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Rainfall intensity-duration-frequency (IDF) curve development using Hazen, Weibull, and Gringorten methods for the upstream Permatang Rawa catchment

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ABSTRACT

The rainfall intensity-duration-frequency curve is an essential design tool in hydrology and hydraulics for stormwater, flood, and infrastructure planning. Its accuracy depends greatly on the probability estimation method used, particularly the plotting position formula. This study aims to draw IDF curves for the upstream Permatang Rawa catchment with the following three commonly used methods, namely Weibull, Hazen, and Gringorten. The annual maximum rainfall values at the rainfall station in the upstream catchment were obtained from DID Malaysia and analysed for various storm durations and return periods for the period 2000-2024. The results indicated that there was a clear inverse relationship between the rainfall intensity and the duration of the rainstorm, which is related to the rainfall intensity. The three plotting methods varied considerably in storm-plotting position, particularly for short-duration storms and high return periods. Rainfall intensities calculated using the Weibull method were about 0.06-7.99% lower than those from the Hazen method for higher return periods, suggesting that the Weibull method may underestimate extreme rainfall events. The Gringorten method, on the other hand, produced more intense and variable intensities because of its more prominent upper tail representation of the probability distribution. In general, the Weibull method exhibited good performance with smooth and consistent IDF curves for all storm durations and return periods. Thus, it was deemed to be the most suitable approach for the upstream Permatang Rawa catchment, considering the curve behaviour and the representation of

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extreme rainfall events. Findings are useful to inform the design of stormwater drainage and urban flood mitigation, and support Sustainable Development Goal 11 (SDG 11) Sustainable Cities and Communities by building more resilient infrastructure and practices for flood management.

1. INTRODUCTION

Rainfall intensity-duration-frequency (IDF) curves are key tools in hydrologic and hydraulic engineering, and they are used to determine the intensity of design storms needed for stormwater drainage systems, flood mitigation structures, and water resources infrastructure [1]. Three empirical relationships among rainfall intensity, storm duration, and return period are established by the IDF, reflecting the probabilistic dependence [2].

Methods for rainfall frequency analysis are very important in determining the reliability of the IDF curves [3]. A crucial step in this process is the estimation of non-exceedance probabilities from ranked annual maximum rainfall data, which is typically done using plotting position formulas. Some of the widely used plotting position methods in hydrological frequency analysis include Hazen, Weibull, and Gringorten methods [4]. These techniques give different probabilities to the ranked rainfall data. As a result, the estimated return periods and rainfall intensities vary, particularly for extreme rainfall events.

The Hazen plotting position gives more weight to the middle of the probability distribution [5]. In doing so, the average rainfall behaviour is well represented whilst extreme rainfall intensities can be underrepresented. The Weibull plotting position method has been used extensively in rainfall frequency analysis and hydrologic studies because it provides a balanced estimation of probability which applies to central values of rainfall as well as extreme events in various sample sizes [6]. By contrast, the Gringorten plotting position method focuses more on the high end of the range of probabilities and is most commonly applied in extreme rainfall analysis. However, higher variability and higher sensitivity can be achieved for relatively short rainfall records [7]. These differences underline the need for using a suitable plotting position method for more accurate and reliable rainfall intensity estimation and development of IDF curves for hydrologic design.

Although a variety of plotting position methods have been used in rainfall frequency analysis, there is no consensus on the best method to use when developing IDF curves for rainfall frequency analysis [4]. Climatic conditions, length of records, and characteristics of storm duration can affect the performance of different plotting position formulae, and thus the reliability of design rainfall intensity estimation. In many areas, IDF curves are created by an individual plotting position method, without comparing alternative methods, and may lead to under- or overestimation of design rainfalls for hydrologic and hydraulic design [8]. A good IDF curve should capture the extreme rainfall behaviour and should yield smooth and consistent relationships between intensity, storm duration, and return period. Furthermore, it should yield sound design rainfall estimates for use in stormwater drainage and flood control design applications [9]. As such, the ability of these various plotting position methods to represent the rainfall characteristics of a particular catchment, beyond the general uncertainty of hydrology, should be compared. This evaluation enables the

choice of the method that gives the most stable and realistic rainfall intensity estimates for local rainfall conditions. This is especially critical for short-duration (typically 15-minute to 1-hour) precipitation events that are directly linked to urban flooding and stormwater drainage system performance [10]. Therefore, it is important to conduct a comparative analysis of plotting position methods to improve the reliability of IDF curve development and design rainfall estimation of the Permatang Rawa catchment.

For this purpose, the present study attempts to develop rainfall IDF curves using rainfall durations of 5, 15, 30, 60, and 24 hours for the Permatang Rawa catchment and to carry out a comparative evaluation of the plotting position methods. Using annual maximum rainfall data, the study compares the Hazen, Weibull, and Gringorten plotting position to examine the effect on rainfall intensity estimation and the development of rainfall IDF curves. IDF relationships recommended in the Urban Stormwater Management Manual for Malaysia (MSMA) are commonly used to determine design rainfall intensities for stormwater drainage infrastructure in Malaysia [11]. However, with rapid urbanisation, land use change, and increasing rainfall variability, the need for revision of the IDFs and site-specific analyses to provide a more reliable estimation of design rainfall for urban stormwater management and flood mitigation planning has become more prominent [12], [13]. Hence, it is important to assess various plotting position techniques with local rainfall data to find an appropriate technique that can adequately describe the extreme rainfall behaviour of the urban catchments [14], [15]. The main goal of this study is to find the most suitable plotting position method to improve the reliability of IDF curves and design rainfall estimates for the hydrologic/hydraulic infrastructure design in the upstream Permatang Rawa catchment.

The upstream of the Permatang Rawa catchment is a part of the Juru Basin and is situated in Seberang Perai Tengah, Pulau Pinang, with an approximate catchment area of 552.94 ha, as shown in Fig. 1. The topography of the watershed is low, which is one factor that makes the watershed flood-prone because it has a high rate of accumulation of rain due to the momentum from the low elevation of the topography [8]. Drainage flows from the catchment area at relatively low velocity in the direction of downstream channels, especially during intense rain events. In addition, rapid urbanisation in the mid-catchment has decreased the natural infiltration capacity and increased impervious surfaces [6]. These integrated hydrological and land use attributes increase the volume of surface runoff, which highlights the importance of localised rainfall intensity analysis for designing effective drainage and planning for flood mitigation [16].

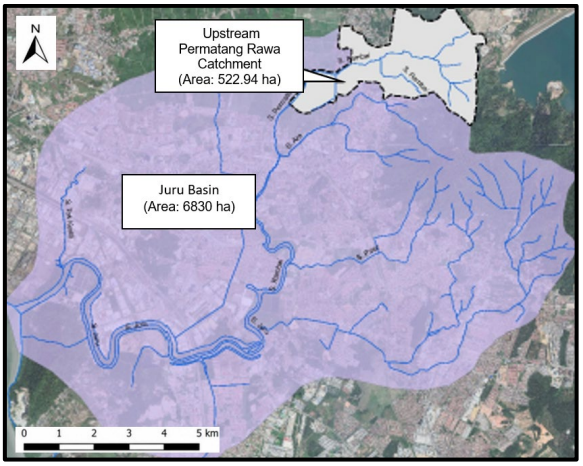


Fig. 1. River System of Juru Basin.

2. METHODOLOGY

In this study, the application of established statistical techniques was used to obtain rainfall frequency analysis and analyse the relationship between rainfall intensity and average recurrence interval (ARI). Data of annual maximum rainfall (AMR) were extracted from DID Malaysia and were used as primary data for analysis from the Permatang Rawa rainfall station over the period 2000-2024 [17].

Before carrying out the rainfall frequency analysis, the rainfall data were subjected to data quality control procedures such as the identification of missing data, verification of data consistency, and assessment of the reliability of rainfall records in order to ensure the suitability of the data for hydrological analysis [18]. The intensities of rainfall were analysed for a range of storm durations from 15 minutes to 24 hours, which are typical short-duration and long-duration storms that are used in hydrologic design [11]. The three widely used plotting position techniques (Hazen, Weibull, and Gringorten) have been used in the analysis to check the effect on the estimation of rainfall intensities [19]. In order to assess the effect on design rainfall estimation for the study catchment using various plotting position methods, a study was carried out using a comparative approach. This analysis used the same rainfall data and analysis procedures for each method to facilitate comparison. In Eq. (1) to Eq. (3), the mathematical expressions used in plotting position formulae were presented [20].

The Hazen plotting position is defined as:

$$Hazen = \frac{(i - 0.5)}{n} \times 100 \tag{1}$$

The Weibull plotting position is given by:

$$Weibull = \frac{i}{n + 1} \times 100 \tag{2}$$

The Gringorten plotting position is given by:

$$Gringorten = \frac{(i - 0.44)}{n + 0.12} \times 100 \tag{3}$$

The following equations describe the situation, where i is the rank of the rainfall event in order (from largest to smallest), and n is the number of rainfall events. The methods used to estimate rain intensity for various return periods and the development of comparative IDF curves for the study area were derived from these methods of plotting position.

In this study, rainfall frequency analysis was performed to determine the rainfall intensities for the average recurrence interval (ARI) of 2, 5, 10, 20, 50, and 100 years. These methods depict the intensity of precipitation that will fall on average once every number of years. The rainfall intensity estimates were subsequently used to create IDF curves for the upstream catchment of the Rawa Permatang. These IDF curves enable a comparison of the variation of rainfall intensity with storm duration and frequency to be used in the design of stormwater drainage and in urban flood mitigation planning.

3. RESULTS AND DISCUSSION

3.1 Settlement of IDF curves

The establishment of IDF curves is regarded as one of the most essential parts of hydrologic design because the safety and cost-effectiveness of drainage and flood control systems are directly dependent on the design rainfall estimate used [21]. In this study, the three most widely used plotting position methods are tested for developing IDF curves, using the same annual maximum rainfall dataset and storm durations. The three methods were compared systematically using a consistent analytical framework to explore how the methods affect the estimation of rainfall intensity and the development of IDF curves. Typically, IDF curves are assumed to have a consistent relationship, with higher precipitation intensities and shorter durations as well as longer return periods [4]. Such relationships can serve as an important reference to assess the suitability and consistency of the rainfall frequency IDF curves developed for the analysis and hydrologic design of rainfall. Each of the plotting position methods described above provides a set of IDF curves that have different characteristics; these characteristics are discussed separately for each of the plotting position methods and are of particular interest in representing the intensity of rainfall for storms of varying duration and intensity [10].

The IDF curves based on the Hazen plotting position method are the first basis for comparison among the three methods. The Hazen method is a commonly used method for hydrological frequency analysis in which the probability of a given rainfall event is assigned, based on its rank in the data set [22]. Its use in the analysis of the IDF makes it possible to get estimates of rainfall intensity consistently for various durations and return periods. The resulting Hazen-based IDF curves are considered in terms of their overall trend, continuity, and representation of the rainfall behaviour over the range of return periods under consideration. Special focus is placed on the changing intensity of rainfall as a function of the duration and recurrence time of storms, and the capacity of the method to capture the rainfall characteristic parameters that are significant for hydrologic and hydraulic design [6].

The Hazen method gave lower rainfall intensities than the Weibull method, with differences between them ranging from about 0.06% to 7.99%. The difference was not large for shorter ARIs, especially at an ARI of 2 years, where the Hazen estimates were only 0.06-0.62% smaller than the Weibull estimates. There was, however, a progressive increase in the discrepancy with increasing return period: at 100 years ARI, it was around 6.29-7.99%. This means that the Hazen method is more likely to underestimate the intensity of the heavy rain that would occur with a longer recurrence interval. These differences are especially significant for estimating extreme rainfall, where the lower estimates based on the Hazen method could result in an underestimate of design rainfall and therefore impact the size and performance of hydraulic infrastructure. Thus, it is important to carefully consider the type of method used for calculating probabilities, particularly for infrastructure that will be exposed to extreme rainfall events and long return periods. The summary of rain intensity estimation from the Hazen plotting position is shown in Table 1, and the IDF curve is shown in Fig. 2 for the upstream catchment of Permatang Rawa.

Moreover, the IDF curves, based on the Weibull plotting position method, give a balanced and physically realistic representation of the rainfall behaviour for various storm durations and return periods. The separation between return periods is more evident, especially at smaller storm durations, suggesting more sensitivity to extreme rainfall events. The rainfall intensity estimates from the Weibull method are higher than those from the Hazen method, and the difference is larger for higher return periods. Using the

estimated values, the Hazen method yields rainfall intensities that are approximately 0.06–7.99% lower than those estimated using the Weibull method; the greatest differences are found at higher return periods. This implies that the Weibull approach is a more suitable representation of the upper tail of the probability distribution without overly smoothing the upper rainfall values [21]. This means that the higher rainfall intensities at longer return periods are better represented, especially important for design rainfall estimation for hydraulic structures.

Table 1. Rainfall intensity estimates based on the Hazen plotting position method.

ARI (Years)	Rainfall Intensity (mm/hr)							
	0.25	0.5	1	2	3	6	12	24
2	126.72	95.52	65.94	40.55	28.52	15.64	8.46	4.79
5	145.08	110.36	78.41	47.78	33.94	19.10	11.31	6.85
10	158.96	121.60	87.84	53.25	38.04	21.72	13.47	8.41
20	172.84	132.82	97.27	58.72	42.14	24.35	15.62	9.97
50	191.20	147.66	109.73	65.95	47.56	27.81	18.47	12.03
100	205.08	158.90	119.16	71.42	51.66	30.44	20.63	13.59

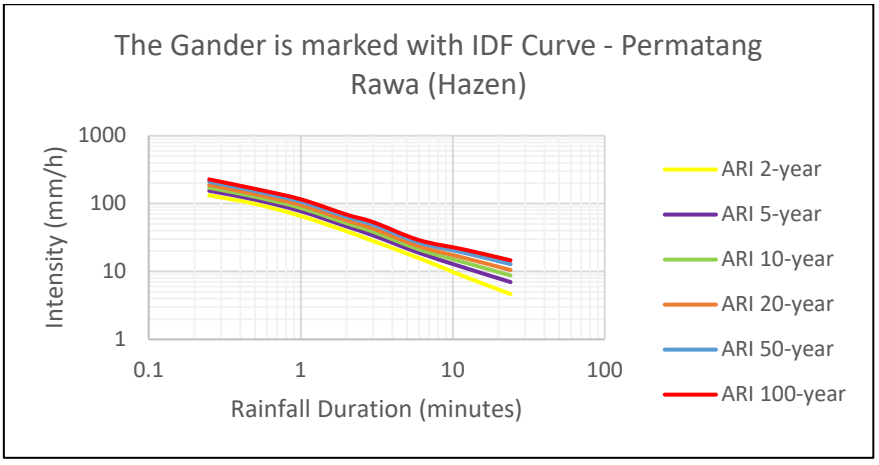


Fig. 2. The IDF curves for upstream Permatang Rawa were obtained from the Hazen method

Meanwhile, the Weibull method does not overestimate extreme values and therefore helps to provide stable and smoothly varying IDF curves with varying storm durations and return periods. This behaviour shows that the central tendency and upper tail of the rainfall distribution are well represented by the Weibull method. The rainfall intensity estimates derived from the Weibull method are summarised in Table 2, and the IDF curves for Permatang Rawa are shown in Fig. 3. The results obtained are in agreement with the recent ones obtained by other researchers who have used the Weibull plotting position method as a

satisfactory method for both stationary and non-stationary IDF analysis [10]. Moreover, its capability to include extreme value distribution families like Gumbel and Generalised Extreme Value (GEV) distribution further justifies its use for design storm estimation.

Table 2. Rainfall intensity estimates based on the Weibull plotting position method.

ARI (Years)	Rainfall Intensity (mm/hr)							
	0.25	0.5	1	2	3	6	12	24
2	126.80	95.62	66.01	40.59	28.57	15.67	8.51	4.82
5	148.36	113.02	80.69	49.08	34.86	19.67	11.75	7.15
10	164.68	126.20	91.79	55.51	39.63	22.74	14.20	8.91
20	180.96	139.38	102.89	61.94	44.39	25.78	16.65	10.68
50	202.52	156.80	117.57	70.43	50.69	29.80	19.90	13.01
100	218.84	169.98	128.68	76.86	55.45	32.84	22.35	14.77

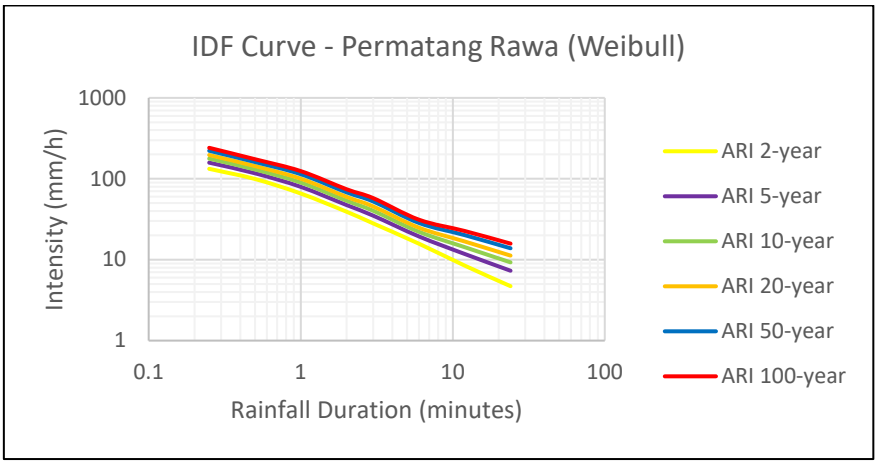


Fig. 3. IDF curves computed using the Weibull method for upstream Permatang Rawa catchment

The IDF curves created using the Gringorten plotting position method exhibit slightly different behaviour, especially for the high return periods and heavy rainfall conditions (Table 3). The Gringorten formula assigns a probability estimate that assigns more weight to the upper tail of the rainfall distribution and could thus be suitable for extreme rainfall analysis [4]. Its performance may depend more upon sample properties and record length, however, as rainfall quantiles increase to longer return periods [23].

In the present study, the trend of the Gringorten-based IDF curves is evident (Fig. 4), with higher and higher rainfall intensities corresponding to lower return periods. However, the rainfall intensities estimated with the Gringorten method are always smaller than intensities estimated with the Weibull method. The percentage difference is between about 0.06% and 6.91% and is relatively small for the 2-year return period, and greater for larger return periods. The Gringorten estimates are about 5.39-6.91% lower at the 100-year return period than the corresponding Weibull estimates for the storm durations listed, on average. This means that, for the present set of data, the Gringorten method is not overestimating the extreme rainfall compared to the Weibull method, but is actually giving more conservative intensity estimates for rainfall at longer return periods. At higher return periods, the rising difference between the different plotting position methods also indicates that the selection of the plotting position method may affect the estimation of the upper tail of the rainfall distribution and, therefore, the design rainfall for hydraulic infrastructure. Hence, the Gringorten method could offer an alternative estimate of extreme rainfall, but should be used in the context of the features and duration of the rainfall record and the chosen probability distribution.

Table 3. Summary of rainfall intensity estimates obtained using the Gringorten plotting position method.

ARI (Years)	**Rainfall Intensity (mm/hr)**							
	0.25	**0.5**	**1**	**2**	**3**	**6**	**12**	**24**
2	126.72	95.52	65.94	40.55	28.52	15.64	8.47	4.79
5	145.52	110.74	78.72	47.96	34.07	19.19	11.37	6.89
10	159.76	122.24	88.39	53.57	38.26	21.87	13.57	8.48
20	174.00	133.74	98.06	59.17	42.45	24.55	15.77	10.07
50	192.80	148.96	110.84	66.58	48.00	28.10	18.67	12.17
100	207.04	160.46	120.51	72.19	52.19	30.78	20.87	13.75

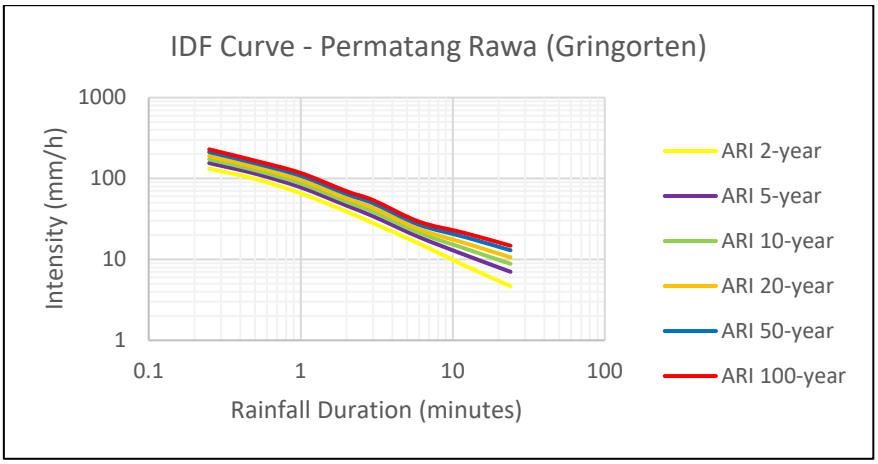


Fig. 4. IDF curves obtained using the Gringorten method for the upstream Permatang Rawa catchment

3.2 Comparative evaluation and selection of the best method

A comparative analysis of all three plotting position methods was carried out to assess the effect of these methods on the estimation of the intensity of rainfall and the corresponding IDF curves for the upstream Permatang Rawa catchment. While the general IDF curve trend is the same in all three (3) methods, some discrepancies were noticed, particularly for short durations and long return periods.

The Hazen method always gives lower estimates of rainfall intensity when compared to the Weibull method. This result suggests that extreme rain events may have been underestimated, and thereby may affect the reliability of design rainfall estimation for stormwater drainage systems.

But for higher values of rainfall intensity, the Gringorten method yields higher values than the Weibull method. This difference was most pronounced for short durations of storms and high return periods. The difference between these two methods is approximately 0.06-6.91%. A tendency to overestimate extreme rainfall events was indicated by this difference. This behaviour is explained by the greater emphasis placed on the upper part of the probability distribution in rainfall frequency analysis by the Gringorten method [24].

This study compared the intensity estimates of rainfall using statistical methods to assess the reliability of the plotting position methods. Using the Weibull method, a consistent pattern of rainfall intensity with return period and duration of storms was demonstrated. The IDF curve transitions were also smoother, and the variability was also reduced as compared to the Hazen and Gringorten methods. The differences between the Weibull estimates and other estimates were negligible for estimation of rainfall intensity. These differences did not exceed acceptable limits for hydrologic design or stormwater drainage design and applications for urban flood management. Moreover, the sensitivity test demonstrates that the Weibull method is less sensitive to variations in sample size and extreme rain events than is the Gringorten method. Moreover, it also eliminates the over-smoothed effect that is associated with the Hazen method of rainfall frequency analysis. Consequently, the rainfall intensity estimated using the Weibull method falls within a reasonable range between the lower estimate of Hazen and the higher estimate of Gringorten, which means the Weibull method is a balanced rainfall behaviour representation.

Furthermore, there are significant design implications for hydraulic infrastructure for changes in the intensity of rainfall estimates. Underestimating rainfall intensity may result in undersized culverts, stormwater drainage, and detention storage facilities, which may contribute to urban flooding during extreme rainfall events [25]. Overestimation of the rainfall intensity, on the other hand, may lead to over-designed infrastructure, higher construction expenses, and poor planning of the stormwater drains. So, for the development of the IDF curve in the upstream Permatang Rawa catchment, the Weibull method is a method that can provide balanced and consistent estimates of rainfall intensities.

4. CONCLUSION AND RECOMMENDATION

The IDF curves for the upstream Permatang Rawa catchment were developed using annual maximum rainfall data and three plotting position methods, namely Hazen, Weibull, and Gringorten. Rainfall intensities were estimated for storm durations from 15 minutes to 24 hours and return periods of 2 to 100 years**.** The results show that rainfall intensity decreases with increasing storm duration and increases with higher return periods**.**

Differences in rainfall intensity estimates were observed among the three methods. These differences were more noticeable for short storm durations and high return periods. Lower values were produced by the Hazen method, while higher values were produced by the Gringorten method due to its focus on the upper tail of the probability distribution**.** However, higher variability was observed when shorter rainfall records were used. The Weibull method showed balanced performance with smooth and stable IDF curves [26].

Based on the results, the Weibull method is suitable for developing IDF curves in the study area [27]. The Weibull-based IDF curves provide reliable design rainfall intensity estimates for hydrological and hydraulic design applications in the upstream Permatang Rawa catchment. According to the findings of this study, the rainfall intensity values from the Weibull method are higher than those from the Hazen method. Besides, they are lower than those from the Gringorten method. Thus, this shows a balanced result. Therefore, the Weibull method can be used for IDF curve development, stormwater drainage design, and urban flood mitigation planning in similar urban catchments.

However, this study mainly compares the behaviour of different plotting position methods and does not include detailed statistical validation. Therefore, further studies are needed to validate the reliability of the developed IDF curves. Future research should use longer rainfall records, more rainfall stations, and statistical methods such as goodness-of-fit testing, confidence interval analysis, and sensitivity analysis to improve rainfall frequency analysis results. Future studies should also use non-stationary rainfall frequency analysis approaches that reflect climate variability and long-term rainfall trends to enhance design rainfall estimation in the changing climate [16]. Non-stationary rainfall frequency analysis techniques, which account for climate variability and long-term rainfall trends, are encouraged for more reliable design rainfall estimates in a changing climate. Furthermore, incorporating the developed IDF curves in hydrologic and hydraulic models would enable a more thorough analysis of flood risk and performance of drainage systems in the event of excessive rainfall [28].

5. ACKNOWLEDGEMENTS/FUNDING

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6. CONFLICT OF INTEREST STATEMENT

The authors declare that this research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The funders had no role in the design of the study, data collection and analysis, interpretation of results, or decision to publish the findings.

7. AUTHORS' CONTRIBUTIONS

Normashita Abdul Halim: Conceptualisation, methodology, formal analysis, investigation, and writing - original draft. **Muhamad Faizal Pakir Mohamed Latiff**: Conceptualisation, methodology, and formal

analysis. **Anas Ibrahim**: Formal analysis and validation. **Mohd Azrizal Fauzi**: Conceptualisation, supervision, writing - review and editing, and validation. **Muhammad Nasri Nasehir Khan**: Review and editing. All authors have read and approved the final manuscript.

8. DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

In this work, the authorsused ChatGPT to assist with language refinement, the organisation of ideas, and the structuring of the research framework. The authors independently conducted the literature review, verified all sources, and take full responsibility for the accuracy, originality, and final intellectual content of the work.

9. DATA AVAILABILITY/SUPPLEMENTARY MATERIALS

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

10. ETHICS STATEMENT

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of Universiti Teknologi MARA (UiTM).

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