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Estimation of spatial correlation structure of gauged rainfall in network under semi-arid situation of Krishna basin at watershed scale

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Abstract
Kriging serves as a geospatial interpolation method for delineating optimal radial zones around existing rainfall stations within the flat land watershed of Machkula (4D5B3) situated in the Krishna basin. This analysis primarily focuses on smaller (15 and 30 minutes) and medium (45 minutes to 1 hour 45 minutes) rainfall events, examining their spatial distribution. For longer duration events (>2 hours), the analysis emphasizes depth across 22 gauging stations. The study utilizes data from 22 gauged rainfall network stations spanning the period of 2014-2020 to establish relationships between recurring events of varying duration (15 minutes to 2 hours). These relationships are evaluated in terms of the weighted influence of both the number and depth of events, considering the spatial morphology and constraints of the watershed. The spatial distribution of rainfall within the Machkula watershed is found to exhibit significant uniformity in both the number and depth of events within a radial zone extending up to 4 kilometers around each station. This uniformity is supported by strong goodness-of-fit statistics (R^2) exceeding 0.8.

Keywords: Gauged rainfall network, geospatial variability, Krishna basin, morphology, semi- arid, spatial rainfall, rain gauge, spatial correlation

Introduction
Rainfall, a phenomenon marked by continuous variability both spatially and temporally [1, 2], is measured using rain gauges, providing localized representations within a limited spatial scope. However, globally, rain gauge networks are often sparse or even absent, unable to fully capture the true variability of precipitation systems. Our understanding of the impact of spatial variability in rainfall, influenced by both geomorphology and climate, remains limited [3]. There is a pressing need to evaluate the significance of spatial rainfall variability in comparison to basin physiography and climatology. This study aims to assess the spatial reliability of rainfall at the watershed scale (approximately 40,000 hectares) using data from existing stations recorded between 2014 and 2020, focusing on both depth and frequency of rainfall events. Observations suggest that basin physiography plays a mitigating role in lower rainfall intensities, whereas higher intensities are expected to be influenced by other factors [4]. The spatial variability of median and higher rainfall depths, though intricate, exhibits significant correlations with changes in geographical location, latitude, and topography [5].

Materials and Methods
The Machkula watershed (4D5B3) lies within the Krishna Lower basin and traverses through the Kalburgi taluk of Kalburgi District in Karnataka. With a drainage area covering 454.41 square kilometers, it spans from northern latitudes of 17°15’33.47” to 17°25’38.38” and eastern longitudes of 77°6’10.00” to 76°40’8.79”, extending along the main valley for a distance of 70.84 kilometers. Throughout its course, the main valley experiences a significant decrease in elevation, losing 195.00 meters (from 505.00 meters to 310.00 meters RL). Initially flowing eastward for 56.5 kilometers, the valley then changes direction, turning southward to eventually

merge within the Ivni village limits of Kalburgi taluk in Kalburgi District.

Geomorphological and Rainfall Analysis

The hierarchical stream network system and its properties were examined using appropriate methods to quantify shapes and relief, with stream orders ranging from 5th to 3rd (see Fig. 1 and Table 1). The temporal distribution of rainfall was assessed at 15-minute intervals each year across the study period (2014-2020) at 22 gauging stations situated within the selected watershed (see Fig. 1). Rainfall depth for each event duration (in multiples of 15 minutes: 30 min, 45 min, 1 h, 1 h 15 min, 1 h 30 min, 1 h 45 min, and 2 h) was analyzed to investigate variations across the network in terms of frequency (see Table 2). Rainfall events for each year were categorized into two classes: those with durations less than 2 hours and those exceeding 2 hours. The former class underwent analysis of rainfall event frequency, while the latter was examined by assessing the cumulative depth for their respective durations (see Table 4). The frequencies accumulated for each 15-minute interval and their multiples (for durations less than 2 hours) were subjected to interpolation using the kriging method. Similarly, the depths accumulated over the 2-hour period were also subjected to interpolation.

Kriging-Based Geostatistical Approach

Event-wise rainfall data from digital rain gauge systems spanning the observational years (2014-2020) were organized into periods ranging from 15 minutes to larger durations (up to 5 hours) in 15-minute intervals, exhibiting spatial variability across stations, numbering between 150 and 260 (see Table 2). Quality, completeness, and consistency of rainfall data were verified, with any missing or erroneous data promptly identified and removed. Spatial distribution of rainfall was investigated using descriptive statistics and visualization methods. This encompassed generating interpolated maps for mean, standard deviation, and coefficient of variation of rainfall across the study area. Spatial analysis techniques such as variogram analysis, kriging, and geostatistics were employed to analyze the spatial structure of rainfall variability and discern spatial patterns and trends. The accuracy and reliability of statistical models were validated using goodness-of-fit tests (R^2) [6].

Kriging, renowned as one of the best linear unbiased estimators in geographical statistics, involves predicting unknown values at unsampled points by extracting information from surrounding known points. Ordinary kriging linearly estimates unknown data based on weighted observations, minimizing estimation errors and ensuring result consistency through weight constraints determined by the semi-variogram. The variogram function characterizes spatial correlations between rainfall variables and between rainfall and elevation within a stochastic interpolation framework [7].

Rainfall events, categorized into small (15 to 30 minutes), medium (45 minutes to 1 hour 45 minutes), and large duration (exceeding 2 hours), were analyzed across 22 gauging stations in terms of frequency using both kriging and descriptive statistics (see Table 3). Events with a duration of 2 hours were assessed for their spatial extent and depth distribution across stations at 15-minute intervals (see Table 4). The likelihood of rainfall events occurring within buffer distances ranging from 1.0 km to 6.0 km around each rain gauging station was estimated, with statistical inference performed to evaluate event means. Additionally, the rate and extent of cumulative rainfall event spread and intensity across all stations were evaluated at each 15-minute interval for probable depth occurrences within the buffer radial distances.

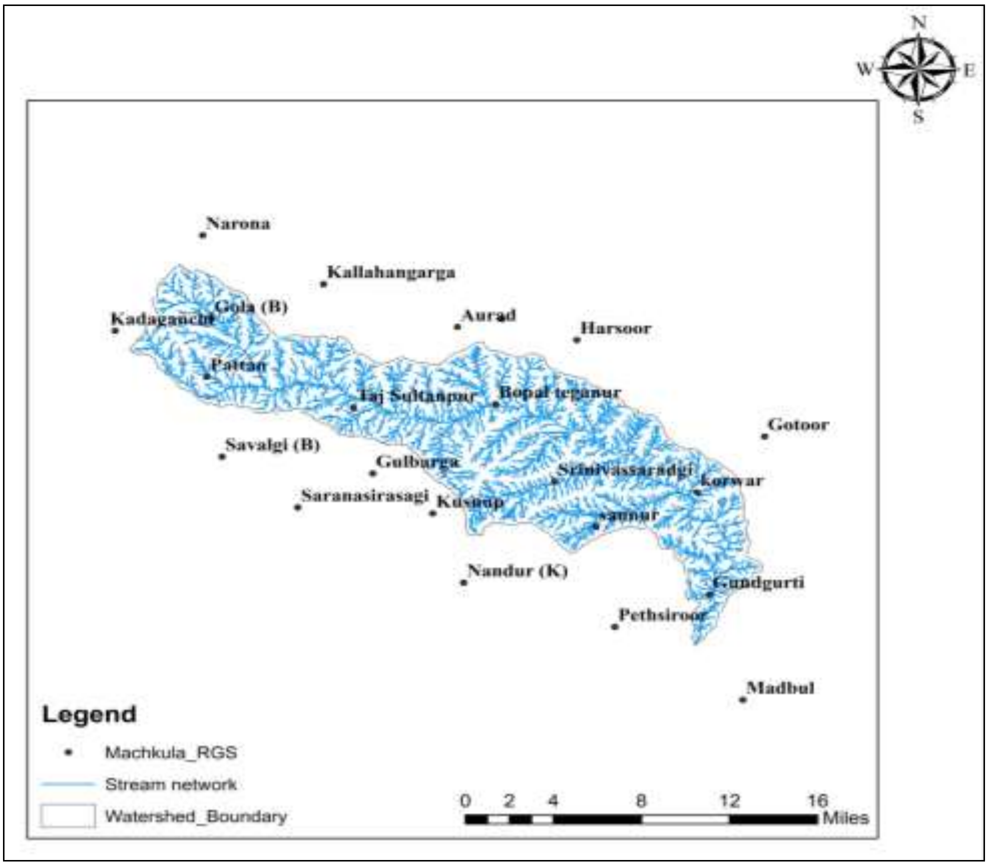


Fig 1: Study watershed (Machkuka) prevailed with semi-arid climatic condition watershed with area of 45,440 ha in Kalaburagi District of Karnataka

Table 1: Stream network properties of Machkula watershed (4D5B3) in Kalaburagi District of Karnataka

Stream network	Watershed scale	Time of concentration range (min)	Number of stream network (No.)	Range of Main valley length (km)	Area (ha)	Relief Ratio (percent)	Elongation ratio	Circular ratio	Bifurcation ratio	Compactness coefficient (Cc)	Shape factor
6th	Synoptic scale	500.24 and 577.31	1	70.84	45441	0.28			3.42-6.37		
5th		450-400	-	-	-	-	0.39-0.61	0.30-0.48		1.44-1.83	3.40-8.56
		250-200	4	13.42-17.77	30-49	0.45-0.77					
		200-150	1	8	15	0.65					
		150-100	1	7.1	15	0.73					
4th	Meso scale	211-150	4	8.67-12.22	1661-2838	0.47-0.71	0.38-0.62	0.35-0.59	0.25-0.75	1.31-1.99	3.21-8.78
		150-100	20	4.12-7.93	373-1272	0.67-1.34					
		100-50	4	2.15-4.07	144-387	0.87-2.31					
3rd		211-150	-	-	-	-	0.35-0.74	0.25-0.70		1.19-2.01	2.31-10.34
		150-100	32	2.63-6.76	135-745	0.27-1.11					
		100-50	98	1.39-4.23	46-410	0.39-3.04					
Total			165								

Table 2: Distribution of rainfall events (15 min to more than 5 h period) received across situated Rain gauge stations (22 No) during 2014-20 across rain gauging station.

Year	Small duration events		Medium duration events					Large duration events			
	15 min RF event (No	30 min RF event (No)	45 min RF event (No)	1 h RF event (No)	1 h 15 min RF event (No)	1 h 30 min RF event (No)	1 h 45 min RF event (No)	2-3 h RF events (No)	3-4 h RF events (No)	4-5 h RF events (No)	>5 h RF events (No)
2014	70-228	23-50	9-23	4-13	2-11	1-7	0-8	3-9	0-3	0-1	0-1
2015	21-104	6-40	1-24	1-16	0-11	0-5	0-7	0-7	0-1	0-1	0-1
2016	81-174	20-52	13-24	3-17	1-10	0-7	0-3	4-14	2-18	0-2	0-4
2017	18-346	5-42	1-20	1-14	0-9	0-9	0-6	0-10	0-7	0-3	0-2
2018	16-144	3-46	2-17	0-13	1-11	0-6	0-5	0-6	0-2	0-1	0-1
2019	33-193	7-54	1-22	1-17	1-14	0-6	0-5	0-7	0-3	0-1	0-0
2020	10-233	7-54	4-31	1-17	0-14	0-11	0-7	0-15	0-4	0-2	0-3
Average	58-145	16-40	8-19	3-11	3-8	1-6	0-4	3-7	0-3	0-1	0-1

Table 3: Goodness of fit (R^2) of predicted rainfall events (15 min to more then 5 h duration) with incremental radial distance (1km to 6Km) around each gauging station

Year	Small duration events		Medium duration events					Large duration events			
	15 min	30 min	45 min	1 h	1 h 15 min	1 h 30 min	1 h 45 min	2-3 h	3-4 h	4-5 h	>5 h
2014	0.80	0.79	0.78	0.79	0.81	0.65	0.29	0.28	0.25	0.08	0.11
2015	0.83	0.85	0.79	0.82	0.80	0.45	0.44	0.39	0.21	0.85	0.41
2016	0.84	0.85	0.81	0.81	0.82	0.76	0.59	0.54	0.30	0.18	0.22
2017	0.81	0.80	0.81	0.83	0.81	0.53	0.65	0.57	0.26	0.53	0.16
2018	0.80	0.78	0.79	0.81	0.80	0.59	0.62	0.55	0.23	0.76	0.73
2019	0.74	0.75	0.80	0.78	0.80	0.56	0.47	0.42	0.28	0.15	0.11
2020	0.79	0.83	0.82	0.77	0.80	0.53	0.50	0.43	0.22	0.49	0.68

Table 4: Variability of Cumulative rainfall depth (mm) of rainfall events (7) of Longer duration (2 h) observed at Rainfall gauging stations (14 No) located in Huti-2 watershed

Year	Date and time	15 min RF (mm)	30 min RF (mm)	45 min RF (mm)	1 h RF (mm)	1 hr 15 min RF (mm)	1 hr 30 min RF (mm)	1 hr 45 min RF (mm)	2 hr RF (mm)
2014	28/08/2014 (1:00 am- 2:45 am and ± 30 min time lag)	0-5	0-7	0-17	0-25.5	0-32	0-38	0-42.5	0-45
2015	11,12/08/2015 (23:00 pm – 1:00 am and ± 30 min time lag)	0-7	0-12.5	0-16	0-19	0-21.5	0-22	0-22.5	0-23
2016	14/09/2016 (20:15 pm-22:00 pm with ± 30 min time lag)	0-2	0-3.5	0-5	0-6.5	0-8.5	0-10	0-10.5	0-11.5
2017	12/06/2017 (20:15 am-22:00 am with ± 30 min time lag)	0-28.5	0-30	0-34.5	0-40	0-46.5	0-47.5	0-48.5	0-49
2018	6,7/06/2018 (22:15 pm-:00 am with ± 30 min time lag)	0-2.5	0-10.5	0-12.5	0-13	0-14	0-15	0-16	0-16.5
2019	21,22/06/20109 (23:15 pm-1:00 am with ± 30 min time lag)	0-8.5	0-23	0-29.5	0-30	0-30.5	0-31	0-32	0-35.5
2020	14/10/2020 (04:00 am-05:45 am with ± 30 min time lag)	0-13	0-49	0-55.5	0-57.5	0-58.5	0-66	0-74.5	0-80
Mean		10	19	24	27	30	33	35	37

Table 5: Goodness of fit (R^2) of predicted rainfall depth (2 h duration) with buffering radius (1-6Km) corresponding to each gauging station

Year	15 min	Cumulative 30 min	Cumulative 45 min	Cumulative 1 hr	Cumulative 1 hr 15 min	Cumulative 1 hr 30 min	Cumulative 1 hr 45 min	Cumulative 2 hr
2014	0.76	0.86	0.79	0.78	0.76	0.84	0.77	0.81
2015	0.24	0.47	0.31	0.27	0.37	0.36	0.35	0.36
2016	0.85	0.87	0.82	0.74	0.74	0.83	0.83	0.82
2017	0.62	0.75	0.87	0.87	0.85	0.86	0.80	0.87
2018	0.04	0.00	0.07	0.27	0.31	0.27	0.52	0.52
2019	0.49	0.48	0.36	0.51	0.52	0.44	0.47	0.53
2020	0.74	0.79	0.81	0.87	0.84	0.82	0.84	0.83

Results and Discussion

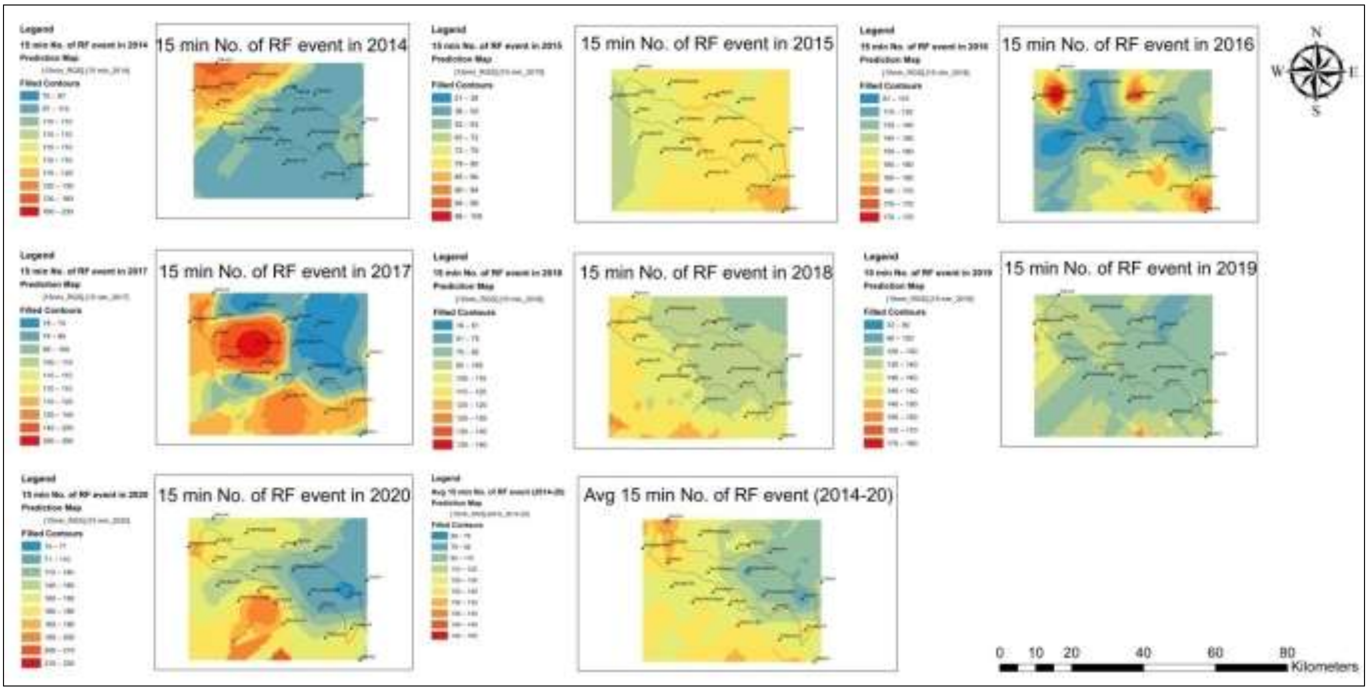
The hypothesis regarding the limited radial extent of variance in rainfall distribution concerning depth, frequency, and intensity has been investigated and tested within the confines of the Machkula watershed, a representative flat land watershed spanning 45,440 hectares in the Krishna basin [7]. The Machkula watershed, characterized by semi-arid conditions, typically experiences a large number of rainfall events, primarily comprising smaller durations (15 to 30 minutes) and medium durations

(45 minutes to 1 hour 45 minutes), with fewer occurrences of larger durations (>2 hours). Analysis of rainfall events spanning from 2014 to 2020 across 22 rainfall gauging stations reveals varying occurrences: small duration events ranging from 3 to 346 occurrences, medium duration events ranging from 0 to 17 occurrences, and only a few instances of longer duration events ranging from 0 to 14 occurrences. This variability highlights the intricate nature of rainfall occurrence both spatially and temporally within the watershed's extent [8].

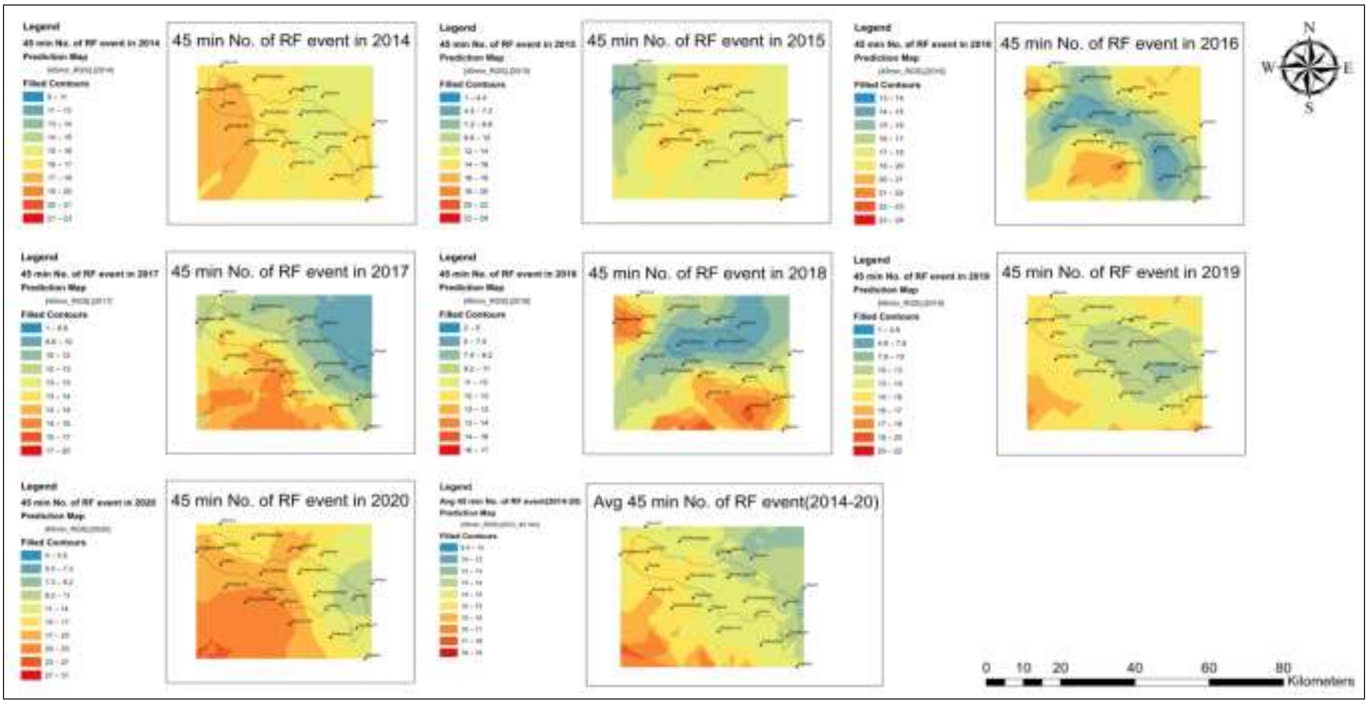
The observed variability underscores the necessity to evaluate spatial differences, serving as a precursor to determining the optimal positioning of rain gauging stations within the watershed area. Given that short and medium-range rainfall events are more numerous but generally have lower depth, their analysis is conducted separately. Conversely, a limited number of longer duration events (7 instances) lasting 2 hours are examined to understand the intensity of their spread across all gauging stations over time, at 15-minute intervals until their cessation.

Using ordinary kriging with a circular model, interpolation was performed for both the number of events for short, medium, and large durations, and the depths for events lasting more than 2 hours. This interpolation considered probable distinctions within radial distances ranging from 1 to 6 km, incremented by 1 km from each station. The depth of accumulation within the buffering zone, varying from 1 km to

6 km, was influenced by the intensity and duration of each event. Across all 22 gauging stations, the measured rainfall events at 15-minute intervals ranged from 58 to 145 instances (see Fig. 3 (a)). This decreased to 16-40 instances for 30-minute events, followed by 8-19 for 45-minute events (see Fig. 3 (b) and Table 2). The trend continued with decreasing numbers as the duration increased: 3-11 for 1-hour events, 3-8 for 1 hour 15 minutes events, 1-6 for 1 hour 30 minutes events, 0-4 for 1 hour 45 minutes events, 3-7 for 2 to 3-hour events, 0-3 for 3 to 4-hour events, and 0-1 for 4 to 5-hour events and events exceeding 5 hours [9]. This variability reflects the fluctuating nature of rainfall under prevailing semi-arid conditions with lower elevations (300-400 m MSL) situated on the leeward side of the Western Ghats in southern India.

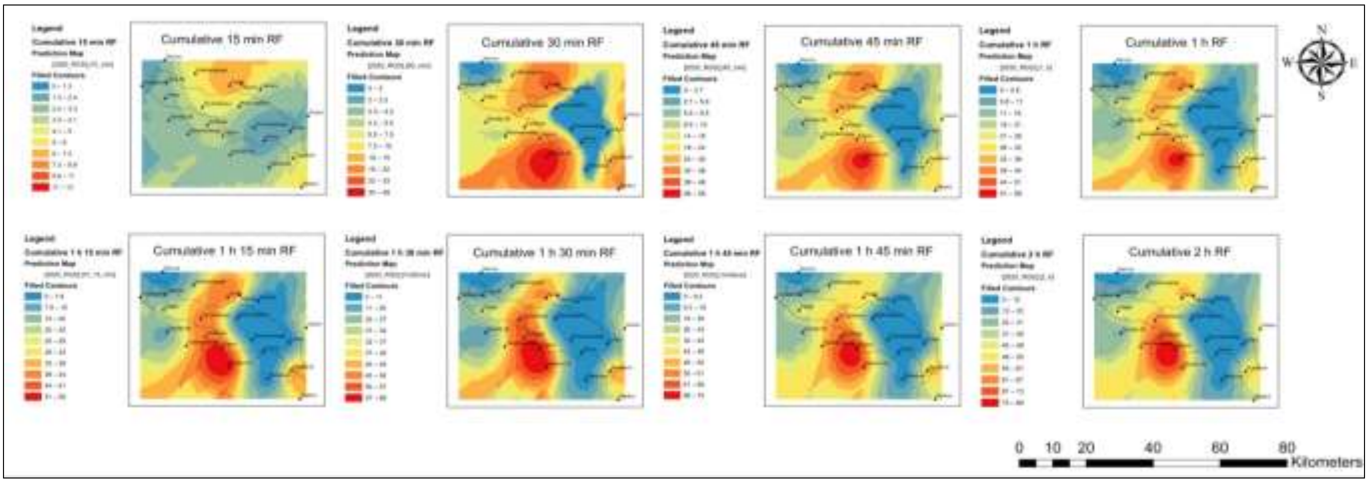


(a)

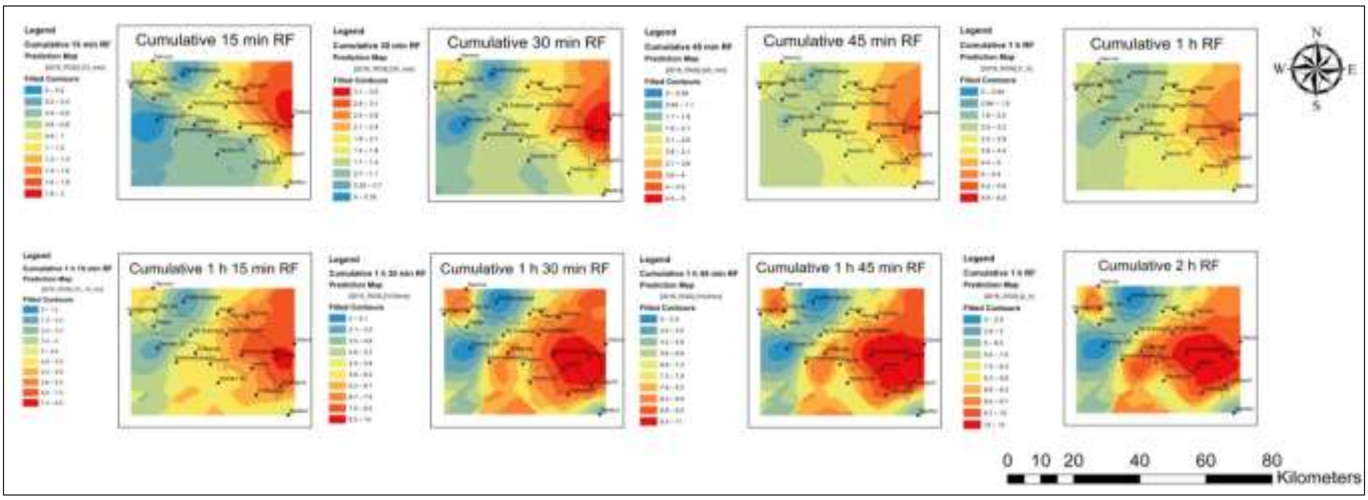


(b)

Fig 3: Distribution of interpolated rainfall events (No) across watershed due to prevailing rain gauging stations with duration (a) 15 min (b) 45 min



(a)



(b)

Fig 4: Sequential interpolated distribution of rainfall depth at 15 min interval measured across existing gauging station (a) event date 14th October 2020 (depth 80 mm), (b) event date 12th June 2016 (depth 11.5mm)

The cumulative depth of rainfall was recorded at 15-minute intervals for durations ranging from 15 minutes to 2 hours. Among these, 7 events were selected for their extensive coverage and significant depth. The maximum depth for a 2-hour event was observed in 2020 (80 mm), while the minimum was recorded in 2016 (11.5 mm), as indicated in Table 4 and depicted in Figure 4 (a) and (b). These findings align with similar results reported by [10].

The range of goodness of fit (R^2), serving as an estimator of spatial correlation, varied annually between rainfall events (number) and incremental radial distance from each station within the watershed. This range extended randomly from 0.11 to 0.85, as documented in Table 3.

For rainfall events lasting longer than 2 hours, the cumulative depth (mm) was analyzed within a reliable influencing zone extending up to a radial distance of 4 km ($R^2 > 0.8$), based on more than 5 years of data, except for three years (2015, 2018, and 2019) where the R^2 value decreased to 0-0.53 (Table 5). These findings suggest that the radial influence within a 4 km range from the gauging station within the watershed can reliably highlight the impact of topographic relief, landforms, and the watershed's location relative to mean sea level. This influence on rainfall patterns indirectly affects the optimal positioning and number of rain gauges in network configurations [11-13].

Conclusions

The rainfall analysis revealed pronounced regional trends, with rainfall increasing from the Bengal branch in the southeast to the northeast. Locally, significant correlations were observed with aspects such as aspect, topography, slope, and altitude. A distinct daily pattern emerged, with the majority of rainfall occurring in the afternoon, between 14:30 and 20:00, followed by a secondary peak in the early morning hours, from midnight to 4:30 am. Rainfall events lasting 15 and 30 minutes are highly localized and likely influenced by local microclimates. In contrast, longer duration rainfall events are more uniformly distributed across the watershed, influenced by factors such as elevation, geographic location (latitude and longitude), vegetation, and land cover. The depth of rainfall in the study area is influenced by the direction of wind flow, movement of clouds, and distance from the sea shore. Spatial variability in rainfall is significant across different locations. However, rainfall exhibits strong correlations at distances of up to 4 km, with a goodness of fit (R^2) exceeding 0.8.

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