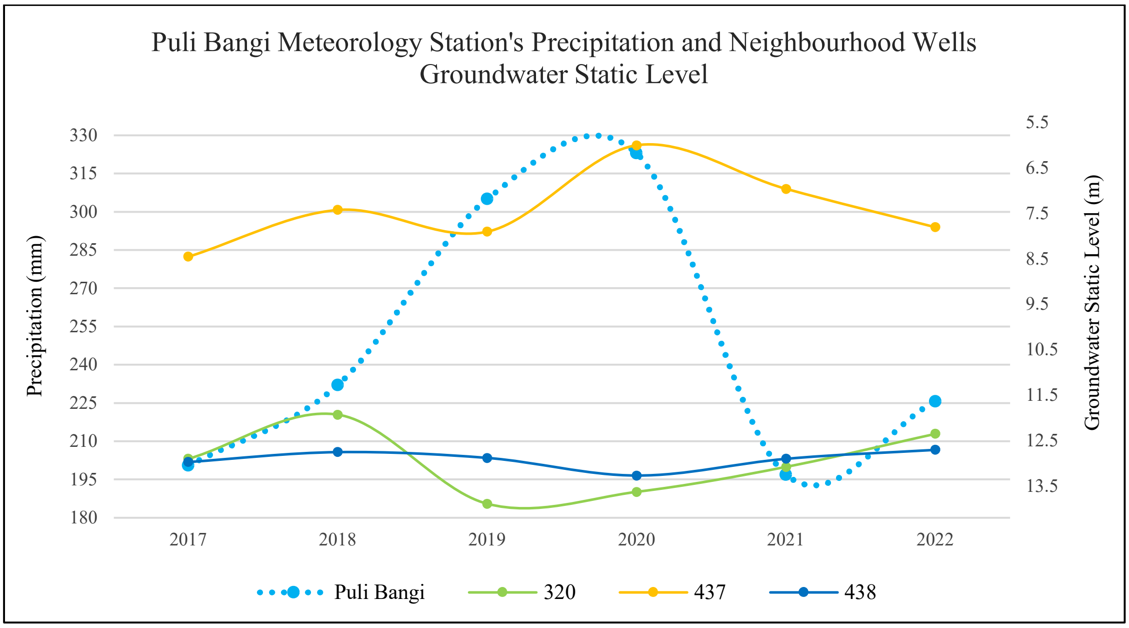


Figure 5.25: Groundwater Level (2017 - 2022) Near Puli Bangi M. Station

The Puli Bangi meteorology station area (Figure 5.8) experiences low precipitation (Figure 5.9). The geology of this region (Figure 5.10) predominantly comprises limestone-chert, loess, limestone-dolomite, and fan alluvium-colluvium, all of which show high permeability. Additionally, the soil texture (Figure 5.14) characterized by haplic yermosols-2ab which has a high infiltration rate. Consequently, the area experiences minimal runoff, and the low precipitation does not impact the groundwater static level (Figure 5.25). Furthermore, two major rivers traverse this region and contributing to the stability of the groundwater static level due to the high permeability and infiltration rate of the area.

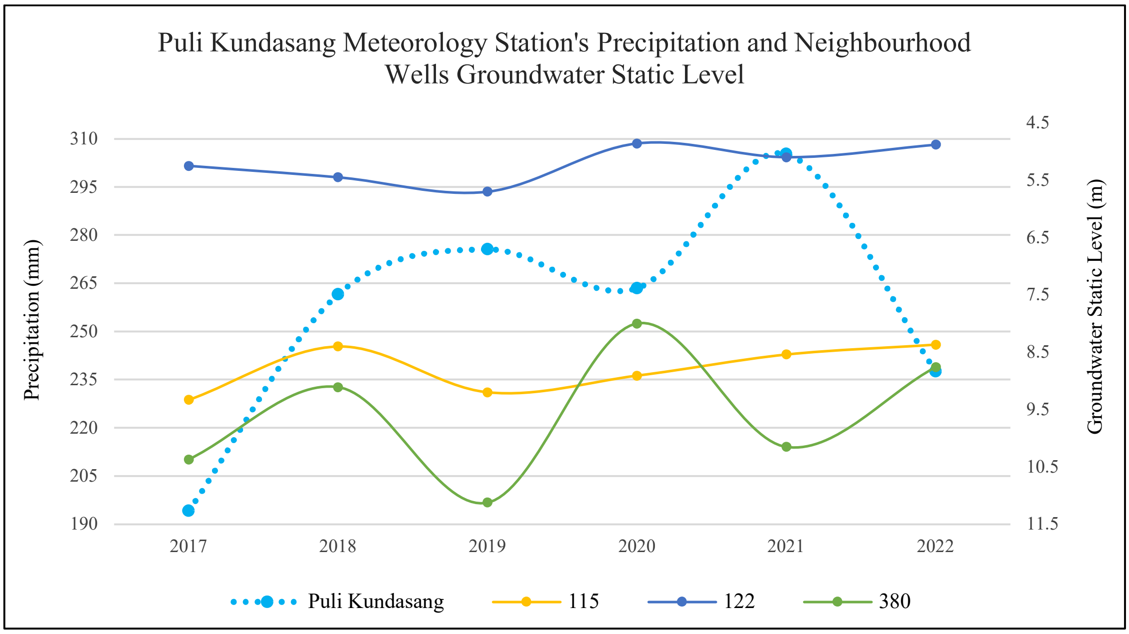


Figure 5.26: Groundwater Level (2017 - 2022) Near Puli Kundasang M. Station

The Puli Kundasang meteorology station area (Figure 5.8) has moderate precipitation (Figure 5.9). The geology of this region (Figure 5.10) consists of different kinds of stones like; andesite, conglomerate-sandstone, sandstone-siltstone, limestone-dolomite, diorite-granodiorite, and clay-siltston which have different permeability. Besides, the area's soil texture (Figure 5.14) includes lithosols-xerosols-c which has moderate infiltration rate. Therefore, the precipitation does not remarkably effect the groundwater static level (Figure 5.25).

The minimum peak points of were showed in (Figures 5.27, and 5.28) with respect to the related region's precipitation, to show that, how and why the ground water level decreased.

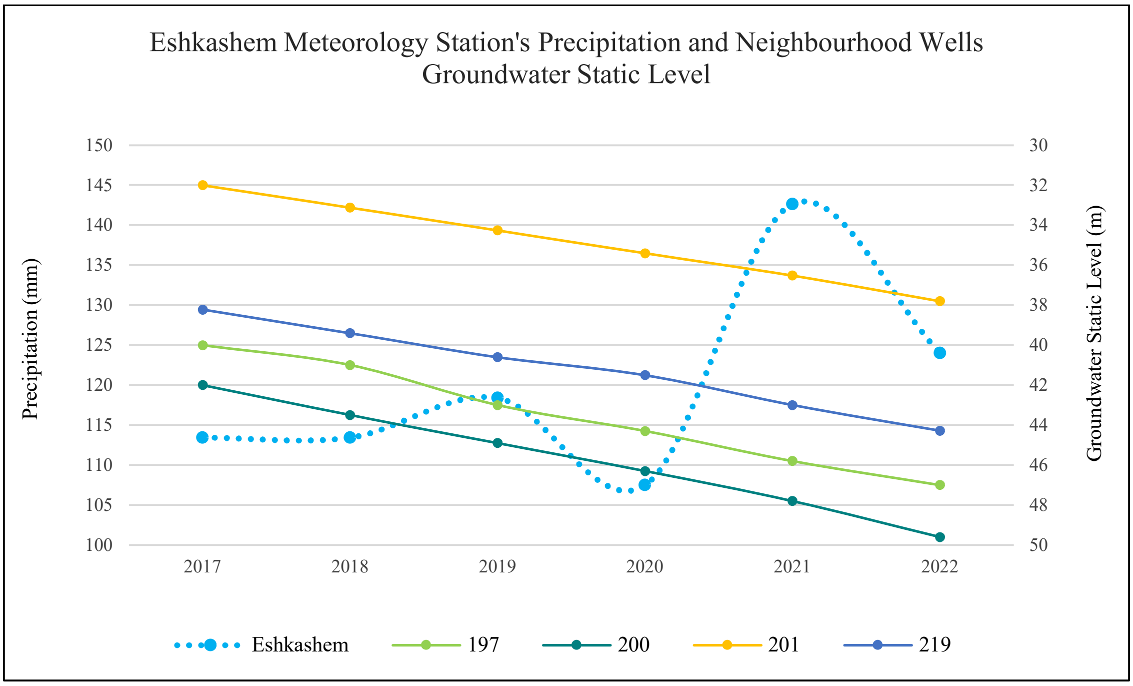


Figure 5.27: Groundwater Level (2017 - 2022) Near Eshkashem M. Station

The Eshkashem meteorology station area (Figure 5.8) experiences moderate precipitation (Figure 5.9). The geology of this region (Figure 5.10) predominantly comprises granodiorite, marble-gneiss, and granodiorite-granosyenite, all of which exhibit low permeability. Additionally, the area's soil texture (Figure 5.14) includes lithosols-cambisols-rankers and lithosols-xerosols, which are characterized by low infiltration rates. As a result, runoff in this area is high, and due to these factors, the precipitation does not significantly affect the groundwater static level of wells number 197, 200, 201, and 219 as shown in (Figure 5.27).

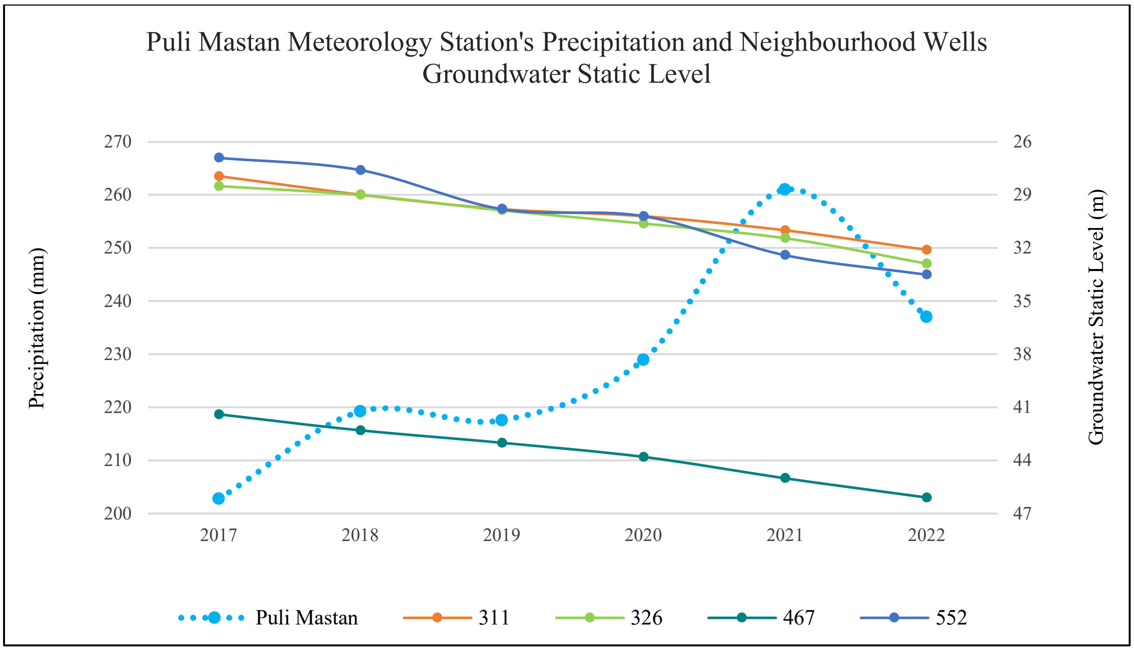


Figure 5.28: Groundwater Level (2017 - 2022) Near Puli Mastan M. Station

The Puli Mastan meteorology station area (Figure 5.8) has low precipitation (Figure 5.9). The geology of this region (Figure 5.10) mostly consists of gabbro-diorite, marble-gneiss, diorite-plagiogranite, and granodiorite-granosyenite, all of which show low permeability. Furthermore, the area's soil texture (Figure 5.14) includes lithosols-xerosols-2c which has low infiltration rate. Therefore, the runoff in this area is also high, and due to these factors, the precipitation does not notably influence the groundwater static level of 311, 326, 467, and 552 wells (Figure 5.28).

Considering the decline in groundwater static levels near the Eshkashem and Puli Mastan meteorological stations, the results align with the groundwater potential maps (Figures 6.1, 6.2, and 6.3). These maps indicate that the above-mentioned areas demonstrate low groundwater potential.

The analyses indicate that changes in water levels are not solely attributed to precipitation. Other influential factors include geology, soil texture, lineament density, drainage density, land use and land cover, curvature, and slope, which play a more significant role in affecting groundwater level changes.

CHAPTER 6

RESULTS AND DICUSSIONS

The sixth chapter deals with the interpretation of the final output maps of the multi-criteria decision analysis (MCDA) and the spatial operations to determine the groundwater potential zones in the Panj Amu River Basin (PARB). The accuracy and efficiency of the MCDA methods in relation to the static level data of the groundwater monitoring wells are derived using AUC-ROC analysis. In chapter five of this study, the three MCDA methods were used and discussed, namely Analytic Hierarchy Process (AHP), Frequency Ratio (FR) and Evidence Belief Function (EBF).

6.1. Groundwater Potential Zones Map of the PARB by AHP Method

In this study, ten proxies (parameters, criteria) and their respective weightings were used with the Analytical Hierarchy Process (AHP) method to create the groundwater potential map (GWPZ). The groundwater potential was calculated in the manner described below, where the weighting of the factors was determined from 1 to 5 with regard to the relevance of groundwater recharge. They were also added to the formula for the weighted image overlay (5.10) in the ArcMap environment via the Spatial Analyst Tools → Overlay → Weighted Overlay. As a result, the GWPZ map was created (Figure. 6.1).

The region is generally categorized by high precipitation, high permeability, high lineament and low drainage density, higher TWI, shallow curvature and low slope for susceptibility to groundwater recharge. According to the results, precipitation, geology, lineament density, drainage density and soil are the five important variables for the assessment of GWP in the current study.

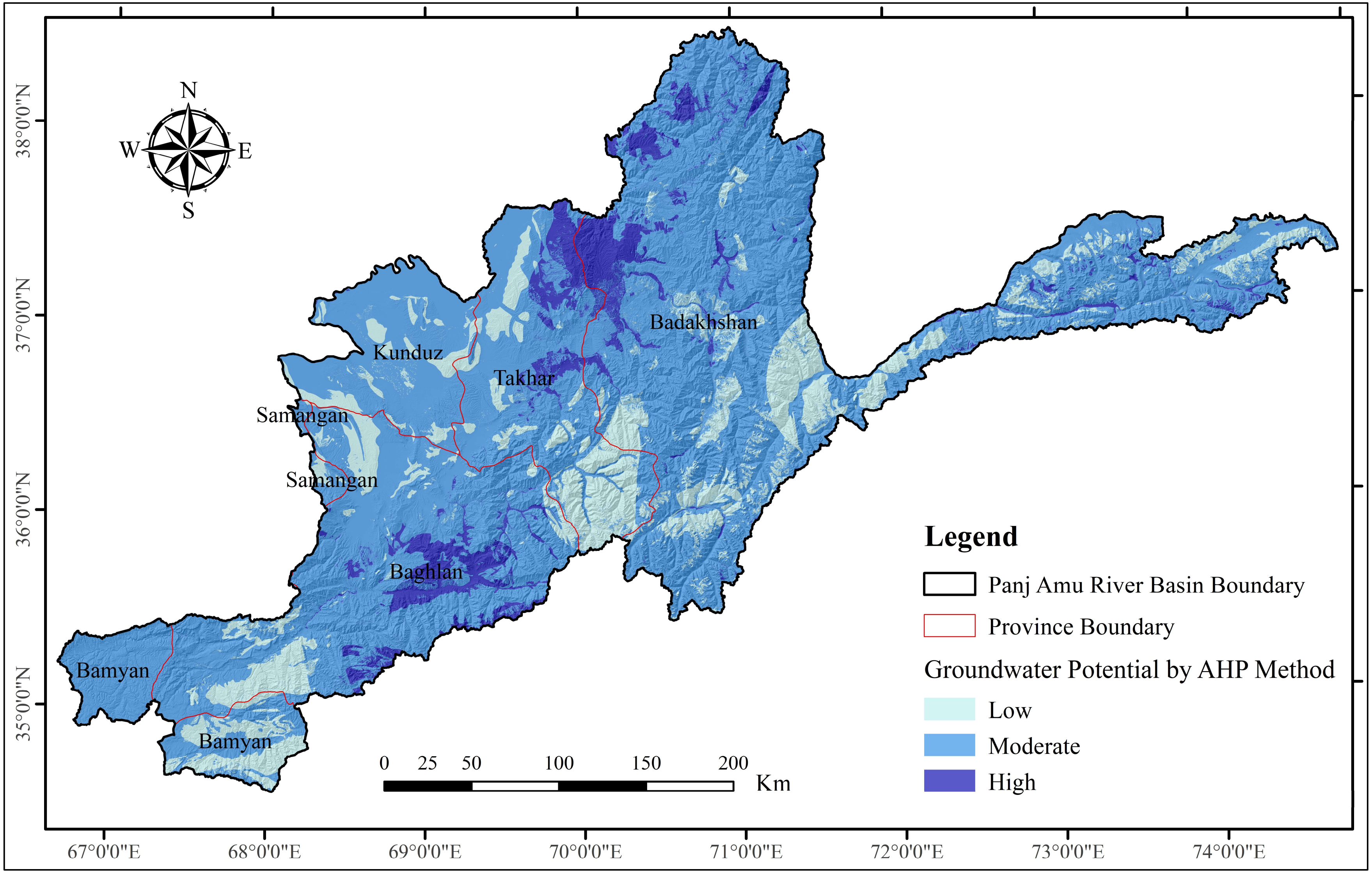


Figure 6.1: Groundwater Potential Zones Map of the Panj Amu River Basin by AHP Method

The AHP model provides a GWP map with three classes (low, moderate and high). The result (Figure 6.1) shows that most of the basin has a moderate GWP, while the north and northwest of Badakhshan, the northeast of Takhar, the south and southeast of Bahglan and part of the Wakhan corridor in the east of Badakhshan have a high GWP, while the southwest and northwest of Baghlan, the northeast of Bamyan, the southeast and northwest of Takhar, the south of Badakhshan and some parts of Kunduz have a low groundwater potential.

Table 6.1: Groundwater potential map classes' distribution based on AHP model.

Groundwater Potential Classes	Area	
	(Km^2)	(%)
Low	15342.01	17.05
Moderate	67521.19	75.017
High	7144.24	7.94
Total	90007.44	100

The outcomes show that the basin has a moderate vulnerability to groundwater potential in around 75% of the area, and 17% of the area is recognized for low GWP, while a highly vulnerable area is just 8% of the research zone (Table 6.1).

6.2. Groundwater Potential Zones Map of the PARB by FR Method

The Frequency Ratio (FR) is the second MCDA method used in this study to find groundwater potential zones. The GWP map (Figure 6.2), derived from the FR calculation considering equations (5.11) and (5.13), was created and categorized into five classes based on the Jenk classification system in ArcMap, ranging from very low, low, moderate and high to very high classes, considering the seven main thematic layers on groundwater potential.

The map categorizes wells with high groundwater level wells data, high precipitation, high permeability, high lineament and drainage density and low gradient for susceptibility to groundwater recharge. According to the results, static water table, precipitation, geology, lineament density, drainage density and soil are the six important variables for the assessment of GWP in this study.

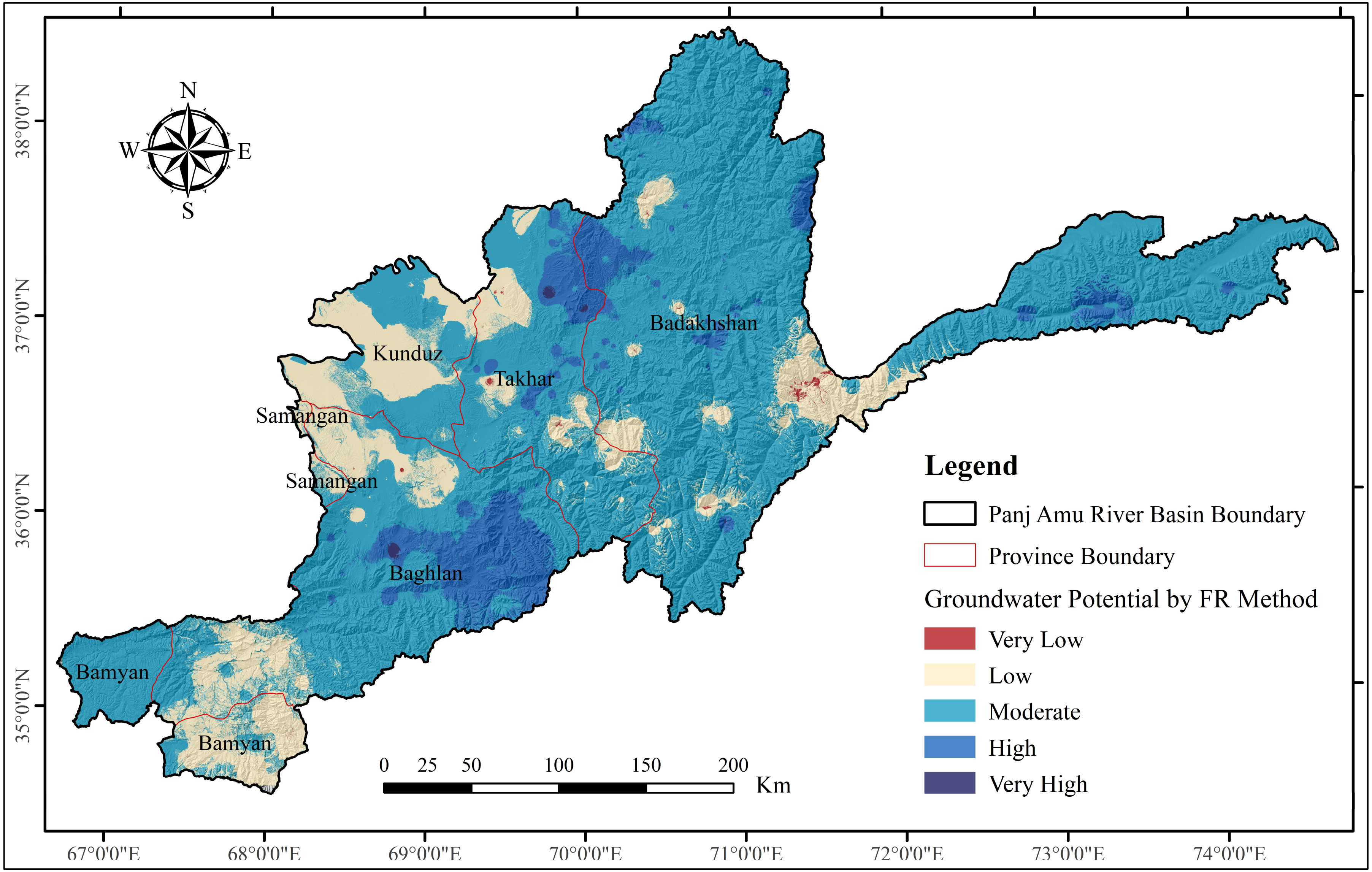


Figure 6.2: Groundwater Potential Zones Map of the Panj Amu River Basin by FR Method

The FR model results indicate that most of the basin has a moderate GWP, while some areas in Takhar and Baghlan with high precipitation have a very high groundwater potential, as well as the northwest of Badakhshan, the northeast of Takhar, the east and southeast of Bahglan up to the central region of the province, and some parts of the Wakhan corridor in eastern Badakhshan have a high GWP, but southwest and northwest Baghlan, northeast Bamyan, northwest Takhar, some areas in southeast Badakhshan and most areas of Kunduz have a low groundwater potential.

Table 6.2: Groundwater potential map classes' distribution based on FR model.

Groundwater Potential Classes	Area	
	(Km^2)	(%)
Very Low	132.34	0.15
Low	16430.4	18.26
Moderate	64845.93	72.05
High	8485.74	9.43
Very High	101.75	0.11
Total	89996.13	100

The result shows that the basin has a moderate vulnerability to groundwater potential in around 72% of the area, and 18% of the area is recognized for low to very low GWP, while a high to very high susceptible area for GWP is just 9.5% of the whole PARB (Table 6.2).

6.3. Groundwater Potential Zones Map of the PARB by EBF Method

The Evidence Belief Function (EBF) is the third MCDA method used in this study to find groundwater potential zones. The GWP map (Figure 6.3), derived from the EBF calculations using the equations (5.14 to 5.23), was created and categorized into five classes in ArcMap, considering the seven most appropriate thematic layers for groundwater potential. The classes of the map ranged from very low, low, moderate and high to very high.

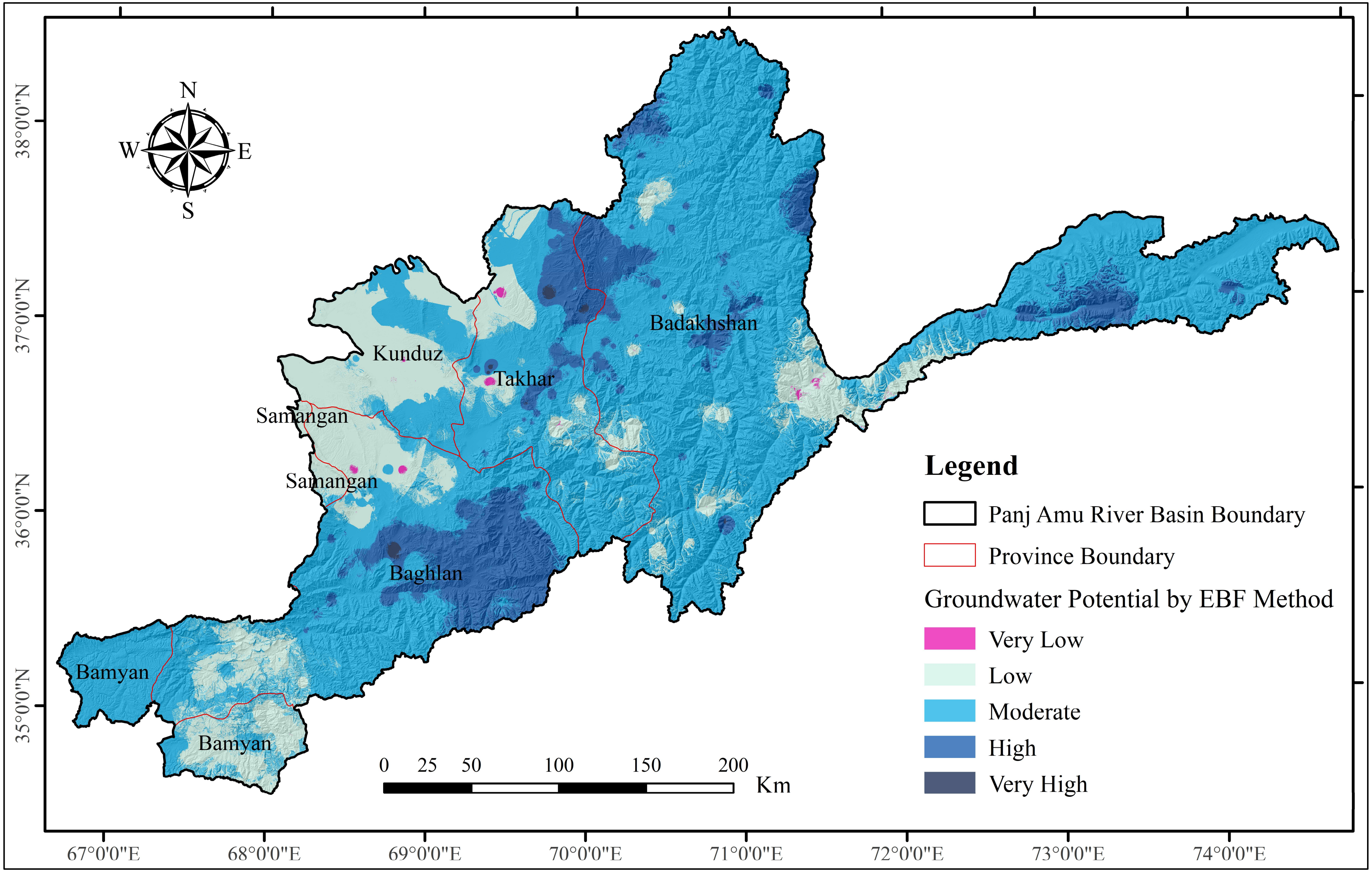


Figure 6.3: Groundwater Potential Zones Map of the Panj Amu River Basin by EBF Method

The map categorizes wells with high water tables, high precipitation, high permeability, high lineament and drainage density and low gradient for susceptibility to groundwater recharge. According to the results, static water table, precipitation, geology, lineament density, drainage density and soil are the six important variables for the assessment of GWP in this study.

The EBF model results show that most areas of the basin have a moderate GWP, while some areas in Takhar and Baghlan have a very high groundwater potential, as well as the northwest and some areas in the northeast and Wakhan corridor of Badakhshan, northeast of Takhar, and southeast of Bahglan to the central region of the province have a high GWP, but the southwest and northwest of Baghlan, the northeast of Bamyan, the northwest of Takhar, some areas in the southeast of Badakhshan and most areas of Kunduz have a low groundwater potential.

Table 6.3: Groundwater potential map classes' distribution based on EBF model.

Groundwater Potential Classes	EBF	
	Area (Km^2)	(%)
Very Low	123.24	0.14
Low	17132.87	19.04
Moderate	61206.95	68.01
High	11396.45	12.66
Very High	139.59	0.16
Total	89999.1	100

The outcome shows that the basin has a moderate vulnerability to groundwater potential in around 68% of the area, and 19% of the area is recognized for low to very low GWP, while a high to very high susceptible area for groundwater recharge is around 13% of the study area (Table 6.3).

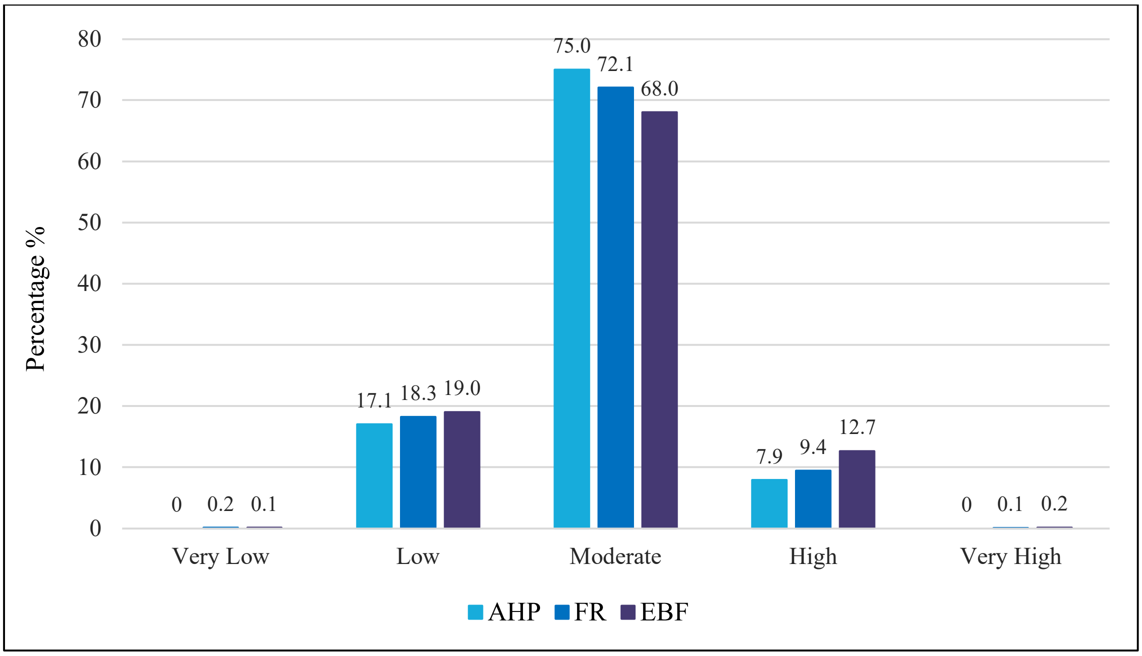


Figure 6.4: Groundwater Potential Classes' Percentages by AHP, FR, and EBF Models

All three models show that most areas of the Panj Amu RB have moderate groundwater potential. All three models indicate that the high potential areas are located in mountainous areas with little or no settlement, and in high precipitation areas mostly covered by conglomerate sandstone, sandstone-siltstone and limestone-sandstone rocks, or in areas with high permeability, such as northeast Takhar, east and southeast Bahglan to the central region of the province, northwest and eastern (some parts of the Wakhan corridor) of Badakhshan. These areas promise significant groundwater resources due to their favorable natural conditions. In contrast, the areas with low groundwater potential are those that receive less precipitation and are mostly covered by granite, gneiss, granite-granodiorite, clay-siltstone, marble-gneiss, diorite-granodiorite, siltstone-shale, granodiorite-granosyenite, clay-shale, ultramafic intrusions, gabbro-mafic metavolcanics, metamorphic rocks and granodiorite rocks or areas with low permeability. The map of the 44-year (1979-2022) average precipitation shows that the area with the highest precipitation represents only 8% of the entire basin and the area with the lowest precipitation 39%. The geological map shows that the most permeable rocks cover 36.04% of the area; however, the less permeable rocks cover 40.93% of the area in the Panj Amu RB. Other factors that have a positive effect on groundwater recharge are high lineament density, low drainage density, permeable soils and low slope covering 67.7%, 32.4%, 3.4% and 23.2% of the area, respectively. In contrast, a low lineament density, a high drainage density, impermeable soils and a steep slope, which cover 10.1%, 26.2%, 28.1% and 42.4% of the area respectively, have a negative effect on groundwater recharge (Table 5.13).

The Frequency Ratio (FR) and Evidence Belief Function (EBF) models are quite similar. Based on the FR and EBF models, the regions with low groundwater potential similarly include the southwestern and northwestern parts of Baghlan, the northeastern areas of Bamyan, the northwestern foothills of Takhar, certain regions in the southeastern part of Badakhshan, and most of Kunduz.

6.4. Validation

Validation is the process of ensuring a model, system, or process meets its intended requirements and produces accurate results. It is crucial for confirming the accuracy and reliability of outputs, thereby enabling informed decision-making. Validation builds trust and credibility among stakeholders by demonstrating that the model has been rigorously tested. It also helps in complying with industry standards and regulations, reducing potential risks. Finally, the insights gained from validation lead to continuous improvement and refinement of the model or system.

The models should be validated because, according to (Chung and Fabbri 2003) a validated model discovers its importance. There are many techniques to verify and authenticate GWP maps generated by AHP, FR, and EBF models. In this study two types of validation have been used: AUC-ROC curve and groundwater level change map.

6.4.1. AUC-ROC Curve Analysis

Classification problem performance is measured at different thresholds using the AUC-ROC curve (Hajian-Tilaki 2013; Streiner and Cairney 2007). AUC is a metric or degree of separability, while ROC is a probability curve. It indicates the degree to which the model can separate between classes. The model performs better in prediction when the AUC has a higher value (Streiner and Cairney 2007). Equations (6.2, 6.5 and 6.6) explain the true-positive and false-positive rates as well as the accuracy of the AUC-ROC model. The true-positive and false-positive rates represent the AUC-ROC curve (Figure 6.6).

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}} \tag{6.1}$$

$$\text{Recall, Sensitivity, TPR} = \frac{\text{TP}}{\text{TP} + \text{FN}} \tag{6.2}$$

$$\text{F1 Score} = \frac{\text{Precision} + \text{Recall}}{2} \tag{6.3}$$

$$\text{Specificity} = \frac{\text{TN}}{\text{TN} + \text{FP}} \tag{6.4}$$

$$\text{FPR}, (1 - \text{Specificity}) \cong \frac{\text{FP}}{\text{FP} + \text{TN}} \tag{6.5}$$

$$\text{Accuracy} = \frac{\text{TP} + \text{TN}}{\text{TP} + \text{TN} + \text{FP} + \text{FN}} \tag{6.6}$$

Where T, F, P, N, and R stand for true, false, positive, negative, and rate respectively.

The Area Under the Curve and Receiver Operator Curve (AUC-ROC) were used to validate the efficiency and accuracy of the models. AUC and ROC analysis are the most practical validation methods; they have been used by a number of academics (Ahmadi et al. 2020; Andualem and Demeke 2019; Das 2019; Elvis et al. 2022; Ghorbani Nejad et al. 2017; Ghosh 2021; Guru, Seshan, and Bera 2017; Manap et al. 2013; Ozdemir 2011; Razandi et al. 2015; Pourghasemi and Beheshtirad 2015; Thanh et al. 2022). A hundred thirty-nine high yield wells and a generated groundwater potential dataset by three models (AHP, FR, and EBF) were used in ArcMap environment (ArcSDM Tools → ROC Tools → Calculate ROC Curves and AUC Values) to calculate ROC curve. The true positive rate on the y-axis and the false positive rate on the x-axis were considered while creating the AUC-ROC curve (Figure 6.5).

The AUC-ROC analysis (Figure 6.6) shows that the accuracy of the AHP, FR and EBF methods are 80.2%, 91.2% and 92.6%, respectively. This evaluation is crucial for assessing the performance and reliability of these models in the context of groundwater potential mapping. The higher AUC-ROC values observed for the FR and EBF models imply that they have better predictive qualities compared to the AHP model. These results emphasize the importance of using robust methods such as FR and EBF in the assessment of groundwater potential to improve decision-making processes and resource management strategies.

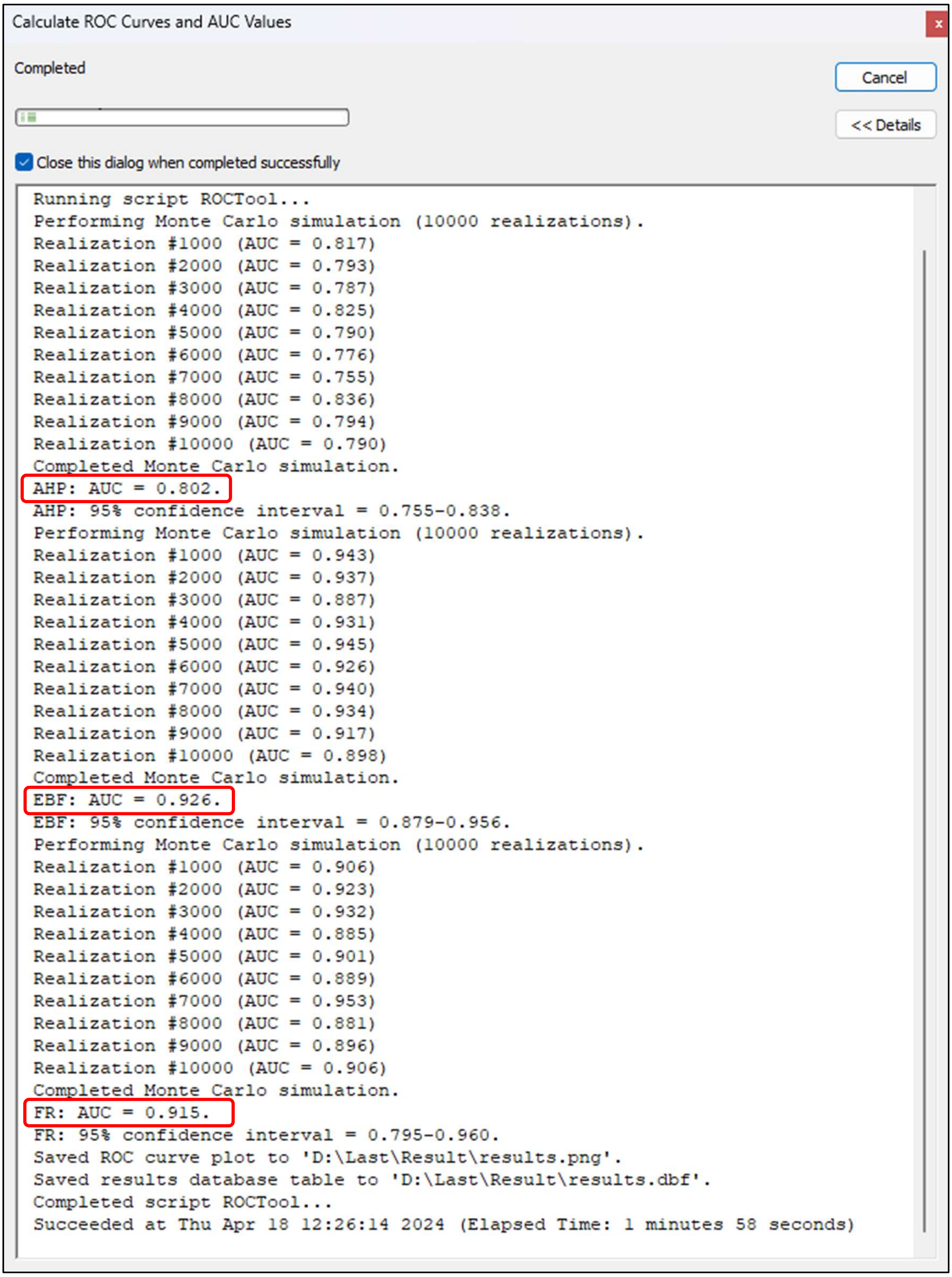


Figure 6.5: ROC Curve and AUC Values Analysis in ArcMap Environment

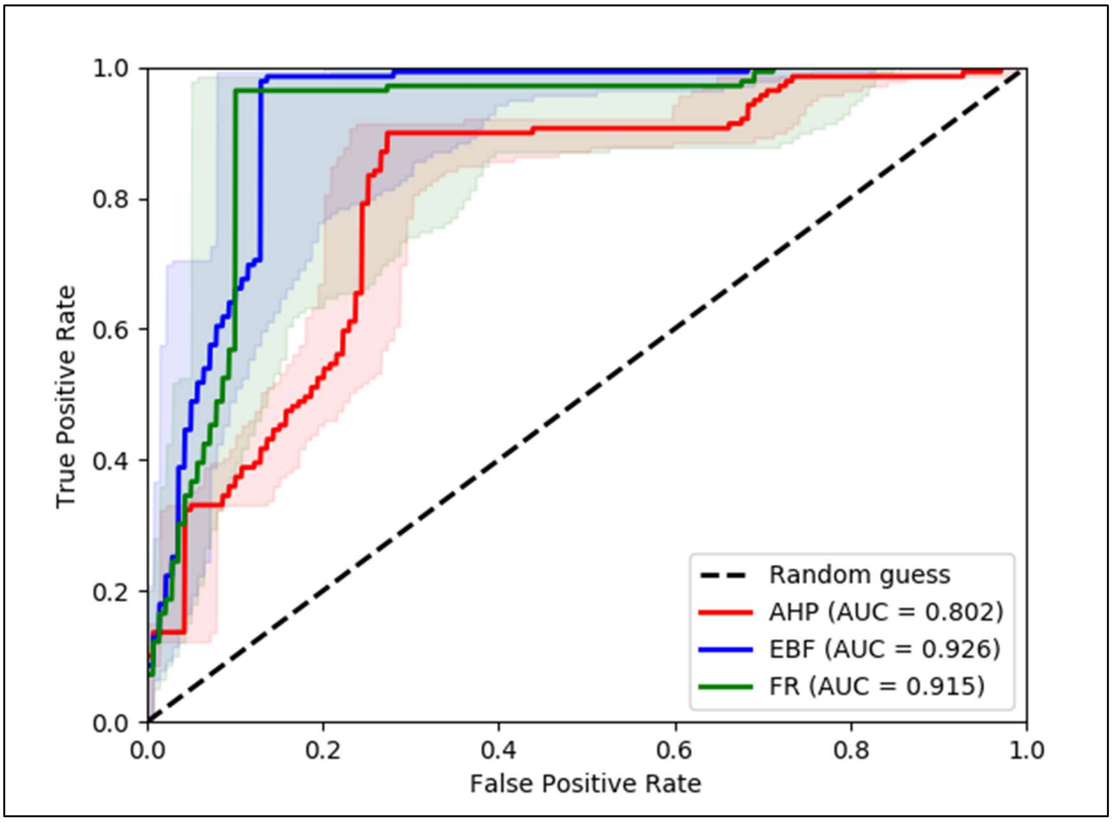


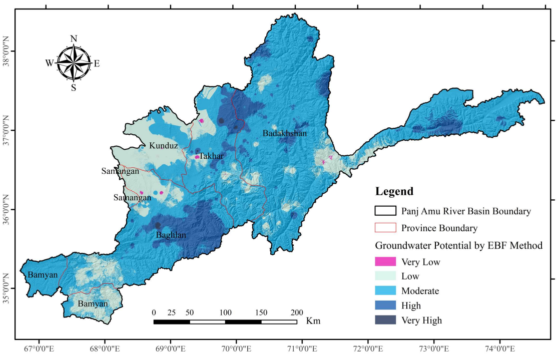
Figure 6.6: AUC Values and ROC Curve for AHP, FR, and EBF methods.

According to (Razandi et al. 2015; Yesilnacar 2005), there are five categories for the AUC values that represent the predictive accuracy: poor (50-60) %, average (60-70) %, good (70-80) %, very good (80-90) % and excellent (90-100) %. Therefore, according to the above values, the AHP method is very good, while the EBF and FR methods show excellent results for this research work.

6.5. Comparison of GWP Map with GW Level Change Map

The step of comparing the groundwater potential map with the available data is crucial for the correctness and accuracy of this study. The final results of this study (Figures 6.7, 6.8, and 6.9) are compared with the map of average groundwater level change (Figure 6.10) from 2017 to 2022 provided by the DACAAR agency working for Afghanistan on water supply and refugee support in all conditions.

If one compares the results of the study with the thematic map on the change in the groundwater table, one can speak of a similarity between these maps. The areas with the highest groundwater potential are the areas that are within the conglomerate sandstone, sandstone-siltstone and limestone-sandstone rocks and receive high precipitation, or the areas that have high permeability, such as the northeast of Takhar, the east and southeast of Bahglan to the central region of the province, and some parts of the Wakhan corridor in the east of Badakhshan. The areas with low groundwater potential are those that receive less rainfall and are mostly covered by granite, gneiss, granite-granodiorite, clay-siltstone, marble-gneiss, diorite-granodiorite, siltstone-shale, granodiorite-granosyenite, clay-shale, ultramafic intrusions, gabbro-mafic metavolcanics, metamorphic rocks and granodiorite rocks or areas with low permeability. And the groundwater areas with moderate potential are distributed throughout the basin.



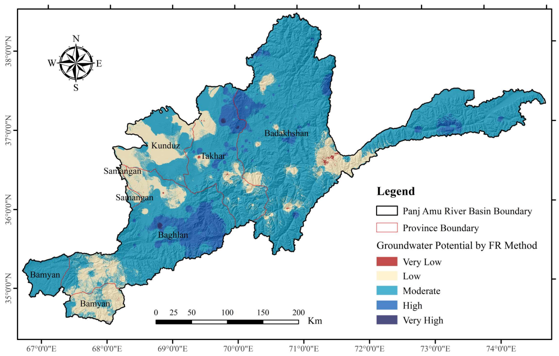
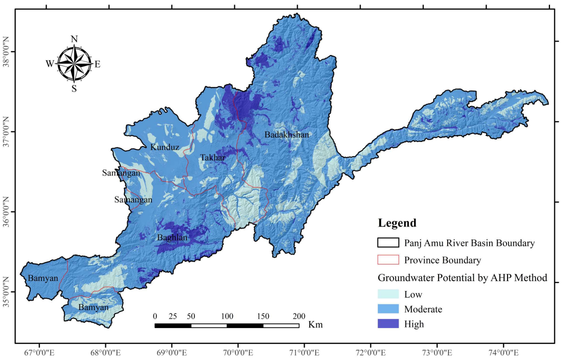


Figure 6.7: GWPZ Map by EBF Method Figure 6.8: GWPZ Map by FR Method



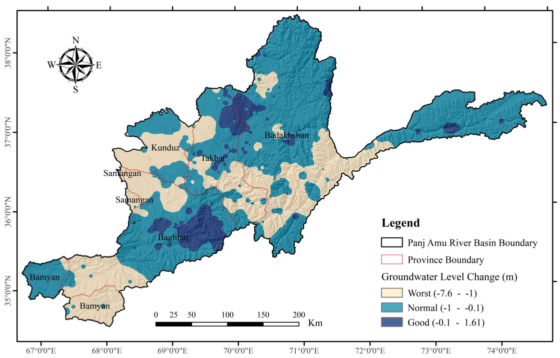


Figure 6.9: GWPZ Map by AHP Method Figure 6.10: GW Level Change Map

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS

This chapter discusses the summary, and conclusion part along with limitation, and recommendations of the study as well as the future direction.

7.1. Summary

In this study, potential groundwater areas and groundwater stability were analyzed and identified using remote sensing data, groundwater level data, rainfall, runoff, evapotranspiration and ArcMap. This study covers the Panj Amu River Basin, where more than 4.5 million people live, and which is located in northeastern Afghanistan. Geographic Information System (GIS) based Multi Criteria Decision Analysis (MCDA) methods (AHP, FR and EBF) were used to model groundwater availability and determine the future risk area according to groundwater availability. In this framework, the rainfall, runoff, and evapotranspiration data along with population, livestock and agriculture data were used to estimate the water balance and understand the future conditions of groundwater in Panj Amu River Basin.

For planners, strategists and authorities, groundwater management and sustainability are important aspects that require a comprehensive assessment of groundwater potential. This includes assessing factors such as hydrogeological conditions, recharge rates, water table fluctuations, water quality, land use patterns, climate change impacts and socio-economic factors. Effective management strategies must be developed based on scientific assessments to ensure sustainable use of groundwater resources, minimize depletion, prevent contamination, and meet the needs of present and future generations.

7.2. Conclusions

In most cities and districts of Afghanistan, groundwater exploration is not based on previous proper investigations. Therefore, the rate of positive drilling is low in most areas of the country and most wells dry up quickly. To identify the location of successful wells, remote sensing satellite imagery processing is very helpful as it enables to determine the priority locations for concentrating hydrogeological and geoelectrical surveys. It reduces the cost and time required to investigate the aquifer and facilitates the identification of suitable drilling sites.

Understanding the interplay of water resources, human settlements, agricultural practices and ecological factors in the PARB is critical to addressing sustainability challenges and promoting informed decision-making. Academic research focused on this region therefore provides valuable insights in the fields of hydrology, environmental science, geography and socio-economic studies. This study investigates groundwater availability and identifies groundwater potential zones in the Panj Amu river basin. The maps of groundwater potential zones serve as valuable tools for sustainable water resources management, land use planning and environmental protection and contribute to better decision making in various sectors, which will help communities to improve groundwater exploration and increase groundwater supply at the local level. Remote sensing data will be combined with different MCDA methods (AHP, FR and EBF) in a GIS environment to create a map of groundwater potential from ten thematic layers. These important factors (thematic layers) play a crucial role in groundwater occurrence. According to the FR method 72.05%, the EBF method 68.01% and the AHP method 75.02%, the study area is characterized by a moderate GWP, which means that the infiltration of surface water and groundwater recharge in the PARB are medium. Regions with high to very high groundwater availability make up between 7.9 and 13 % of the study area for all three MCDA methods, while 17 to 19 % of the study area has a low groundwater potential.

A comparison of the spatial distribution of the groundwater potential map with the ten thematic maps reveals strong correlations. Areas with high groundwater potential correlate with high rainfall, high line density and high permeability of the rocks and soils in the region. Some other factors, namely low drainage density, flat environment covered by water bodies and farmland or vegetation, low slope and low population, also play an important role in groundwater potential and availability in the Panj Amu catchment. Two remote sensing-based indices (NDVI and MNDWI) were to be used in this study. The groundwater potential of the study area was determined consistently with the NDVI proxy, but the MNDWI proxy provided less consistent results. It is more advantageous to use only the NDVI parameter than the combined use of the MNDWI and NDVI indicators.

Despite the lack of previous studies in the region to compare the results, the results of this work are comparable to the DACAAR groundwater monitoring program data for the static level of wells throughout the Panj Amu region. And to check the accuracy, AUC-ROC analysis was performed.

The general status of groundwater in the region was determined by calculating the groundwater balance in terms of rainfall, runoff and evaporation for the last fifteen years in the region. In the Panj Amu catchment area, the water balance plays a crucial role in maintaining the hydrological balance. The annual water balance, which is estimated at 1.887 billion cubic meters, indicates the total water inflows and outflows within the catchment area. Of this, around 1.078 billion cubic meters are attributable to groundwater recharge, which illustrates the replenishment of the groundwater system. At the same time, 808.84 million cubic meters of water per year are withdrawn from the groundwater reservoirs in the catchment area (Figure 5.7).

Recharge mechanisms, including precipitation infiltration and surface water contributions, contribute significantly to the maintenance of groundwater levels. This recharge helps to replenish the aquifers and ensure a sustainable water table. The positive water balance also ensures that sufficient water is available even in dry periods. It acts as a buffer against droughts and reduces the likelihood of water shortages and their impact on people and ecosystems. The water balance in the PARB can be increased beyond current levels through effective river control and water management strategies. Understanding and managing this water balance is essential for sustainable management of water resources in the PARB. It requires comprehensive assessments of both natural recharge processes and human-induced abstractions to ensure the long-term viability of the groundwater system and the overall water security of the basin.

To address the study topic about the significance of groundwater for urban planning, one needs consider the fact that groundwater is necessary for the water supply, whether it be for industrial or household purposes (i.e., drinking water for urban populations). It is also essential to sustainability since it is a consistent source that is resistant to seasonal and climatic change. In addition, it may serve as a buffer during dry seasons, preserving water supply when surface sources are depleted. In addition to mitigating difficulties like foundation problems and subsidence, an understanding of the groundwater system is crucial for urban development building projects. It can also be utilized to irrigate parks and other green areas, improving the quality of life and sustainability of urban areas. Adequate groundwater supply is essential for maintaining hygiene and sanitation, reducing the spread of waterborne diseases. In conclusion, groundwater is fundamental to urban planning because it supports sustainability, water supply, economic development, climate adaptation, public health, and environmental protection. Effective groundwater management guarantees the prosperity of urban areas against various challenges. In the other hand the PARB has a moderate groundwater potential with positive water budget indicates that about 1 BCM/year of water recharges the groundwater system, which is sufficient to meet household drinking water demands even during droughts, and will fulfill all kind of needs, whether they are about public health, sustainability, urban development, or environmental protections.

7.3. Limitation

During this study, we encountered several limitations that affected our assessment of groundwater potential in the Panj Amu River Basin.

1. Data availability: Thorough assessments are hampered by the lack of information and data on hydrogeologic factors, including water quantity and quality, hydraulic conductivity, hydraulic gradient, aquifer characteristics, and groundwater recharge rates.
2. Monitoring infrastructure: Inadequate groundwater monitoring infrastructure, particularly in remote or conflict-affected regions, leads to interruptions in data collection and monitoring of groundwater levels and quality.
3. Socio-economic factors: Lack of data and information on socio-economic factors such as population growth, urbanization, agricultural practices and water demand projections pose a challenge in predicting future groundwater availability and sustainability.

Addressing the above limitations requires coordinated efforts that include improved data collection and management, capacity building for hydrogeological expertise and technology adoption, strengthening government frameworks and promoting community engagement for sustainable groundwater management.

7.4. Recommendations and Future Directions

The ten proxies were used in this study in order of their compatibility with groundwater potential. The accuracy of the result of this study will increase with the addition of high order factors in the calculation with larger weighting values. Therefore, for further and future studies of groundwater in the Panj Amu region, hydraulic conductivity and aquifers characteristics and as well as high-resolution terrain topography less than 10 meter should be used, which can have a significant impact on the result of the study.

The impact of the built environment and current natural conditions on water resources should be assessed and appropriate planning guidelines should be established to ensure sustainable development of the city. In urban planning, groundwater can be considered in two ways: Reducing harmful impacts on people and eliminating negative impacts on groundwater resources and ensuring the effective use of existing groundwater resources. Therefore, it is important to define building boundaries and avoid polluting structures in areas with high GWP and to establish infiltration zones or urban open spaces (parks, gardens, recreational zones, etc.).

Local authorities in the Panj Amu region need to prioritize the development of a comprehensive strategic plan that focuses on water issues and particularly emphasizes integrated water resources management. There is a great need to improve groundwater resources through regular monitoring, implementation of mitigation strategies and application of practical and efficient water-related policies, strategies, and regulations. Improved and ongoing data collection and updating, making the data and information available as a public resource, using advanced technologies, capacity building (providing training and capacity building programs for local professionals in hydrogeology, geospatial data analysis, and groundwater modeling to strengthen expertise in groundwater assessment procedures), outreach to the county's public water suppliers, and stakeholder integration (promoting collaboration between government agencies, (promoting collaboration between government agencies, research institutions, non-governmental organizations and local communities to ensure participatory approaches to groundwater management and decision-making processes), sustainable management practices (promoting sustainable groundwater management practices through the implementation of water conservation measures, groundwater recharge enhancement techniques and pollution prevention strategies), policy and regulatory frameworks, climate change adaptation and increased research and innovation.

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