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Spatiotemporal Distribution Analysis of Rainfall in the Harirud-Murghab River Basin, Afghanistan

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ABSTRACT

The execution of hydrological, climatological, agricultural, and development projects frequently encounters a key challenge: missing rainfall data at specific locations. This limitation can be addressed using various spatial interpolation techniques, including Spline, Inverse Distance Weighted (IDW), Kriging, and the widely used Thiessen Polygon method. The primary objectives of this study were: 1) to estimate the annual mean precipitation in the Harirud-Murghab River Basin (HMRB) in Afghanistan for the period 1979-2023; and 2) to evaluate and compare the accuracy of different spatial interpolation and average precipitation estimation methods in the region. For this purpose, 45 years of precipitation data from 11 hydrometeorological stations within the basin were employed. The methods tested included the Arithmetic Mean, Thiessen Polygons, and Isohyetal Lines generated through Kriging, IDW, and Spline techniques. The Root Mean Square Error (RMSE) was used to evaluate the performance of each method. The results revealed that Kriging produced the highest accuracy and the lowest error (RMSE = 18.74 mm), making it the most suitable method for estimating spatially averaged precipitation in the HMRB. The IDW, Thiessen Polygon, and Spline methods followed with RMSE values of 19.07, 19.21, and 19.56 mm, respectively. Although the differences in mean values were not statistically significant, the Kriging-based isohyetal map produced the most accurate estimate of 240.75 mm. Therefore, Kriging is recommended as the preferred technique for estimating both rainfall and solid precipitation (snow) in this basin. The study's findings are expected to support climate anal-ysis, water resource modeling, and flood forecasting in the region.

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1. Introduction

Precipitation refers to all forms of water rainfall – rain, snow, and hail – from the atmosphere to the Earth's surface. Along with evaporation and condensation, precipitation manifests one of the three main components of the hydrological cycle (Parks, 2024). The condensation of water vapor in rising air masses during the adiabatic process cools it to the saturation point, leading to the formation of cloud droplets and, eventually, rain. Most rain clouds contain both ascending and descending air currents. On the one hand, the ascending ones determine the cloud's growth and height, and thus the height of the cloud is proportional to the volume of ascending currents. On the other hand, as liquid water accumulates in the atmosphere, ascending currents weaken, and descending currents strengthen, resulting in precipitation (Gebremichael & Kragewski, 2004). Rainfall creates surface water, replenishes soil moisture, and recharges underground aquifers. The climate in a region predetermines the major forms of local precipitation (Viessman & Lewis, 1996).

Continuous and accurate monitoring of rainfall is pivotal for understanding the climate of an area and relevant water resource management measures, predicting floods, planning agriculture, and many other applications. Moreover, hydrological modeling and evaluation of water resources depend on existing knowledge about precipitation amounts. The average rainfall in a region may be considered a primary input in the process of basin modeling, especially for surface flow models. This is because, to an extent, rain is the only climatic variable that can generally explain rapid flow fluctuations. However, certain studies indicate that the spatial rainfall variability in a basin, its distribution, as well as its interaction with other catchment elements significantly impact the generated surface flow response (Sheau et al., 2022). Therefore, determining mean rainfall is crucial, as this information helps to better understand water resources in a given watershed, carry out proper water and agricultural planning. It is likewise important for the sustainable management of water resources and economic development of a host country.

For this reason, in Afghanistan several departments have installed hydrometeorological stations in domestic river basins over the past years. Measuring and collecting rainfall data, as well as continuously monitoring precipitation quantitatively at each measurement point are done by the national Meteorological Department and Ministry of Energy and Water (MEW). However, due to several decades of war rainfall monitoring in most constituencies has been intermittent leading to gaps in hydrometeorological data, including these pertaining to rainfall (Pathak et al., 2022). Considering these historical observations, general studies point to significant rainfall variability across Afghanistan due to the presence of mountain ranges and high elevations. The mountainous regions in the north and northeast typically receive the most rainfall, while the desert areas from the southeast to the southwest get the least. For instance, whereas the annual precipitation in the North Salang exceeds 1,100 mm, in Zaranj City (country's southwest) it is below 35 mm (DAAD, 2014). According to the study by Arez (1981), the average rainfall over Afghanistan ranges between 80 and 1,200 mm. This study confirms the positive correlation between rainfall and elevation bands.

For the purposes of integrated water resources management (IWRM) and effective monitoring of hydrometeorological parameters, Afghanistan is divided into five major river basins (Ministry of Justice, 2009). The Harirud-Murghab River Basin (HMRB) – one of the five – is located in the northwest, extending from east to west, and then to north. In terms of surface water resources, the HMRB is the fourth largest domestic catchment (Favre & Kamal, 2004). Knowing the mean rainfall in a basin is essential for effective and continuous climatic, hydrological, as well as agricultural efforts, in turn critical for effective IWRM implementation. In the calculations of weighing and adjusting the water balance components and hydrometeorological activities, the knowledge of the precise average rainfall in a watershed is considered important. Therefore, determining and estimating the average rainfall in a river basin manifests one of the primary objectives for identifying the water balance equation.

Major data gaps still remain for the Harirud-Murghab, albeit several thematic studies in the past revealing the spatial distribution of rainfall across other catchments. For instance, Nafez (1992) examined the statistical characteristics of rainfall distribution in Kabul Province. Historical rainfall characteristics were also reported by Arez, Zelhard, Hemlum, and Titov (Nafez, 1992). The study by Wahed & Ghafari (1982) on rainfall characteristics in Afghanistan faced the lack of accessibility to other basins. Nafez critiqued certain aspects of the aforementioned historical studies, with the main criticism directed at Arez's study claiming an increase in rainfall with elevation throughout Afghanistan. Nafez challenged this significant claim, deeming it incorrect in the general manner. His second critique alleged that most of the studies had used very short and insufficient (5 to 8 years) rainfall data series without qualitative data evaluation. It should be noted that the study by Nafez (1992) utilized the data from six meteorological stations (Kabul Airport, Surobi, Guzargah, Darulaman, Karizmir, and Paghman) located in Kabul Province and three stations (Kandahar, Tarinkot, and Qalat) located in southwestern Afghanistan. The rainfall data from Kabul Province's stations covered periods of 10 to 32 years; the data coverage from other stations ranged from 7 to 12 years during 1957-1988.

In his research, Nafez applied statistical analysis to determine monthly, seasonal and yearly precipitation variation. Moreover, he applied the simple regression method to discover the alterations in rainfall volumes versus elevations within the target area. One important finding of that study was that the total rainfall during the six cold months was significantly greater (in certain instances, 50-fold) than during the six warm months.

Recently, Azizi (2022) calculated the mean rainfall in Afghanistan's river basins and determined the annual average rainfall for the entire country. That investigation used eight years (2008-2016) of data from nine rainfall stations in the HMRB and employed three methods (arithmetic mean, weighted mean, and Thiessen Polygons) to determine mean annual rainfall. According to this study, the average annual rainfall in the HMRB was estimated at 238 mm, and 246 mm for the entire country's territory. Additionally, Azizi (2022) found that the average annual rainfall during 1975 was between 250 and 300 mm. Although this study did not cover the whole country, including HMRB, the data utilized was limited to only eight years – not enough for long-term climate research, as according to Ahrens & Henson (2019) proper climatic analysis requires an averaged data series over at least 30 years.

Arian (2021) evaluated the accuracy of methods for calculating average rainfall based on the case of the Kokcha River Basin. He applied different averaging methods – including arithmetic mean, weighted mean, and spline technique – within the framework of the study. Among various mathematical averaging methods, the author highlighted the spline method as the best for preparing isohyet maps and estimating mean rainfall in the Kokcha Basin. In addition, the case study conducted by Noori (2021) evaluated various methods for determining the rainfall mean in the Central Kabul River Basin. Under that investigation, the average rainfall was calculated based on the arithmetic mean, Thiessen polygons, and isohyetal (contour) methods. The study's outputs showed that the average annual rainfall in the Kabul Basin amounted to 200 mm, with the isohyetal method providing the most consistent results. These last two studies covered neither the HMRB nor any of the adjacent catchments.

Despite the aforementioned research projects, no comprehensive targeted studies to estimate the mean rainfall and its spatial distribution specifically in the Harirud-Murghab Basin were conducted for many years. Another major drawback of all of the previously mentioned studies was the lack of precipitation gradient analysis to reflect the spatiotemporal precipitation variation over the studied areas. Hence, the absence of possible moist air mass trajectories within the areas. In addition, while initial rainfall data should be subjected to conversion into mean values at the basin levels and across the entire country for optimal use, no extensive studies or thorough efforts to determine and/or obtain rainfall means for Afghanistan's river basins took place over the past two decades.

Considering the above gaps and challenges, estimating the average rainfall values in the HMRB, as well as identifying the most appropriate averaging and spatial interpolation method appeared rather relevant. Also, the spatial-temporal distribution of monthly rainfall across the basin likewise required elaboration.

2. Materials and methods

2.1. Study area

The Harirud-Murghab Basin is located in Afghanistan's western part and is mainly shared by three provinces (Ghor, Herat, and Badghis). The catchment narrowly extends from the central highlands to the western part of the country, and consists of two main rivers – Harirud and Murghab – originating in the western slopes of the Koh-e-Baba Mountains with elevations up to 4,000 m ASL in central Afghanistan (CAREC & USAID, 2025). The Harirud branch originates from the highlands of Lal-wa-Sarjangal District in the east and flows westwards through the provinces of Ghor and Herat. From its source to Ghorian District of Herat Province, the river flows for 460 km east to west. From Ghorian District to the town of Islam Qala, it flows 65 km northwest, and from Islam Qala to the Zulfiqar area, it flows 100 kilometers north. The Murghab branch originates from the mountains of Murghab District in northern Ghor Province, descends into northeastern Herat, reaches Little Marv, and then turns north towards Big Marv. There, it branches into several canals and eventually disappears into the sands of the Ghaz Desert. The river's length is 965 km, flowing westward and then entering Turkmenistan to the north (Arez, 1981). The HMRB is shared by three countries, namely Afghanistan, Iran, and Turkmenistan. The area of the basin's Afghan portion is approx. 80,000 km^2, i.e. about 15.5% of the total area of the country (Mahmoodi, 2008). The target catchment accounts for roughly 4.5% of Afghanistan's surface water resources (GDWR 2022; Azizi, 2022).

The historical rainfall means in the watershed's Harirud section were reported to fluctuate between 238 and 245 mm (Thomas, Azizi, and Behzad, 2016; Azizi, 2022), recorded at four meteorological stations (Herat, Ghelman, Shahrak, and Qadis) – 222.5, 219.9, 276.1, and 344.8 mm, respectively (Favre & Kamal, 2004). The streamflow of the rivers inside this basin primarily relies on rainfall and snow accumulation, as no glaciers or glacial lakes exist currently. For this reason, rivers reach their minimum peaks or even dry up during July-September against the background of no rainfall events (Nepal et al., 2021; Maharjan et al., 2021; Maharjan et al., 2021). Fig. 1 below shows the geographical dimensions of the target catchment.

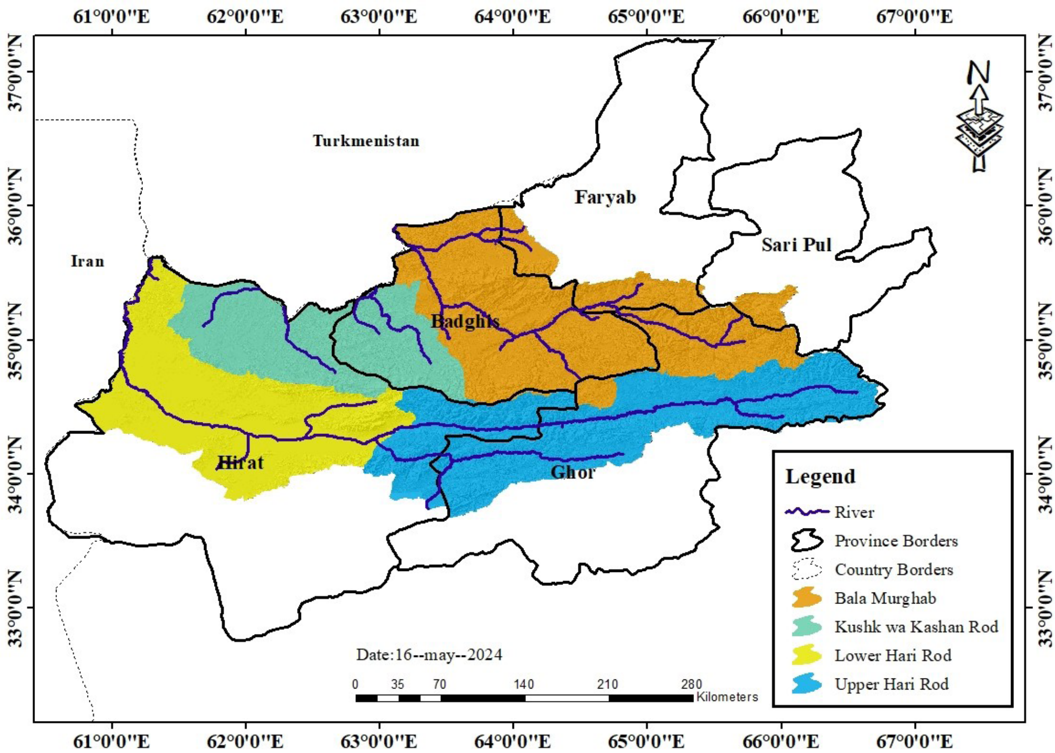
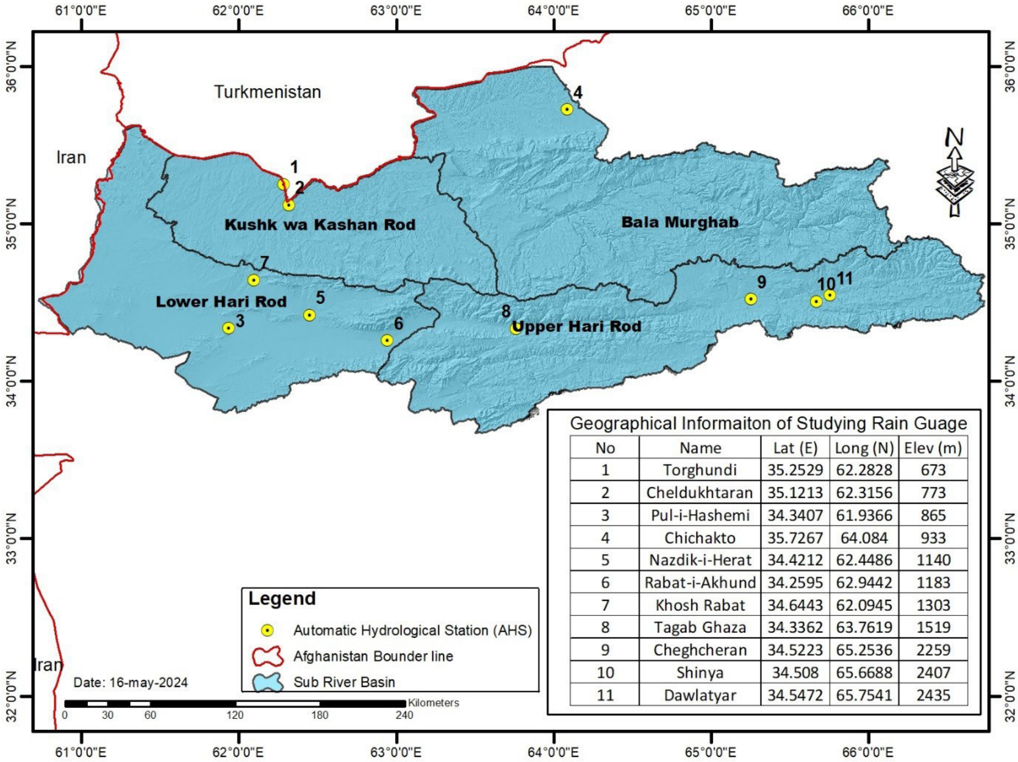


Figure 1. Study area boundaries.

2.2. Rainfall data

The rainfall observations with homogeneous characteristics for the purpose of this study were obtained from 11 selected hydrometeorological stations installed in the HMRB by MEW (Fig. 2). The recorded hourly rainfall measurements from these stations covered the period of 14 years (2009-2023). In addition to the observations, the study utilized the re-analyzed data (gaps filled) for 1979-2008 generated by MEW with the technical assistance of the JICA-HYMEP Project (MEW, 2024). Thus, the complete data set encompassed the period of 45 years. It deserves noting that the data utilized within the framework of the study included only total liquid precipitation (rainfall) and excluded solid precipitation. The hourly rainfall data were converted to a monthly series, and then the annual total rainfall for the entire study period was extracted at the basin level.



No	Name	Lat (E)	Long (N)	Elev (m)
1	Torghundi	35.2529	62.2828	673
2	Cheldukhtaran	35.1213	62.3156	773
3	Pul-i-Hashemi	34.3407	61.9366	865
4	Chichakto	35.7267	64.084	933
5	Nazdik-i-Herat	34.4212	62.4486	1140
6	Rabat-i-Akhund	34.2595	62.9442	1183
7	Khosh Rabat	34.6443	62.0945	1303
8	Tagab Ghaza	34.3362	63.7619	1519
9	Cheghcheran	34.5223	65.2536	2259
10	Shinya	34.508	65.6688	2407
11	Dawlatyar	34.5472	65.7541	2435

Figure 2. Geographical properties of the rain gauges located in the Harirud-Murghab Basin.

2.3. Methods

The recorded rainfall data pertain to point measurements typically referred to as point rainfall. This data often need to be generalized across the area of a basin or region. Generalizing the rainfall amount over the entire area is necessary both to estimate the rainfall at any given point within the area and to determine the average rainfall across the whole area (Alizadeh, 2010). Various methods developed by different specialists can be used to achieve these objectives. This study was confined to the application of three commonly used methods for most hydrometeorological purposes. Fig. 3 shows the flowchart illustrating all practical steps executed within the framework of this research to elaborate the spatial rainfall distribution.

As Fig. 3 shows, the application method under this study consisted of five main steps, each depicted as a rectangular box with red dashed lines. The 1st step started with collecting the set of rainfall data described in the previous section. The collected data were then checked for any gaps and processed for further averaging calculations. After that, during the 2nd step simple arithmetic means of the annual data were obtained as described in the following subsection (arithmetic mean method). During the 3rd step, using GIS software and the proximity tools, the Thiessen polygons for the entire Harirud-Murghab Basin were delineated.

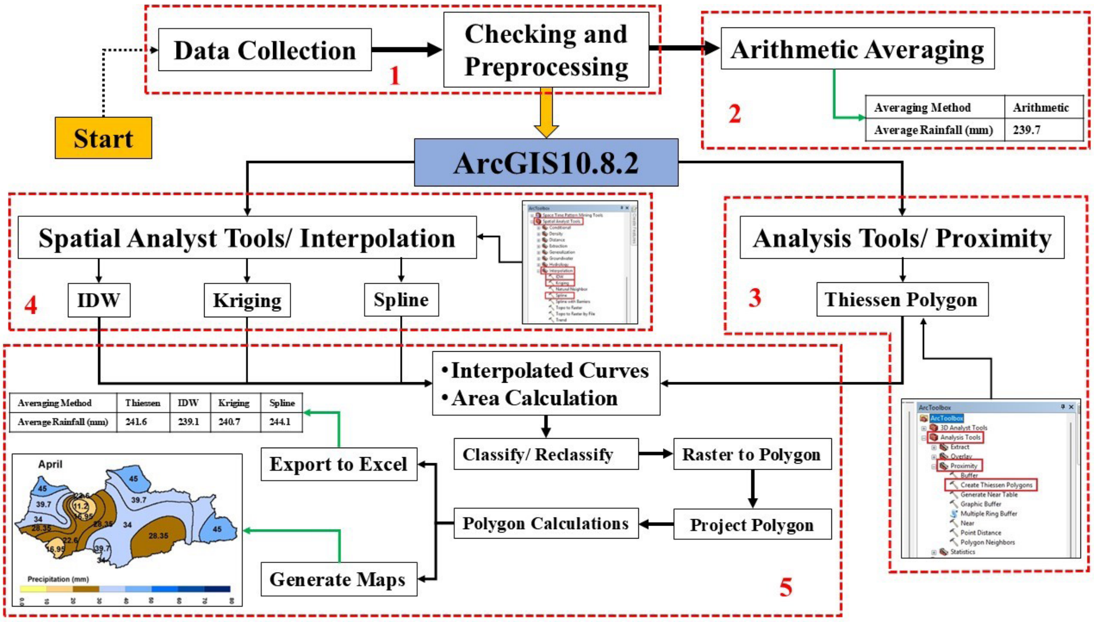


Figure 3. The study's flow chart.

The 4th step involved applying three well-known interpolation techniques for the study area using GIS tools. Initially, monthly isohyets using the IDW method were generated by employing the relevant tools from the Spatial Analyst Tools set. Similarly, in the subsequent steps the respective tools to draw monthly isohyets based on the Spline and Kriging methods were applied for the entire target basin. After delineating the Thiessen polygons and drawing the isohyets, the research team proceeded to calculating the areas enclosed by the closed lines (either polygons or isohyets) in order to apply the weighted average method to each of the four mentioned techniques (Thiessen polygons, IDW, Kriging, and spline). For this purpose, in the 5th step the polygons/curves were classified and then converted to shape-files/polylines by utilizing the Raster-to-Polygon tool. Next, the polylines were projected for area calculation purpose. Subsequently, the area bounded by each polygon or closed isohyet was calculated using the Polygon Calculation tool, and all computed values were exported to Excel format for further analysis. Moreover, the maps of generated polylines (Thiessen polygons and isohyet curves) were exported as JPG files. The exported Excel file was then used to calculate rainfall means using the weighted method for each of the aforementioned techniques; and the generated maps were used to explain the spatial distribution of rainfall within the HMRB. The following subsections provide a detailed calculation description for each of the methods employed to determine the investigated parameter.

2.3.1. Arithmetic Mean Method.

Theoretically, if a basin's surface is relatively flat (or can be considered largely flat), and the rain gauges are spaced relatively equally from each other, the simplest approach to determine the mean average rainfall in that basin is to use the arithmetic mean technique (Alizadeh, 2010). Meanwhile, one can take a simple arithmetic average of all the point rainfall measurements to obtain the rainfall mean across the entire catchment. Mathematically, it can be expressed as follows:

$$\bar{P} = \frac{P_1 + P_2 + \cdots + P_n}{n} \quad (1)$$

where P_1, P_2.... and P_n are the point rainfall values measured at the existing stations, n is the number of stations, and $\bar{P}$ - is the mean rainfall across the watershed.

Whereas in arithmetic averaging all point rainfall values are given equal weight, the impact of point rainfall amounts on the overall mean rainfall value varies. Due to the fact that the target area under this study was not uniformly flat, and the distribution of rain gauges in the HMRB was not balanced or equally spaced, weighted averaging methods were deemed more reliable compared to arithmetic averaging for determining rainfall means. The commonly used weighted averaging methods for rainfall differ based on how the weights of rainfall amounts are determined. This study utilized those methods to determine the average rainfall in the Harirud-Murghab Basin. The general form of weighted averaging according to (Spiegel et al., 2009) is as follows:

$$\bar{P} = \frac{W_1 P_1 + W_2 P_2 + \cdots + W_n P_n}{W_1 + W_2 + \cdots + W_n} = \frac{\sum W_i P_i}{\sum W_i} \quad (2)$$

where W_1, W_2.... and W_n are the respective weights assigned to rainfall values of P_1, P_2.... and P_n.

2.3.2. Triangular Thiessen Polygons.

This technique also called the proximal method is the most common approach for calculating rainfall in an area, and is primarily used for flat regions. As per this method, a study area is divided into different triangular polygons based on existing observation stations (Arianti et al., 2018). Each station represents its respective polygon, and the rainfall amount across all points within a polygon is assumed to be equal to the rainfall recorded at the station inside that polygon. Next, the area of each Thiessen polygon is calculated and assigned as the weight for the rainfall amount at the corresponding station (Bayraktar et al., 2004). For drawing and calculating the area of Thiessen polygons for the HMRB, ArcGIS10.8.2 software and the Proximity Analysis tools were employed. To do this, the polygons were first drawn and then converted into a shape-file. Under this study, this process was followed for both Thiessen polygons and the isohyets. Next, the area of each polygon region was calculated. If the areas of the polygons are denoted as A_1, A_2.... and A_n, rainfall values at the stations inside the polygons are denoted as P_1, P_2.... and P_n, the rainfall mean for the study area ($\bar{P}$) is calculated as follows:

$$\bar{P} = \frac{P_1A_1 + P_2A_2 + \cdots + P_nA_n}{A_1 + A_2 + \cdots + A_n} = \frac{\sum P_iA_i}{\sum A_i} \quad (3)$$

2.3.3. Isohyet Interpolation Method.

To obtain the average precipitation value for a given area, mathematically the isohyets technique does not differ from the Thiessen polygons method, but geometrically it utilizes different area polygons between two isohyet lines. Isohyets are widely considered the best method for estimating precipitation in rugged areas. Isohyets are geometric locations where the precipitation value at each point is the same over a specified period, such as one year (Guillermo and Salas, 1985). Drawing isohyet lines is similar to drawing contour lines of equal elevation (contours). Therefore, within the framework of this research ArcGIS10.8.2 software was utilized to draw isohyets and calculate the areas between each pair of isohyets using three methods – inverse distance weighting (IDW), spline, and Kriging – to accurately determine the volume of precipitation in the mountainous area.

When the area between each pair of isohyet lines is A_1, A_2.... and A_n, respectively, and the average precipitation in each of these areas (which is actually the mean precipitation between the upper and lower isohyets) is P_1, P_2.... and P_n, then the average precipitation in the entire watershed is calculated as per the following formula (Galilvand et al., 2016):

$$\bar{P} = \frac{\left(\frac{P_0 + P_1}{2}\right)A_1 + \left(\frac{P_1 + P_2}{2}\right)A_2 + \cdots + \left(\frac{P_{n-1} + P_n}{2}\right)A_n}{A_1 + A_2 + \cdots + A_n} = \frac{\sum \bar{P}_i A_i}{\sum A_i} \quad (4)$$

Finally, to compare different methods of averaging and spatial interpolation of rainfall in the Harirud-Murghab Basin, the root mean square error was calculated for all the methods applied within this study. That was done according to the following formula adapted from (Daie, 2021):

$$\text{RMSE(mm)} = \left[\frac{1}{n}\sum_{i=1}^{n}(P_i - \bar{P})^2\right]^{\frac{1}{2}} \quad (5)$$

In the above formula, P_i represents the average monthly rainfall (Table 1) for the months of i=1.2.3….n, and $\bar{P}$ denotes the mean annual rainfall. According to the formula, the RMSE value can only be positive – its approaching zero indicates higher accuracy and better performance of the model.

3. Results and findings

3.1. Mean precipitation assessment

The average rainfall in the HMRB over the 45-year period was calculated using three common methods (arithmetic mean, Thiessen polygons, and isohyetal lines). Table 1 presents he results in monthly and annual terms, and Fig. 4 illustrates the annual variation of mean values obtained. As Table 1 shows, the outcomes of applying the aforementioned three methods were very close to each other, indicating the average annual rainfall of 241.1 mm in the watershed. Whereas the highest mean rainfall value (244.1 mm) was obtained using the spline method, the lowest (239.1 mm) was obtained using the IDW technique. It is noteworthy that all the rainfall values calculated under this study exceeded the historical value (237.73 mm) reported by Azizi (2022), with the closest value of 239.1 mm generated as per the IDW method. Also, comparing these results with the historical observations recorded at the four meteorological stations as in (Favre & Kamal, 2004) showed an increase of annual precipitation in the eastern (Herat) and western (Ghelman) sections and a decrease in the central sections (Qadis and Shahrak Stations) of the HMRB.

Before comparing the methods – as emphasized by Abasizadah (2024) – it is important to note that the most suitable methods in terms of accuracy for obtaining mean precipitation amount over a catchment area are, respectively, the isohyets, Thiessen polygons, and then arithmetic means. Hence, considering Table I and mean values calculated using the isohyetal method, the annual mean precipitation in the HMRB was estimated at 241.32 mm.

Table I. Mean monthly and annual rainfall values obtained via various averaging methods.

Month	Arithmetic Mean	Thiessen Method	Isohyet Method		
			IDW	Kriging	Spline
Jan	39.8	39.7	39.8	39.7	41.6
Feb	46.1	46.3	45.9	46.0	45.8
Mar	55.6	56.9	56.1	54.8	58.2
Apr	32.3	33.0	32.7	33.0	33.4
May	12.5	13.1	12.0	13.2	13.1
Jun	1.1	1.1	1.0	1.4	0.8
Jul	0.4	0.5	0.5	0.6	0.5
Aug	0.3	0.2	0.3	0.3	0.2
Sep	1.0	1.0	1.0	1.0	1.0
Oct	5.8	5.7	5.4	6.9	6.0
Nov	16.7	16.4	16.5	16.0	16.0
Dec	28.0	27.7	27.8	28.0	27.4
Total	239.7	241.6	239.1	240.7	244.1

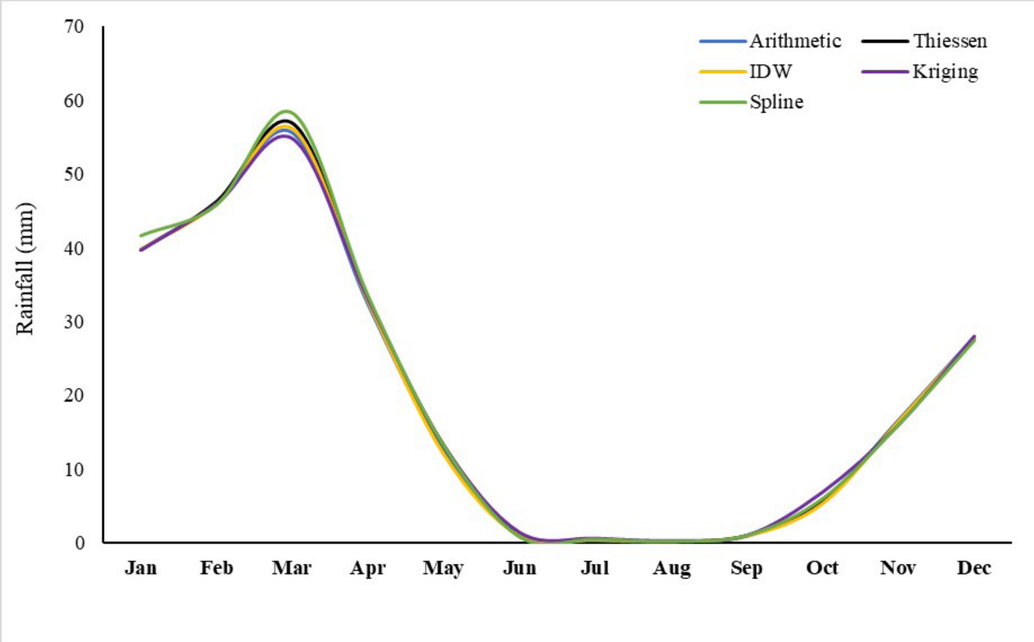


Figure 4. Annual mean rainfall variation in the Harirud-Murghab Basin.

3.2. Spatial distribution of precipitation

To understand the monthly spatial distribution of average rainfall in the target basin, Figures 5 to 8 present the corresponding contour maps and Thiessen polygons. In the maps, purple and blue sectors indicate zones with the highest rainfall concentration, and orange and yellow sectors depict zones with the lower rainfall amounts. As per Figures 5 to 7, March demonstrates the highest values across the watershed, while June, July, August, and September receive the lowest amounts. Hence, the rivers reaching their minimum flow peak or even drying up during exactly this period (Nepal et al., 2021; Mahrajan et al., 2021; Mahrajan et al., 2021). Additionally, comparing the April and May isohyets under the IDW and Kriging methods clearly points that the period of dry days without rain begins from the basin's western section and gradually expands eastwards. Although this pattern is relatively evident in the spline method as well, the distribution of rainfall during these two months appears slightly different, with rainfall amounts somewhat higher across the entire catchment territory. Similarly, the comparison of precipitation distribution during December and January using each of the three methods (IDW, Kriging, and Spline) shows that moist air masses and rainy weather initially enter the HMRB from the west and cover the entire basin towards the east in subsequent months. This ingress and cessation of dry and moist periods in the watershed from west to east may occur due to the influence of global-scale westerly winds (Westerlies) and changes in high/low pressure centers in the region, as described by (Ahrens & Henson, 2019; Roland, 2016). It means that the climate of the target basin is strongly influenced by the yearly changes in mid-latitude continental pressure centers, as well the global circulation of wind patterns in the northern hemisphere (Ahrens & Henson, 2019). Another significant and interesting observation that can be derived from Figures 5 to 7 is that monthly precipitation – except in a small mountainous zone in the basin's eastern section – remains below 20 mm for seven consecutive months (May through November) across the basin's entirety. This suggests that farming during warm months and critical agricultural periods heavily depends on groundwater or surface water from rivers, underscoring the need for greater emphasis on water control and management through the reconstruction of water diversion installations (Shrestha et al., 2021).

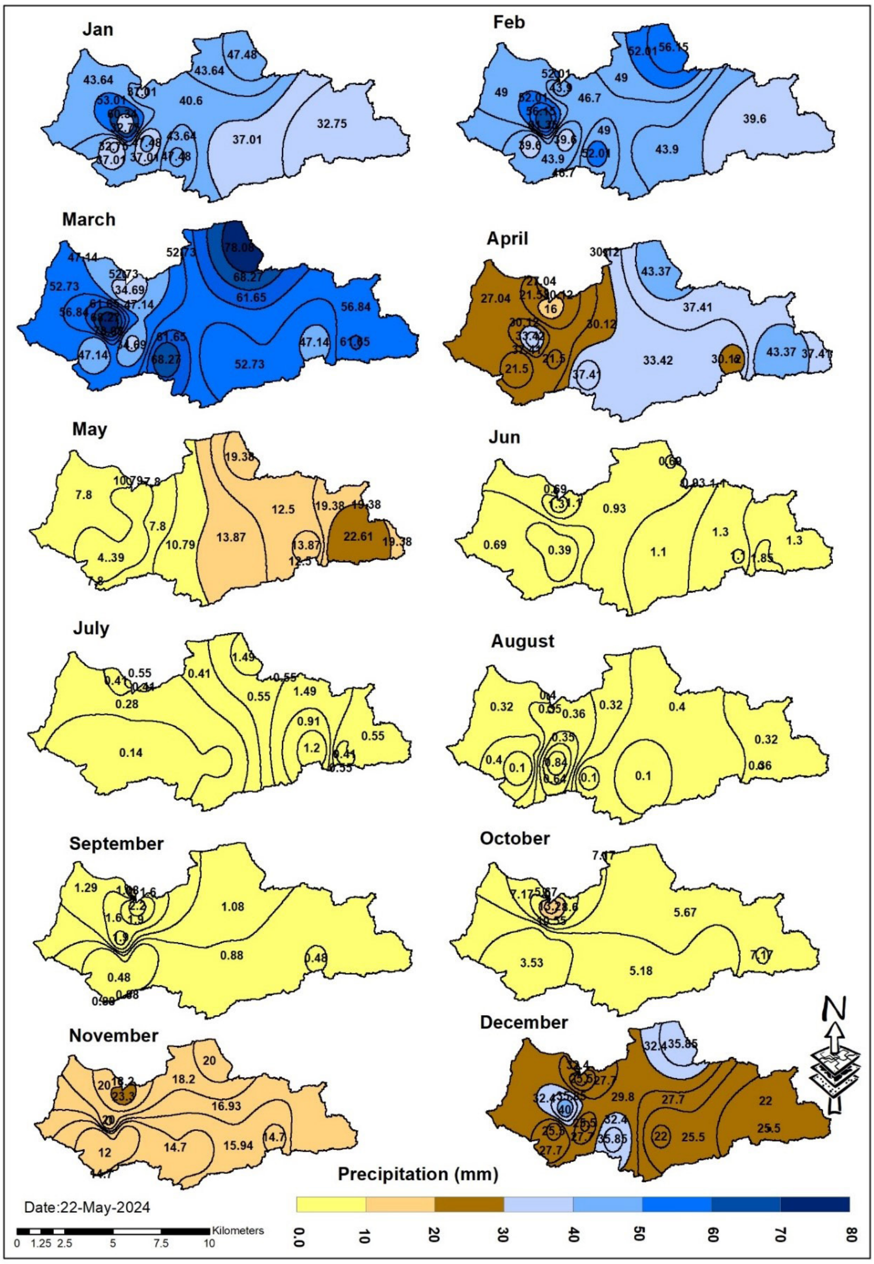


Figure 5. Isohyet (IDW) and monthly rainfall distribution maps for the HMRB.

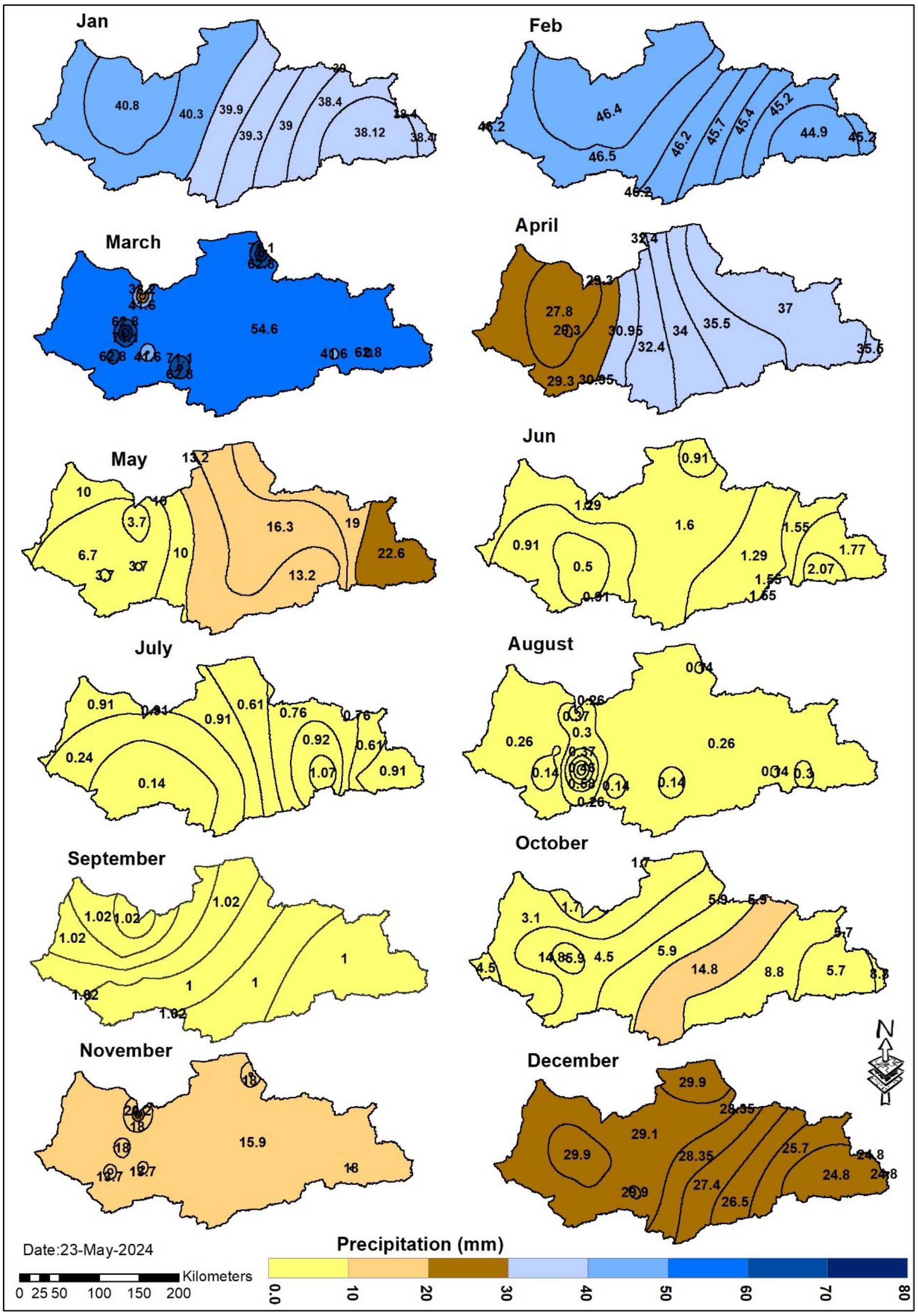


Figure 6. Isohyet (Kriging) and monthly rainfall distribution maps for the HMRB.

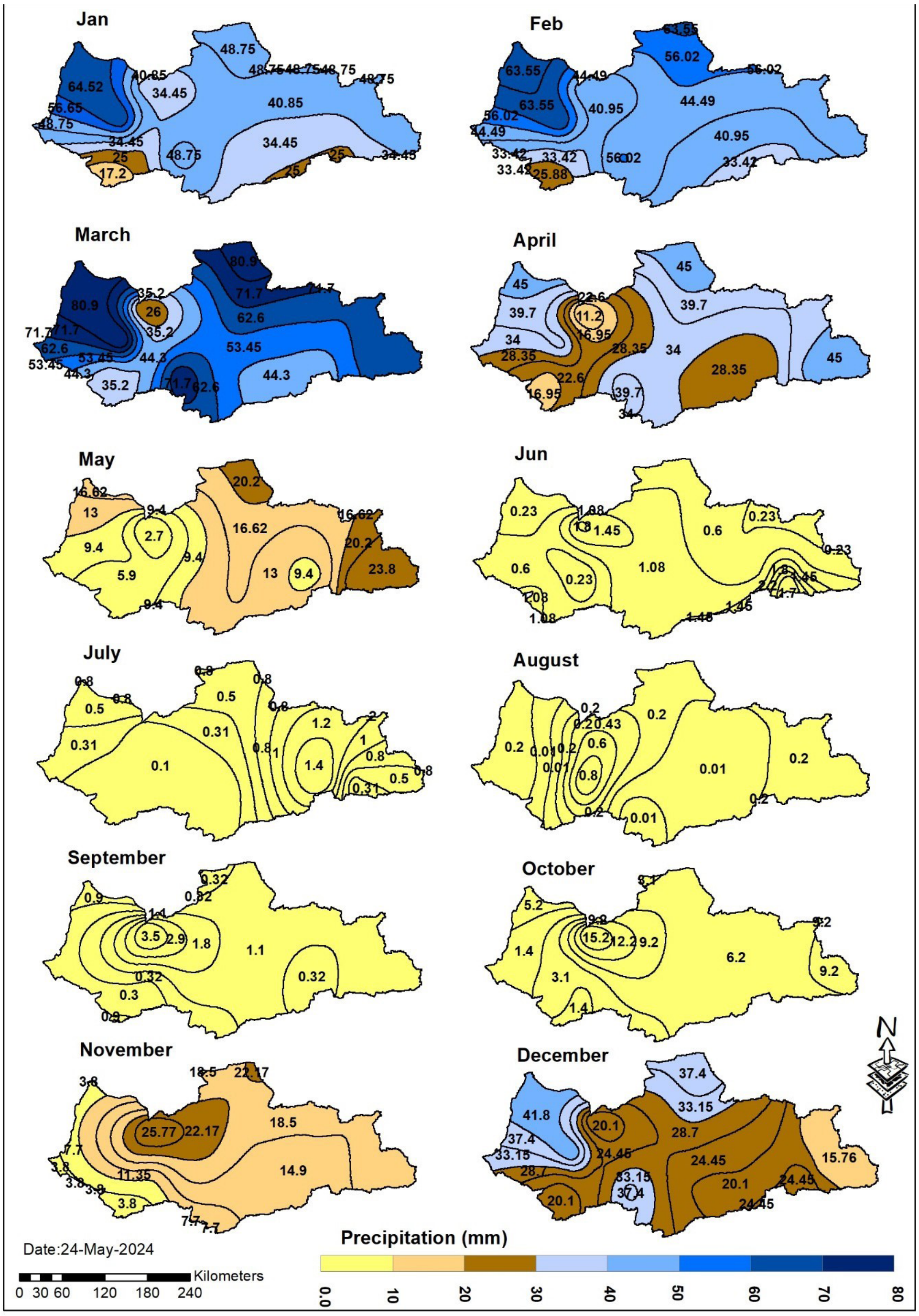


Figure 7. Isohyet (spline) and monthly rainfall distribution maps for the HMRB.

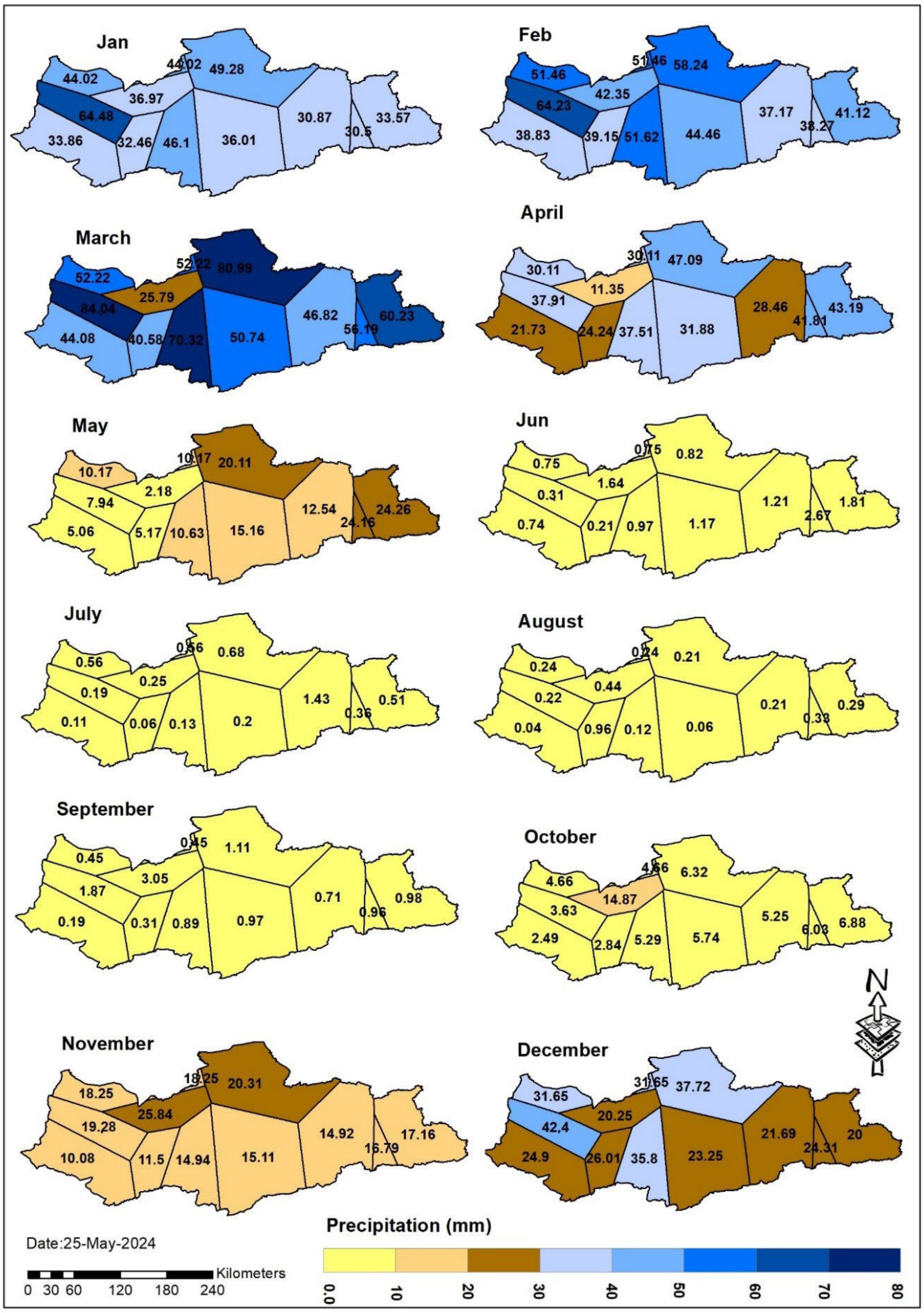


Figure 8. Thiessen polygons and monthly rainfall distribution maps for the HMRB.

4. Discussion

As mentioned in previous sections, the root mean square error index was applied to compare the efficiency of methods for estimating precipitation means. The index was calculated separately for each method (see Table II). As per Table

II, among the tested methods of averaging and spatial interpolation, the Kriging technique with higher accuracy and lower error (18.74 mm) appeared as the most optimal for the Harirud-Murghab Basin, followed by IDW (error of 19.07 mm) – ranking the second, Thiessen polygons (error of 19.21 mm) – ranking the third, and spline interpolation (error of 19.56 mm) – ranking the forth.

The best performance of the Kriging method is probably due to multiple reasons, including its geostatistical and stochastic nature, i.e. incorporating a combination of statistical properties and geometric (distance and spatial) characteristics of the measured data in generating interpolated values. It means that whereas the Kriging technique uses autocorrelation to determine the relation between a known value and its variation over space, deterministic and exact methods (e.g. IDW and splines) assume certain mathematical relationships and the measured values as exact inputs while generating interpolated values (Firdaus & Talib, 2014). Moreover, within deterministic methods the measured values exert a certain local effect decreasing with distance. Considering this, the new values in some points between the measured values could be interpolated (estimated) either by applying the IDW law or based on a combination of high-order polynomial functions (splines). Therefore, the IDW technique produces an interpolated value surface usually using three nearest (neighbor) measured values, while the spline technique forces a line composed of different order polynomial segments to pass through points with measured values. The strong spatial (elevation-specific) correlated nature of rainfall data in some zones itself could also be a reason making the Kriging method work better (Sluiter, 2009). Furthermore, in multiple cases – when data points are not uniformly distributed – the Kriging technique stands as a more appropriate interpolation method (Yahya et al., 2023; Hairong et al., 2015). Moreover, since the Kriging produced area between each pair of isolines is narrower, this allows more accurate definition of spatial distribution (Arianti et al., 2018). The Kriging technique assumes that the spatial distribution of a property (e.g. precipitation, temperature, etc.) is neither completely random nor deterministic – in many areas, it works more realistically than deterministic methods. Hence, considering the measured and interpolated values together while producing a predicted surface in the HMRB case the Kriging method allowed generating more accurate sections compared to deterministic methods. Yet, the method's application is more challenging compared to IDW and splines – the corresponding calculation procedures are more complex as well as time- and space-consuming.

Although no significant difference between the mean values obtained using different methods, the most accurate average precipitation value for the HMRB was calculated to be 240.75 mm using the isohyetal lines, particularly as per the Kriging method, which can be also extended for solid precipitation (snow). The tested methods are ranked based on their spatial distribution performance in Table II below.

Table II. Accuracy of methods for estimating mean precipitation.

Method	Mean annual precipitation (mm)	RMSE (mm)	Rank
Kriging	240.75	18.74	1st
IDW	239.14	19.07	2nd
Thiessen Polygons	241.60	19.21	3rd
Spline	244.07	19.56	4th
Arithmetic	239.75	18.96	-

5. Conclusion

This study manifested the first attempt of spatiotemporal rainfall analysis specifically for the Harirud-Murghab River Basin over the 45-years period, using various methods, particularly the isohyet technique. In addition, it allowed identifying the optimal approach among the selected averaging protocols, as well as the most suitable spatial interpolation method for estimating average precipitation.

More specifically, the study's results indicate that the mean estimated precipitation in the HMRB varies between 239.14 mm (as per the IDW method) and 244.07 mm (as per the spline interpolation method). Determining the best method was based on the Root Mean Square Error Index evaluation. This research findings point to the Kriging method as the most accurate among all tested averaging and spatial interpolation techniques - in case of the target catchment, it showed higher accuracy and lower error (18.74 mm). The IDW, Thiessen polygons and spline methods ranked second, third and fourth, respectively. According to the calculations within the framework of this investigation, based on the most suitable method (isohyetal lines) the average precipitation in the Harirud-Murghab River Basin over 45 years (1979 to 2023) amounted to 240.75 mm.

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