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DETERMINATION OF BASIN-SPECIFIC FREQUENCY FACTOR FOR ESTIMATING PROBABLE MAXIMUM PRECIPITATION IN HADEJIA JAMARE RIVER BASIN NIGERIA

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Abstract

Extreme rainfall events pose significant challenges to the design of flood control infrastructure, especially spillways. This study evaluates three scenarios for estimating the frequency factor, a vital component of the Hershfield method of determining probable maximum precipitation (PMP). The study examines the impact of multiple outliers on frequency factor estimation through three scenarios. The study employed the Hershfield procedure in the derivation. Daily annual maximum rainfall data was collected from three stations (Kano, Bauchi and Dutse). The data was subjected to outlier checks using the box and whisker plot for simplicity and easy visualization. The results were analyzed using the Analysis of Variance (ANOVA). The ANOVA results clearly showed the number of outliers and the selection of the highest observed daily rainfall depth (X_{max}) have a significant effect on the frequency factor. The frequency factor obtained ranges from 2.1 to 4.88. Among the three Scenarios, Scenario 2 provided a more reliable estimate due to its ability to account for extreme outliers effectively. The results underscore the importance of considering outliers in hydrologic analysis to avoid underestimating risks in flood-prone areas. This ensures that infrastructure is better equipped to withstand rare, high-magnitude rainfall events, reducing the risk of catastrophic failures.

1.0 INTRODUCTION

Extreme precipitation events are intense periods extending the bound of typical weather patterns and can significantly impact the environment and human activities. These events are becoming more frequent and intense as global temperatures rise, increasing risk and damage to hydraulic structures [1], [2] [3][4]. To effectively mitigate the risks associated with these extreme events, robust estimation methods for PMP are critical. The concept of Probable Maximum Precipitation is widely used by Engineers in the design of hydraulic structures like dams and spillways especially when it is envisaged that failures of such structures could lead to loss of lives and properties. PMP represents the greatest theoretically possible precipitation depth over a specific area and time, given prevailing meteorological conditions [5]. The initial belief was that the PMP is so large to the extent that the value cannot be exceeded that is, it has a theoretical exceedance probability of zero [6]. However, this assumption has been proven to be wrong [7]. Therefore, studies have been carried out which assign a risk statement to PMP estimates [8][9]. There are two main methods of estimating PMP- the

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physical method and the statistical method [10][11][12]. The review of available literature indicates that the Hershfield approach is the most widely statistical method used when estimating for basins where there are sufficiently long precipitation data but other meteorological data such as dew point and wind records are not available [13]. The physical method involves storm transposition and maximization techniques, which rely on detailed meteorological data, making it less applicable in data-sparce regions [14].

The frequency factor (*Km*) is a statistical value that is transposed and corrected by the mean and standard deviation of the precipitation data to represent a maximum observed storm, according to the World Meteorological Organization (WMO) [5]. The Hershfield approach of determining PMP depends on the accuracy of the *Km* estimation hence the right method should be applied for its determination. A high value of *Km* leads to overestimation of PMP, which in turn results in an uneconomical design; conversely, a lower value of *Km* results in underestimation of PMP, which could eventually cause the structure built with such specifications to fail [15]. Hershfield's survey of 2700 rain gauge stations, 90% of which were in the United States and the remaining 10% spread across other countries, was the first significant work in the statistical estimation of PMP. The survey found that the *Km* values ranged from 3 to 14.5 [16]. The researcher rounded the upper limit to 15 which was then adopted as *Km* in the estimation of 1 day-PMP. While the Hershfield approach is widely used due to its simplicity, its reliance on a universal frequency factor of 15 has been criticized for overestimating PMP in certain regions. This highlights the need for regionally calibrated frequency factor to improve design accuracy [17][11]. To correct this anomaly, an envelope curve that inversely relates the average maximum annual precipitation and the frequency factor for different durations was developed [18]. This curve gives each average precipitation its proper value termed K envelope. Since then, several types of envelope curves have been developed in different countries. For instance, the polynomial curve in Malaysia [19] the linear curve in Japan and Algeria respectively [17], [20], the exponential curve in Thailand [21], third-degree polynomial curve in Iran [22]. The exponential and second-degree polynomial curves are also in Malaysia [23]. Furthermore, a new enveloping technique called the “composite envelope curve” was also developed in India [24]. In addition, five types of envelope curves (linear, exponential, 2nd degree polynomial, composite, and the proposed linear) were compared in the coastal regions of Algeria [17]. The researchers adopted the new technique proposed in India: a composite of a straight line parallel to the axis of average maxima values and a decreasing exponential curve [24]. Globally, studies have derived varying frequency factors for different regions, as summarized in Table 1. This variability underscores the importance of developing localized approaches to PMP estimation. In a related study [25] estimated the PMP for Lafia using the statistical method. Some other researchers have used the Gumbel method to estimate the frequency factor [26][27][28].

Table 1: Frequency factors for different regions of the World

Region/Basin	Country	K_{env}	Source
Hershfield	World	15.0	[16]
Atrak	Iran	9.6	[29]
Puigcerda	Spain	8.7	[30]
Tigray	Ethiopia	5.9	[31]
Mountainous	Pakistan	4.8	[32]
Selangor	Malaysia	8.7	[33]

Meanwhile, some researchers have argued that the original Hershfield approach has not taken care of the effect of multiple outliers in the determination of frequency factor [34]. Based on this, they used a new approach where the outlier test was applied first to the yearly maximum daily rainfall numbers. Unlike the original Hershfield, where only the highest value is eliminated regardless of the number of outliers, in the case of multiple outliers, the number of outliers was eliminated from the numerator after adjusting for the mean and standard deviation. Additionally, samples were used entirely without removing any values in cases where there was no outlier. Comparing this modified strategy to the original Hershfield method, the results showed that the presence of many outliers overestimated the PMP by up to 45%. Consequently, they suggested include some outliers in the application of statistical method. Given the variability in regional climatic conditions and the impact of outliers on PMP estimation, there is a pressing need to derive basin-specific frequency factors. This study aims to address this gap for the Hadejia-Jamare River Basin.

2.0 METHODOLOGY

2.1 Description of the Study Area

Hadejia-Jamare River Basin covers an area of about 45,000 km^2 consisting of the whole of Kano and Jigawa States, about two-thirds of Bauchi State and small parts of Plateau State as shown in Figure 1.

The Basin is located between the latitudes of 11°32′08.4″ N and 12°26′24.8″ N, and the longitudes 8°07′50.0″ E and 10°01′50.9″ E . The hydrology of the basin is dendritic. Annual mean rainfall is about 600 mm in the northeastern parts to 800 mm in the midstream area to 1,000 mm in the extreme south of the basin [35]. The socio-Economic and hydrological importance of the basin are immeasurable as it provides water for irrigation, domestic uses, and helps to control flooding through dams construction [36].

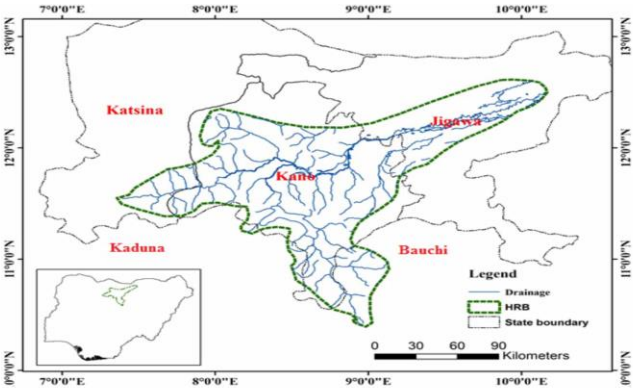

Figure 1: A map showing the Hadejia-Jamare river basin drainage system [37]

2.2 Data Collection

Daily rainfall data for 50 years, 39 years, and 38 years for Kano, Dutse, and Bauchi towns respectively were obtained from the Institute of Agricultural Research (IAR), Ahmadu Bello University, Zaria, and the Nigerian Meteorological Agency (NiMet). Daily annual maximum rainfall depths were extracted for each year's record. These stations were selected based on the area coverage of the basin. The presence of trends in the annual maximum rainfall series for the three rainfall stations was checked using the Mann-Whitney (M-W) test with the aid of Microsoft Excel 2016.

2.3 Identification of Outliers

Identification of outliers is very important in data analysis, as it points out the inconsistencies that may be present in a dataset. This could be a result of incorrect data entry or the use of faulty equipment [38]. Outliers can significantly impact statistical analysis, leading to biased estimates, misleading correlations, and inaccurate predictions. Various methods are used to detect outliers including the Grubb's test and Box and Whisker Plots. The Box and Whisker plot offers a visual and non-parametric approach to detecting outliers, making it more robust to non-normality and easier to interpret than Grubbs' test [39]. It is a standardized method of displaying data distribution based on five key metrics: minimum, first quartile (Q_1), median (Q_2),), third quartile (Q_3),), and maximum. The interquartile range (IQR), which is the difference between Q_3 and Q_1, helps define the limits. Data points are considered outliers if they are above the upper limit or below the lower limit as shown in Equations 2 and 3.

$$IQR = Q_3 - Q_1 \tag{1}$$

$$Lower\ limit = Q_1 - (1.5 \times IQR) \tag{2}$$

$$Upper\ limit = Q_3 + (1.5 \times IQR) \tag{3}$$

2.4 Derivation of the study Area's Basin-Specific Frequency Factor (K_m)

As previously mentioned, numerous studies conducted worldwide have demonstrated that the application of a frequency factor of 15 overestimates PMP values in areas with high annual rainfall and underestimates PMP statistics for areas with low annual rainfall [40]. To address this issue, some researchers used Equation 4 to modify the Hershfield approach to obtain site-specific frequency factor for Selangor in Malaysia [41].

$$K_m = \frac{X_{max} - \overline{X}_{n-1}}{S_{n-1}} \tag{4}$$

Where, X_{max} is highest observed annual maximum rainfall, $\overline{X}_{n-1}$ *is* mean of annual maxima, without the highest value and S_{n-1}: standard deviation of annual maxima without the highest value.

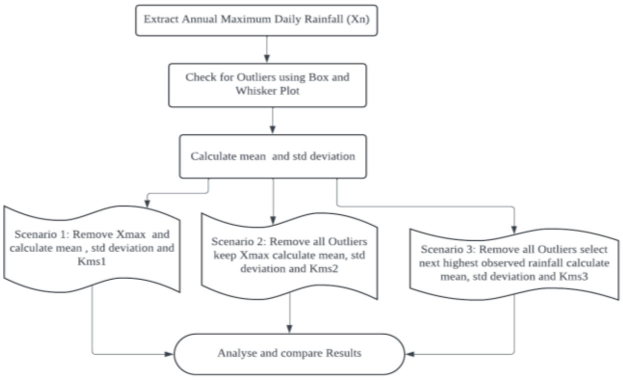

Figure 2: Flow chart of the research methodology

To develop an appropriate envelope frequency factor $K_{envelope}$ for the study area, this study considered three different scenarios out of which the best one was selected. These scenarios are defined as follows:

The first scenario which followed the original Hershfield approach was denoted as S_1. The second scenario removed all the outliers present in the data and still maintained the highest observed value, denoted as S_2. The last scenario removed all outliers present as well as the highest observed value in the data and was denoted as S_3. For each of these scenarios, the frequency factors were calculated. Some researchers have adopted the first and third scenarios [34][42]. However, the second scenario which is a hybrid of the two was introduced in this study to underscore the effect of removing the highest observed rainfall data from the data under consideration. The flowchart of the methodology is shown in Figure 2.

2.5 Derivation of the K_m Factor Considering the First Scenario S_1

Envelopment is the procedure adopted for choosing the largest value from a given set of data [5]. Several researchers have adopted this technique in applying Hershfield statistical method [43]. In this case, the parameters of Equation 4 were determined that is X_{max}, $\bar{X}_{n-1}$ and S_{n-1}. The K_m values for the three stations were calculated.

2.6 Derivation of the K_m Factor Considering the Second Scenario S_2

The second scenario where all the outliers detected were removed, Equation 4 was slightly modified depending on the number of outliers present in the data set. For the Jigawa station with only one outlier, Equation 4 remained the same as in scenario 1. However, in the case of the Bauchi station with two outliers, the equation was modified as shown in Equation 5. Whereas in the case of the Kano station with three outliers Equation 4 was adjusted accordingly as shown in Equation 6.

$$K_m = \frac{X_{max} - \bar{X}_{n-2}}{S_{n-2}} \tag{5}$$

Where, X_{max} is highest observed annual maximum rainfall, $\bar{X}_{n-2}$ is mean of annual maxima, after removing two outliers and S_{n-2} *is* The standard deviation of annual maxima after removing two outliers.

$$K_m = \frac{X_{max} - \bar{X}_{n-3}}{S_{n-3}} \tag{6}$$

Where, X_{max} *is* highest observed annual maximum rainfall, $\bar{X}_{n-3}$ *is* mean of annual maxima, after removing three outliers and S_{n-3} is the standard deviation of annual maxima after removing three outliers.

2.7 Derivation of the K_m Factor Considering the Third Scenario S_3

In scenario 3 all the outliers were removed and the next highest observed value considered. In this case, to calculate the frequency factor for the kano station, the same Equation 6 was maintained. However, the highest observed value changed. Similarly, in the case of Bauchi station, Equation 5 still holds while the highest observed rainfall changed. For the Dutse station, Equation 4 was applied as it has only one outlier. The procedure for the calculation of the K_m factor for each of the scenarios is illustrated in Table 2 which shows extracted annual maximum daily rainfall depths for each of the stations. The calculations were carried out using Microsoft Excel 2016. Table 3 shows the summary statistics of annual maximum daily rainfall of all stations with kano having the highest mean of 94.0 mm and Dutse having the least figure of 71.6 mm.

Table 2: Annual maximum daily rainfall depths for the three stations

	Kano			Bauchi			Dutse	
Year	**Rainfall depth (mm)**	X_{n-1}	X_{n-3}	**Rainfall depth (mm)**	X_{n-1}	X_{n-2}	**Rainfall depth (mm)**	X_{n-1}
1972	61.7	61.7	61.7	-	-	-	-	-
1973	152.7	152.7	152.7	-	-	-	-	-
1974	57.9	57.9	57.9	-	-	-	-	-
1975	51.6	51.6	51.6	-	-	-	-	-
1976	76.7	76.7	76.7	-	-	-	-	-
1977	52.3	52.3	52.3	-	-	-	-	-
1978	165.1	165.1	165.1	-	-	-	-	-
1979	51.1	51.1	51.1	-	-	-	-	-
1980	51.9	51.9	51.9	-	-	-	-	-
1981	47.1	47.1	47.1	-	-	-	-	-
1982	60.1	60.1	60.1	-	-	-	-	-
1983	101.6	101.6	101.6	47.0	47.0	47.0	39.67	39.67
1984	70.0	70.0	70.0	50.9	50.9	50.9	47.6	47.6
1985	47.6	47.6	47.6	72.9	72.9	72.9	52.07	52.07
1986	52.0	52.0	52.0	69.4	69.4	69.4	50.8	50.8
1987	48.4	48.4	48.4	63.9	63.9	63.9	46.1	46.1
1988	53.0	53.0	53.0	68.2	68.2	68.2	53.0	53.0
1989	104.2	104.2	104.2	56.3	56.3	56.3	55.0	55.0
1990	110.0	110.0	110.0	49.8	49.8	49.8	48.55	48.55
1991	81.6	81.6	81.6	52.7	52.7	52.7	55.12	55.12
1992	68.0	68.0	68.0	96.9	96.9	96.9	75.33	75.33
1993	56.6	56.6	56.6	80.8	80.8	80.8	66.0	66.0
1994	46.5	46.5	46.5	68.0	68.0	68.0	48.78	48.78
1995	72.5	72.5	72.5	112.0	112.0	112.0	79.1	79.1
1996	102.3	102.3	102.3	70.5	70.5	70.5	86.12	86.12

1997	162.5	162.5	162.5	110.2	110.2	110.2	108.5	108.5
1998	104.2	104.2	104.2	96.8	96.8	96.8	96.18	96.18
1999	78.5	78.5	78.5	71.3	71.3	71.3	80.4	80.4
2000	101.4	101.4	101.4	62.7	62.7	62.7	70.46	70.46
2001	163.8	163.8	163.8	55.4	55.4	55.4	77.27	77.27
2002	79.6	79.6	79.6	91.1	91.1	91.1	68.7	68.7
2003	94.3	94.3	94.3	83.9	83.9	83.9	50.59	50.59
2004	73.2	73.2	73.2	78.8	78.8	78.8	54.23	54.23
2005	97.2	97.2	97.2	49.0	49.0	49.0	53.14	53.14
2006	105.4	105.4	105.4	145.2	145.2	145.2	56.82	56.82
2007	80.5	80.5	80.5	110.6	110.6	110.6	112.0	112.0
2008	240	240	73.3	101.8	101.8	101.8	70.26	70.26
2009	241	73.3	90.4	125.8	125.8	125.8	103.09	103.09
2010	73.3	90.4	143.0	132.9	132.9	132.9	140.31	44.95
2011	90.4	143.0	99.3	80.2	80.2	80.2	44.95	78.13
2012	143.0	99.3	95.0	200.0	80.0	80.0	78.13	85.59
2013	99.3	175.5	75.3	80	97.4	97.4	85.59	95.79
2014	175.5	95.0	104.5	97.4	92.5	92.5	95.79	65.43
2015	95.0	75.3	97.8	92.5	111.5	111.5	65.43	64.1
2016	75.3	104.5	90.9	111.5	72.0	72.0	64.1	52.46
2017	104.5	97.8	74.0	72.0	91.0	91.0	52.46	95.95
2018	97.8	90.9	114.7	91.0	69.5	69.5	95.95	71.01
2019	90.9	74.0	-	69.5	187.6	-	71.01	82.83
2020	74.0	114.7	-	187.6	-	-	82.83	109.51
2021	114.7	-	-	-	-	-	109.51	-

Table 3: Summary statistics of annual maximum daily rainfall of the three stations

Station	Mean	Median	Standard dev	range
Kano	94.0	81.1	44.7	184.5
Bauchi	88.3	80.1	34.5	153
Dutse	71.6	68.7	22.8	100.6

3.0 RESULTS AND DISCUSSION

3.1 Result of Outlier Detection

The outlier detection was done using the box and whisker plot in Microsoft Excel 2016. Some researchers have also adopted this procedure [42].

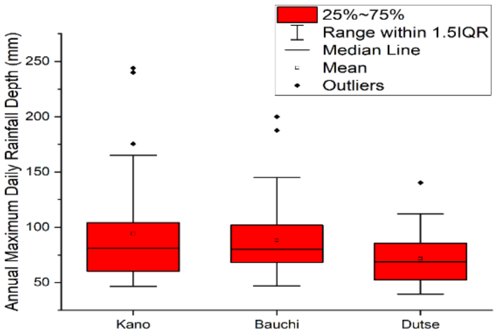

Figure 3: Number of Outliers for the different stations

3.2 Discussion of the Outlier

As shown in Figure 3, Kano station has the most outliers, with three, followed by Bauchi and Dutse stations, with two and one outliers, respectively. This outcome is consistent with the findings of two researchers who examined a few stations and found that roughly 50% of them had several outliers that the Hershfield procedures often do not handle [34]. Consequent upon this, multiple outliers can result in biased estimates and inaccurate predictions which subsequently lead to overestimation of PMP.

3.3 Basin-Specific Frequency Factors under the Three Scenarios

Table 4 shows the K_m calculations for each of the stations across the scenarios while Table 5 shows the summary of the results.

Table 4: K_m calculations for the three stations

Station	S_1		S_2		S_3	
Kano	X_{max}	241.00	X_{max}	241.00	X_{max}	165.10
	$\bar{X}_{n-1}$	90.96	$\bar{X}_{n-3}$	85.99	$\bar{X}_{n-3}$	85.99
	S_{n-1}	39.88	S_{n-3}	31.76	S_{n-3}	31.76
	Kms_1	3.76	Kms_2	4.88	Kms_3	2.49
Bauchi	X_{max}	200.00	X_{max}	200.00	X_{max}	145.20
	$\bar{X}_{n-1}$	85.31	$\bar{X}_{n-2}$	82.47	$\bar{X}_{n-2}$	82.47
	S_{n-1}	29.58	S_{n-2}	24.51	S_{n-2}	24.51
	Kms_1	3.88	Kms_2	4.80	Kms_3	2.56
Dutse	X_{max}	140.31	X_{max}	140.31	X_{max}	112.00
	$\bar{X}_{n-1}$	69.75	$\bar{X}_{n-1}$	69.75	$\bar{X}_{n-1}$	69.75
	S_{n-1}	20.10	S_{n-1}	20.10	S_{n-1}	20.10
	Kms_1	3.51	Kms_2	3.51	Kms_3	2.10

Table 5: Scenario results

			S_1		S_2		S_3	
Station	**Record length**	**No. of Outliers**	X_{max}	Kms_1	X_{max}	Kms_2	X_{max}	Kms_3
Kano	50	3	241	3.76	241	4.88	165.1	2.49
Bauchi	38	2	200	3.88	200	4.8	145.2	2.56
Dutse	39	1	140.31	3.51	140.31	3.51	112	2.1

3.4 Discussion of the Frequency Factors under the Three Scenarios

As seen in Table 5, Kano station has three outliers, significantly higher than other stations. It is also noticed that as multiple outliers were removed and the maximum observed data maintained, the frequency factors increased as shown by Scenario 2 for both Kano and Bauchi stations. However, the trend changed when the outliers were removed as well as the maximum observed data as seen in Scenario 3 where the frequency factors reduced drastically.

Visual observation of Table 5 shows that the number of outliers have a significant effect on the K_m . Kano station has more outliers and generally higher K_m values, especially in Scenario 2. Dutse station with the fewest outliers generally has lower K_m values, especially in Scenario 3. The change in the highest observed rainfall (X_{max}) across scenarios significantly affects K_m values. Considering Scenario 1 and Scenario 2 where X_{max} is constant for Kano and Bauchi stations but the K_m increases significantly in Scenario 2. For Scenario 3, X_{max} decreases across the board so also the K_m values implying a strong relationship between X_{max} and K_m values. To underscore the effect of X_{max} and the number of outliers on K_m factors, two-way analysis of variance (ANOVA) was performed to quantify this relationship. The hypotheses are:

Null Hypotheses (H_0)

1. H_{01} (Effect of X_{max}): There is no significant effect of X_{max} on K_m values.
2. H_{02} (Effect of Number of Outliers): The number of outliers has no significant effect onK_m values.
3. H_{03} (Interaction Effect): There is no significant interaction effect between X_{max} and the number of outliers on K_m values.

Alternate Hypotheses (H_1)

1. H_{11} (Effect of X_{max}): There is a significant effect of X_{max} on K_m values.
2. H_{12} (Effect of Number of Outliers): The number of outliers has a significant effect on K_m values.
3. H_{13} (Interaction Effect): There is a significant interaction effect between X_{max} and the number of outliers on K_m values.

Table 6: ANOVA result

Source	**Sum of Square (SS)**	**df**	**F-Value**	**P-Value**
X_{max}	5.57	1	23.49	0.0047
No. of Outliers	1.85	1	7.8	0.0383
X_{max}	0.24	1	1.03	0.3562
Residual	1.18	5		

Table 7: Correlation coefficient for each scenario

Predictors	r_1	r_2	r_3
Record length	0.13	0.48	0.30
X_{max}	0.74	0.94	0.85
No of outlier	0.66	0.89	0.79

From the ANOVA results shown in Table 6, the P-value for the X_{max} (0.0047) is less than 0.05, so we reject the null hypothesis (H_{01}) which implies that at a confidence level of 95% X_{max} has a significant effect on the K_m values. Similarly, for the number of outliers the P-value is also less than 0.05 indicating that the number of outliers significantly affects the K_m values. However, for the interaction between the two factors, the P-value (0.3562) is greater than 0.05. Therefore, we fail to reject the null hypothesis (H_{03}) which suggests that the interaction between X_{max} and the number of outliers does not have a significant effect on the K_m values.

The ANOVA results indicate that variations in the two independent variables (X_{max} and the number of outliers) individually lead to significant differences in the K_m factors across the scenarios. From this finding, it is important to take caution when removing outliers not to remove the highest observed rainfall data as these factors have a measurable impact on the K_m especially when predicting extreme events such as PMP.

Furthermore, correlation analysis between the K_m values and the predictors record length, X_{max} and the number of outliers was conducted using the Pearson correlation coefficient the result of which is shown in Table 7. From the result, it shows that across the scenarios the record length shows a weak positive correlation compared to X_{max} and the number of outliers. However, this result is contrary to [11][44] probably due to the limited number of stations.

3.5 Implication of Frequency Factor on PMP

The frequency factor is employed to adjust observed maximum precipitation values to estimate the Probable Maximum Precipitation (PMP). A higher frequency factor leads to larger PMP estimates, as it accounts for more extreme events. In regions with highly variable precipitation, the selection of the frequency factor introduces uncertainty into PMP calculations. If the factor is too high, the PMP estimate may become unrealistically large, potentially resulting in the overdesign of hydraulic structures.

4.0 CONCLUSION

From the study, it can be inferred that the change in the choice of the highest observed daily rainfall depth affects the frequency factor significantly as exemplified in Scenario 3. Moreso, the existence of more than one outlier led to higher K_m values. This finding aligns with [34] [28], who reported that multiple outliers tend to overestimate frequency factors. For extreme event prediction, Scenario 2 is recommended for the study area because it provides a more conventional estimate by yielding higher K_m factors. This would ensure that the spillway design or other flood control measures are strong enough to handle extreme rainfall events in case they occur. In addition, more rain gauge stations within the same basin can be considered to verify the assertions made as they concern the effect of multiple outliers on the frequency factor. Also, similar studies should also be conducted across the other river basins across the country.

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