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RESEARCH ARTICLE

Spatiotemporal analysis of rainfall and water levels in Kuala Krai, Kelantan, from 2009 to 2020: interpolation, trend assessment and flood risk ,apping

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ABSTRACT

Kelantan experiences annual flood events, many of which are triggered by rainfall exceeding historical norms. This study investigates the spatiotemporal patterns of rainfall and water levels in Kuala Krai, Kelantan, Malaysia, using data collected from 2009 to 2020 by the Department of Irrigation and Drainage (DID). Missing data were addressed through arithmetic mean interpolation, and trend analyses were conducted using the Mann-Kendall test. The total rainfall ranged from 28,698.3 mm to 30,610.4 mm across Dabong, Ldg. Kuala Gris, Kg. Laloh, Ldg. Lepan Kabu, Ldg. Kuala Nal, and JPS Kuala Krai, reflecting spatial variability in precipitation within the district. Among these stations, Dabong recorded the highest average monthly rainfall at 212.572 mm, followed closely by Ldg. Kuala Nal at 210.868 mm. The comparison between interpolated and missing rainfall datasets was minimal at Dabong station (average 0.286 mm; total 41.4 mm), indicating that the observed data were largely complete and reliable. By contrast, Kg Laloh station recorded the highest difference (average 7.287 mm; total 1049.3 mm), suggesting substantial gaps in the original dataset and a heavy reliance on interpolation to reconstruct rainfall values. According to the map created in the present study, the high-risk flood-prone area is concentrated in the central part of Kuala Krai, where almost 70% of the district was inundated during major flood events. The findings emphasise the significance of precise rainfall monitoring and underscore the wider effects of extreme weather on hydrological systems and community readiness.

1. INTRODUCTION

Kelantan, on the east coast of Peninsular Malaysia, has experienced several devastating floods, making flooding an almost annual occurrence in the state (Majid et al., 2021). The first major flood in 1967 affected about 70% of the population (Muhammad et al., 2020), while the 2014 flood, locally known as *Bah Kuning* due to its high mud content, was the most catastrophic in recorded history. It forced more than 200,000 people to leave their homes and was called a "tsunami-like disaster (Ng et al., 2024; Bahar et al., 2020). These events underscore the close relationship between extreme rainfall, hydrological responses, and severe flood disasters in Kelantan.

The complex relationship between rainfall variability, flooding occurrences, and climate dynamics is therefore of paramount importance in understanding the environmental vulnerabilities of Kelantan. Within this context, Kuala Krai has emerged as a focal study area due to its geographical characteristics and repeated exposure to extreme rainfall and recurrent floods (Muhammad et al., 2021). Investigating the spatio-temporal dynamics of rainfall in this district offers vital information about the hydrological factors influencing flood risk and long-term climate trends.

Rainfall, a primary climatic variable, influences the natural environment and dictates the frequency and intensity of floods, directly affecting agriculture, infrastructure, and community resilience. In Kuala Krai, fluctuations in rainfall intensity and distribution have disrupted local hydrological systems and increased the incidence of flood disasters. Understanding these patterns is thus crucial for the development of effective flood management and climate adaptation strategies.

To support such understanding, this study conducted a preliminary assessment of rainfall and water level dynamics in Kuala Krai, using data from 2009 to 2020. The dataset was limited to this period because complete and validated records beyond 2020 were not yet available at the time of analysis. Accurate estimation of rainfall across the district is essential, yet rainfall data are often spatially sparse due to the limited number of rain gauge stations. To address this challenge, interpolation methods were applied to generate continuous spatial rainfall surfaces from point-based observations. These methods are vital in bridging data gaps (Salami, 2024), improving the representation of rainfall distribution, and enhancing the reliability of subsequent flood risk analysis and mapping.

2. METHODOLOGY

2.1 Study Area

This research was conducted in Kuala Krai, Kelantan, Malaysia (Figure 1). Tropical rainforests have historically covered the hilly terrain of the district. It shares borders with Machang to the north and Gua Musang to the south. Kuala Krai is particularly suitable as a study area due to its geographical setting and repeated exposure to flood events (Muhammad et al., 2020). Located at the confluence of several tributaries that feed into the Kelantan River, the district is highly vulnerable to intense rainfall and subsequent flooding (Muhammad et al., 2021). Rural villages situated near the riverbanks are especially prone to flood hazards, with past events resulting in significant loss and disruption.

The area has experienced recurrent and severe flood events, most notably the catastrophic 2014 flood, which displaced thousands of residents and caused widespread damage. This frequency and severity of flooding highlight the importance of detailed hydrological and climatological analyses in Kuala Krai. Rainfall variability across the district further contributes to its vulnerability, making the study of spatio-temporal rainfall dynamics particularly relevant.

2.2 Data Collection

This study collected both primary and secondary data. Primary data was obtained by performing geological mapping to produce a flood-prone map. The information taken when doing the mapping is geographical information such as topography, land use, river morphology, and the demographics of the study area. Elevation and ground clearance value data were collected and marked using GPS during mapping.

Secondary data was obtained from authoritative organisations, such as the Department of Irrigation and Drainage (DID). This study required rainfall distribution and water level data to be processed in producing a map. This study analyses data from 6 rainfall stations and 2 water level stations in Kuala Krai, Kelantan. The data was collected from 2009 to 2020. The United States Geological Survey (USGS) website was used to obtain satellite images and land use data. Digital Elevation Model (DEM) was also used to look into the influence of geology on the geomorphological features of the land. All elevation data and subsequent derivations, like slope and aspect, were calculated from the created DEM.

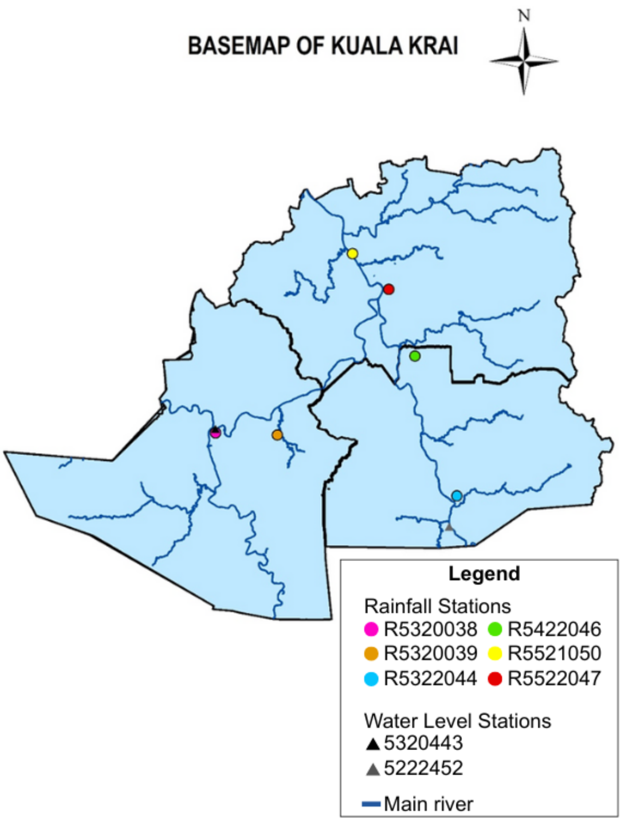

Figure 1: Basemap of Kuala Krai, Kelantan, with rainfall and water level stations.

Secondary data was obtained from authoritative organisations, such as the Department of Irrigation and Drainage (DID). This study required rainfall distribution and water level data to be processed in producing a map. This study analyses data from 6 rainfall stations and 2 water level stations in Kuala Krai, Kelantan. The data was collected from 2009 to 2020. The United States Geological Survey (USGS) website was used to obtain satellite images and land use data. Digital Elevation Model (DEM) was also used to look into the influence of geology on the geomorphological features of the land. All elevation data and subsequent derivations, like slope and aspect, were calculated from the created DEM.

2.3 Data Interpolation

The arithmetic average (AA) method is the simplest method typically used to fill in the missing meteorological and hydrological data (Ismail et al., 2017). Rainfall and water level data missing from a particular station can be recovered by taking an average over a group of stations geographically close on the same date as the station of interest but from different years.

2.4 Flood Analysis

2.4.1 Flood trend analysis

Mann-Kendall statistics (S) for a time series $x_1, x_2, x_3, ...$, x_n are calculated as described by Sa'adi et al. (2019).

$$S = \sum_{k=1}^{n-1} \sum_{i=k+1}^{n} sgn(x_i - x_k), \#(1)$$

The application of the trend test is done to a time series x_i that is ranked from $i = 1,2,3, \ldots, n-1$ and x_j, which is ranked from $j = i + 1,2,3, \ldots, n$. Each of the data points x_i is taken as a reference point, which is compared with the rest of the data points x_j, so that the signum function (sgn) is

$$sgn(x_i - x_k) = \{+1 \ if \ (x_i - x_k) > 0 \ 0 \ if \ (x_i - x_k) = 0 \ -1 \ if \ (x_i - x_k) < 0 \ \#(2)$$

It has been documented that the sample size plays a significant role in the normal distribution (Krithikadatta, 2014).

$$E(S) = 0 \ \#(3)$$

The variance statistic is given as;

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} \ t_i(i)(i-1)(2i+5)}{18} \ \#(4)$$

where t_i is considered as the number of ties up to the sample i. The test statistics Z_c is computed as

$$Z_c = \{\frac{S-1}{\sqrt{Var(S)}} \qquad 0, S = 0 \qquad \frac{S+!}{\sqrt{Var(S)}}, S < 0 \ \#(5)$$

Z_c here follows a standard normal distribution. A positive value of Z signifies an upward trend, while a negative value of Z signifies a downward trend. A significance level α is also used to test an upward or downward trend. If Z_c where α depicts the significance level, then the trend is considered significant.

2.4.2 Flood risk mapping

The data collected during the field study were recorded and processed using the Geological Information System (ArcGIS) software to produce a flood risk map. The DEM was processed using elevation data. The topographic map for the study was analysed during fieldwork. The DEM data were analysed to identify the morphology, such as the land surface, that is used to represent the hydrological process. The DEM can also be used to perform a slope analysis. The overall procedures were evaluated using a GIS environment. The slope of the land in the river flow area plays an important role in determining the water velocity. Moreover, the steeper the slope, the higher the run and, consequently, the higher the peak discharge. Flow accumulation is one of the methods of determining the drainage network and area. All the depressions in the DEM will be conducted using a spatial analysis tool to ensure that the data is perfect. This method was developed to identify water accumulation points using the flow accumulation tool and a flow direction raster as input. For areas with concentrated flow, output cells with a high accumulation will be identified and used to create stream channels or networks.

3. RESULTS AND DISCUSSION

3.1 Trend Analysis of Rainfall Data

3.1.1 Descriptive statistics of rainfall stations and the dataset from 2009 to 2020.

Table 1 presents the descriptive statistics of six rainfall stations in Kuala Krai from 2009 to 2020, including records with missing data. The total rainfall ranged from 28,698.3 mm to 30,610.4 mm across Dabong, Ldg. Kuala Gris, Kg. Laloh, Ldg. Lepan Kabu, Ldg. Kuala Nal, and JPS Kuala Krai, reflecting spatial variability in precipitation within the district. Among these stations, Dabong recorded the highest average monthly rainfall at 212.572 mm, followed closely by Ldg. Kuala Nal at 210.868 mm, suggesting that these locations experienced more frequent or intense rainfall events compared to others. According to Udin et al. (2018), Dabong experienced a major flood event in 2014, largely triggered by excessive and prolonged rainfall. However, the increased water depth along the Galas River was not solely due to meteorological factors. Anthropogenic activities and natural hazards also played a significant role. Over time, human interventions such as sand mining, deforestation, and unplanned agricultural practices have altered the natural topography of Dabong, reducing the land's ability to absorb rainfall and increasing surface runoff. These changes collectively intensified the flooding event and its subsequent impact on the surrounding communities.

In terms of rainfall variability, the highest standard deviation was observed at Ldg. Kuala Nal (191.328 mm), indicating greater fluctuations in monthly rainfall totals at this station. At present, most weather stations rely on rain gauge networks that continuously record rainfall accumulation over time, providing valuable measurements of temporal variability in rainfall intensity. However, because rain gauges capture only point-based data, their measurements may not accurately represent broader spatial patterns due to the high spatial variability of rainfall across different locations (Cristiano et al., 2017). In addition, such variability could be further attributed to localised topographic or climatic factors, such as orographic effects or proximity to major river systems that merit further investigation. Interestingly, Ldg. Kuala Nal has also been identified as one of the key locations within the Kelantan River Basin where early flood warning systems have been developed and installed (Anuar et al., 2017). The choice of this site highlights its hydrological significance, as significant fluctuations in rainfall frequently lead to increased flood risks and responsive catchment dynamics. This correlation suggests that the significant fluctuations observed in this study are consistent with its strategic role in regional flood monitoring and early warning initiatives. Previous studies have actively explored the relationship between rainfall, topography, and geographical features across various time scales using diverse techniques, including geostatistical methods (Shetty et al., 2022). Therefore, the pronounced variability at Ldg. Kuala Nal reflects its climatic sensitivity and validates its suitability as a critical node in the early warning infrastructure for flood management in the Kelantan River Basin.

Conversely, stations with lower standard deviations may experience more consistent rainfall patterns throughout the year. These preliminary findings, derived from descriptive statistics, offer basic information about rainfall distribution and temporal variability in the Kuala Krai region, which are crucial for subsequent trend analysis. As highlighted by Feidas et al. (2014), summary statistical measures can be effectively employed to explore the underlying mechanisms linking climate with topographical and geographical features.

Table 1: Descriptive analysis for rainfall datasets from 2009 to 2020 in Kuala Krai.

Station	Latitude (N)	Longitude (E)	Average (mm)	Maximum (mm)	Total (mm)	Standard Deviation (mm)
Dabong	5.378	102.015	212.572	1340.1	30610.4	173.759
Ldg Kuala Gris	5.375	102.082	208.240	1177.0	29986.5	150.632
Kg Laloh	5.308	102.275	199.294	1254.5	28698.3	162.242
Ldg Lepan Kabu	5.460	102.231	199.767	1338.0	28766.5	184.043
Ldg Kuala Nal	5.571	102.164	210.868	1414.5	29844.5	191.328
JPS Kuala Krai	5.532	102.203	200.815	1208.4	28917.4	186.827

3.1.2 Total of annual rainfall for 2009 - 2020

Figure 2 illustrates the total annual rainfall recorded over 12 years (2009-2020) at six rainfall stations in Kuala Krai, Kelantan. The Dabong station observed a noticeable peak in total annual rainfall in 2020, suggesting a possible anomaly or unusually wet year. Regional weather disturbances like the Northeast Monsoon, known to influence rainfall intensity in Peninsular Malaysia, may be associated with this peak. A study by Shukor et al. (2020) also found that Dabong had the highest annual rainfall increase in the Kelantan region, which backs up the results of this study even more. This consistent observation suggests that Dabong experiences significant long-term increases in precipitation, likely influenced by both regional climatic patterns and local geographical factors.

In addition to 2020, the years 2009, 2013, 2014, and 2017 also recorded higher rainfall totals compared to other years. These years coincide with major flood events reported in Kelantan, supporting previous studies by Alias et al. (2016), Zulkepli et al. (2022), Muhammad et al. (2020), and Shakirah et al. (2016), which established a direct link between excessive rainfall and flooding in the region. This study suggests that rainfall anomalies may serve as precursors or contributing factors to hydrological disasters, particularly in flood-prone districts such as Kuala Krai.

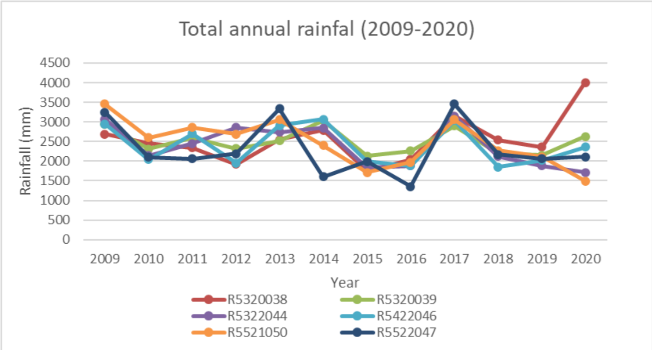

Figure 2: Graph of total annual rainfall (2009-2020).

Furthermore, inter-station variability in annual rainfall trends is evident. For instance, while Dabong experienced the highest total in 2020, other stations such as Ldg. Kuala Nal and Kg. Laloh exhibited peak rainfall in different years, possibly influenced by local topography, land-use changes, or microclimatic effects as reported by te Wierik (2021). This spatial variation points to the need for site-specific monitoring and forecasting to strengthen early warning systems and disaster preparedness. Recent work by Calvo-Solano (2024) examined the global landscape of research on continental flood early warning systems, highlighting significant trends, geographic disparities, and emerging research priorities. These insights underscore the need for more localised and data-driven approaches, particularly in regions such as Kelantan, where hydrological variability is pronounced and flood vulnerability remains high.

3.1.3 Trend analysis of rainfall using Mann-Kendall

The results of the Mann-Kendall trend analysis are summarised in Table 2. Among the six rainfall stations assessed in Kuala Krai, only Dabong and JPS Kuala Krai exhibited positive S statistics (637 and 130, respectively), indicating a slight upward trend in annual rainfall over the 12-year period. In contrast, the remaining four stations: Ldg. Kuala Gris, Kg. Laloh, Ldg. Lepan Kabu, and Ldg. Kuala Nal are displayed negative S values, suggesting a downward trend in rainfall. Despite these observed trends, none of the stations recorded a statistically significant result at the 5% significance level, as all p-values were greater than 0.05. This implies that fluctuations in rainfall over time may be attributed to natural variability rather than a persistent or directional climatic shift. These findings are consistent with those reported by Muhammad et al. (2021), who similarly noted the absence of statistically significant rainfall trends across selected stations in Kelantan using the same non-parametric approach.

Comparable outcomes were observed in Sarawak (Sa'adi et al., 2019), where Sang et al. (2015) reported that while the Mann-Kendall test indicated an increasing rate of rainfall during the Northeast monsoon and drier conditions during the Southwest monsoon, the modified Mann-Kendall test revealed no statistically significant trend for either season. This suggests that apparent fluctuations may not represent long-term climatic changes but rather seasonal or localised variations. Applying similar reasoning to the present study, the absence of significant trends in Kuala Krai may reflect the influence of complex monsoonal dynamics and local topographical conditions, which modulate rainfall distribution without establishing a clear long-term trajectory. Such insights emphasise the importance of incorporating both seasonal and spatial perspectives in rainfall trend analysis to enhance the precision of forecasting and strengthen regional flood early warning systems and disaster preparedness.

Table 2: Mann-Kendall analysis of rainfall data

Station	Kendall's Tau	S	Var(S)	p-value	Alpha
Dabong	0.062	637	335182.3	0.272	0.05
Ldg Kuala Gris	-0.016	-165	335178.3	0.777	0.05
Kg Laloh	-0.102	-1049	335177.7	0.070	0.05
Ldg Lepan Kabu	-0.004	-44	335176.0	0.941	0.05
Ldg Kuala Nal	-0.079	-814	335181.3	0.160	0.05
JPS Kuala Krai	0.013	130	335168.7	0.824	0.05

3.2 Trend Analysis of Water Level

3.2.1 Descriptive statistics of water level stations and dataset from 2009 to 2020

A descriptive analysis is presented in Table 3. Water level data from two stations were analysed using descriptive statistics, including latitude, longitude, average, maximum, and total values. The range values for the Sungai Galas and Sungai Lebir stations were 842.34 m and 1351.24 m, respectively. The Sungai Galas station recorded a higher average and maximum water level compared to Sungai Lebir. The difference in total annual water levels between the two stations (508.9) was large, indicating substantial hydrological variability within the Kuala Krai river system. The higher mean and peak levels at Sungai Galas may be attributed to its lower elevation and wider catchment area, which enhance runoff accumulation during periods of intense rainfall (Han et al., 2014). This observation aligns with rainfall peaks recorded at nearby stations such as Dabong and Ldg. Kuala Nal, highlighting the strong rainfall-runoff interaction within the basin. The pronounced variability also suggests a higher susceptibility of the Sungai Galas sub-basin to flood occurrence, particularly during the Northeast Monsoon season. This observation aligns with the findings of Kundzewicz (2019), who emphasised that variability in flood-related variables, such as rainfall intensity, river discharge, and water level, can significantly influence the frequency and magnitude of flood events. According to Kundzewicz, increased variability within hydrological systems not only heightens the likelihood of extreme flooding but also reduces the reliability of conventional flood forecasting models, particularly in regions experiencing climatic oscillations and irregular precipitation patterns. In the context of the current study, the variable water levels at Sungai Galas exemplify this dynamic, indicating that even slight variations in rainfall intensity can elicit swift hydrological responses within the sub-basin. These patterns reinforce the need for adaptive, data-driven flood management strategies, including real-time monitoring and early warning systems, to mitigate potential impacts on vulnerable downstream communities such as Kuala Krai.

Table 3: Descriptive analysis of water levels

Station	Latitude (N)	Longitude (E)	Average (m)	Maximum (m)	Total (m)
Sungai Galas	5.3819	102.015	719.159	1351.24	103558.93
Sungai Lebir	5.275	102.267	641.752	842.34	92412.34

3.2.3 Total annual water level from 2009 to 2020

Figure 3 presents the graph of the total annual water level over 12 years in Kuala Krai, Kelantan. The results show that the Sungai Galas station recorded the highest water level in 2017 (10,982.2 m), which was during a time of heavy monsoonal rain. This pattern may be attributed to the geomorphological characteristics of the Galas catchment, which promotes greater runoff accumulation and slower discharge during heavy rainfall events. The sharp decline observed at Sungai Lebir in 2015 likely reflects post-flood adjustments following the severe 2014 Kelantan flood, which altered channel morphology and flow pathways. As reported by Nardi and Rinaldi (2015), major flood events often cause significant alterations in water flow and channel morphology, resulting in changes in discharge behaviour and storage capacity within the affected river systems. Temporal fluctuations in water levels also mirror the rainfall peaks recorded at nearby stations, such as Dabong and Ldg. Kuala Nal, underscoring the strong hydrological coupling between rainfall and river response within the basin.

3.3 Interpolation data

3.3.1 Descriptive statistics of rainfall stations and dataset from 2009 to 2020

Table 4 presents the descriptive statistics of six rainfall stations in Kuala Krai from 2009 to 2020 with no missing data. The rainfall data were analysed using descriptive measures, such as average, maximum, total, and standard deviation. Conducting descriptive statistics was an essential step prior to further analyses, as misplaced outliers can significantly affect trend detection (Abdulkareem et al., 2016). The range of rainfall across the six stations was between 1053 mm and 1340.1 mm. The highest average rainfall was observed at the Ldg. Kuala Nal station (217.848 mm), followed by Dabong station (212.858 mm). The greatest standard deviation (184.043 mm) was recorded at Ldg. Lepan Kabu, indicating higher variability at this station. Ldg. Kuala Nal also recorded the highest maximum value (1053.0 mm) compared to the other stations. In terms of totals, Dabong station had the highest overall rainfall (30,651.6 mm), while Ldg. Lepan Kabu recorded the lowest (28,766.5 mm).

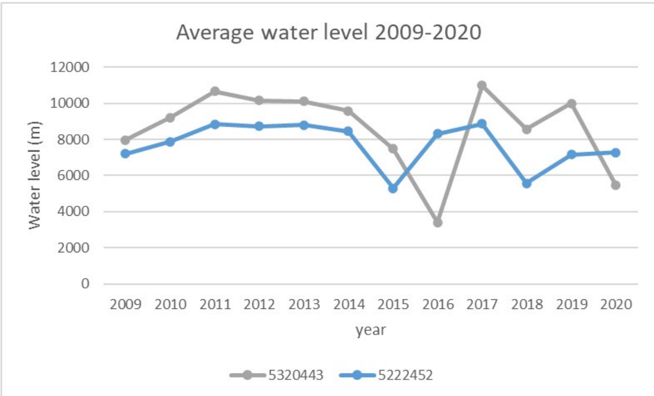

Figure 3: Graph of total annual water level (2009-2020)

Table 4: Descriptive analysis after imputed rainfall datasets

Station	Latitude (N)	Longitude (E)	Average (mm)	Maximum (mm)	Total (mm)	STDEV (mm)
Dabong	5.378	102.015	212.858	1340.1	30651.6	173.494
Ldg.Kuala Gris	5.375	102.082	208.240	1177.0	29986.5	150.632
Kg.Laloh	5.308	102.275	206.581	1254.5	29747.6	159.875
Ldg.Lepan Kabu	5.460	102.231	199.767	1338.0	28766.5	184.043
Ldg.Kuala Nal	5.571	102.164	217.848	1053.0	30365.0	180.518
JPS Kuala Krai	5.532	102.203	207.253	1054.0	28917.4	174.554

The comparison between interpolated and missing rainfall datasets is presented in Table 5 and reveals notable differences across stations, reflecting both the strengths and limitations of interpolation. At Dabong, the difference was minimal (average 0.286 mm; total 41.4 mm), indicating that the observed data were largely complete and reliable. By contrast, Kg Laloh recorded the highest difference (average 7.287 mm; total 1049.3 mm), suggesting substantial gaps in the original dataset and a heavy reliance on interpolation to reconstruct rainfall values. Similarly, Ldg Kuala Nal (average 6.98 mm; total 520.5 mm) showed significant adjustments, while the negative maximum differences at Ldg Kuala Nal (-361.5 mm) and JPS Kuala Krai (-154.4 mm) illustrate how interpolation tends to smooth extreme values, potentially underestimating localised heavy rainfall events. Stations with no difference (nd) indicate complete or unaffected datasets, which enhance confidence in their recorded patterns. These findings highlight that while interpolation is essential for filling gaps and improving the spatial continuity of rainfall data, caution must be exercised when interpreting results from stations with high differences, as the underestimation of extremes may affect the accuracy of flood risk mapping.

Wagner et al. (2012) reported that the accuracy of interpolation decreases as the distance between stations increases and when localised convective systems influence rainfall. In the context of Kelantan, where rainfall is often driven by short-duration, high-intensity convective storms, this limitation becomes particularly significant. The smoothing of extreme values during interpolation can reduce the accuracy of flood risk assessments, especially in data-sparse regions such as Kg Laloh and Ldg Kuala Nal. To mitigate these limitations, a denser network of monitoring stations, supported by satellite data integration, could substantially enhance spatial rainfall representation.

Table 5: Difference between the interpolated rainfall dataset and the missing dataset.

Station	Difference (interpolated data – missing data)		
	Average (mm)	Maximum (mm)	Total (mm)
Dabong	0.286	nd	41.4
Ldg.Kuala Gris	nd	nd	nd
Kg.Laloh	7.287	nd	1049.3
Ldg.Lepan Kabu	nd	nd	nd
Ldg.Kuala Nal	6.98	-361.5	520.5
JPS Kuala Krai	6.438	-154.4	nd

*nd refers to no difference.

3.3.2 Total annual rainfall from 2009 to 2020

Figure 4 presents the total annual rainfall for 12 years across six stations in Kuala Krai, Kelantan. The results indicate that the maximum rainfall occurred in 2020 at Dabong. Similarly, the years 2009, 2013, and 2017 also recorded relatively high rainfall compared to other years. In contrast, during 2010, 2012, 2015, 2016, and 2018, most stations experienced a decrease in precipitation relative to other years.

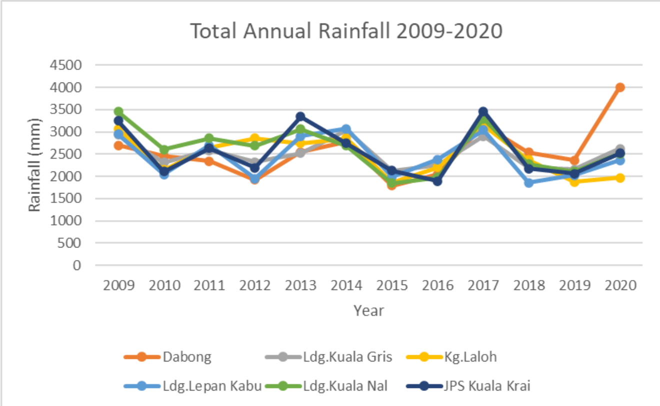

Figure 4: Graph of total annual rainfall (2009-2020)

3.3.3 Trend of rainfall dataset using Mann-Kendall analysis

The results of the Mann-Kendall analysis are presented in Table 6. Dabong and JPS Kuala Krai stations recorded positive S values (608 and 206), indicating an upward tendency, while the remaining four stations exhibited negative S values, reflecting downward trends. However, the overall results indicate no statistically significant trends in the interpolated rainfall dataset. This outcome suggests that the interpolation process, while improving data completeness, may have smoothed out natural variability and reduced the sensitivity of the trend test. The present study is consistent with Muhammad et al. (2024) in neighbouring Jeli, where several stations remained non-significant after linear gap-filling, indicating that interpolation can preserve data completeness while dampening interannual variability relevant to trend tests.

Furthermore, the twelve-year temporal span of the dataset is relatively short for detecting long-term climatic signals, as rainfall trends in tropical regions are often influenced by decadal oscillations such as El Niño-Southern Oscillation (ENSO) and other low-frequency variability (Gu et al., 2007; Guilyardi et al., 2020). Gu et al. (2007) demonstrated that tropical rainfall exhibits inter-annual to inter-decadal variability, complicating the identification of monotonic trends with short records. Likewise, Guilyardi et al. (2020) found that ENSO-induced precipitation anomalies dominate decadal rainfall patterns in tropical zones, thereby emphasising that detecting a reliable long-term signal requires a much longer time series than twelve years.

In addition, the absence of a significant trend may therefore reflect the predominance of natural variability over systematic climatic change within the study period. Spatial differences among stations further highlight the influence of local topography and catchment characteristics, which create site-specific rainfall responses. Although no significant trend was detected, the presence of alternating upward and downward tendencies implies dynamic rainfall variability, which can still pose challenges for hydrological planning and flood risk management. This reinforces the importance of establishing dense, real-time monitoring networks.

Table 6: Mann-Kendall analysis of imputed rainfall dataset

Series/ Test	Kendall's tau	S	Var(S)	p-value (two-tailed)
Dabong	0.059	608	335179.3	0.294
Ldg.Kuala Gris	-0.016	-165	335178.3	0.777
Kg.Laloh	-0.075	-767	335185.0	0.186
Ldg.Lepan Kabu	-0.004	-44	335176.0	0.941
Ldg.Kuala Nal	-0.028	-287	335185.0	0.621
JPS Kuala Krai	0.020	206	335177.3	0.723

*alpha value at 0.05

3.4 Flood-Prone Area

Figure 5 shows the flood-prone map of Kuala Krai with three levels of risk, ranging from low to high. The map was produced using several parameters and is also informed by the hydrograph data of the Kelantan River. The parameters considered in generating the flood-prone map include DEM, flow accumulation, slope, and precipitation. According to the map, the high-risk flood-prone area is concentrated in the central part of Kuala Krai, where almost 70% of the district was inundated during major flood events. Conversely, the southern and western regions demonstrate a significantly reduced risk of flooding.

Very low flood-prone zones are characterised by steeper slopes, extensive plantations, lower rainfall, and reduced water levels. Some plantation areas fall within the medium-risk category, largely due to gentler slopes compared to low-risk zones. High-risk flood areas primarily consist of flat regions with low slopes, frequently situated near urban centres. In such areas, heavy rainfall significantly increases the likelihood of flooding.

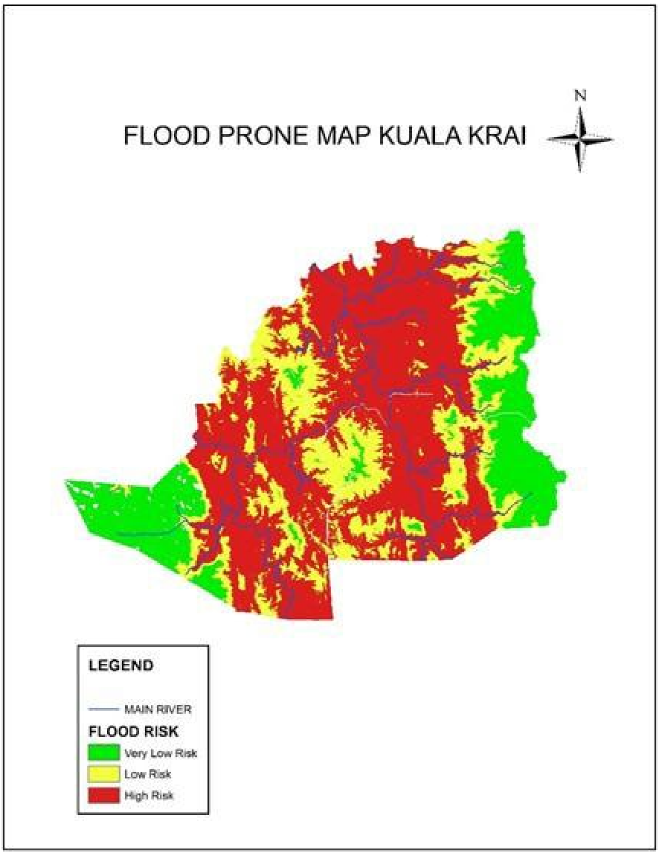

Figure 5: Flood-prone area map in Kuala Krai, Kelantan.

3.5 Spatial analysis of rainfall dataset

A spatial analysis of rainfall distribution was conducted by generating 12 annual rainfall maps for Kuala Krai, Kelantan, covering the period from 2009 to 2020. These maps were constructed using the average annual rainfall recorded at each station, classified by year, and are presented in Figure 6. The graphical representation facilitated the identification of both spatial and temporal variability in rainfall distribution across the six selected stations, even in the presence of missing data. In each map, the symbol size and intensity were adjusted proportionally to the average rainfall received at each station in a given year, thereby enabling clearer visual interpretation of spatial disparities.

From 2009 to 2011, the Ladang Kuala Nal station consistently recorded the highest rainfall, indicating its susceptibility to intense precipitation during that period. A notable shift occurred in 2012, when Kg. Laloh registered the highest average rainfall, while Dabong experienced the lowest, suggesting the influence of localised climatic factors or microenvironmental changes.

Further analysis of rainfall distribution maps for 2013, 2014, 2016, and 2017 revealed that JPS Kuala Krai and Ladang Lepan Kabu alternately received the highest precipitation. These patterns may reflect the effects of localised convective rainfall systems or variations in catchment characteristics. In 2015, rainfall amounts at Ladang Kuala Gris and JPS Kuala Krai were nearly identical, indicating a more even distribution of precipitation across the district that year.

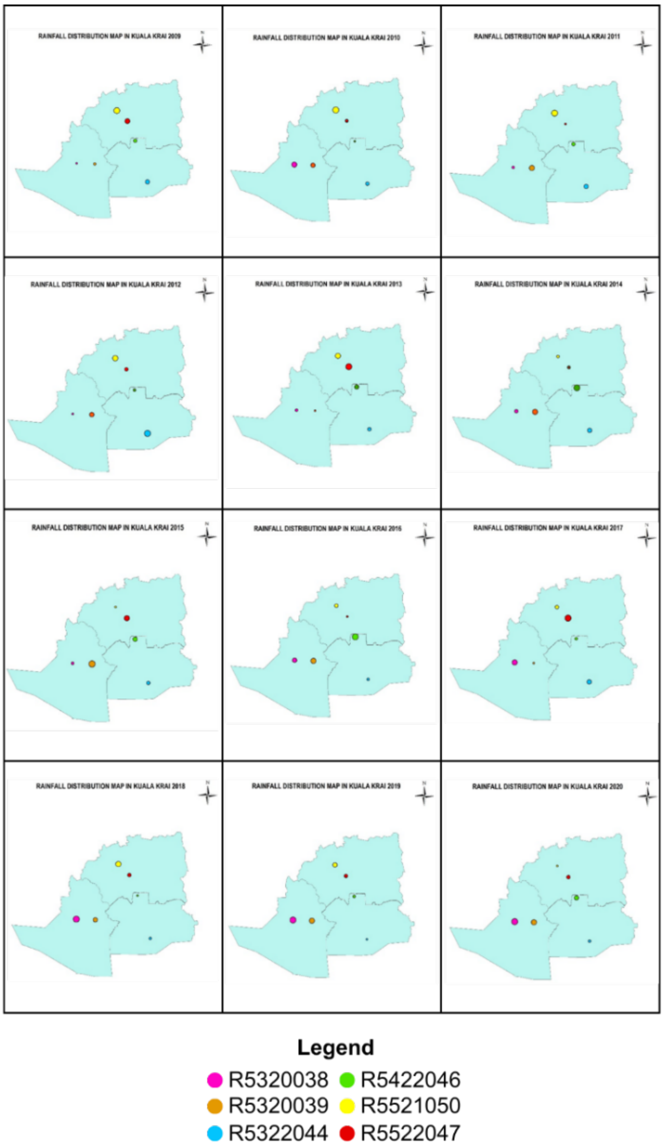

Figure 6: Distribution of rainfall by year with missing data

Another shift was observed in 2018 and 2019, when Dabong recorded the highest rainfall among all stations. This pattern suggests a recurring increase in rainfall at Dabong in recent years, possibly influenced by its topographic position near the Titiwangsa Range, which may enhance orographic rainfall effects. The spatial distribution maps not only highlight inter-annual fluctuations but also demonstrate how rainfall concentration shifts geographically over time, which is crucial for understanding localised flood risk, water resource allocation, and land-use planning in Kuala Krai.

Figure 7 shows the annual rainfall distribution maps without missing data. Between 2009 and 2013, Ladang Kuala Nal consistently received high precipitation. In 2014, Ladang Lepan Kabu recorded the highest rainfall, while JPS Kuala Krai experienced the lowest. In 2015, JPS Kuala Krai received the highest rainfall, whereas from 2016 to 2020, Ladang Lepan Kabu and JPS Kuala Krai recorded mostly similar average rainfall values. During 2018 and 2019, Dabong again registered the highest rainfall. Overall, the comparison demonstrates significant differences between datasets with and without missing values, underscoring the importance of complete records for accurate rainfall analysis.

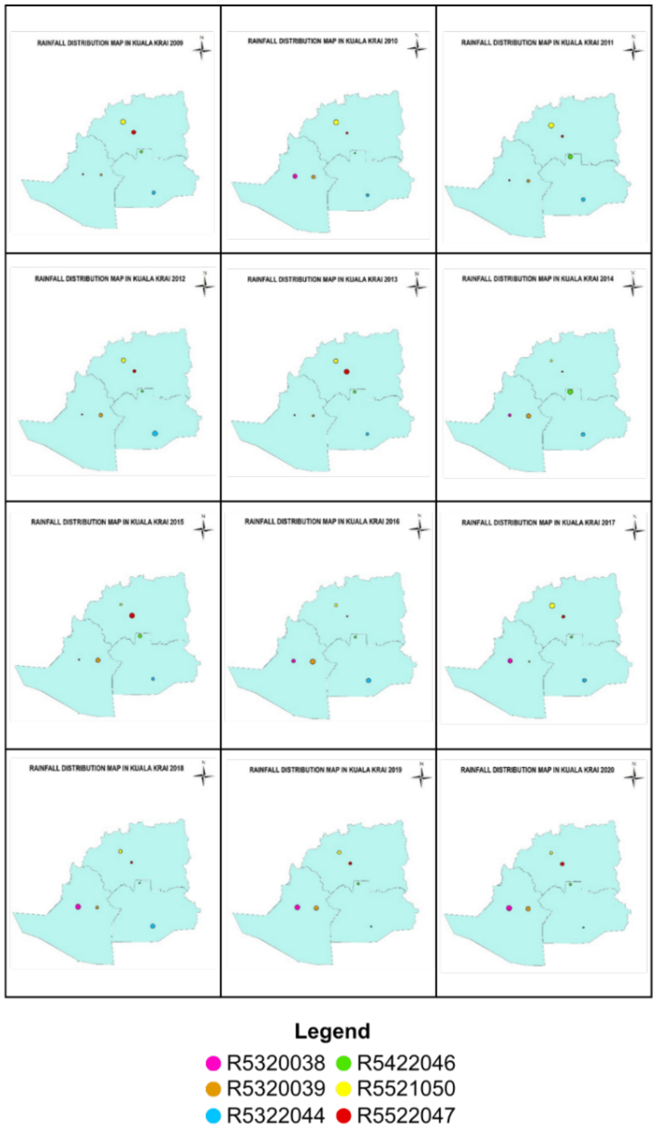

Figure 7: Distribution of rainfall by year without missing data

4. CONCLUSION

This study successfully achieved its primary objective of identifying rainfall distribution patterns in Kuala Krai through spatio-temporal analysis. The Mann-Kendall test indicated the presence of trends across all stations, although these were not statistically significant. Notably, the years 2014 and 2020 recorded the highest rainfall, coinciding with major flood events, which highlights the role of intense rainfall in triggering severe flooding. The findings also revealed that rainfall patterns vary considerably across months, seasons, and years, with marked fluctuations in annual totals.

These results provide valuable baseline information on rainfall dynamics in Kuala Krai and their potential implications for flood occurrence. While this study does not include predictive modelling, the insights gained emphasise the importance of continued monitoring and extended spatio-temporal analyses. Such efforts would improve understanding of extreme rainfall variability and support more effective flood risk management and climate adaptation strategies in flood-prone regions like Kuala Krai.

The AA method was employed to fill missing rainfall data in the present study due to its simplicity and suitability for datasets with small gaps and similar rainfall regimes among neighbouring stations. This approach has been widely used in hydrological analyses within tropical regions, including Malaysia, where monsoonal influences yield spatially consistent rainfall patterns. However, the AA method assumes equal weighting of all stations, disregarding spatial factors such as distance and elevation. This simplification may reduce accuracy in areas with complex terrain, as distant stations might not reflect localised rainfall events. To improve accuracy, future studies could apply distance-weighted or geostatistical methods such as Inverse Distance Weighting (IDW) or Kriging, which better account for spatial dependence and topographic variability.

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