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TREND AND STATISTICAL ANALYSIS OF ANNUAL MAXIMUM DAILY RAINFALL (AMDR) FOR SARAWAK RIVER BASIN, SARAWAK, MALAYSIA

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ABSTRACT

The Sarawak River Basin is one of the major river basins located in the southern part of Sarawak, Malaysia, and has experienced frequent extreme rainfall resulting in flash floods in recent years. This study aims to carry out trend and statistical analysis of annual maximum daily rainfall (AMDR) for 10 rainfall stations distributed evenly in the basin from 1975 to 2020. From the analysis, the AMDR records high variability for most of the rainfall stations, with the month of January having the highest occurrence of AMDR events. The linear regression plot of the mean AMDR showed a slight decreasing trend over the past four decades. The threshold rainfall value of 180 mm was used to perform frequency analysis, and the result shows that the return period for daily rainfall exceeding 180 mm was 2.71 years. The occurrence probability of the flood event at least once in 1, 2, 3, 4 and 5 years was 0.37, 0.60, 0.75, 0.84 and 0.90, respectively. A frequency curve based on the mean AMDR data with Gumbel distribution fitting was also developed from the current study and can be applied to the planning and design of flood infrastructures in the basin.

Keywords: Annual maximum daily rainfall, Extreme events, Frequency analysis, Rainfall trend, Urban drainage

INTRODUCTION

One of the causes of flood disasters is high maximum daily rainfall (Aroua, 2020; Hafnaoui et al., 2022). Recently, 622.7 mm of rainfall within 24 hours in Henan, China, caused casualties, and 100,000 people evacuated (Davies, 2021), while in the Rhine basin, Germany, 154 mm of rain within 24 hours killed at least 58 people and flooded tens of thousands of homes (Watts, 2021).

Since severe rainfall rarely lasts more than a day (Haktanir et al., 2013), maximum daily rainfall is an important parameter for storm analysis rather than total rainfall (Ghenim and Megnounif, 2016). Annual maximum daily rainfall (AMDR) is defined as the highest maximum daily rainfall for a particular year. Hence, to develop proper strategies for managing and reducing flood risk, statistical analysis of AMDR events that cause floods must be carried out.

Studies on the frequency and trend analysis of AMDR have been performed in various parts of the world, such as Brazil (Porto de Carvalho et al., 2014), Wadi Alaqiq, Saudi Arabia (Abd Rahman et al., 2016) and Nelspruit, South Africa (Masereka et al., 2018). By conducting studies on AMDR, the return period of flood and extreme events can be determined. Work by Vivekanandan (2017) and Zamir et al. (2021) used the Gumbel distribution to represent extreme events. Other statistical analyses have also been conducted on AMDR, such as coefficient of variation (*CV*) and linear regression analysis (Hasan et al., 2014), as well as the contribution of AMDR to annual totals (Ghenim and Megnounif, 2016). For Malaysia, to understand the extreme rainfall trend, statistical methods such as Mann-Kendall and linear regression have been used in Peninsular Malaysia (Suhaila et al., 2010; Syafrina et al., 2015) and Sarawak (Sa'adi et al., 2017). A more localized study of the Sarawak River Basin by Bong et al. (2009) found a general upward trend for annual rainfall, temperature and evaporation for the past 3 to 4 decades. A study on drought using the SPI index by Bong and Richard (2020) for the Sarawak River Basin showed an increase in the number of dry months in the most recent decade compared to the previous 30 years. At the city scale, a study by Tang (2019) on historical rainfall data for Kuching city (located in the Sarawak River Basin) showed high variability, with monthly rainfall peaking at the end of 2009 and early 2010. Another study using a single rainfall station in Kuching city by Bong et al. (2022) recently showed that although there is a slight decreasing trend in terms of AMDR, the return period for a rainfall event exceeding 180 mm was 2.69 years. The probabilities of flood occurrence at least once in 1, 2, 3, 4 and 5 years were 0.37, 0.60, 0.75, 0.84 and 0.90, respectively, for Kuching city (Bong et al., 2022).

The current study extends previous work, especially that by Bong et al. (2022), to incorporate basin-wide AMDR data for the Sarawak River Basin. This will provide a better representative AMDR analysis for the Sarawak River Basin. Additionally, the data used will be more recent (up to 2020) than the study by Bong et al. (2022), which only used AMDR data up to 2017 for a single rainfall station, namely, Kuching Airport (station ID: 1403001). According to Davies (2016), Kuching city's drainage system was designed for a maximum of 180 mm of rain. Most of the flooding events in Kuching city and surrounding areas were observed to occur when the rainfall exceeded 180 mm per day. The current study uses this threshold value to carry out statistical and trend analyses for AMDR events in the Sarawak River Basin and identify the occurrence probability of flood events due to AMDR.

METHODOLOGY

Study area

The Sarawak River Basin is one of the major river basins situated in the southern part of the state of Sarawak in Malaysia on Borneo Island. The Sarawak River Basin has a catchment area of approximately 2,456 km^2 with a river length of approximately 120 km. The basin experiences two main monsoon seasons, namely, the northeast monsoon season (November to March), during which the wet season is recorded, and the southwest monsoon season (June to September), during which the dry season is recorded. The river basin generally experiences high rainfall throughout the year, with a total rainfall of approximately 3,830 mm (Abdillah et al., 2013). Fig. 1 shows the location of the Sarawak River Basin with the selected rainfall stations. A total of 10 rainfall stations were chosen for the current study. The stations were chosen based on consistent and reliable data (less than 10% missing data) for the study period and are evenly distributed throughout the Sarawak River Basin to give a better representation of the basin.

Rainfall data

Daily rainfall data (in mm) for 1975 to 2020 for 10 selected rainfall stations in the Sarawak River Basin were obtained from the Department of Irrigation and Drainage, Sarawak. From the daily rainfall data, the annual maximum daily rainfall (AMDR) was extracted for each year. Table 1 shows the AMDR events for the period 1975 – 2020 for the 10 selected stations. From Table 1, the AMDR for each of the stations, the month with the highest occurrence of AMDR, standard deviation (*SDev*), coefficient of variation (*CV*) and the mean AMDR for the whole basin are presented.

Coefficient of variation (*CV*)

The coefficient of variation (*CV*) was used to determine the temporal variability of rainfall and defined as follows:

$$CV = 100 \times \frac{\sigma}{\mu} \tag{1}$$

where σ and μ are the standard deviation and mean rainfall for the chosen timescale, respectively. The degrees of variability of rainfall events as defined by Asfaw et al. (2018) are low ($CV < 20$), moderate ($20 < CV < 30$) and high ($CV > 30$).

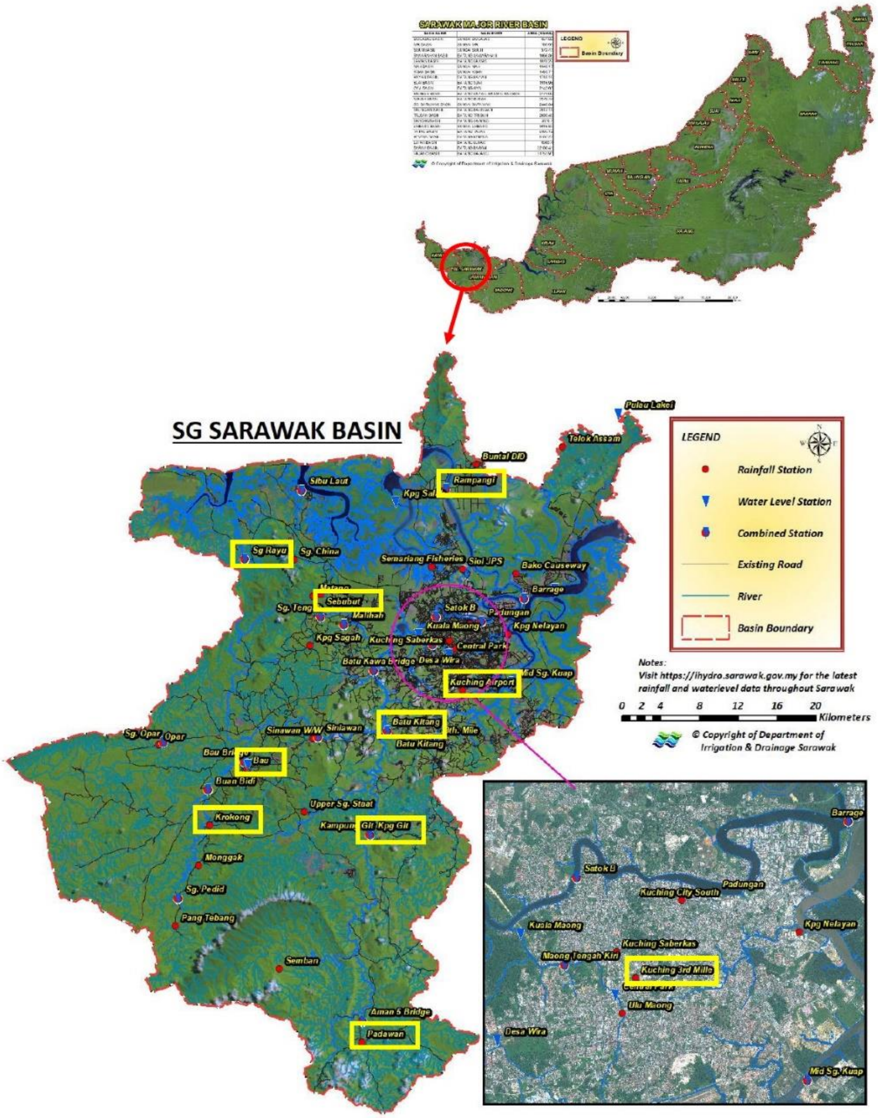

Figure 1: Sarawak River Basin and location of the selected rainfall stations (DID, 2022)

Trend analysis using the Mann-Kendall (MK) test

A general linear regression graph was plotted to determine the trend of the mean AMDR throughout the years for the current study. A positive slope of the linear regression plot defines an increasing trend, while a negative slope indicates a decreasing trend (Ghenim and Megnounif, 2016). The Mann-Kendall (MK) test was used to further determine the trend significance. The Mann-Kendall (Mann, 1945; Kendall, 1970) test is a nonparametric statistical test widely used to determine trends in hydrological time series (Othman et al., 2016). For the current study, the null hypothesis H_O assumes no trend in the AMDR data series, while the alternative hypothesis H_1 assumes there is a trend. The null hypothesis was tested at the 95% confidence level (α = 0.05). Two-tailed tests were applied for the probability value (*p* value). To perform the MK test for the current study, the Excel add-in downloadable from real-statistics.com/free-download/(Zaiontz, 2022) was used. In the Mann-Kendall statistics, *S* is given as:

$$S = \sum_{k=1}^{n-1} \left[\sum_{j=k+1}^{n} sign\left(x_j - x_k\right) \right] \tag{2}$$

$$sign\left(x_j - x_k\right) = \begin{cases} 1, x_j - x_k > 0 \\ 0, x_j - x_k = 0 \\ -1, x_j - x_k < 1 \end{cases} \tag{3}$$

where x_j and x_k are sequential data values and *n* is the number of observations. For the number of observations larger than 10, the *S* statistic is approximately normally distributed with a mean value equal to 0. A positive *S* value indicates an increasing trend, while a negative value indicates a decreasing trend. The equation of variance for the *S* statistics is given by:

$$Var\left(S\right) = \frac{n\left(n-1\right)\left(2n+5\right)}{18} \tag{4}$$

To measure the statistical significance of the trends, the standardized *Z* statistic is given by:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{Var\left(S\right)}}, if\ S > 0 \\ 0, if\ S = 0 \\ \dfrac{S+1}{\sqrt{Var\left(S\right)}}, if\ S < 0 \end{cases} \tag{5}$$

The null hypothesis is rejected if the Z value is larger than the chosen significance/confidence level. The p value approach is defined as the probability of rejecting the null hypothesis. If the p value is larger than α, the null hypothesis fails to be rejected.

Empirical frequency analysis

The probability of exceedance (p) for AMDR events was determined by ordering from the largest to the smallest event. Rank 1 was assigned to the largest event and rank 46 to the smallest event since the sample size was 46. The Weibull formula (Weibull, 1951) was applied to obtain p for each event:

$$p = \frac{i}{n} + 1 \tag{6}$$

where p is precisely the exceedance probability for an event with rank i and n is the sample size. The return period for each event was defined as the inverse of the exceedance probability (Weibull, 1951):

$$T = \frac{1}{p} \tag{7}$$

For the current study, AMDR events ≥ 180 mm were identified as possibly causing flood disasters in the Sarawak River Basin based on Kuching city's drainage system capacity (Davies, 2016). Hence, an AMDR event with a magnitude of 180 mm was adopted as the threshold to perform flood risk analysis. Equation (8) was applied to determine the occurrence probability of flood disaster risk associated with AMDR events of magnitude ≥ 180 mm at least once in 1, 2, 3, 4 and 5 years:

$$p\left(X \geq x_T \; at\, least\ once\ in\ N\ years\right) = 1 - \left(1 - \frac{1}{T}\right)^N \tag{8}$$

Gumbel distribution

To fit the Gumbel distribution to the data in the current study, Eq. (9), which is the general equation for hydrologic frequency analysis, was used:

$$x_T = \bar{x} + K\,\sigma_{n-1} \tag{9}$$

where x_T is the value of the variate X of a random hydrologic series with a return period T and $\bar{x}$ is the mean of the variate. The standard deviation σ_{n-1} of the sample of size N is given as:

$$\sigma_{n-1} = \sqrt{\frac{\sum\left(x-\bar{x}\right)^2}{N-1}} \tag{10}$$

The frequency factor *K* is expressed as:

$$K = \frac{y_T - \overline{y_n}}{S_n} \tag{11}$$

The reduced variate y_T, which is a function of the return period *T,* is given by:

$$y_T = -\ln\left(\frac{\ln T}{T-1}\right) = -\left(0.834 + 2.303\log\log\frac{T}{T-1}\right) \tag{12}$$

The reduced mean y_n and reduced standard deviation S_n for a function with sample size *N* were obtained from the tables developed specifically for Gumbel's extreme value distribution (Gumbel, 1958).

Table 1: Annual maximum daily rainfall (AMDR) events for 10 rainfall stations in the Sarawak River Basin for 1975 – 2020

Year	Padawan	Krokong	Kpg Git	Bau	Batu Kitang	Kuching Airport	Sebubut	Kuching 3rd Mile	Sg Rayu	Rampangi	Mean (mm)
1975	160.0 (Dec)	351.7 (Dec)	215.9 (Dec)	276.4 (Dec)	208.2 (Dec)	282.5 (Dec)				151.3 (Mar)	235.1
1976	139.9 (Jan)	220.9 (Jan)	201.6 (Jan)	226.2 (Jan)	231.6 (Jan)	222.3 (Jan)		157.8 (Jan)		176.2 (Jan)	197.1
1977	117.0 (Mar)	247.4 (Feb)	207.4 (Feb)	231.5 (Feb)	214.6 (Jan)	260.1 (Jan)		255 (Jan)		193.8 (Feb)	215.9
1978	137.0 (Dec)	142.2 (Jan)	216.5 (Feb)	156.5 (May)	200.2 (Feb)	210.1 (Jan)		128.1 (Jan)		208.8 (Jan)	174.9
1979	117.0 (Dec)	141.7 (Jan)	140 (Jan)	117.2 (Dec)	190.5 (Nov)	131.8 (Mar)		137.2 (Mar)		238.8 (Mar)	151.8
1980	121.0 (Jan)	108.2 (Oct)	205.5 (Jan)	109.3 (Jan)	175.3 (Jan)	290.0 (Jan)	265.0 (Jan)	283.8 (Jan)		315 (Jan)	208.1
1981	118.0 (Dec)	157.5 (Dec)	296.5 (Dec)	132.4 (Dec)	143.0 (Mar)	134.9 (Dec)	175.5 (Oct)	140.7 (Dec)		116.3 (Dec)	157.2
1982	155.0 (Feb)	86.4 (Mar)	183.5 (Jan)	130.3 (Feb)	92.7 (Feb)	102.0 (Feb)	156.5 (Feb)	122.5 (Dec)		119.9 (Jan)	127.6
1983	203.0 (Jan)	208.3 (Jan)	115 (Jan)	148.6 (Jan)	188.5 (Nov)	141.9 (Jan)	190.0 (Jan)	120.0 (Feb)		215.8 (Jan)	170.1
1984	89.0 (Jan)	112.0 (Aug)	141 (Mar)	105.0 (May)	117.0 (Jan)	208.2 (Jan)	188.0 (Jan)	137.5 (Jan)		142.5 (Jan)	137.8
1985	96.5 (Jul)	119.0 (Mar)	120 (Mar)	94.0 (Sep)	165.0 (Mar)	137.5 (Jan)	147.0 (Jan)	93.5 (Mar)	118.0 (Mar)	152 (Feb)	124.3
1986	80.7 (Jan)	182.0 (Jan)	156.0 (Jan)	101.6 (Jan)	165.0 (Jan)	222.6 (Jan)	270.0 (Jan)	250.0 (Jan)	302.5 (Mar)	193.5 (Mar)	192.4
1987	71.0 (Feb)	135.0 (Dec)	83.0 (Jan)	114.5 (Jan)	98.0 (Dec)	158.4 (Jan)	229.0 (Jan)	126.6 (Mar)	290.0 (Jan)	168.0 (Mar)	147.4
1988	118.5 (Feb)	131.0 (Dec)	90.0 (Feb)	125.0 (Jan)	168.0 (Dec)	170.8 (Dec)	182.0 (Feb)	153.8 (Dec)	253.5 (Jan)	158.0 (Jan)	155.1
1989	97.5 (Jul)	219.0 (Dec)	192.0 (Dec)	182.5 (Dec)	226.0 (Dec)	190.8 (Dec)	247.5 (Dec)	162.2 (Feb)	317.5 (Dec)	238.5 (Feb)	207.4
1990	111.5 (Feb)	87.0 (Feb)	105.0 (Dec)	94.5 (Jan)	105.0 (Feb)	86.8 (Jan)	127.0 (Apr)	103.0 (Feb)	144.5 (Feb)	113.5 (Dec)	107.8
1991	116.0 (Jan)	138.0 (Jan)	172.0 (Nov)	66.5 (Jan)	82.0 (Jan)	103.2 (Apr)	256.5 (Jan)	114.0 (Jan)	141.5 (Feb)	70.0 (Nov)	126.0
1992	253.5 (Jan)	305.0 (Jan)	204.0 (Jan)	381.0 (Jan)	267.0 (Sep)	160.2 (Dec)	260.0 (Jan)	138.5 (Jan)	345.5 (Jan)	168.0 (Jan)	248.3
1993	125.5	115.0	97.0	99.5	80.0	135.8	218.0	159.5	167.5	76.0	127.4

	(Mar)	(Nov)	(Sep)	(Sep)	(Mar)	(Aug)	(Jan)	(Jan)	(Jan)	(Jul)	
1994	69.5 (Jan)	197.0 (Dec)	202.0 (Jan)	250.0 (Jan)	151.0 (Jan)	157.4 (Jan)	202.0 (Dec)	293.0 (Mar)	378.5 (Dec)	190.0 (Mar)	209.0
1995	94.5 (May)	217.0 (Feb)	160.0 (Feb)	200.3 (Feb)	185.0 (Feb)	175.6 (Feb)	254.1 (Feb)	191.0 (Feb)	186.7 (Feb)	96.5 (Feb)	176.1
1996	206.0 (Jan)	133.0 (Feb)	167.0 (Feb)	134.9 (Feb)	143.0 (Jan)	155.9 (Jan)	173.5 (Jan)	82.0 (Oct)	237.0 (Jan)	112.5 (Feb)	154.5
1997	98.0 (Jun)	115.0 (Feb)	185.5 (May)	92.0 (Apr)	113.0 (Oct)	96.3 (Apr)	239.0 (Jan)	98.0 (Dec)	224.0 (Jan)	77.5 (Dec)	133.8
1998	123.0 (Mar)	106.5 (Mar)	189.5 (Jan)	137.5 (Jan)	242.5 (Jan)	302.3 (Jan)	266.0 (Jan)	270.5 (Jan)	275.0 (Jan)	185.5 (Jan)	209.8
1999	119.0 (Dec)	197.5 (Dec)	205.0 (Dec)	147.0 (Dec)	97.0 (Feb)	109.8 (Feb)	184.0 (Dec)	143.0 (Dec)	219.5 (Feb)	159.0 (Feb)	158.1
2000	108.5 (Dec)	179.0 (Jan)	161.0 (Feb)	239.0 (Jan)	206.5 (Feb)	284.6 (Jan)	244.5 (Jan)	263.0 (Jan)	305.5 (Jan)	231.0 (Jan)	222.3
2001	65.5 (Nov)	95.5 (Oct)	115.5 (Jan)	132.0 (Jan)	90.0 (Jan)	153.0 (Jan)	135.0 (Feb)	119.5 (Feb)	143.5 (Feb)	143.5 (Jun)	119.3
2002	97.0 (Apr)	180.0 (Feb)	146.5 (Feb)	119.0	185.0 (Jan)	265.2 (Jan)	370.5 (Jan)	295.0 (Jan)	209.5 (Jan)	202.5 (Jan)	207.0
2003	181.5 (Feb)	323.0 (Feb)	91.0 (Jan)	412.5 (Feb)	327.5 (Feb)	364.2 (Feb)	242.5 (Feb)	330.0 (Feb)	293.0 (Jan)	163.5 (Feb)	272.9
2004	206.0 (Jan)	250.0 (Jan)	274.0 (Jan)	283.0 (Jan)	333.5 (Jan)	302.6 (Jan)	307.0 (Jan)	270.5 (Jan)	268.0 (Jan)	268.0 (Jan)	276.3
2005	110.0 (Jan)	129.5 (Jan)	147.5 (Nov)	137.5 (Jan)	93.0 (Jan)	131.6 (Jan)	161.0 (Feb)	105.5 (Jan)	259.5 (Jan)	106.5 (Feb)	138.2
2006	161.5 (Aug)	120.0 (Jan)	87.5 (Jan)	124.0 (Jan)	102.5 (Dec)	159.8 (Feb)	148.5 (Dec)	99.5 (Jan)	198.0 (Feb)	177.0 (Feb)	137.8
2007	157.0 (Jan)	106.0 (Jan)	89.5 (Apr)	134.0 (Jan)	166.5 (Dec)	191.4 (Oct)	279.0 (Jan)	206.0 (Nov)	96.0 (Mar)	279.5 (Jan)	170.5
2008	127.5 (Oct)	124.0 (Oct)	102.5 (Mar)	168.0 (Dec)	147.5 (Dec)	127.0 (Aug)	224.0 (Dec)	125.5 (Dec)	213.5 (Dec)	128.5 (Feb)	148.8
2009	135.5 (Jan)	231.5 (Jan)	166.0 (Jan)	274.0 (Jan)	190.5 (Jan)	165.5 (Jan)	171.5 (Jan)	189.5 (Jan)	177.0 (Jan)	159.0 (Jan)	186.0
2010	79.5 (Jan)	134.5 (Jun)	119.5 (Jul)	144.0 (Jan)	126.5 (Jan)	149.5 (Jan)	131.5 (Jan)	146.5 (Jan)	175.5 (Jan)	178.0 (Jan)	138.5
2011	88.5 (Nov)	201.5 (Jan)	131.0 (Dec)	258.0 (Jan)	238.5 (Jan)	218.0 (Jan)	210.5 (Dec)	240.0 (Jan)	245.5 (Dec)	205.0 (Dec)	203.7
2012	95.5 (Dec)	161.0 (Jan)	124.0 (Dec)	112.5 (Jan)	130.5 (Jan)	106.0 (Jan)	185.5 (Mar)	193.5 (Jan)	136.5 (Mar)	113.5 (Mar)	135.9
2013	74.5 (Dec)	139.5 (Dec)	184.0 (Dec)	126.5 (Feb)	111.5 (Mar)	113.0 (Mar)	162.0 (Dec)	129.0 (Oct)	171.5 (Feb)	138.4 (Mar)	135.0
2014	79.5 (Mar)	101.0 (Dec)	98.0 (Jan)	100.0 (Jan)	85.5 (Mar)	135.5 (Feb)	125.0 (Sep)	229.5 (Feb)	89.5 (Jan)	147.0 (Sep)	119.1
2015	148.5 (Jan)	162.0 (Jan)	201.0 (Jan)	198.0 (Jan)	204.0 (Jan)	252.0 (Jan)	218.0 (Jan)	261.5 (Jan)	259.5 (Jan)	180.5 (Feb)	208.5
2016	219.5 (Feb)	230 (Feb)	282.5 (Feb)	294.0 (Feb)	199.5 (Feb)	153.5 (Feb)	237.0 (Feb)	160.5 (Feb)	270.0 (Feb)	164.0 (Feb)	221.1
2017	92.5 (Oct)	111.5 (Feb)	132.5 (Feb)	153.0 (Feb)	139.5 (Feb)	142 (Dec)	214.5 (Feb)	191.0 (Dec)	114.0 (Feb)	225.5 (Feb)	151.6
2018	131.5 (Apr)	103.5 (Nov)	102 (Oct)	112.0 (Mar)	120.0 (Feb)	168.5 (Feb)	172.5 (Sep)	137.5 (Feb)	225.5 (Jan)	158.0 (Sep)	143.1
2019	111.5 (Oct)	109.5 (Dec)	101 (Nov)	120.5 (Jan)	131.0 (Nov)	85.5 (Dec)	220.5 (Dec)	88.0 (Jan)	267.0 (Dec)	209.5 (Jan)	144.4
2020	119.5 (Feb)	113.5 (Nov)	122.5 (Apr)	118.5 (Jan)	156.0 (Feb)	145.5 (Feb)	273.0 (Feb)		388.5 (Feb)	263.5 (Feb)	188.9
Sum	5728.1	7479.3	7229.9	7614.2	7534.1	8161.1	8664.1	7642.2	8107.7	7878.8	7921.4
Mean	124.5	162.6	157.2	165.5	163.8	177.4	211.3	173.7	225.2	171.3	172.2
Sdev	42.5	63.5	53.6	77.3	60.8	66.5	53.8	67.3	76.9	54.7	42.0
CV	34.2	39.1	34.1	46.7	37.1	37.5	25.5	38.8	34.1	32.0	24.4

RESULTS AND DISCUSSION

General trend of AMDR

Referring to Table 1, AMDR was observed to occur mostly in January (42% of the total data), which is during the northeast monsoon season. The mean AMDR for the 10 selected rainfall stations ranged between 107.8 mm and 292.2 mm. In terms of the coefficient of variation (*CV*) value, except for the Sebubut rainfall station, all the rainfall stations were observed to have high variability. However, for the mean AMDR, the variability was moderate. The linear regression plot between the mean AMDR and year is shown in Fig. 2. From Fig. 2, the mean AMDR was observed to have a slight downward trend (slope = - 0.2139) from 1975 to 2020. Further analysis of the trend significance was performed using the Mann-Kendall (MK) test. The results from the MK test on the mean AMDR showed that the *S* value was - 61 (confirming a downward trend); however, the *Z* statistic value of - 0.57 (which is more than α = - 0.05) shows that the null hypothesis H_o of no trend cannot be rejected.

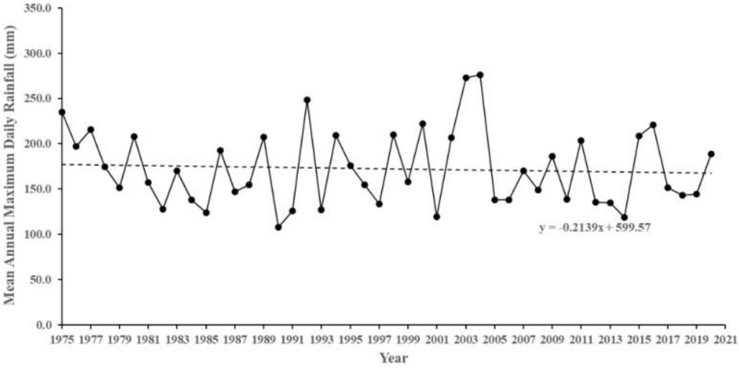

Figure 2: Linear regression plot of mean AMDR for the period 1975-2020

Plotting position and return period

The plotting position and return period were calculated using Equation (6) and Equation (7). For the current study, the mean AMDR (X) from the 10 rainfall stations for each respective year were ranked, and the plotting position and return period were calculated. The calculated plotting position and return period are shown in Table 2.

Table 2: Plotting positions and return periods for the mean AMDR for the 10 rainfall stations

				Gumbel's Parameter		
Rank	**Mean AMDR (X) (mm)**	P_i	T **(years)**	y_T	K	x_T
1	276.3	0.02	47.00	3.84	2.85	292.19
2	272.9	0.04	23.50	3.14	2.24	266.53
3	248.3	0.06	15.67	2.72	1.88	251.35
4	235.1	0.09	11.75	2.42	1.62	240.45
5	222.3	0.11	9.40	2.18	1.42	231.90
6	221.1	0.13	7.83	1.99	1.25	224.83
7	215.9	0.15	6.71	1.82	1.11	218.77
8	209.8	0.17	5.88	1.68	0.98	213.45
9	209.0	0.19	5.22	1.55	0.87	208.71
10	208.5	0.21	4.70	1.43	0.77	204.40
11	208.1	0.23	4.27	1.32	0.67	200.45
12	207.4	0.26	3.92	1.22	0.58	196.79
13	207.0	0.28	3.62	1.13	0.50	193.37
14	203.7	0.30	3.36	1.04	0.43	190.15
15	197.1	0.32	3.13	0.96	0.35	187.11
16	192.4	0.34	2.94	0.88	0.29	184.22
17	188.9	0.36	2.76	0.80	0.22	181.46
18	186.0	0.38	2.61	0.73	0.16	178.80
19	176.1	0.40	2.47	0.66	0.10	176.25
20	174.9	0.43	2.35	0.59	0.04	173.78
21	170.5	0.45	2.24	0.52	-0.02	171.38
22	170.1	0.47	2.14	0.46	-0.08	169.04
23	158.1	0.49	2.04	0.40	-0.13	166.75
24	157.2	0.51	1.96	0.34	-0.18	164.52
25	155.1	0.53	1.88	0.28	-0.24	162.32
26	154.5	0.55	1.81	0.22	-0.29	160.15
27	151.8	0.57	1.74	0.16	-0.34	158.01
28	151.6	0.60	1.68	0.10	-0.39	155.88
29	148.8	0.62	1.62	0.04	-0.44	153.77
30	147.4	0.64	1.57	-0.02	-0.49	151.66
31	144.4	0.66	1.52	-0.07	-0.54	149.55
32	143.1	0.68	1.47	-0.13	-0.59	147.43
33	138.5	0.70	1.42	-0.19	-0.64	145.29
34	138.2	0.72	1.38	-0.25	-0.69	143.13
35	137.8	0.74	1.34	-0.31	-0.74	140.93
36	137.8	0.77	1.31	-0.37	-0.80	138.68
37	135.9	0.79	1.27	-0.44	-0.85	136.36
38	135.0	0.81	1.24	-0.50	-0.91	133.96
39	133.8	0.83	1.21	-0.57	-0.97	131.45
40	127.6	0.85	1.18	-0.64	-1.03	128.80
41	127.4	0.87	1.15	-0.72	-1.10	125.96
42	126.0	0.89	1.12	-0.81	-1.17	122.87
43	124.3	0.91	1.09	-0.90	-1.26	119.41

44	119.3	0.94	1.07	-1.01	-1.35	115.39
45	119.1	0.96	1.04	-1.15	-1.47	110.38
46	107.8	0.98	1.02	-1.35	-1.64	103.15

Flood disaster risk analysis

In the current study, the AMDR event of magnitude 180 mm (x_T) was taken as the threshold. AMDR events equal to or greater than (x_T) were considered flood events for the Sarawak River Basin. Referring to Table 2 for the mean AMDR for the 10 rainfall stations, the number of occurrences of events for $x_T \geq 180$ mm was 18, and the number of intervals was 17. Hence, the empirical return period of event X_T was 2.71 years (46/17 = 2.71 years).

The exceedance probability of flood disaster events (mean AMDR event: $X_T \geq 180$ mm at least once in 1, 2, 3, 4 and 5 years as calculated using Eq. (8) is presented in Table 3. Comparing the results from exceedance probability analysis of the flood disaster for the mean AMDR (for the 10 rainfall stations) with the earlier work by Bong et al. (2022) for Kuching city, which used only a single rainfall station at Kuching Airport, shows that the values are comparable. This shows that the AMDR data were uniform for the 10 selected rainfall stations, which are distributed evenly in the Sarawak River Basin. Hence, the mean AMDR is a good representative value for all the rainfall stations in the basin. These results are important for decision-making on the acceptable level of flooding risk that is associated with designing infrastructure related to flood reduction in the Sarawak River Basin.

Table 3: Exceedance probability of flood event *X* ≥ 180 mm in the Sarawak River Basin

Year	**1**	**2**	**3**	**4**	**5**
P (> 180 mm)	0.37	0.60	0.75	0.84	0.90

Fitting of the Gumbel distribution to AMDR data

The Gumbel distribution was chosen based on the findings from previous studies (Vivekanandan, 2017; Zamir et al., 2021) that have found the distribution to be suitable to represent extreme events. From Equation (9), Eq. (13) was derived from the mean AMDR data of the current study:

$$x_T = 172.2 + 42.05\,K \tag{13}$$

Equation (13) was used to calculate the plotting position for the mean AMDR based on the return period *T*, which fit the Gumbel distribution. The calculated mean AMDR (x_T) for the respective return period *T* for the Gumbel distribution is shown in the right column of Table 2. The result of fitting the Gumbel distribution to the mean AMDR data for the Sarawak River Basin is plotted in Fig. 3. This can be used to determine the magnitude of AMDR events for frequency analysis in the Sarawak River Basin.

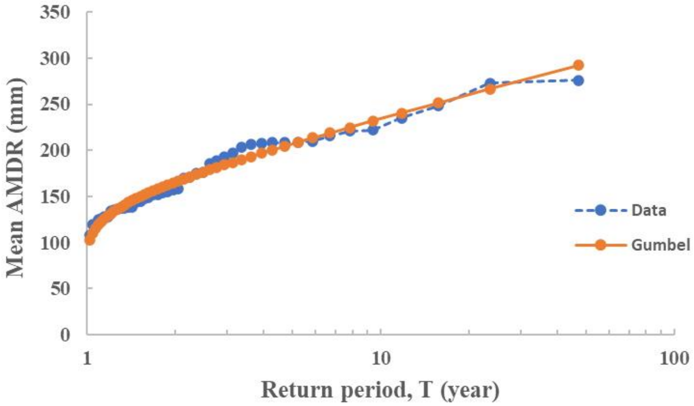

Figure 3: Frequency curve for mean AMDR for the Sarawak River Basin for the 1975-2020 period

CONCLUSIONS

In the current study, the data for annual maximum daily rainfall (AMDR) for 10 rainfall stations in the Sarawak River Basin for 1975 to 2020 were analyzed. Most of the rainfall stations (except the Sebubut rainfall station) showed high variability in the AMDR data, with the month of January (during the northeast monsoon) having the highest occurrence of AMDR. Additionally, a slight downward trend in the mean AMDR was observed throughout the decades, although the trend was not significant. From the study, the return period for mean AMDR events of magnitude 180 mm or more was 2.71 years. It was also observed that the exceedance probability values calculated using the mean AMDR (for the 10 rainfall stations) are comparable with the values calculated from a single rainfall station from a previous study. Hence, the mean AMDR values in the current study are representative of the whole Sarawak River Basin. A frequency curve for the mean AMDR data based on the Gumbel distribution was also developed for the Sarawak River Basin, which can be applied in the planning and design of flood infrastructures. For further study, hydrological deterministic studies should be carried out for the Sarawak River Basin to determine the critical magnitude of AMDR events that caused flooding since the magnitude of 180 mm adopted in this study was based on the literature. Furthermore, a study on the effect of climate change on the magnitude and frequency of AMDR events in the Sarawak River Basin can be carried out.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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