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Analysis of Climate Change Impacts on Water Resources in Harirod-Murghab River Basin

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ABSTRACT

Climate change represents one of the paramount challenges confronting humanity today. The profound impacts of phenomena such as changes in precipitation patterns, global warming, polar ice melt, floods, and the onset of untimely and extreme temperatures worldwide have instilled a sense of urgency and concern. This critical issue has been placed at the forefront of climate change. To understand the ramifications of climate change on water resources within the Harirud-Marghab River basin, an analysis of average precipitation and temperature variations (including minimum, maximum, and average values) across different time frames (annual, monthly, seasonal, and during wet and dry seasons) has been conducted using data from hydrometeorological stations in the catchment area from 1979 to 2022. the non-parametric Mann-Kendall and PCI methods were chosen as the analytical tools. The findings reveal a notable decline in annual rainfall within the Harirud-Marghab River basin, with a pronounced reduction during the winter, the basin's primary water season. Conversely, an increase in seasonal rainfall has been observed in summer and autumn. Overall, rainfall in this river basin tends to be intense, occurring on limited days throughout the year. Furthermore, a significant rise in the annual average temperature has been documented, alongside fluctuations and changes in water flow across most stations within the basin. Consequently, the surface water resources of the Harirud-Marghab River basin have experienced a substantial decrease, amounting to approximately 29% of its capacity, equivalent to a reduction of 0.98 billion cubic meters of water.

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INTRODUCTION

The Earth's climate has changed over the past century, with notable precipitation and temperature pattern shifts. Climate change has become one of the most critical issues concerning the sustainability of life on Earth, with effects being felt worldwide. This phenomenon intensifies environmental, social, and economic consequences, including adverse effects on agriculture and water resources, especially in agriculture-based countries like Afghanistan (Iqbal & Koenen, 2021). Various factors can disrupt the balance of the Earth's climate system, and these are generally divided into two categories: internal factors (arising from interactions within the climate system) and natural external factors (such as solar radiation and volcanic activity), with the unnatural increase in greenhouse gases being a major contributor. The increase in greenhouse gases, primarily from human activities, is the only factor unnaturally influencing the global climate system (NEPA, 2012). Greenhouse gases are a group of gases that keep some of the sun's energy in the earth's atmosphere and cause the atmosphere to heat up. Greenhouse gases trap some of the sun's energy in the Earth's atmosphere, causing warming. While these gases exist naturally in the atmosphere, human activities and related pollution have caused their levels to rise, thereby intensifying the warming effect and leading to climate change (Azizi, 2004; Falsafizadeh & Sabouni, 2012; Ansari et al., 2017; McSweeney et al., 2010; Tenzing, 2020; Topfer & Nuristani, 2003).

The changing nature of precipitation and its impact on water resources is among today's most pressing climatic challenges. Evidence strongly suggests that precipitation and temperature shifts occur on both global and regional scales (Bahak, 2013; Falsafizadeh & Sabouni, 2012; Río et al., 2011; Shahid, 2010). Future climate changes could result in further shifts in climate patterns and changes in average temperature and precipitation (Geden, 2016; Momeni, 2011; Vaseghi & Esmaeili, 2008). Numerous studies have examined climate trends across different regions, and nearly all identify precipitation and air temperature as key variables in climate and hydrometeorological research. Understanding the behavior of these variables is essential for grasping climate variability, as they vary significantly across local, regional, and global scales (Bahak, 2013; Bagherpour et al., 2017; Reshteen et al., 2024)

These climatic changes have particularly impacted regions like the Harirud-Morghab River basin. This basin, which relies on snowfall in its upper regions and rainfall for its water resources, is highly vulnerable to fluctuations in water availability. Population growth, fossil fuel consumption, and excessive use of surface and groundwater have amplified the impacts of climate change (M. W. Iqbal et al., 2018; Sidiqi et al., 2018; Xu et al., 2015). The average annual rainfall in the Harirud-Morghab River basin is about 243 millimeters, with the highest rainfall—approximately 498 millimeters—occurring in higher areas in the basin's northeast and southeast (its primary water sources). According to recent analyses, the basin's average precipitation has decreased by around 33% compared to levels before 2000, equating to a reduction of approximately 97 millimeters. This significant decrease in precipitation underscores the basin's growing vulnerability to climate change and highlights the urgent need for adaptive management strategies.

The broader issue of human contributions to climate change becomes evident when examining the drivers of these shifts. Humans are considered the main drivers of climate change, primarily due to disregarding natural laws and lacking awareness of related environmental issues. Climate change refers to abnormal shifts in the Earth's atmospheric conditions and their effects across different regions (Momeni, 2011). The Earth's average temperature is about 15 degrees Celsius, though in past periods, it has fluctuated between 5 degrees warmer and 10 degrees colder than today. Given the significant impact that climate change has on the Earth's environmental structure and its inhabitants, it is essential to understand how climate change occurs. This need is even more pressing today, as global warming has become a critical issue (Kemfert, 2008). Among the many vulnerable areas in nature, natural resources—particularly water resources—are some of the most affected by climate change. These effects are evident nationwide, especially in the Harirud-Morghab River basin. A more detailed investigation into these changes in the basin's water resources requires comprehensive analysis and evaluation, which has been conducted to compare current conditions with those of the past.

Afghanistan's geographic and climatic conditions make it particularly susceptible to these changes. Located in South Asia, it is classified by the Intergovernmental Panel on Climate Change (IPCC) as part of the world's dry and semi-arid regions. Historical meteorological data and climate predictions for this region, as with much of the world, indicate climate change in recent decades and suggest that this trend will continue (IPCC, 2007). Afghanistan's challenges are compounded by natural factors such as drought and glacier melt, alongside human activities that intensify these processes. Information on Afghanistan's climate has been limited, creating a significant need for data and research to understand these phenomena better. Research has shown that climate change in Afghanistan threatens the country's water, food, and economic security. These effects are particularly pronounced in regions like the Harirud-Morghab River basin, which requires focused analysis to develop effective adaptation strategies (M. Iqbal & Koenen, 2021; V. Pellet, 2007; Nasrati, 2018).

The importance of understanding Afghanistan's historical and ongoing climate change trends cannot be overstated. Victor Pellet (2007) found that most Afghans rely on agriculture for food production and trade. This sector accounts for 75% of Afghanistan's export income but is highly sensitive to climate and weather conditions. During droughts, wheat production can drop by 1–2 million tons, significantly impacting food security. In 2016–2017, about 13 million Afghans, or 45% of the population, were considered food insecure, a number that increases in drought years. Nasrati (2018), in a review of the last half-century of droughts in Afghanistan, found that the country's average temperature has risen by 1.8 degrees Celsius since 1950. He predicts that temperatures could increase by another 2.5 to 5 degrees Celsius by the end of this century. Afghanistan's southwest, west, and northwest, already dominated by desert climates, are expanding. Once temperate and tropical, the central and northeastern regions are becoming hotter and drier. High mountain areas with sub-arctic climates are also experiencing warming, leading to significant ecosystem changes and a reduction in glaciers (Thomas, 2016; Wafa, 2024).

Further emphasizing the urgent need for action, Nasrati (2018) also found that rainfall patterns are changing significantly. The number of rainy days in Afghanistan varies widely, ranging from fewer than 10 days in the southwest to over 150 days in the east, where rainfall intensity is highest. These changes and rising temperatures directly impact water availability and agricultural productivity. The National Environmental Protection Agency (NEPA, 2012), in its report on the state of Afghanistan's environment, notes that Afghanistan's topography creates diverse rainfall patterns across its mountain ranges. Moist air is pushed upward by the mountains in the direction of the wind, which cools and increases precipitation; for instance, the Salang Pass receives over 1,000 mm of rain annually. Conversely, the air descends and warms on the leeward side of the mountains, resulting in semi-arid conditions and reduced precipitation.

To address these challenges and increase our understanding of climate change's impacts on Afghanistan, this study focuses on the Harirud-Morghab River basin. This analysis aims to calculate and understand the effects of climate change on the basin's water resources, using data on rainfall, temperature, water flow, and water potential across various years. By analyzing trends in parameters such as rainfall, temperature, river regime changes, and water potential on monthly, annual, seasonal, and wet/dry seasonal bases over different time intervals, this study aims to provide critical insights into the changes in water resources and occurrences of floods and droughts in the Harirud-Morghab river basin.

Through these investigations, the research addresses the following research questions:

1. What have been the effects of climate change and global warming over the past four decades in the Harirud-Morghab River basin?
2. What is the seasonality of rainfall in this river basin?
3. How have precipitation and temperature parameters changed (monthly, yearly, seasonally, and during wet and dry seasons) over different time intervals (1979–2022, TW1: 1979–1999, and TW2: 2000–2022)?
4. How does the water flow regime or discharge data fluctuate in recent years (2008–2022) compared with historical data (1948–1980)?

By addressing these questions and examining the Harirud-Morghab River basin in-depth, this research aims to inform policies and practices that can mitigate the effects of climate change and support sustainable water resource management in the region.

METHODS AND MATERIAL

Scientific models and methods commonly used to analyze and investigate the effects of climate change in most regions of the world and validated by prestigious international organizations (such as the WMO) have been employed in the current study. These models and methods provide results that help monitor and analyze climate change's adverse effects on water resources in the Hariroud-Marghab River basin.

In this study, precipitation and temperature data from hydrometeorological and hydrological stations in the Harirod-Marghab River basin during the time interval 1979–2022 have been analyzed to assess changes in climatic parameters. The purpose of using these data is to obtain results that allow for practical analysis in evaluating the effects of rainfall and high temperatures on water resources in the mentioned river basin. To study the trends in precipitation and temperature changes, the Mann-Kendall model and the Precipitation Concentration Index (PCI) have been used (EE et al., 2017; Oliver, 1980). The aspects examined during this study, based on the outputs of the Mann-Kendall and PCI models, are as follows:

1. Analyzing and receiving trends (monthly, yearly, seasonal, and wet and dry seasons) of precipitation and temperature parameters.
2. Analysis of changes in rainfall and temperature during the last four decades in the river basin of Harirod-Marghab.
3. Analysis of water flow regime (discharge).
4. Analysis of the seasonality of rainfall and rainfall time in the area.

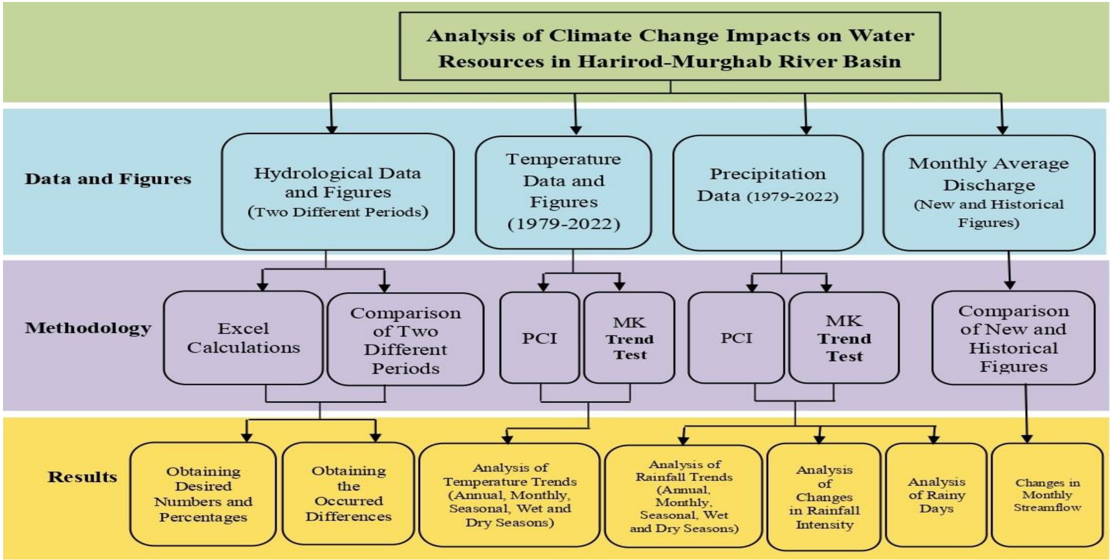

Figure 1: Conceptual Model for Analyzing the Impacts of Climate Change on Water Resources in Harirod –

Mann-Kendall Method

Considering the purpose of this research and the lack of data normality in the climate series of temperature and precipitation, the non-parametric Mann-Kendall method has been used to analyze the rainfall trend and temperature changes in the Harirod-Marghab River basin. The Mann-Kendall method (Mann,1945; Kendall,1975), one of the widely used non-parametric methods, is commonly applied to determine time trends in fields such as hydrology and climatology (Jafarabadi & Mohammadi, 2015; Nejad & Qasemi, 3013; Nourani et al., 2019).

The World Meteorological Organization (WMO) also strongly recommends this method for planning and calculating climatic phenomena, including climate change studies (Nasrati, 2018). In addition, the method is widely used to detect annual trends and changes in parameters such as rainfall and temperature. Kendall's method is a non-parametric technique for trend analysis (Ansari et al., 2017; Azizi, 2004; Bagherpour et al., 2017). (Mann, 1945) was the first to use this method, and (M.G. Kendall, 1975) derived its numerical distribution. The WMO recommends this method for evaluating trends in time series of environmental data, as it is suitable for cases where the trend may be assumed to be uniform and seasonal aspects are not present in the data (Azizi, 2004; Soltani & Sabohi, 2008; Wang, 2010). (Yadav et al., 2014) in their research, explain the main advantage of the Mann-Kendall method as follows:

- This method does not rely on assumptions about data distribution, as it is non-parametric. Therefore, no specific data distribution is required as a prerequisite, reducing uncertainty related to data distribution.
- This method can be directly applied to assess the impacts of climate change on climate data for specific months or seasons.

The parameters of the Mann-Kendall (MK) method are calculated using the following equations:

$$\mathrm{S} = \sum_{\mathrm{i}=1}^{\mathrm{n}-1} \sum_{\mathrm{j}=\mathrm{i}+1}^{\mathrm{n}} \mathrm{sign}(\mathrm{X_j} - \mathrm{X_i}) \tag{1}$$

In the above formula, n represents the number of data points for the desired parameter, while x_j and x_i are the consecutive data values of that parameter. The function $Sign$ () is a sign function calculated by the following relationship (Equation 2):

$$\mathrm{sign}(\mathrm{X_j} - \mathrm{X_i}) = \begin{cases} +1, & \mathrm{X_j} > \mathrm{X_i} \\ 0 & \mathrm{X_j} = \mathrm{X_i} \\ -1 & \mathrm{X_j} < \mathrm{X_i} \end{cases} \tag{2}$$

Positive values of S indicate an upward trend of a parameter (such as rainfall, temperature, or another variable), while negative values of S indicate a downward trend. When $n > 10$, the distribution of S is approximately normal. The Average S is 0, and the variance can be calculated as shown in Equation 3:

$$\mathrm{Var(S)} = \frac{[\mathrm{nx(n-1)(2n+5)} - \sum_{\mathrm{i}=1}^{\mathrm{m}} \mathrm{tx(t-1)x(2t+5)}]}{18} \tag{3}$$

where m is the number of tied groups, with each group having t_x Identical observations. A set of data points with the same value is called a tied group. The standard $Z - value$ is calculated as shown in Equation 4:

$$\mathrm{z} = \begin{cases} \dfrac{\mathrm{S}-1}{\sqrt{\mathrm{Var(S)}}} & \mathrm{S} > 0 \\ 0 & \mathrm{S} = 0 \\ \dfrac{\mathrm{S}+1}{\sqrt{\mathrm{Var(S)}}} & \mathrm{S} < 0 \end{cases} \tag{4}$$

In the two-tailed trend test, the null hypothesis is evaluated at a given significance or confidence level (α), which indicates the trend's strength. For practical application of the Mann-Kendall method, a confidence level of 95% ($\alpha = 0.05$) is typically used. This level is consistent with the calculated values of S and ($Z = 1.96$) and should be accepted. A positive $Z - value$ indicates an upward trend in a parameter (e.g., rainfall, temperature, or other data), while a negative $Z - value$ suggests a downward trend. Here, the $Z - value$ is derived from the Mann-Kendall method and measures the mean relative to a normal distribution with a mean of 0 and a variance of 1. In general, the results of the Mann-Kendall method can be classified as follows:

1. If, when calculating a parameter (e.g., rainfall, temperature, etc.), the values of S and Z are positive at the end of the calculation, it indicates an upward trend in that parameter. This work demonstrates that the logic in question is influenced by the negative consequences of climate change, particularly the temperature rise.
2. If, when calculating a parameter (e.g., rainfall, temperature, etc.), the values of S and Z are negative at the end of the calculation, it indicates a downward trend in that parameter. This work suggests that the studied area is affected by the consequences of climate change, particularly the decrease in rainfall.
3. If, when calculating a parameter (e.g., rainfall, temperature, etc.), the values of S and Z are equal to zero at the end of the calculation, it indicates a normal distribution of that parameter, suggesting optimal climatic conditions according to the Man-Kendall method.

PCI[1](Precipitation Concentration Index

The Precipitation Concentration Index (PCI) reflects rainfall's concentration or temporal dispersion and other significant climatic parameters such as rainfall intensity (Oliver, 1980). As an index of rainfall dispersion, PCI can be calculated on an annual time scale for each year, and averaging is performed based on the available data for a climatic period (EE et al., 2017).

The calculation of precipitation concentration using the PCI model and equations (5, 6, 7) is done as follows:

$$\text{PCI annual} = \frac{\sum_{i=1}^{12} \text{Pi}^2}{(\sum_{i=1}^{12} \text{Pi})^2} * 100 \tag{5}$$

$$\text{PCI seasonal} = \frac{\sum_{i=1}^{3} \text{Pi}^2}{(\sum_{i=1}^{3} \text{Pi})^2} * 25 \tag{6}$$

$$\text{PCI supra\_seasonal} = \frac{\sum_{i=1}^{6} \text{Pi}^2}{(\sum_{i=1}^{6} \text{Pi})^2} * 50 \tag{7}$$

Pi is the monthly precipitation for each month.

The results of the PCI model can be classified as follows:

1. Suppose the result of the PCI calculation is below 10. In that case, it indicates a uniform distribution of precipitation throughout the year, meaning the analyzed

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climate parameter has a consistent distribution with no significant changes in the area.

2. If the results of the PCI calculations fall between 10 and 20, it indicates the seasonality and concentration of rainfall or other climatic parameters during specific seasons. This suggests that seasonal variations influence the analyzed climate parameters.
3. If the results of the PCI calculations are greater than 20, it indicates irregularity in the behavior of the discussed parameter (rainfall) throughout the year. In this case, rainfall is not confined to the rainy season and may occur during other seasons, even in seasons where it has never occurred before. In fact, rather than benefiting the studied area, this irregularity can be harmful, leading to adverse outcomes such as sudden floods.

Table 1: *Classification of PCI*

Rainfall Concentration Index (PCI)	PCI
Uniform (Consistent)	<10
Relatively Uniform (Relatively Consistent)	11-15
Intense	16-20
Very Intense	>20

For further clarification, this study evaluates changes in annual rainfall intensity, seasonal variations, and the shifts between wet and dry seasons. Based on the months of the year, the Wet Season is defined as the period from December 1 to May 31, while the Dry Season spans from June 1 to November 30. Additionally, the four water seasons of the year, each consisting of three months, are clearly illustrated in Table 2.

Table 2: *Seasonal Classification Based on Months of the Water Year*

Winter			**Spring**			**Summer**			**Autumn**		
Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
(Wet season)						(Dry season)					
12	1	2	3	4	5	6	7	8	9	10	11

The data used in this research consists of observational data collected from the network of hydrometeorological and hydrological stations operated by the Ministry of Energy and Water for the Harirod-Marghab River basin. The details of the data are as follows:

- Annual and daily rainfall data from 11 hydrometeorological stations in the Harirod-Marghab River basin from 1979 to 2022.
- Temperature data from 11 stations in the Harirod-Marghab River basin from 1979 to 2022.
- River discharge (flow) data from two historical periods: before 1980 and after 2000.

- Water potential (water capacity) data for two intervals: before and after 1980.

Study Area

The Harirud-Marghab River basin is one of Afghanistan's five main river basins. It is geographically bordered by the Panj Amu River basin and Turkmenistan to the north, the Helmand River basin to the south, the Panj Amu River basin to the east, and Iran to the west. The basin spans the provinces of Ghor, Herat, Badghis, and Farah.

With an area of 77,604 square kilometers, it constitutes 11.8% of Afghanistan's total land area. Approximately 304,485 hectares of land in the basin are irrigated. The Harirud-Marghab basin is divided into four sub-basins: the upper Marghab River (Qala Naw), the upper Harirud River (Chagcharan), the lower Harirud River (Herat), and the Kashk and Kashan Rivers.

Table 3: *General Information on the Harirod - Murghab River Basin (Kamal, 2004)*

Harirod - Murghab River Basin						
Area		Population			Arable Land	
Square Kilometers	Share of the Total Area of the Country %	Number of Individuals (People)	Share of the Total Population of the Country %	Population Density per Square Kilometer	Hectares	Share of the Total Arable Land Area of the Country %
77604	12.02	1722275	8.32	22	1725	11.06

The Harirud-Marghab River basin is one of Afghanistan's four major river basins in terms of water resource capacity (surface water). Its annual water capacity is approximately 2.42 billion cubic meters, of which around 1.88 billion cubic meters are consumed within the country. Climate change has also significantly affected the basin, which has impacted its water resources.

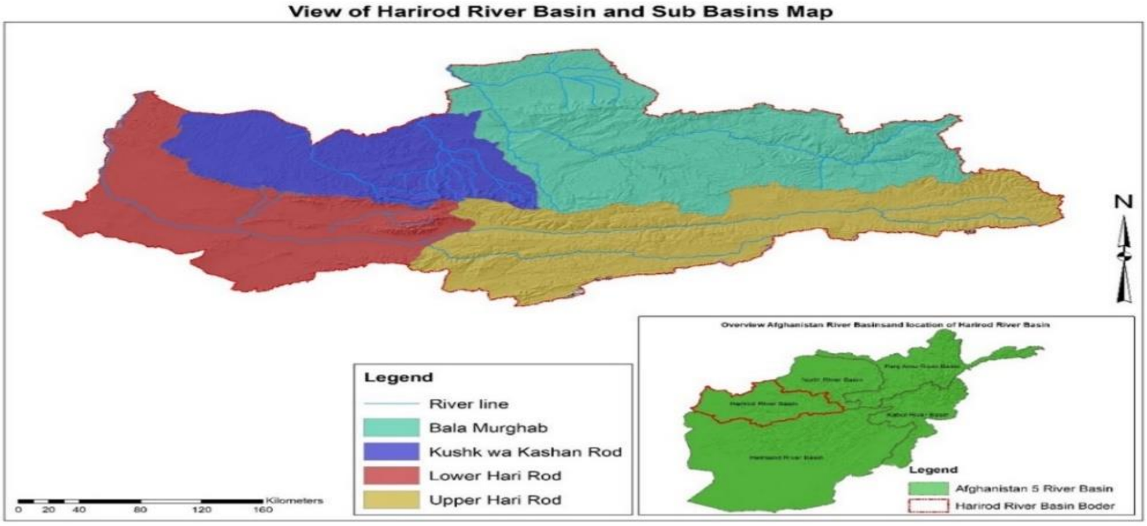

Figure 2: *Statudy Area, Harirud-Marghab River basin*

The primary river in the Harirud-Marghab basin is the Harirud River, which originates in the western part of the Baba Mountain range. This river flows westward, eventually reaching the Karakoram plains in Turkmenistan. The Harirud originates from the Baba range, the western extension of the Hindu Kush Mountain range, and forms the border between Afghanistan and Iran. It then continues to form the boundary between Iran and Turkmenistan before reaching the ancient region of Turkmenistan and the Qaraqom Desert, known as the Tejen River.

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The Marghab River originates from the Hindu Kush Mountain range and flows northward toward Turkmenistan. The flow of both rivers in the basin is primarily determined by snow and rainfall in the upper reaches, with peak flow typically occurring in April and May. The Harirud-Marghab River basin covers the regions of Herat and Badghis. Due to population growth and the increasing demand for water and energy, Afghanistan is expanding its water storage capacity in this area.

Afghanistan has no bilateral or tripartite cooperation agreements with its downstream neighbors in this basin. However, the Islamic Republic of Iran and Turkmenistan have constructed the "Dam of Friendship" on their shared border. The Salma Dam, with a storage capacity of 547 million cubic meters (MCM), was built on the Marghab River and provides irrigation for 25,500 hectares of agricultural land in addition to generating energy (World Bank, 2021)

RESULTS AND DISCUSSION

The first parameter we examine to assess the effects of climate change in the Harirud-Marghab River basin is precipitation. This has been analyzed using the MK and PCI models across several time frames, including annual, monthly, seasonal, and wet and dry seasons, as outlined below:

Annulal Precepitiation Trend

The results of the annual analysis using the MK method for precipitation in the Harirud-Marghab River basin are presented in Table 4. The average, minimum, and maximum annual rainfall in the basin are 243 mm, 81 mm, and 498 mm, respectively. A confidence level of 95% ($\alpha = 0.05$) was used for the analysis. The results indicate a significant decreasing trend (-3.60) in the Harirud-Marghab River basin annual rainfall.

Table 4: *The Annual Precipitation Trend in Harirod – Murghab River Basin*

River Basin Name	α=0.05 (Z)	Annual Average PPT (mm)	Minimum PPT (mm)	Maximum PPT (mm)	Data Period	Result	Trend
Harirod – Murghab	1.96	243	(2001) 81	(1991) 498	1979-2022	-3.6	↓

To assess the annual rainfall situation in the Harirud-Marghab River basin, the average rainfall data from 11 hydrometeorological stations between 1979 and 2022 have been analyzed. The resulting graph shows a downward trend in annual precipitation, as illustrated in Figure 3.

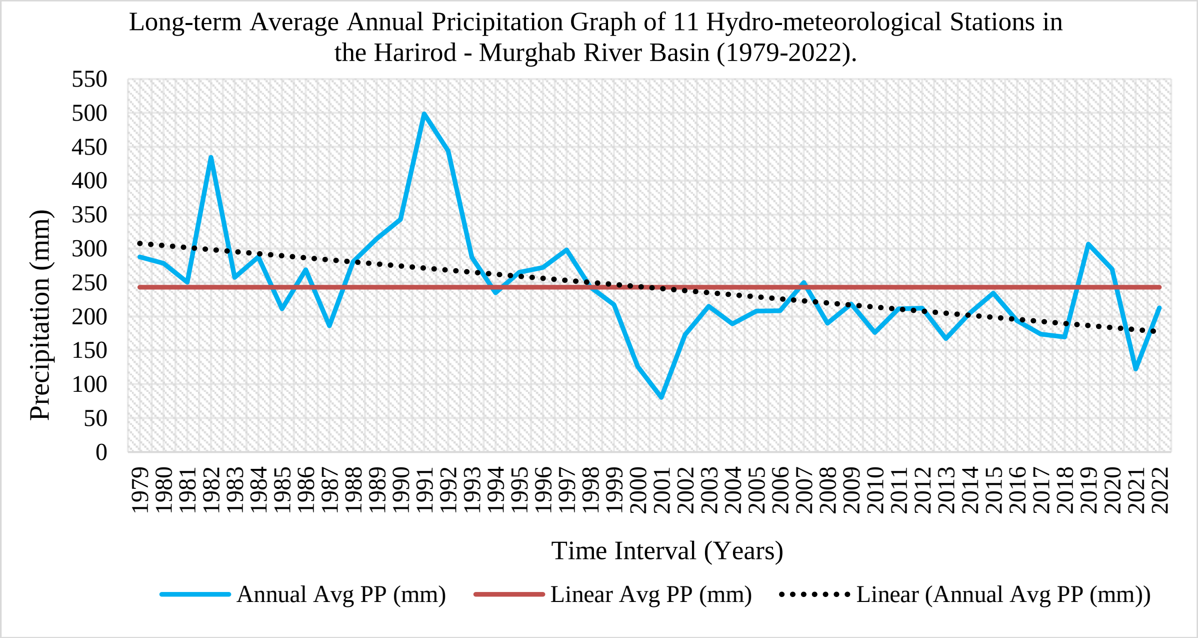

Figure 3: *The Average Annual Precipitation in the Harirod – Murghab River Basin*

Monthly Precipitation Trend

The MK model was used to analyze the trend of monthly rainfall in the Harirud-Marghab River basin from 1979 to 2022; the results are shown in Table 5.

Table 5: *Monthly Precipitation Trend in Harirod - Murghab River Basin (1979-2022)*

River Basin Name	Monthly Trend Analysis of Precipitation in Harirod - Murghab River Basin (Z)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	**Dec**
Harirod – Murghab	-2.79	-1.92	-2.87	-0.79	1.07	1.67	1.03	1.27	0.92	-0.45	2.69	**-3.32**
	↓	↓	↓	↓	↑	↑	↑	↑	↑	↑	↑	↓

In November of each year, there is a noticeable increase in rainfall within this time interval, while rainfall tends to decrease in January, March, and December. A slight decrease in rainfall is observed in February, April, and October, whereas from May to September, there is a modest increasing trend. Therefore, it can be concluded that precipitation significantly increases during these months. December, January, February, and March are usually the periods of rainfall most commonly in Afghanistan. However, in the Harirud-Marghab River basin in the period of 1979-2022, there was a significant decrease in rainfall in these months, which had negative results in the agriculture sector. It is a clear example of the effects of climate change in this river area.

Seasnal Precepitition Trend

The seasonal analysis of the mentioned river basin shows that the long-term rainfall has suffered a significant downward and upward trend; the fall and summer rainfall has increased relatively, while the spring and winter rainfall has decreased significantly. In the first time interval, from 1979 to 1999, the rainfall changes in this river basin sometimes increased or decreased inconspicuously. However, in the second time interval, which has been studied since 2000, it is clear that due to the effects of climate change on water resources of the Harirud-Morghab river basin, the rainy season in the basin has changed significantly, which has turned into summer and late spring, Tabel-6.

Table 6: *Seasonal Precipitation Trend in Harirod - Murghab River Basin (1979-2022)*

Seasonal Trend Analysis of Precipitation in Harirod - Murghab River Basin (Z)				
Mann-Kendall Result	Autumn (Z)	Summer (Z)	Spring (Z)	Winter (Z)
Long-term (1979-2022)	1.52	1.92	-2.18	-3.78
Time window 1 (1979-1999)	-0.63	1.36	0.82	-1.18
Time window 2 (2000-2022)	1.61	2.61	2.77	-0.87

It is evident from Table 6 that the rainy season has shifted from winter to the latter part of spring and summer. Furthermore, there has been a decrease in winter precipitation, transforming the typically rainy winter season into one with significantly lower rainfall. Consequently, the summer showers have resulted in regrettable occurrences like flash floods within this basin. These floods are primarily attributed to the inadequate capacity to absorb water into subterranean aquifers, soil pore blockages, and the absence of small water storage dams along the watercourse. Such events have inflicted substantial harm on both the economy and the environment.

Wet and Dry Seasonal Precipitation Trend

As previously stated, the initial half of the water year (December to May) is classified into the wet season, while the latter (June to November) is classified as the dry season. Through the utilization of the MK model, a thorough examination of the overall precipitation levels has been conducted for each of these delineated periods, with the findings presented in Table 7.

Table 7: *Dry & Wet Supra-Seasonal Precipitation Trend in Harirod - Murghab River Basin (1979-2022)*

No	Mann-Kendall Result	)Wet season(	) Dry season(
1	Long-term (1979-2022)	-3.99(↓)	1.62
2	Time Window 1 (1979-1999)	-0.33	-0.33
3	Time Window 2 (2000-2022)	0.77	1.77

Based on the data presented in Table 7, a notable reduction in wet-season precipitation is observed over the long term. Furthermore, it can be inferred that the shift in precipitation patterns during the specified time frame, specifically from 2000 to 2022, has resulted in a marked increase in precipitation levels during the dry season instead of the wet season. Consequently, it can be deduced that the peak rainfall in the Harirud-Murghab river basin typically occurs during the summer months and infrequently during early autumn in the monsoonal form. This phenomenon contributes to sudden monsoonal floods in the aforementioned river basin in light of the preceding discussion.

Rainfall Intensity

The Precipitation Concentration Index (PCI) has been employed to ascertain the precipitation trend in the Harirod-Marghab river basin. Similar to the MK model, this analysis utilizes the monthly average rainfall data spanning from 1979 to 2022 in the Harirod-Margab river basin, along with the average count of rainy days per month from 2008 to 2022. Please refer to Figure 6 for detailed insights.

Figure 6 shows that the peak average precipitation in the Harirud-Marghab River basin occurs during January-April and December, reaching around 58.3 millimeters. Furthermore, the period from January to May experiences the highest frequency of rainy days in this basin, totaling 38 rainy days. Conversely, the months spanning June to October observe a decrease in rainy days, while November and December record 6 and 5 rainy days, respectively.

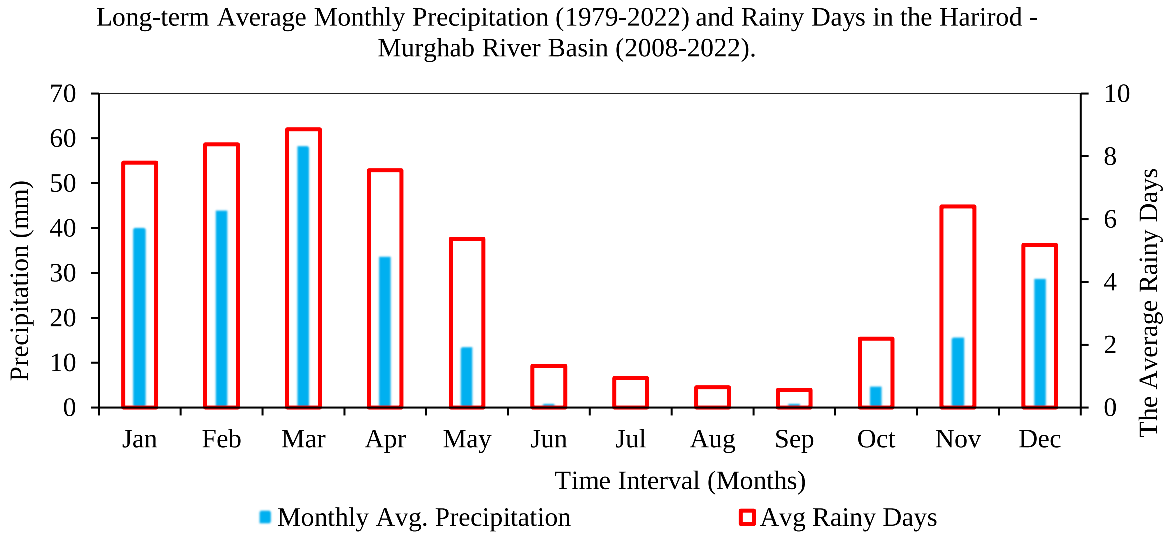

Figure 4: *Long-term Average Precipitation along with Rainy Days (2008-2022) in HMRB*

According to the precipitation concentration index results, the amount of rainfall in this river basin is very intense, and the rainfall duration is shorter. Therefore, it can be said that there is a significant variation. Based on the precipitation concentration index findings, the rainfall intensity in this river region is significant, yet the rainfall duration is relatively brief. Consequently, a notable disparity exists in the timing of precipitation within the specified river basin, potentially leading to flooding due to substantial rainfall during monsoon and seasonal periods. Based on the observations from Figure 5, it is evident that the annual precipitation concentration index within the Harirud-Marghab River basin displays consistent values between the long-term and second-time intervals, falling within the severe category. However, a notable divergence is noted in the first-time interval, where the index is categorized as very severe. These findings indicate a persistent pattern of intense precipitation across all three intervals, with a tendency towards heightened intensity. Conversely, the duration of precipitation appears to be relatively limited. These trends suggest a potential risk of climatic adversities such as severe droughts and sudden, intense floods in various regions of the Harirud-Marghab River basin.

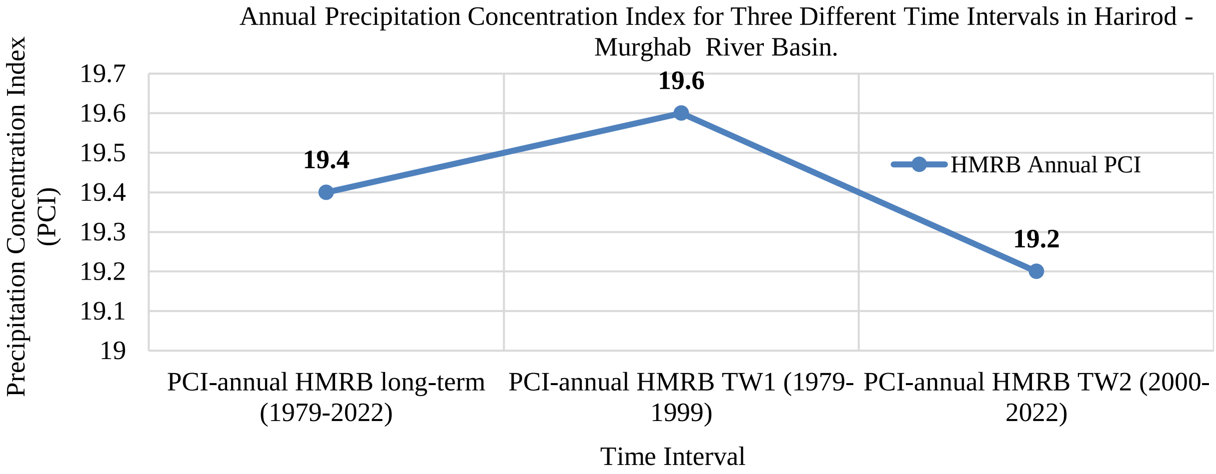

Figure 5: *Annual Precipitation Concentration Index for Three Different Time Intervals in HMRB*.

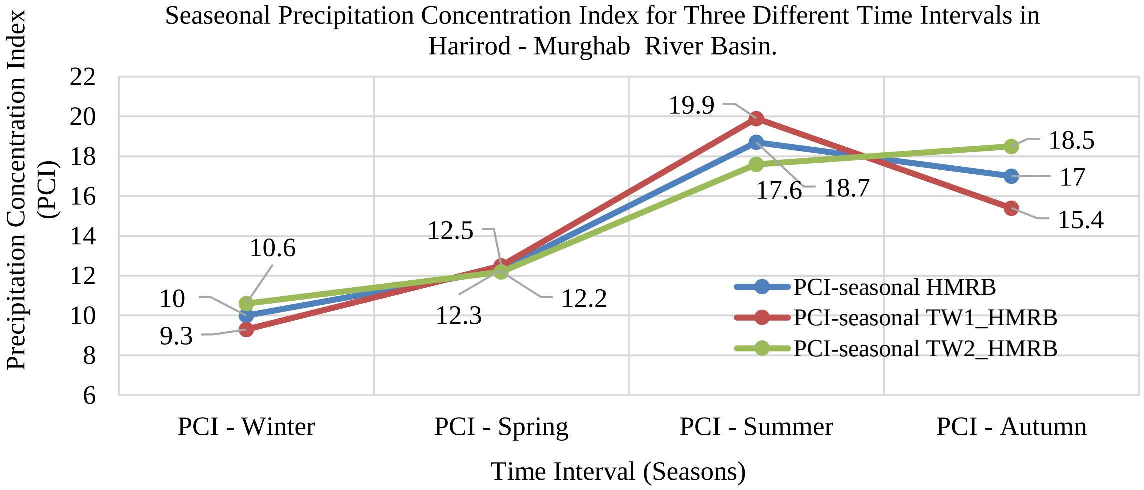

Figure 6: *Seaseonal Precipitation Concentration Index for Three Different Time Intervals in HMRB*

In Figure 6, the data illustrates a consistent and notably high level of precipitation across various seasons and time intervals, except the winter season of time interval 1 and the summer of time interval (1979-1999). This intensity remains relatively constant throughout all seasons and the three defined time intervals.

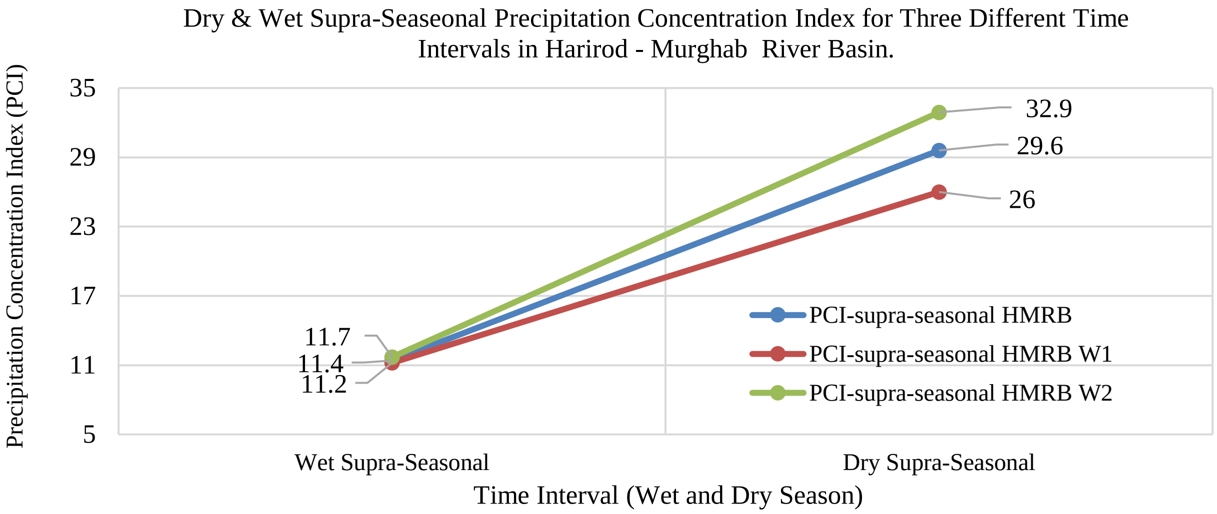

Figure 7: *Dry & Wet Supra-Seasonal Precipitation Concentration Index for Three Different Time Intervals in HMRB*

The findings of the PCI model indicate that the Harirood-Murghab river basin is projected to undergo a seasonal shift in precipitation patterns due to the adverse impacts of climate change, leading to instances of flash floods resulting from the heightened intensity and irregularity of rainfall. These events are anticipated to have significant adverse implications on the socio-economic and environmental landscape of the impacted regions.

Temperature Trend

The second parameter under consideration pertains to the evaluation of temperature, which has been studied by applying the Man-Kandel and PCI methodologies alongside the analysis of precipitation within the Harirod-Marghab River basin across various temporal segments.

Table 8: *Annual Temperature Trend (Minimum, Maximum, and Average) in Haririod - Murghab River Basin (1979-2022).*

Annual Temperature (°C)	Time Interval	Mann-Kendall Trend Test Result	Trend
Minimum Annual Temperature (°C)	2022-1979	0.71	Negligible Increase
Maximum Annual Temperature (°C)	2022-1979	(↑) 4.53	Significant Increase
Average Annual Temperature (°C)	2022-1979	(↑) 4.88	Significant Increase

Annual Temperatur Trend Analysis

The meticulous examination of the annual minimum, maximum, and average temperature patterns within the Harirud-Marghab River basin shows that the annual average and maximum temperatures have experienced notable increases. In contrast, the annual minimum temperature has shown marginal escalation. The comprehensive outcomes derived from the MK method for this specific river basin, as delineated in Table 8, unequivocally indicate a substantial upward trajectory in annual temperatures.

Upon thorough consideration of the data presented in Table 8, it can be deduced that the average temperature exhibits the most pronounced shift in its pattern, as evidenced by a $Z-value$ of 4.88, indicative of a discernible upward trend. The average annual temperature has demonstrably surged over the entire temporal span from 1979 to 2022, thereby underscoring the palpable impacts of climate change within the Harirod-Marghab river basin. Table 8 encapsulates the Annual Temperature Trend (Minimum, Maximum, and Average) in the Haririod-Murghab River Basin spanning the years 1979 to 2022, serving as a poignant testament to the repercussions of climate change in the Harirod-Marghab River basin.

Based on the data presented in Figure 8, observations reveal a discernible upward trajectory in temperature throughout the comprehensive study and analysis period from 1979 to 2022. Notably, the average annual temperature in 2022 within this timeframe has peaked at 15 degrees Celsius. Given these insights and the absence of viable strategies to address and adjust to climate change within this marine region, there exists a strong possibility that this escalating temperature trend will persist, potentially leading to a further elevation in temperatures in the forthcoming years.

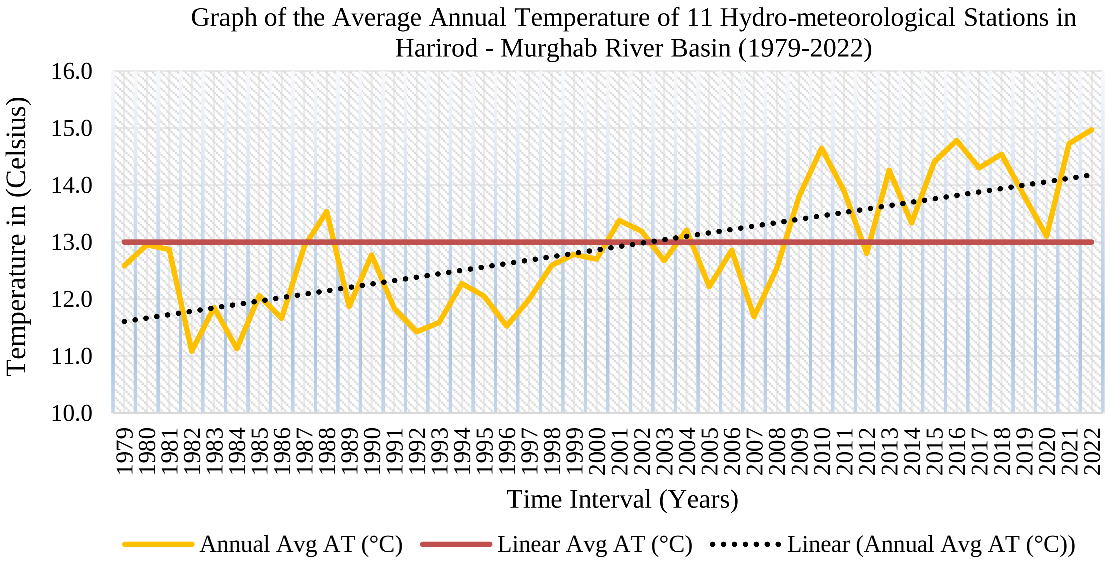

Figure 8: *Temporal Changes in the Annual Average Temperature Trend in the Harirod - Murghab River Basin.*

Monthly Temperature Trend Analysis

Based on Analysis of the minimum, maximum, and average monthly temperature trends utilizing the MK model, as outlined in Table 9, it becomes apparent that the Harirud-Marghab River basin experiences a distinct upward trend in average monthly temperature during February, March, April, and May, June, July, August, September, and October. Conversely, the months of January, November, and December show a less significant increase in temperature.

Table 9: *Monthly Temperature Trend (Minimum, Maximum, and Average) in the Harirod – Murghab River Basin (1979-2022).*

Annual Temperature (°C)	**Monthly Temperature Trend (Minimum, Maximum, and Average) in the Harirod – Murghab River Basin**											
Minimum Annual Temperature (°C)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum Annual Temperature (°C)	-1.01	0.61	2.85 (↑)	0.85	2.29 (↑)	-0.75	-1.83	-2.83 (↓)	-0.45	-0.12	-0.53	-0.04
Average Annual Temperature (°C)	2.70 (↑)	3.16 (↑)	4.45 (↑)	2.99 (↑)	2.69 (↑)	2.51 (↑)	3.30 (↑)	2.93 (↑)	2.06 (↑)	1.62	0.79	1.66
Annual Temperature (°C)	1.84	2.43 (↑)	4.65 (↑)	2.93 (↑)	3.54 (↑)	3.96 (↑)	3.80 (↑)	3.54 (↑)	4.29 (↑)	3.05 (↑)	0.16	1.17

Figure 9 below illustrates the minimum, maximum, and average temperatures of the Harirod-Marghab River basin alongside the average long-term rainfall data from 1979 to 2022. The data reveals that the peak precipitation in the Harirud-Marghab River basin typically occurs in January and March, ranging between 40.2-58.3 mm annually. Conversely, July has the highest average annual temperature, registering at 24.6 degrees Celsius. Notably, the period from June to November experiences rainfall below 15 mm. The summer months of June to August emerge as the hottest months of the year, characterized by average temperatures exceeding 38.7 degrees Celsius. Conversely, the winter months of January to March and November mark the coldest period, with minimum air temperatures plummeting between -20.8 and -17.1 degrees Celsius.

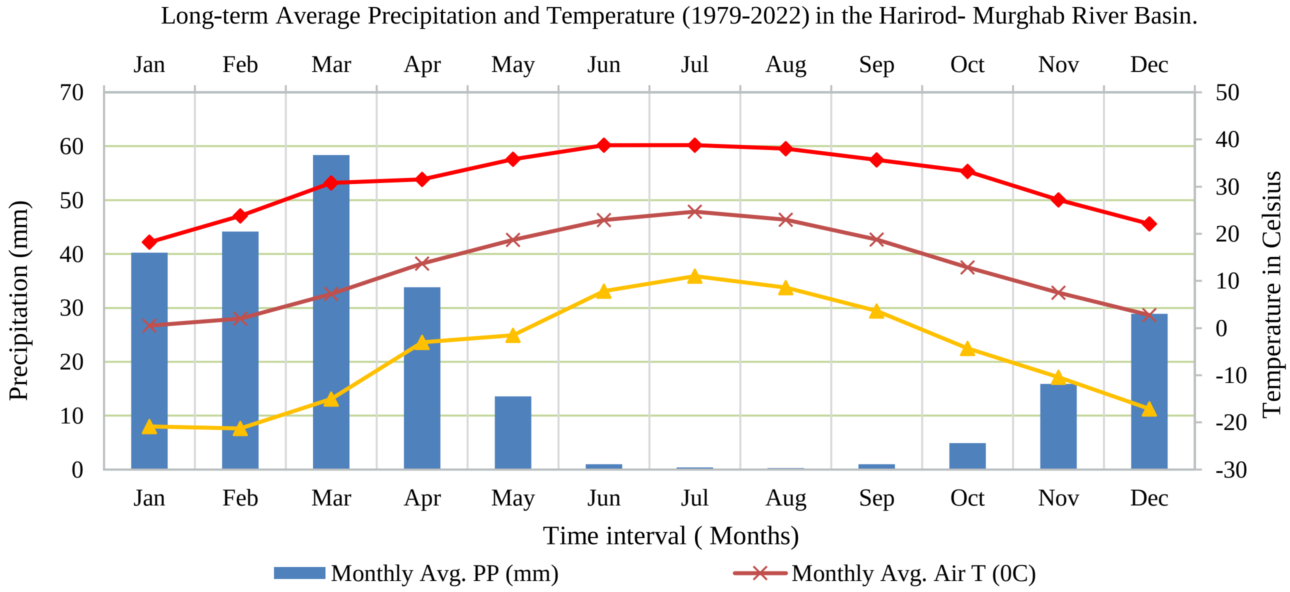

Figure 9: *Long-term Average Precipitation and Temperature (Minimum, Maximum, and Average) in HMRB.*

In examining the seasonal temperature trends within the Hariroud-Murghab river basin, a comprehensive study has been conducted to scrutinize and interpret the temperature patterns across the four seasons over three distinct time spans spanning from 1979 to 2022. The findings reveal a significant inclination towards temperature escalation in the long-term perspective across all seasons, notably in spring and autumn, with respective values of 4.77 and 4.53. Moreover, a pronounced upward trend is observed in the winter season, registering a value of 2.18 within the extended timeframe, indicating a substantial temperature surge during this particular season. Furthermore, during the second period (2000-2022), a discernible upward trajectory in temperature is noted in the summer season, with a trend value of 3.3. Conversely, the temperature fluctuation in the winter, spring, and summer seasons during the initial time frame (1979-1999) exhibits decreases and increases.

***Table 10:** Seasonal Temperature Trend in Harirod - Murghab River Basin (1979-2022).*

Analysis of Seasonal Temperature Trend (Z)				
Mann-Kendall Result	Autumn	Summer	Spring	Winter
Long-term (1979-2022)	4.53(↑)	4.45(↑)	4.77(↑)	2.18(↑)
Time Interval 1 (1979-1999)	1.24	-0.21	-1.06	-0.39
Time Interval 2 (2000-2022)	1.14	3.3(↑)	0.45	1.16

Overall, the notable rise in temperature during the second time interval of the analysis (2000-2022) is prominently observed, providing substantial evidence for the impact of climate change on the water resources of the Harirod-Morghab River basin.

Wet-Dry Seasonal Temperature Trend Analysis

Based on the findings, it is evident that the Z index value of the MK model shows a slight decrease during the wet seasons compared to the dry seasons throughout the entire study period (1979-2022), indicating cooler weather during the wet season.

***Table 11:** Temperature Trend for Wet and Dry Seasons in the Harirod– Murghab River Basin for Three Time Intervals*

No	**Time Intervals**	**(Wet Season)**	**(Dry Season)**
1	Long-term (1979-2022)	4.23(↑)	4.69(↑)
2	Time Interval 1 (1979-1999)	-0.33	0.45
3	Time Interval 2 (2000-2022)	1.35	2.51(↑)

Based on the data presented in Table 11, it is evident that there is a discernible variance in air temperature between dry and wet seasons, with the former exhibiting slightly higher temperatures. Furthermore, a more pronounced trend in temperature fluctuations is observed. Notably, the most significant alterations in temperature trends are observed during dry seasons, particularly post-2000 AD (the second time interval). This shift in the long-term temperature trend is substantiated by statistical evidence (z = 4.69).

Climate Change Impact on Discharge of Harrirod-Murghab River Basin

The comparison of surface water changes, including temporal variations and alterations in the maximum peak of water flow, was conducted by analyzing historical and updated water flow data. This analysis was carried out at the Chagcharan station, which boasts the most comprehensive dataset among all stations within the Harirod-Morghab River basin. Utilizing the conventional method of comparing new data with historical records, the water flow regime at this station was calculated and determined. The primary objective of this study was to assess the impact of climate change on the water flow regime within the Harirud-Marghab River basin, specifically focusing on temporal variations and alterations in the maximum peak of water flow at the Chagcharan station. This station is renowned for its extensive data duration and vast coverage area of 6076 square kilometers. To facilitate comparison, the average flow value over several years was considered.

At the Chaghcheran station, an analysis of the average water flow over multiple years reveals noteworthy disparities between the new dataset spanning 2022-2009, particularly from April to July, and the historical data encompassing 1962-1980. Notably, while the new data aligns with historical trends around mid-February, a deficiency in the average flow during the specified months is evident.

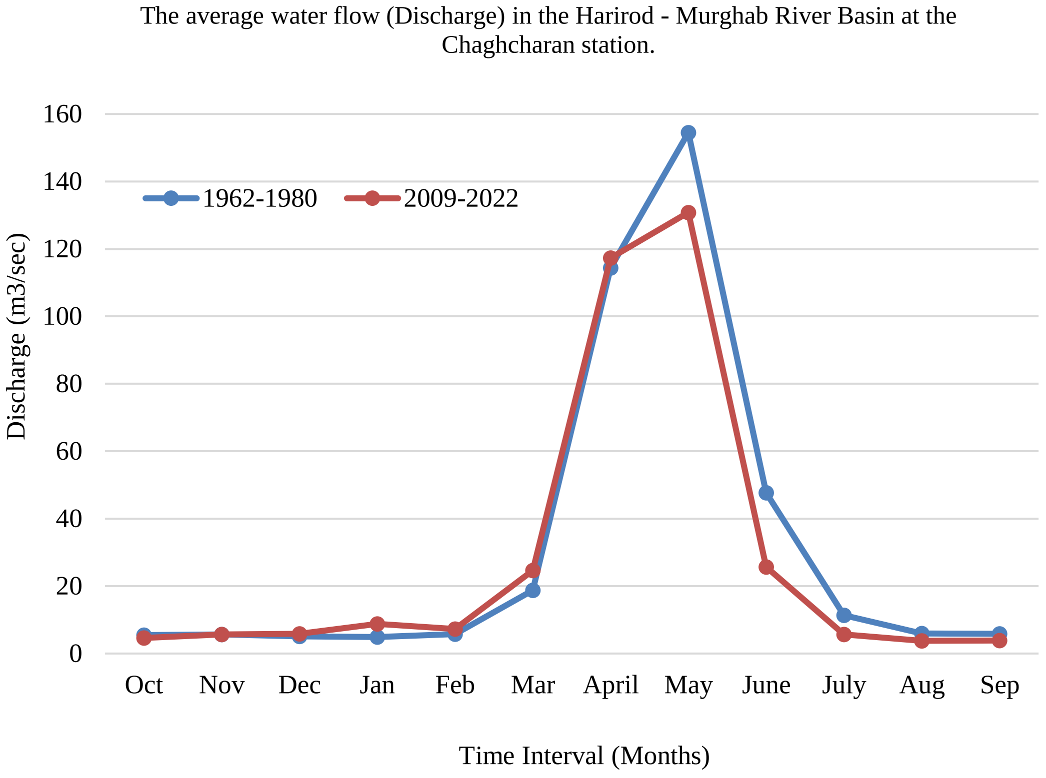

Figure 10: *A graph comparing the average flow rate (Discharge) over several years at the Chaghcharan station in the HMRB.*

The comparison further highlights that the maximum peak of the new water flow data in May is notably lower at 130.8 cubic meters per second compared to the historical peak of 154.4 cubic meters per second during the same month. This approximately 24.4 cubic meters per second discrepancy underscores significant climate variations impacting the river basin.

Climate Change Impact on Surface Water Ponetional of Harrirod-Murghab River Basin

Based on the assessment of the surface water potential of the Harirod-Murghab river basin, conducted during the periods spanning from 1948 to 1980 and from 2008 to 2022, it has been determined that the surface water capacity of this river basin, as depicted in Figure 11, has experienced a reduction of approximately 29 percent. This decline, amounting to roughly 0.98 billion cubic meters of water, has been attributed to the adverse impacts of climate change.

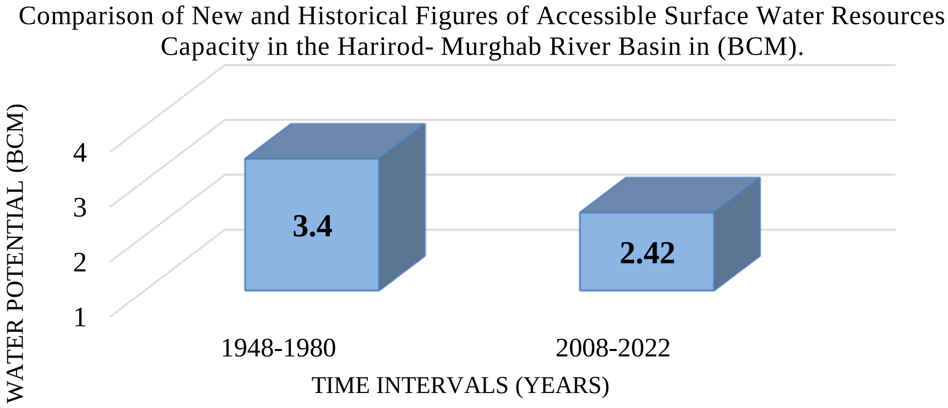

***Figure 11:** Comparison of Accessible Surface Water Capacity at HMRB in Two Different Time Intervals.*

CONCLUSION

Key findings have emerged from the comprehensive analysis of the impact of climate change on water resources and climatic variables (such as rainfall, temperature, water flow, and water potential) within the Harirud-Marghab River basin over a span of 44 years (1979-2022). The forthcoming initiatives aimed at mitigating the adverse effects of climate change and adapting to these climatic shifts will be crucial in aligning projects and water infrastructure development with the specific characteristics of the river basin. During the aforementioned period, annual precipitation in the Harirud-Marghab River basin has decreased by approximately 33%, corresponding to a reduction of 97 mm in rainfall. This decline was especially pronounced in the latter half of the observation period (2000-2022), which was directly influenced by global climate change, particularly in semi-arid regions such as Afghanistan. Overall, there has been a reduction in winter snowfall and an increase in seasonal rains. Consequently, the rainy season in the Harirud-Marghab River basin has shifted, with precipitation now primarily occurring in autumn, summer, and late spring. Precipitation during these seasons significantly surpasses that of winter, which has notably declined since 1979-2022. Additionally, the precipitation patterns have undergone significant changes, including a decrease in winter snowfall and a marked increase in monsoonal rains, which have contributed to severe climatic events such as droughts and sudden floods in the region. These changes are direct outcomes of climate change.

The effects of climate change on the Harirud-Marghab River basin have notably influenced two key aspects of precipitation: intensity and timing. Rainfall events have become more intense, while the frequency of rainy days throughout the year remains limited, averaging only 38 rainy days. In the absence of adequate and timely adaptation measures, the situation is expected to worsen in the coming decades, potentially leading to more frequent monsoonal floods and droughts in the region.

From 1979 to 2022, the average annual temperature in the Harirud-Marghab River basin has risen by approximately 1.4°C, representing an increase of 11.5%. This shift can be attributed to rising levels of greenhouse gases and the depletion of the ozone layer, particularly in semi-arid regions. The resulting impacts are profoundly adverse, especially on water resources within the basin. These climate changes have altered water flow patterns, leading to a significant reduction in volume compared to historical data from before 1980. Furthermore, the surface water capacity of the Harirud-Marghab River basin has decreased by 29%, equivalent to a loss of 0.98 billion cubic meters of water.

RECOMMENDATION

- Enhancing the monitoring and evaluation system for the equipment and instruments used in the hydrometeorological stations of the Harirud-Marghab River basin. This should be done sustainably to improve their capacity to accurately measure climatic variables such as precipitation, temperature, etc.
- Strengthening the data collection system for rainfall, temperature, and other climatic parameters. These measurements should be conducted and documented following established criteria at the monitoring stations within the river basin.
- The development of efficient irrigation systems is crucial for modern agriculture. Innovative techniques, such as drip irrigation and intelligent systems, conserve water and significantly boost productivity.
- Improving water resources management is essential. This involves effective planning for water management, including rainwater collection and storage, as well as water conservation in dams and reservoirs, ensuring a stable water supply in the face of climate variability.
- Conservation of natural resources is critical for mitigating the impacts of climate change. This includes preserving forests, pastures, and watersheds, improving soil quality, and protecting biodiversity.
- The development of climate-resilient infrastructure is key to addressing the challenges posed by climate change, particularly in mitigating the impacts of floods, droughts, and fluctuations in groundwater levels.

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Conflict of Interest: The author(s) declared no conflict of interest.

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