Probable Maximum Precipitation Estimation Considering Homogeneous Regions Using Hershfield Statistical Method

Rasnavi Paramasivam[1], Nor Eliza binti Alias [1*]

[1]School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Malaysia

[*] noreliza@utm.my

ABSTRACT. The probable maximum precipitation (PMP) for stations in Peninsular Malaysia using Hershfield formula is routinely estimated considering the state boundary and homogeneous region from yearly 1-day maximum rainfall values. In this paper, yearly maximum 1-day rainfall data of more than 25 years for 161 stations in the Peninsular Malaysia, were analysed in an attempt to estimate PMP for 1-day duration based on an appropriate frequency factor. Based on the actual rainfall data of the stations, the highest value of this frequency factor was used to estimate 1-day PMP values for the 161 stations. Using these PMP estimates, a generalised graph was prepared showing the spatial distribution of 1-day PMP. It was found that 1-day PMP over Peninsular Malaysia by considering state boundary, varied from 146 to 5052 mm and by considering the homogeneous regions, varied from 247 to 6250 mm. The PMP considering homogeneous regions is considered as important to determine reliable and consistent PMP estimate for any location in Peninsular Malaysia, for designing costly and large hydraulic structures.

Keywords: Probable Maximum Precipitation, Homogeneous Region, Peninsular Malaysia

INTRODUCTION

A flood is an overflow of water that submerges land that is usually dry. Flooding may occur as an overflow of water from water bodies, such as a drainage, river and lake, which the water overtops resulting in some of that water escaping its usual boundaries. Some floods develop slowly, while others can develop in just a few minutes and without visible signs of rain.(Ching et al., 2013). International reports such as The Asia Pacific Disaster Report, 2010 published by The Economic and Social Commission for Asia and the Pacific (ESCAP) and the United Nation International Strategy for Disaster Reduction (ISDR) reported that record-breaking extreme rainfalls had been increasing especially since the 2000's. In accordance to the increasing trend of extreme rainfalls, flood occurrences are also observed to increase (Bhatia et al., 2010).

In Malaysia, some of the recent major extreme rainfall events were floods in December 2014 and January 2015. Flood causes losses of lives and property of thousands of people. This does not only impact the society but also the economics of the country will be affected too. Thus, mitigation measures to deal with problems or disasters generated from the increasing of this extreme rainfall needs to be assessed. There are various steps and approaches that can contribute to the preparation of future extreme rainfall. One of them is to predict the probability of occurrence of an extreme rainfall event. A popular and conventional method is to use frequency analysis. Another acceptable method is to predict the most possible highest rainfall amount that could occur by using the probable maximum precipitation (PMP) estimates.

PROBLEM STATEMENT

In Malaysia, water released from the Sultan Abu Bakar hydroelectric dam in Cameron Highland after the siren was sounded which was either not heard or went unheeded brought death and destruction to Bertam Valley in Ringlet. Three people were confirmed dead, nearly 100 houses destroyed or under water and over 100 vehicles badly damaged. Thirty-eight people from about 80 families have been placed at the Ringlet community hall. This was due to increase in the level of water in the dam from 3498 to 3508 meter. The water level rises due to heavy rainfall at a short period of time. (Manjit Kaur,2013)

In order to minimize such events from occurring, the future events of the precipitation are very important to be determined. There are few various methods to determine the future events. One of the methods is PMP. PMP estimates the most possible rainfall data in different regions in Peninsular Malaysia. There are two methods in estimating the PMP which are physical method and statistical method. However, physical method is not suitable to be used as it requires large amount of data and the meteorological parameters such as the dew-point temperature, relative humidity, and surface temperature. Hershfield statistical method is the most suitable to estimate PMP as an initial estimation in determining the extreme precipitation that could occurred in Peninsular Malaysia as it only requires precipitation data. However, PMP estimation using state boundary gives values that are closer to the highest rainfall data. For example, Chin Chin (Tepi Jalan) station in Melaka has PMP estimated value of 146mm which is much closer to the 1-day annual maximum rainfall value of 141.5 mm. Therefore, it is more suitable to estimate PMP considering homogeneous region and state boundary.

OBJECTIVES

The research objectives can be summarized as follows:

1. To estimate probable maximum precipitation (PMP) using Hershfield statistical method,
2. To estimate probable maximum precipitation using Hershfield statistical method considering homogeneous regions, and
3. To assess the difference between the probable maximum precipitation (PMP) estimation using Hershfield method with state boundary region and with the homogeneous region.

SCOPE OF STUDY

This research is aimed to estimate statistical probable maximum precipitation using conventional Hershfield method considering the homogeneous regions. The area of study is limited to only within the Peninsular Malaysia. The rainfall station with data of more than 25 years within the Peninsular Malaysia. This study employs the statistical method. This study will analyze the differences between the PMP estimation using Hershfield method with state boundary region and with the homogeneous region.

LITERATURE REVIEW

In 1959, the American Meteorological Society defined probable maximum precipitation (PMP) as “the theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage area at a certain time of year” (American Meteorological Society, 1959). However the current definition by the World Meteorological Organization is "the theoretical maximum precipitation for a given duration under modern meteorological conditions. Such a precipitation is likely to happen over a design watershed, or a storm area of a given size, at a certain time of year" (WMO, 2009).

The PMP is defined as the greatest depth of precipitation for a given duration that is meteorologically possible over a given station or a specified area (WMO, 1986). There are two main methods to calculate the magnitude of the PMP. The first is the physical approach in which the PMP for different durations are determined by maximizing the major historic storm events. Storm transposition and envelopment techniques are incorporated to achieve the level of PMP, to compensate for the lack of an adequate storm database. Over the past 20 years or so, many estimates of PMP have been made for dam sites in Peninsular Malaysia using transposition and maximization techniques. (M.N. Desa, 2001)

The second is a statistical approach where the estimates of PMP rainfall at a particular location or area are determined from the frequency distribution fitted to the annual maximum rainfall data was developed by Hershfield (1961, 1965) based on a general frequency equation given by Chow (1951). The statistical method is more useful when meteorological data such as dew point temperatures and wind speed are not available but where there is a large amount of rainfall data. The use of Hershfield method has shown that the PMP estimates obtained by this method are closely comparable to those obtained by the elaborate physical method (WMO, 1969 ;1970 ;1986) suggests this method for estimating PMP for those stations whose daily rainfall data are available for a long period of time but where data for dew point temperatures are lacking. Considering this several workers world over have employed, the Hershfield’s statistical techniques extensively for estimating PMP for stations having a long period of rainfall record. ((M.N. Desa, 2001).

Extreme-rainfall homogeneous regions refer to regions that contain sites with similar characteristics of extreme rainfall data such as means, skewness and kurtosis. This indicates that the areas within the homogeneous regions have similar conditions, climatic exposure, and source of extreme rainfalls. L-moments method is the most popular method to identify these homogeneous regions as it uses an application that is statistically efficient and straightforward to implement (Hosking and Wallis,2008). In Malaysia, the homogeneous region created by Department of Irrigation and Drainage. (DEPARTMENT OF IRRIGATION AND DRAINAGE , 2015)

METHODOLOGY

This research consisted of two key activities; data collection and acquisitions and PMP analysis using Hershfield method considering state boundary and homogeneous region.

Data Collection and Acquisitions

Peninsular Malaysia is chosen as the study-site throughout the analysis. In general, Malaysia is located near the equator, Malaysia's climate is categorised as equatorial, being hot and humid throughout the year. The average rainfall is 250 centimetres (98 in) a year and the average temperature is 27 °C (80.6 °F).

This study uses the annual maximum daily-rainfall to represent the extreme rainfalls. The study uses daily rainfall series and the long historical surface stations from Department of Irrigation and Drainage (DID) Malaysia stations. A total of 162 of rainfall stations were used for the analysis. Figure 1 and Figure 2 shows the dense distributions of the rainfall stations within state boundary and homogeneous regions. respectively. There are much more stations owned by DID, however after data screening only stations with more than 25 years of observation period and no missing data were selected for this study. Thus, for N years of data the annual maximum series will consist of N rainfall values. As such, the 1-day annual maximum rainfall values (X) for each year were extracted for all stations and an array of annual maximum values of rainfall was formed for each station to estimate PMP.

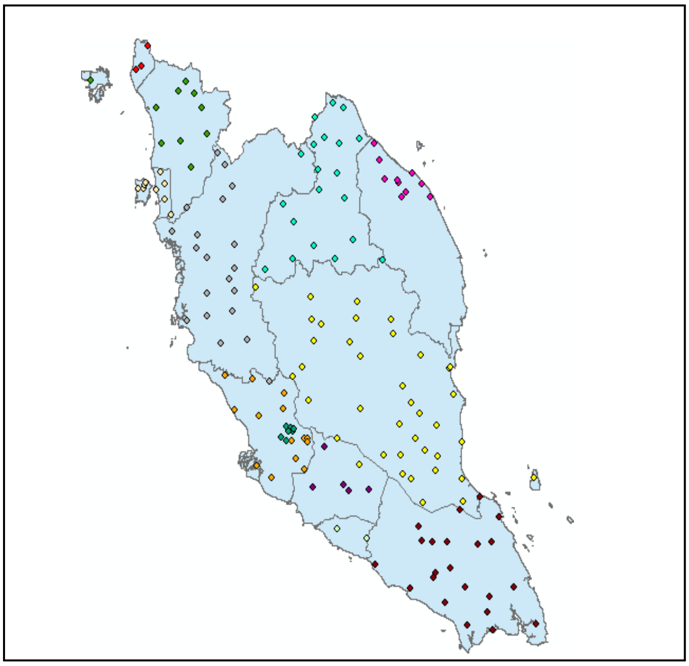

Figure 1 shows the rainfall stations within state boundary

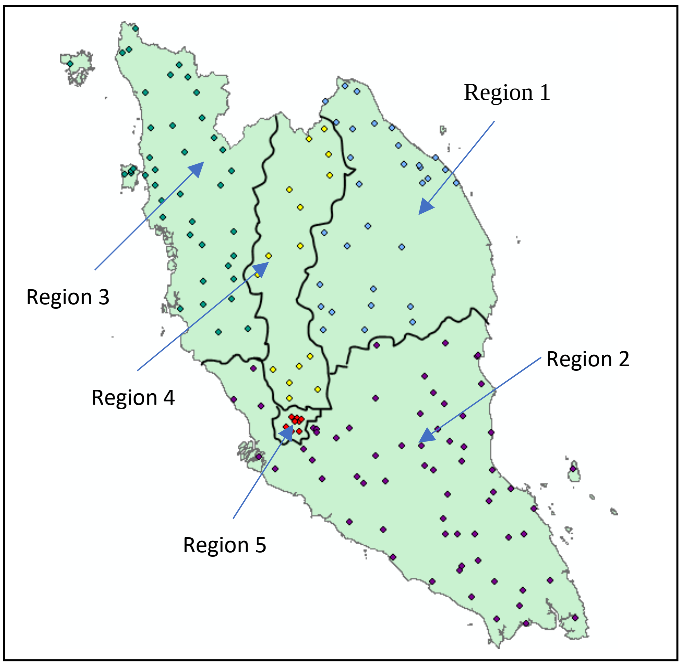

Figure 2 shows the rainfall stations within homogeneous region

PMP analysis using Hershfield method

The Hershfield technique for estimating the PMP value for a station uses the following equations.

$$X_{PMP} = X_n + S_n \times K_m \quad \text{Eq. 1-1}$$

$$K_m = \frac{X_{max} - X_{n-1}}{S_{n-1}} \quad \text{Eq. 1-2}$$

where, X_{PMP} is the PMP estimates for a station, X_n is the mean of the annual extreme series, S_n is the standard deviation of the annual extreme series, K_m is the frequency factor which depends on the availability of data period,

X_{max} is the highest rainfall value at the station, X_{n-1} is the mean of the annual extreme series without the largest value, and S_{n-1} is the standard deviation of the annual extreme series without the largest value.

First, the parameters X_n, S_n and K_m are calculated. Then, K_m values for all stations are plotted against the Xn values respectively and an envelope curve is drawn. The new K_m value is picked up from the envelope line for each station's X_n. Finally, the PMP values for each station are calculated using Eq. 1-1 by replacing K_m with the new transposed value and the highest K_m value.

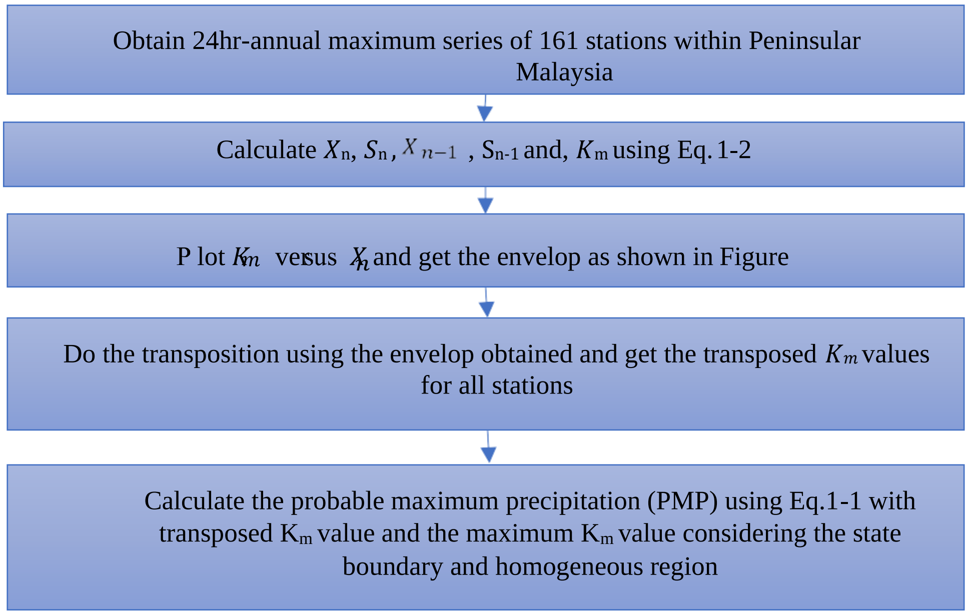

Figure 3 shows Hershfield statistical procedure as recommended by WMO (2009)

RESULTS AND DISCUSSION

The magnitudes of the highest rainfall are useful in efficient design of waterway openings in bridges, highway and railway culverts, urban storm drainage, airfield drainage, flood control works and many other hydraulic structures. This study covers all the states in Peninsular Malaysia which are Perlis, Kedah, Pulau Pinang, Perak, Selangor, Kuala Lumpur, Negeri Sembilan, Pahang, Melaka, Johor, Terengganu and Kelantan.

For this paper, Johor state and Region 2 were selected. The highest recorded annual maximum rainfall values of 1-day duration for each of the 22 rainfall stations within the state of Johor and for each of 67 rainfall station within Region 2 are given in Table 1 and Table 2 respectively. Ibu Bekalan Kahang, Kluang station recorded the highest rainfall of 433.5 mm for within the state of Johor. Sg. Cabang Kanan, Pahang station recorded the highest rainfall of 621.5 mm for within the Region 2.

The 1-day annual maximum rainfall values for all stations were analyzed to obtain estimates of PMP. For this purpose, the values of X_n, S_n , X_{n-1} and S_{n-1} were calculated. The frequency factor, K_m for each station was determined by using Eq. 1-2. Table 1 shows the highest recorded rainfall values of 1-day duration and the values calculated for within the state of Johor and Table 2 shows the values calculated within the Region 2.

Table 1 shows the highest recorded rainfall values of 1-day duration and the values calculated for within the state of Johor

Station	One-day highest(mm)	Xn	Sn	Xn-1	Sn-1	Km
1437116	285.3	115.1953	43.70273	111.1452	35.12781	4.957746
1534002	198.5	106.5171	34.47098	103.8118	30.98913	3.055531

1541139	406.4	151.2098	83.36519	144.83	73.59628	3.55412
1636001	250.5	106.0333	50.8917	101.5188	44.48852	3.348757
1732004	215.5	97.49714	37.93537	94.02647	32.37794	3.751737
1737001	298	114.5897	53.79652	109.7632	45.15736	4.168464
1829002	198.5	81.27857	50.45057	76.93704	45.77211	2.65583
1834001	327.5	117.0167	55.3109	107.8652	33.12122	6.631241
1839196	397.5	148.1953	79.40483	142.2595	70.04923	3.64373
1931001	149	20.7725	39.66055	17.48462	34.21354	3.843958
1931003	167	97.4	32.24532	95.08	30.05007	2.393339
2025001	187	108.6026	34.44133	106.5395	32.36945	2.485693
2033001	204	124.08	37.05561	120.75	33.81632	2.461829
2230001	185.4	94.676	36.99381	90.89583	32.48492	2.90917
2231001	202.9	104.0324	42.21509	101.2861	39.31913	2.584337
2232001	331.1	135.3818	69.03697	129.2656	60.37855	3.342816
2235163	433.5	161.6758	64.68601	153.1813	43.14249	6.49751
2237164	355.9	158.8349	71.0337	154.1429	64.80059	3.113508
2330009	310.7	110.3209	55.18853	105.55	46.01557	4.458273
2438001	311.5	58.70476	88.3668	52.53902	79.7954	3.245312
2534160	363.5	194.5947	90.86335	190.0297	87.58764	1.980534
2636170	400.1	221.9674	85.54849	217.7262	81.88215	2.227272

Table 2 shows the highest recorded rainfall values of 1-day duration and the values calculated for within the Region 2

Station	One-day highest(mm)	*X*n	*S*n	Xn-1	Sn-1	Km
1437116	285.3	115.1953	43.70273	111.1452	35.12781	4.957746
1534002	198.5	106.5171	34.47098	103.8118	30.98913	3.055531
1541139	406.4	151.2098	83.36519	144.83	73.59628	3.55412
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1732004	215.5	97.49714	37.93537	94.02647	32.37794	3.751737
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1839196	397.5	148.1953	79.40483	142.2595	70.04923	3.64373
1931001	149	20.7725	39.66055	17.48462	34.21354	3.843958
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2224038	185.4	94.676	36.99381	90.89583	32.48492	2.90917
2230001	202.9	104.0324	42.21509	101.2861	39.31913	2.584337
2231001	331.1	135.3818	69.03697	129.2656	60.37855	3.342816
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2237164	310.7	110.3209	55.18853	105.55	46.01557	4.458273
2321006	311.5	58.70476	88.3668	52.53902	79.7954	3.245312
2330009	363.5	194.5947	90.86335	190.0297	87.58764	1.980534
2438001	400.1	221.9674	85.54849	217.7262	81.88215	2.227272
2534160	141.5	87.45116	23.5821	86.16429	22.28749	2.482815

2630001	160	92.95897	33.34394	91.19474	31.89354	2.157342
2634193	149.6	91.32558	22.74725	89.9381	21.10115	2.827424
2636170	171.5	82.5093	28.277	80.39048	24.92664	3.655106
2719001	125	80.07857	22.88693	78.41481	21.52837	2.163898
2722002	165.5	88.39767	32.43699	86.5619	30.48564	2.589354
2723002	138.7	54.18364	28.41068	52.61852	26.17492	3.288701
2725083	180.7	87.17442	24.76982	84.94762	20.25059	4.728375
2815001	214.9	90.56047	27.94552	87.6	20.34553	6.256903
2818110	522.5	105.31	75.60292	94.61282	34.18449	12.517
2828173	194	101.4263	33.62222	98.92432	30.28809	3.139045
2829001	144.9	101.1349	20.89793	100.0929	19.98865	2.24163
2831179	207.8	92.31628	34.21075	89.56667	29.42611	4.017974
2834001	139.6	58.54048	49.10142	56.56341	47.98907	1.730323
2841001	109	23.27619	38.4391	21.18537	36.41852	2.411263
2913001	193.5	94.49487	33.38287	91.88947	29.54056	3.439695
2917001	190	94.06047	30.84509	91.77619	27.2907	3.599168
2924096	121	111.9884	63.66658	111.7738	64.42259	0.143214
3020016	423.9	143.3333	86.89336	134.5656	71.94017	4.021875
3026156	472.9	208.7563	106.0241	200.2355	95.99508	2.840401
3028001	223	92.21053	45.08843	88.67568	40.01789	3.356606
3030178	235.3	126.8758	51.55129	123.4875	48.4994	2.305441
3032167	430.5	144.2385	92.4599	136.7053	80.66507	3.642156
3117070	401.4	174.6464	100.3536	166.2481	91.69165	2.564594
3118102	339	164.5107	82.41422	158.0481	76.413	2.368077
3119001	305.7	85.56842	48.48994	79.61892	32.15828	7.030261
3119002	362.6	80.36744	55.82669	73.64762	34.69246	8.328969
3121143	181	101.6703	29.88232	99.46667	27.08626	3.010136
3129177	228.8	86.63429	65.17002	82.45294	61.19936	2.391317
3134165	298.5	151.5219	65.85535	146.7806	61.14063	2.481482
3228174	142	83.94211	24.10561	82.37297	22.38437	2.66378
3231163	232.5	110.6658	56.72563	107.373	53.70024	2.330102
3314001	410.8	174.7698	82.20216	169.15	74.36979	3.249303
3330109	621.5	133.55	98.57499	119.6086	52.9145	9.484951
3411017	280	145.6128	53.54465	142.0763	49.43244	2.790145
3424081	305	125.9103	65.53529	121.1974	59.34053	3.097421
3429096	155.7	85.22093	32.77706	83.54286	31.24901	2.309102
3533102	90.1	4.115385	17.84744	0.676	3.38	26.4568
3613004	510	194.8767	107.9166	187.3738	97.21301	3.318755
3628001	317	102.4053	59.21162	96.60541	47.85019	4.60593
3833001	423	80.56279	99.52978	72.40952	84.96831	4.126132
3833002	433	171.5393	85.44869	161.8556	69.68233	3.891151
3924072	143.3	88.6186	23.66953	87.31667	22.34383	2.505539
3930012	417.5	148.4372	82.2201	142.031	71.53501	3.850828

A plot of K_m versus the mean 1-day highest rainfall were plotted for all the station within the state and regions. Figure 3 shows the graph of K_m versus the mean 1-day highest rainfall, X_n within the state of Johor and Figure 4 shows the graph for within the region 2. From that, the new K_m values of all the station within the state and homogeneous regions are transposed using the envelop equation obtained. For example, in the Johor state, the K_m transposition uses the envelope equation of: $K_m = -0.003X_n + 6.9816$ and in the region 2, the K_m transposition uses the envelope equation of: $K_m = -0.1112X_n + 26.915$. As shown in Figure 4, the slope of the envelope for Johor state is very flat. However, if the homogeneous region of Region 2 is to be used, a more gentle envelopment and uniform plots can be obtained Figure 5. As for the Johor state, it can be clearly seen that without considering the homogeneous regions higher envelopment will be missed. In general, this shows that overlooking sites with higher maximum rainfall values or K_m and X_n values can be avoided by considering the homogeneous region.

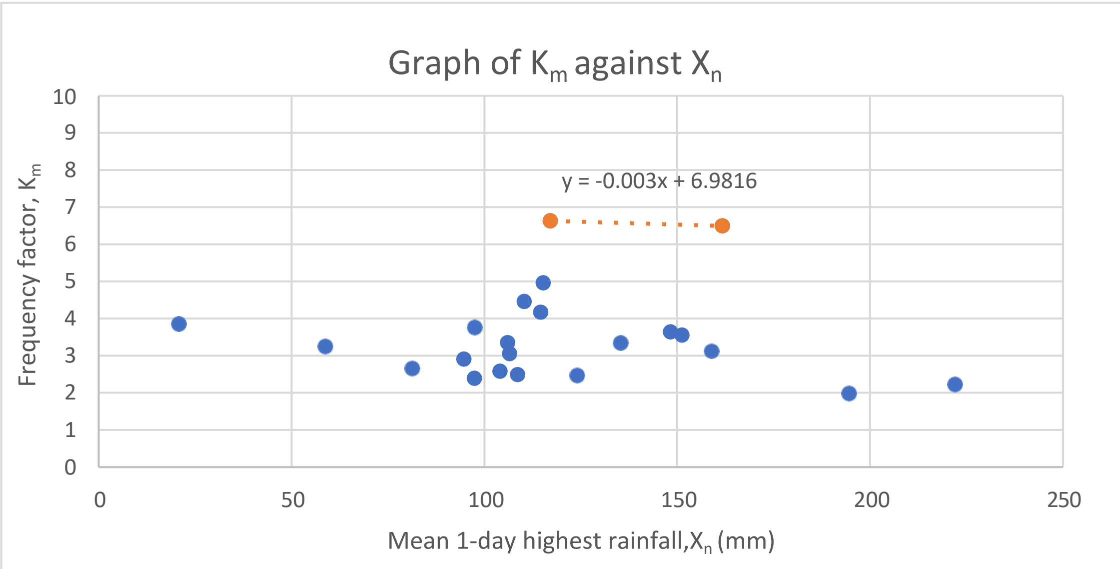

Figure 4 shows the graph of frequency factor, K_m against the mean 1-day highest rainfall, X_n within the state of Johor

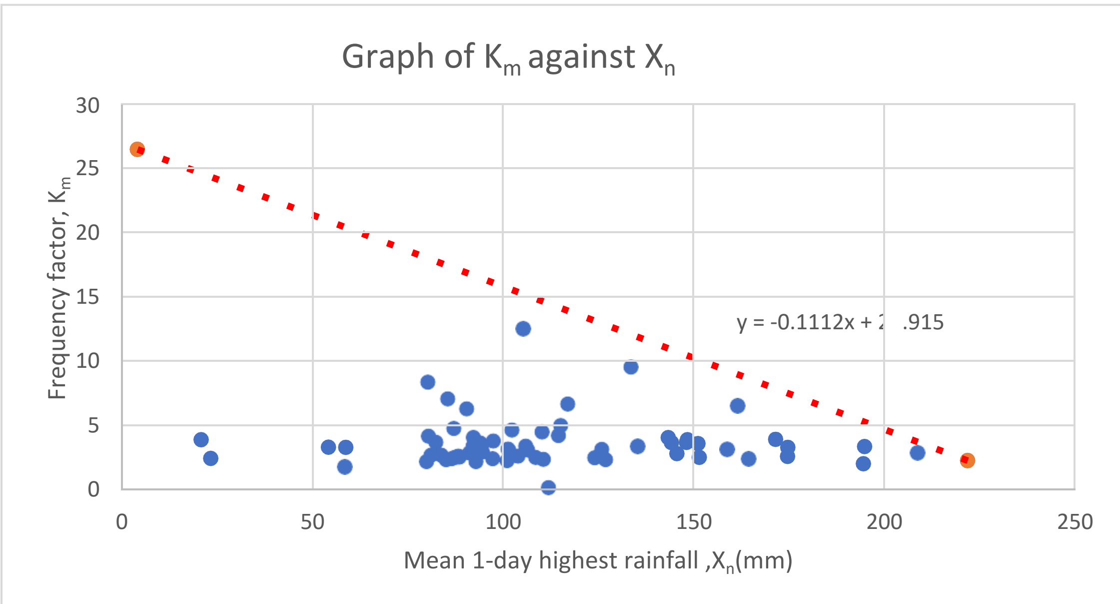

Figure 5 shows the graph of frequency factor, K_m against the mean 1-day highest rainfall, X_n within homogeneous region 2

After the determination of the envelopes and obtaining the transposed Km values, the statistical PMP estimated for both within the Johor state and region 2 were conducted using Eq 1-1. However, the transposed Km are smaller and were only slightly different from the old K_m value. According to the M.N. Desa (2001), it was considered that using highest K_m value will give more reasonable PMP value. Using the mean, X_n, standard deviation, S_n and K_m values equal to the maximum value within state boundary and homogeneous regions, PMP values for a 1-day duration for all station were computed using Eq. 1-1 again. The results are presented in Figure 6 for Johor state and Figure 7 for homogeneous region 2..

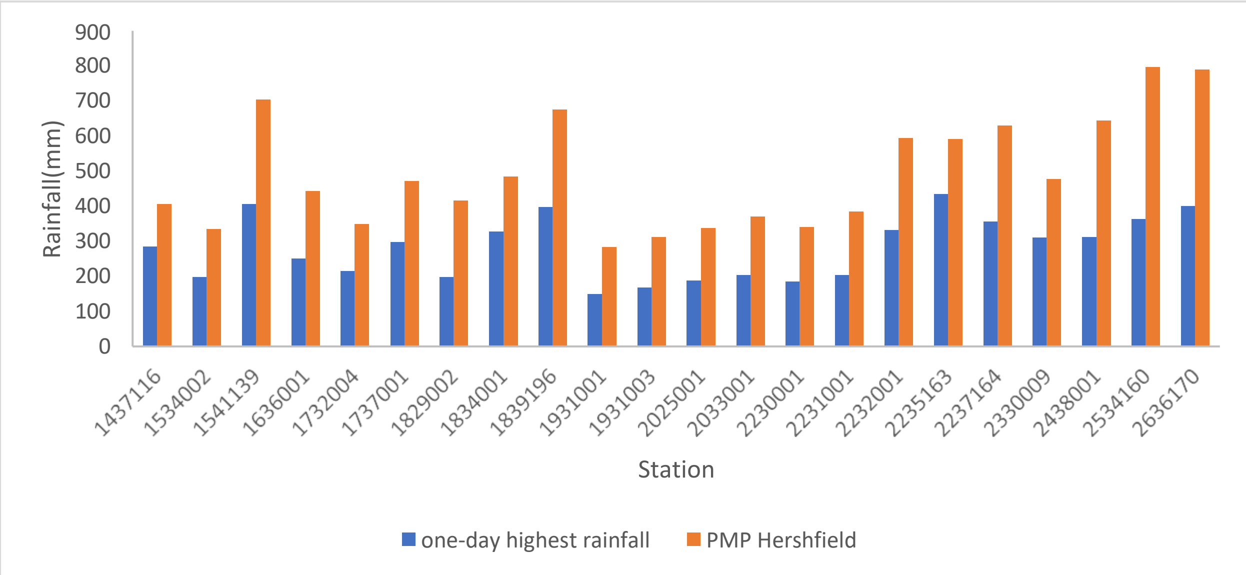

Figure 6 shows the 1-day highest rainfall and the PMP value calculated using Hershfield method for the Johor state (transposed using highest K_m value

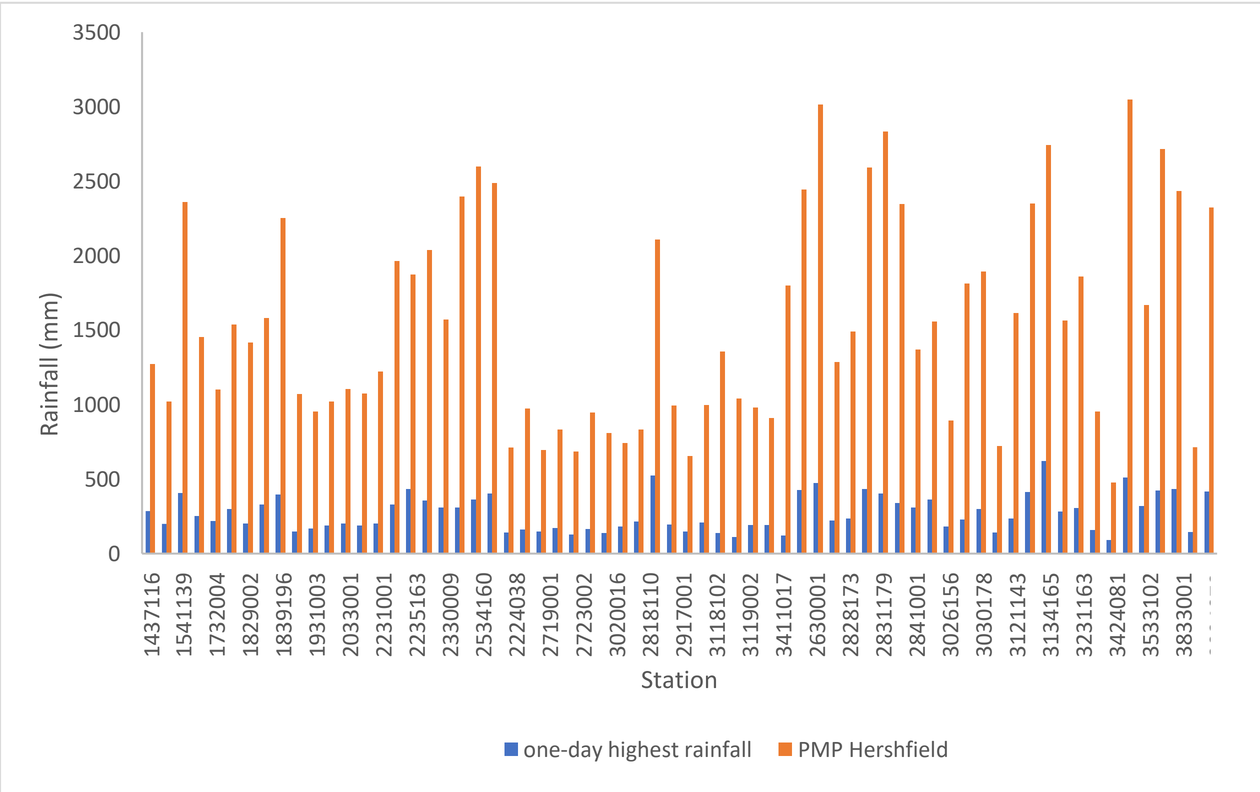

Figure 7 shows the 1-day highest rainfall and the PMP value calculated using Hershfield method for homogeneous region 2 (transposed using highest K_m value)

Validations of the statistical PMP estimates are conducted using current observation records. By referring to the summary of the validation analysis of Johor state by considering state boundary and homogeneous region presented in Table 3, for PMP estimated using the maximum K_m value, considering the state boundary have higher values. However, other results show the improvement of the PMP estimates by considering the homogeneous regions as the transposition boundary. For example, significant improvements can be observed for station Stor JPS Johor Bahru (1437116) whereby considering Johor state as the boundary, the PMP estimates of 405.0 mm. However, if the homogeneous region is to be used as the boundary, the PMP estimated is 1271.4 mm. This provides higher precautions measure if the PMP estimate is to be used for flood defense structures' designs. Similar assessment can be made for the station in Peninsular Malaysia. The PMPs estimated using state boundary for the station are very close to their record-breaking rainfall events (405.0 mm PMP estimates to 285.3 mm record-breaking rainfall event of Stor JPS Johor Bahru). If the homogeneous region 2 is considered, then the statistical PMP estimates will not be reached yet (1271 mm PMP estimate against the 285.3 mm record-breaking rainfall amount).

Table 3 shows summary of the validation analysis of Johor state by considering state boundary and homogeneous Region 2

Station	1-day highest rainfall from 1969 to 2020 (mm)	1-day PMP estimated from 1969 to 2012 (mm)	
		State boundary	Region 2
1437116	285.3	405.0	1271.4
1534002	198.5	335.1	1018.5
1541139	406.4	704.0	2356.8
1636001	250.5	443.5	1452.5
1732004	215.5	349.1	1101.1
1737001	298	471.3	1537.9
1829002	198.5	415.8	1416.0
1834001	327.5	483.8	1580.4
1839196	397.5	674.7	2249.0
1931001	149	283.8	1070.1
1931003	167	311.2	950.5
2025001	187	337.0	1019.8
2033001	204	369.8	1104.5
2230001	185.4	340.0	1073.4
2231001	202.9	384.0	1220.9
2232001	331.1	593.2	1961.9
2235163	433.5	590.6	1873.1
2237164	355.9	629.9	2038.2
2330009	310.7	476.3	1570.4
2438001	311.5	644.7	2396.6
2534160	363.5	797.1	2598.5
2636170	400.1	789.3	2485.3

CONCLUSION

Statistical estimates of 1-day PMP rainfalls for 161 stations in Peninsular Malaysia, were made by considering state boundary and homogeneous region. It was found that 1-day PMP over Peninsular Malaysia by considering state boundary, varied from 146 to 5052 mm and by considering the homogeneous regions, varied from 247 to 6250 mm. The long duration PMP rainfalls are found to occur from the southwest and the northeast monsoons over the area. The main purpose of this study was to assess the difference between the probable maximum precipitation (PMP) estimation using Hershfield method with state boundary region and with the homogeneous region.

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