Comparison of Different Interpolation Techniques for Mean Areal Rainfall Estimation of Uttarakhand using Geographical Information System

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ABSTRACT

Quantitative estimates and the geographical distribution of rainfall are necessary for efficient water resource management. Information on spatial rainfall distribution is essential for monitoring and managing both the deficit and excess rainfall regions. Measuring rainfall at a single place is acceptable, but such data must be extrapolated (temporally and geographically) to the entire area under consideration. Research in rainfall distribution in hydrology is vital since it influences the accuracy of the continuous surface created from discrete point rainfall data. Many geographical information systems (GIS) statistical approaches interpolate precipitation values based on rainfall data from unevenly spaced rain gauges. The mean annual rainfall of Uttarakhand has been estimated by the arithmetic mean, Thiessen polygon and isohyetal interpolation techniques. Results showed that mean annual rainfall in Uttarakhand pertains to 1562.7 mm, 1576.2 mm, 1570.6 mm and 1577 mm using arithmetic mean, district area-weighted mean, isohyetal interpolation, and Thiessen polygon methods, respectively.

Keywords: Mean areal rainfall, Thiessen polygon, Isohyetal approach, Inverse Distance Weighted (IDW)

Introduction

Rainfall is a complex climatological process (Richardson, 1981), and the topography and orography of the region control the magnitude and spatial distribution of the rainfall to a greater extent (Smith, 1979). Quantitative estimation and rainfall distribution are required for various purposes like water resource management, hydrologic modelling, flood forecasting, climate change studies, water balance computations, soil moisture modelling for crop production, irrigation scheduling, etc. (Guenni and Hutchinson, 1998). Rainfall information at various scales is crucial for its applications ranging from flash-flood monitoring to climate study. Unfortunately, rainfall is a complex parameter to measure due to its highly variable nature. Rain gauges measure rainfall at a specific point, which can be extrapolated to the nearby area but with questionable accuracy, especially over complex topographical regions. Spatial modelling of rainfall is an important area of research in hydrology (Bonacina, 1945; Anders *et al.*, 2006, Austin and Dirks, 2006).

Geographic Information Systems (GIS) offer a range of statistical methods to interpolate precipitation based on data recorded at several

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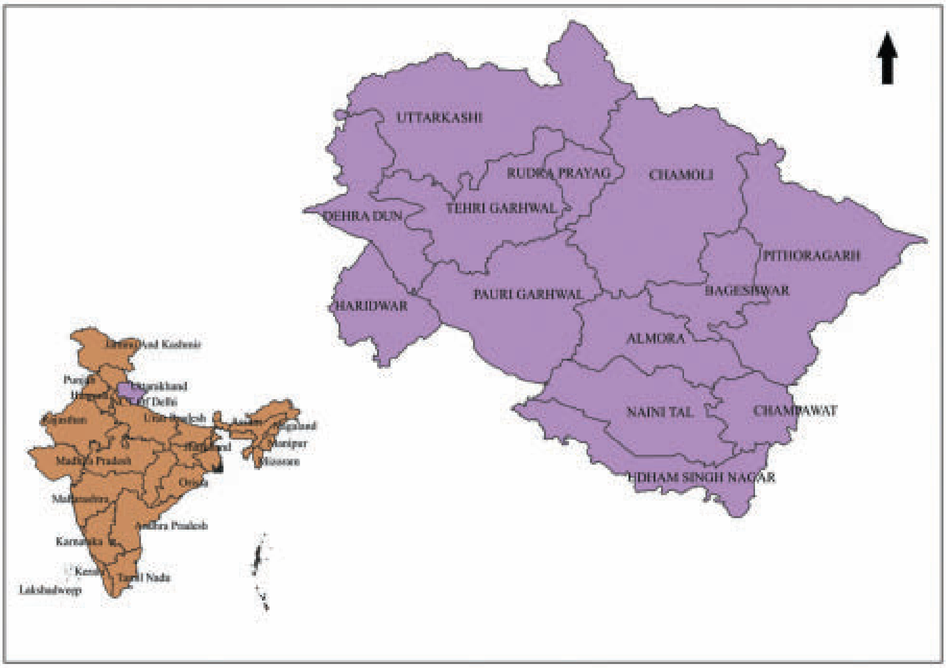

Figure 1. Map of the study area.

irregularly spaced rain gauges. However, it is challenging to select the best interpolation technique that reproduces the actual surface with minimum error (Caruso and Quarta, 1998*)*. The choice of the interpolation technique generally depends on the rain-gauge network density, topography, aim of the study, the Spatio-temporal scale of the data analysis, and characteristics of the local rainfall (Wackernagel, 2003; Grimes and Pardo, 2010). Different approaches such as the Thiessen polygon, Isohyetal method interpolation have been used to estimate rainfall values at ungauged points using the observations in the neighborhood. Geostatistical interpolation techniques incorporate the spatial correlation between neighboring observations (Lang and Barros, 2002; Barros and Lang, 2003).

Several studies have been performed in the mountainous terrain of the Himalayas to determine the processes controlling the precipitation distribution. They carried out a study in the Himalayas to investigate topography and relief on rainfall amount (Lang and Barros, 2002; Barros and Lang, 2003; Anders *et al.,* 2006; Andermann *et al.,* 2011). Wulf *et al.* (2010). Basistha *et al.* (2007) evaluated the deterministic and geostatistical methods for the spatial distribution of rainfall in the Indian Himalayas. In present study, an attempt has been made to estimate the mean annual areal rainfall of the Uttarakhand, India by the arithmetic mean, district weighted average, Thiessen polygon and isohyetal interpolation techniques.

Materials and Methods

Description of study area – With many glaciers, rivers, lush woods, and snow-capped mountain peaks, Uttarakhand is rich in natural resources, notably water and forests, due to its location on the southern slope of the great Himalayas. Uttarakhand is known for its significant peaks, such as Nanda Devi, Kamet, and Kedarnath; important rivers, such as Ganga, Yamuna, Bhagirathi, Alaknanda, Kosi, and Mandakini; and enormous glaciers, such as Gangotri, Nandadevi, Maiktoli, and Chorbani (Basistha, 2008). It has a total area of 53,484 km^2 and is located in North India between the latitudes of 28°42′N and 31°28′N, and the longitudes of 77°35′E and 81°05′E (Fig. 1). The state is split into 13 districts, separated into two administrative divisions: Garhwal and Kumaon.

Monthly and yearly rainfall data for 13 districts in Uttarakhand, seven stations in Uttar Pradesh, and three in Himachal Pradesh were obtained from the India Meteorological Department (IMD),

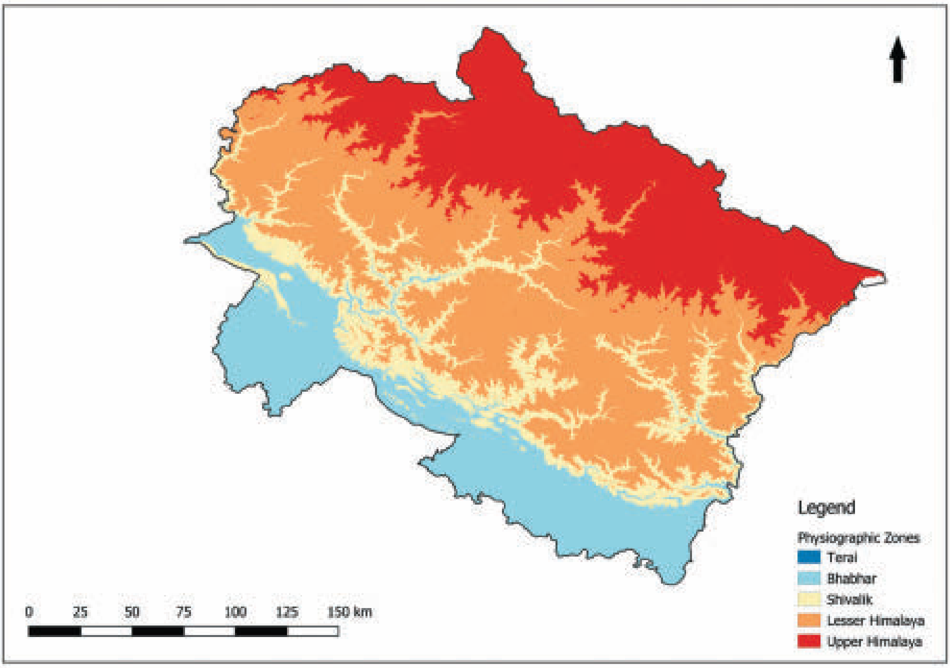

Figure 2. Physiographic classification of the study area.

Pune, from 1951 to 2000 (http://dsp.imdpune.gov.in/). Long-term annual rainfall statistics for four districts in Nepal (Dadeldhura, Darchula, Baitadi, and Kanchanpur) were acquired from the Central Bureau of Statistics, Government of Nepal's Environment Statistics of Nepal (https://wedocs.unep.org).

Physiographical classification of the Uttrakhand state has been done in the five classes (Fig. 2). The Terai is a lowland region in northern India, lying south of the Sivalik Hills and north of the Indo-Gangetic Plain. Tall grasses, scrub savannah, sal forests, and wetlands are characteristics of it. In contrast, Bhabar is a part of the Lower Himalayas and the Sivalik Hills in Uttarakhand, India having an alluvial apron of sediments that washes down from the Shivalik to the north of the Indo-Gangetic Plain.

Mean areal rainfall estimation – Interpolation is the technique of utilising known sample points to estimate values at unknown places. Geographic data such as elevation, rainfall, chemical concentrations and so on may be estimated using this tool. It is the technique of approximating the value of characteristics in areas that lack point observations or data. There are several data interpolation methods, models, and approaches depending on characteristics that influence the quality of the output (Burrough, 1986). Interpolation methods from point data may be categorised into three groups: graphical, topographical, and numerical. Isohyet mapping and Thiessen polygons techniques are graphical. Topographical techniques correlate point rainfall data with a set of topographic and synoptic characteristics, such as slope, exposure, elevation, the position of barriers, and wind speed and direction – inverse Weighted Distance (IDW). Interpolation is a numerical analytic process used to build new data points within the range of discrete known data points.

Arithmetic mean method – This is the simplest and easiest technique of spatial interpolation it takes the simple average of the number of stations (Chow, 1964). As the name implies, the result is produced by dividing the sum of rain depths recorded at various rain-gauge stations across the basin by the number of stations. If the rain gauges are spread equally over the region, and the rainfall fluctuates in a highly regular pattern, the results produced by this approach will be pretty good and will not differ much from those obtained by other methods. This approach may be used to compute storm rainfall, monthly or yearly rainfall averages. Thus, if P_1, P_2, P_3,..., P_i,...P_m are the rainfall values in a given period in m stations within catchment then the value of the mean precipitation P_{avg} is given as:

$$P_{avg} = \frac{\sum_{i=1}^{m} P_i}{m} = \frac{P_1+P_2+P_3 \ldots\ldots P_m}{m} \quad \ldots(1)$$

This method will give reasonable results if the variability among P_i is not too large. If the standard deviation of P_i is <10% of P_{avg}, then the arithmetic average will be an accurate estimator of P_{avg}.

Weighted mean was also calculated using the formula:

$$P = \frac{\sum_{i=1}^{n} P_i A_i}{\sum_{i=1}^{n} A_i} \quad \ldots(2)$$

where,

P_i = rainfall at ith station

A_i = area of ith station

District Weighted Average Value

Uttarakhand state has 13 administrative districts. In this approach the 13 districts of Uttarakhand are weighted averaged with their representative rainfall. The rainfall data for each district is taken as representative. This method is more complex than the arithmetic average method. This method estimates the values at un-sampled points by the weighted average of observed data at district level.

$$P = \frac{\sum_{i=1}^{n} P_i A_i}{\sum_{i=1}^{n} A_{id}} \quad \ldots(3)$$

P_i = rainfall at ith station

A_{id} = area of ith district

Thiessen Polygon Method

The Thiessen polygon technique is a prominent method for calculating average areal rainfall. This approach is primarily based on proximal mapping or finding the nearest distance neighbor (Tabios and Salas, 1985; Basistha et al., 1985). Thiessen polygons perform better than the arithmetic mean technique in estimating regional rainfall averages (Thiessen, 1911). Every time a station is added or removed from the network, the polygon must be updated (Chow, 1964; Nalder et al., 1998). The approach necessitates the creation of a Thiessen polygon network. This approach is not appropriate for hilly locations due to the orographic impact of the rain (Chow, 1964). Thiessen polygons establish an area of influence around their sample point, so any place within the polygon is closer to that point than any of the other sample points. This approach uses nearby samples to count the value of a recognised point by taking the perpendicular bisectors between points. The location and structure of the area are determined by sampling design, the value of interest is measured by a single sample, and space from the point is not considered in the interpolation (Goovaerts, 1999). If P_1, P_2,....P_n are the rainfall magnitudes recorded by the stations $1,2,\ldots,n$ respectively, and $A_1, A_2, \ldots, A_n$ are the respective areas of the Thiessen polygons then the average rainfall P can be computed by the following equation:

$$P = \frac{\sum_{i=1}^{n} P_i A_i}{\sum_{i=1}^{n} A_i} \quad \ldots(4)$$

Isohyetal Method

Based on point measurements, this approach includes drawing estimated lines of equal rainfall or isohyets over a map of the area. Isohyetal maps are frequently utilised with any network design to obtain region averages or to study rainfall patterns. Isohyetal maps, which describe a more precise geographical distribution of rainfall than Thiessen polygons, can be used to determine the total of the investigated region (Hallaq, 2002).

For creating the isohyet, the inverse distance interpolation technique is used in current study. The Inverse Distance Weighting interpolation method assumes that each input point has a local influence that diminishes with distance. The main characteristic of this method is that all the points on the earth's surface are considered to be interdependent, on the basis of distance

The interpolation is performed using following equation:

$$Z = \frac{\sum_{i=1}^{n} z_i * W_i}{\sum_{i=1}^{n} W_i} \quad \ldots(5)$$

where,

Z = interpolated grid-cell value

W_i = the weighting function

Such weighing function (W_i) depends on the distance between the grid cell and the point-in-space observation, and is calculated as:

$$W_i = \frac{1}{d_i^m} \quad \ldots(6)$$

where,

d_i = distance between the grid cell and the point-in-space observation

m = parameter that controls the significance of surrounding points upon the interpolated value.

The Isohyetal technique takes advantage of the watershed region bounded by neighboring isohyets. Isohyetal lines are created on a watershed similarly as topographic lines are drawn on a topographical map, but with precipitation depth as the governing variable rather than height. The mean areal rainfall (MAR) is calculated using this approach as a weighted average of adjacent gauges.

$$MAR_i = \sum T_i P_i \qquad ...(7)$$

where,

MAR_i = the mean areal rainfall

T_i = the isohyetal weight

Computed as: $T_i = A_i/A_T$

where,

A_i = area defined by the two enclosed isohyetal lines

A_T = total area

P_i = the i average rainfall in each sub-area between any two isohyets.

Results and Discussion

The rainfall variation with altitude for different districts of Uttarakhand is shown in Table (1). It is evident that Rudraprayag district receives maximum rainfall of 2150.9 mm and Haridwar receives minimum rainfall of 1143.9 mm. It can also be seen that Udham Singh Nagar is at a minimum elevation of 230 m, whereas Chamoli is at a maximum elevation of 2039 m. Earlier studies on the Himalayan terrain showed a linear relationship between rainfall and elevation in a smaller homogenous region. But on complex terrain, the effect is nullified, and the rain depends on the morphology of local terrain. The rainfall data in the data set in complex terrain is partitioned based on its location in smaller homogenous regions (Kumari *et al.,* 2017). The rainfall data in the months of monsoon (June, July and August) contributes to around 84% of the annual rainfall and pre-monsoon rainfall in the months of (March, April and May) contributes 11%. In contrast, post-monsoon rainfall occurring in the month of (September, October, November and December) is the least (5%).

The maximum rainfall was observed in July, having the value of 39.41 cm, whereas the minimum precipitation occurs in November with 0.82 cm (Fig. 3). In the Thiessen polygon method, rainfall recorded at each station was given a weightage on a polygon closest to the recording station. In this study, 27 stations were chosen to draw Thiessen polygon over the study area. Out of 27 stations, thirteen were from Uttarakhand, three from Himachal Pradesh, seven from Uttar Pradesh, and four from Nepal considered during computation of mean annual rainfall. The basic concept is to divide the study area into several polygons, with each polygon around a measurement point and then take a weighted

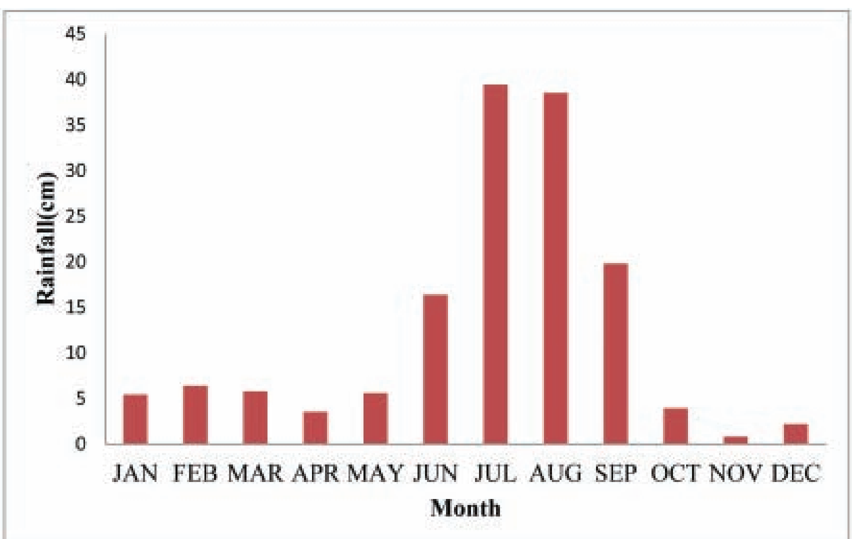

Figure 3. Average monthly rainfall variation from 1901-2015.

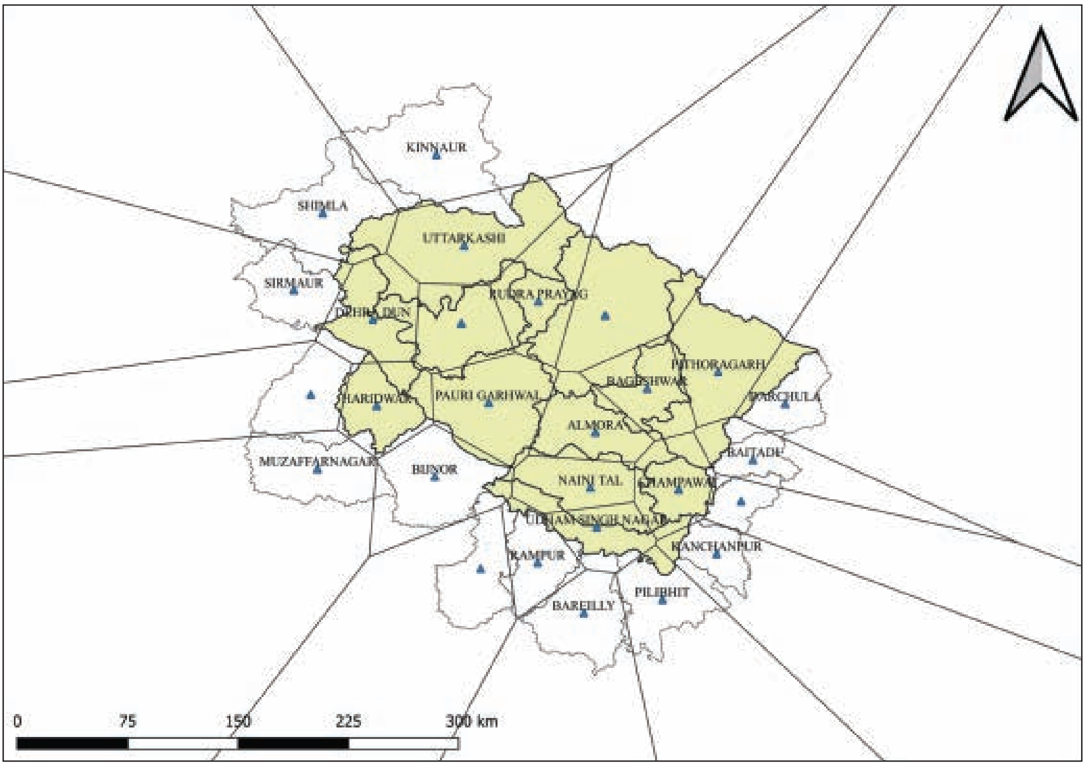

Figure 4. Thiessen polygon method for MAR estimation over the study area.

average of the measurements based on the size of each polygon. The individual weights are multiplied by the rainfall observed at the station, and the values are summed to obtain the MAR. The station in each district was considered to be located at the centroid of the district. Stations were joined to form a network of triangles, and then perpendicular bisectors to each of the sides of the triangle were drawn to create polygons around the stations. Open source QGIS 2.16 software was used for all the spatial interpolation techniques adopted in the current study.

Isohyetal method involves drawing estimated lines of equal rainfall or isohyets over a map of the area based on point measurements. An isohyetal map showing contours of equal rainfall is more accurate picture of the rainfall over the basin. Inverse Distance weight (IDW) technique was adopted to draw isohyetal map of the study area. QGIS 2.16 was used to create contour lines of equal rainfall on the state of Uttarakhand which express the Isohyetal lines. The isohyetal weights were then calculated for each sub-area between the isohyets and subsequent calculation of MAR (Hallaq and Akram, 2002).

In India, the India Meteorological Department (IMD) is in charge of commissioning and maintaining observatories and archiving meteorological data records. The Meteorological Centre, Dehradun, now monitors 24 Automatic Weather Stations (AWS) and 5 Surface Observatory in Uttarakhand. The Indian Standard (IS: 4987-1968) specifies the following densities as adequate for practical considerations of Indian circumstances. In plains: 1 station per 520 km^2, in regions of average elevation of 1000 m: 1 station per 260-390 km^2 and for predominantly hilly areas with heavy rainfall: 1 station per 130 km^2. The density of rain gauges in the state is increasing with time. The present study is restricted due to limited number of rain gauges station.

As per Table 1, the mean areal rainfall (MAR) in Uttarakhand is 1562.7 mm, 1576.2 mm, 1570.6 mm, and 1577.0 mm using the arithmetic mean, district weighted average, Thiessen polygon, and isohyetal interpolation approaches, respectively. The annual volumes of the rainfall over the area of state will be 83579.45, 84301.48, 84001.97 and 84344.26 million cubic meters respectively for arithmetic mean, district

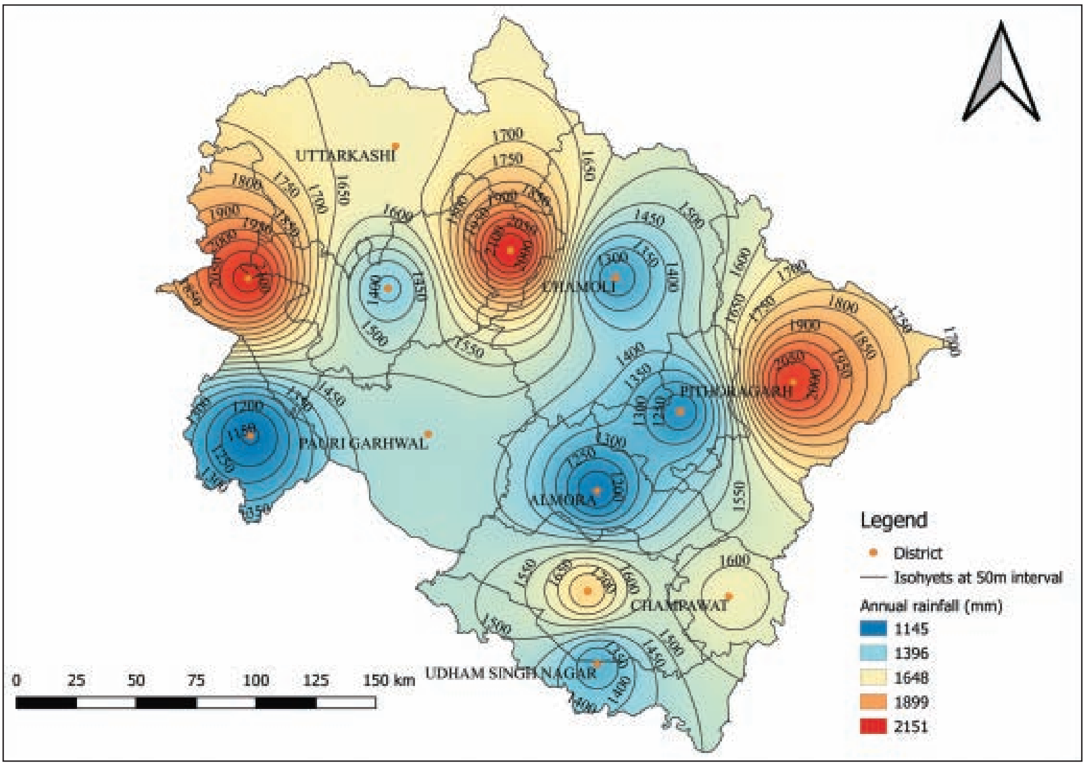

Figure 5. Isohyetal method for MAR estimation over the study area.

Table 1. Comparison of results obtained from various interpolation methods.

Sl. No.	Interpolation methods	Mean Annual Rainfall (mm)
1	Arithmetic Mean	1562.7
2	District weighted average value	1576.2
3	Thiessen polygon	1570.6
4	Isohyetal method	1577.0

weighted average, Thiessen polygon, and isohyetal interpolation approaches. From this study it can be suggested that the mean areal rainfall varies between 1562.7 to 1577, however the difference between the interpolation technique's result is a few mm. In literature isohyetal method is considered most suitable (Tabios and Salas, 1985). The simplest technique is arithmetic mean with least computational efforts.

Conclusion

Precise distribution pattern of rainfall over a region gives the planes useful information and free hand plan accordingly. This study analysed the rainfall pattern of Uttarakhand state and investigate the mean areal rainfall conversion from the point rainfall data. The present study led to the conclusion that the mean areal rainfall (MAR) in Uttarakhand comes out to be 1562.7 mm, 1576.2 mm, 1570.6 and 1577.0 mm according to arithmetic mean, district weighted average, Thiessen polygon and isohyetal interpolation techniques respectively. The rainfall data in the months of monsoon (June, July and August) contributes to around 84% of the annual rainfall. For the Uttarakhand state the maximum rainfall was observed in July, having the value of 39.41 cm, whereas the minimum rainfall occurs in November with 0.82 cm. Using the arithmetic mean, district weighted average, Thiessen polygon, and isohyetal interpolation methods, the mean areal rainfall (MAR) in Uttarakhand are 1562.7 mm, 1576.2 mm, 1570.6 mm, and 1577.0 mm, respectively. According to this study, the mean areal rainfall ranges from 1562.7 to 1577, although the variation among the interpolation techniques results is just a few millimetres. According to the literature, the isohyetal technique is the best, which could be employed for estimation of mean rainfall estimation. However, the simplest approach is the arithmetic mean, which requires the least computational effort and gave result in similar manner, so this could also the alternative of spatial interpolation techniques in current situation.

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