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Simulating the Rainfall-Runoff using Hydrological Model in the Tropics

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Abstract

Floods are considered the most destructive forces that impacts the human lives,ambient environment and property. Thus, the current research targeted to estimate Probable Maximum Flood (PMF) for the Perak River using HEC-HMS Hydrological Model. The methods adopted herein this research includes the collection of the related meteorological data and process it using Hershfield's statistics to produce the PMP values and Geographic Information Systems (ArcGIS) to be used in developing the targeted model. Results show that the performance parameters for both events are considered very good and good whereby for calibration, NSE and PBIAS of 0.873 and -1.76% are obtained while NSE and PBIAS of 0.679 and -8.78% are obtained for validation. Although slight differences are observed from the comparison, it can be concluded that the differences are considered acceptable as the general trend is similar for those simulations. Furthermore, the developed hydrologic model is credible and applicable to describe the hydrological process in Perak River Watershed.

Keywords: PMP, PMF, Modelling, Malaysia.

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نمذجة الامطار والجريان السطحي باستخدام موديل هيدرولوجي في الأماكن الرطبة

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الملخص

تعتبر الفيضانات من أكثر القوى تدميراً التي تؤثر على حياة الإنسان والبيئة المحيطة وبالتالي فإن البحث الحالي يهدف الى تقدير الحد الأقصى المحتمل للفيضان لنهر بيراك باستخدام النموذج الهيدرولوجي HEC-HMS. تتضمن الأساليب المعتمدة في هذا البحث جمع بيانات الأرصاد الجوية ذات الصلة ومعالجتها باستخدام إحصائياتHershfield لاستحصال قيم PMP وأنظمة المعلومات الجغرافية (ArcGIS) لاستخدامها في تطوير النموذج. أوضحت النتائج أن معاملات الأداء تعتبر جيدة جدًا وجيدة حيث تم الحصول على NSE و PBIAS من 0.873 و -1.76٪ بينما تم الحصول على NSE و 0.679 PBIAS و -8.78٪ للتحقق من صحتها. على الرغم من وجود اختلافات طفيفة من المقارنة، يمكن الاستنتاج الى أن الاختلافات تعتبر مقبولة لأن الاتجاه العام مشابه لتلك المحاكاة. علاوة على ذلك، فإن النموذج الهيدرولوجي المطور موثوق به وقابل للتطبيق لوصف هيدرولوجية مستجمعات المياه في نهر بيراك.

الكلمات المفتاحية: اعلى قيمة للامار، اعلى قيمة للفيضان، النمذجة، ماليزيا

1.0 Introduction

Malaysia is a humid tropical country where the rainfall is abundant and contributes to an average of 2000-4000 mm a year (Al-Hadu, et.al.,2011). The annual average precipitation may exceed the above range with the exception of extreme events which results in many times of flooding for several areas are during the monsoon periods (Suhaila & Jemain, 2007). The heavy rainfall and the high concentration of runoff are the main reasons that cause floods in Malaysia. Population growth, climate change and socio-economic development can be considered the affective factors that leads to additional flood frequencies.

Dams provide a range of economic, environmental, and social benefits, including flood control, water supply, hydroelectric power, irrigation, recreation, river navigation, and wildlife habitat which requires constant maintenance and monitoring, regular safety inspections as well as scheduled rehabilitation to function well. Structural failure of these dams may threaten public safety, local and regional economies, and the environment, as well as cause the loss of services provided by a dam. There were approximately 200 notable dam failures worldwide in the 20th century. Overtopping is one of the most serious modes of failures for all dams causing great numbers of human fatalities and material damages. Statistics show that overtopping failures are the highest, especially for embankment dams. The main reason for this is the erroneous prediction of the inflow design discharge, which has resulted from lack of realistic flow data and imperfect hydrological procedures (Jing, et al., 2019; Adamo, et al., 2020). Based on that, it is essential to adopt a policy to assess the flood discharge (Bosamiya & Gandhi, 2018). Since the measurement of all parameters affect the runoff is crucial, there is a need to choose the appropriate model with minimum input data requirements, simple structure, and realistic accuracy (Sharifi, et.al.,2004). HEC-HMS Model is a hydrological model that match the mentioned criteria and has been developed by the Hydrologic Engineering Center of the US Army Crops of Engineers (US Army Crops of Engineers, 2016) and extensively adopted in various researches (Arekhi, et al., 2011; Kneble , et.al.,2005; Garcia , et.al.,2005). HEC-HMS is a mathematical model for watershed representation which involves various approaches for simulating the response of runoff of a catchment by demonstrating the catchment with communicated hydrologic and hydraulic components. The basin model composes of three main models; the loss, the transform and the base flow. Each element in the model fulfils various roles of the precipitation-runoff process within a part of the catchment known as a sub-basin. The main result of modelling is the computation of stream flow hydrographs at the catchment outlet (Oleyiblo & Li, 2010).

(Oleyiblo & Li, 2010) applied the HEC-HMS model for flood forecasting in Wan'an Catchments in China in which the model has been calibrated and verified using the collected data and the errors in peak discharges were within the allowable limits. (Mokhtari, et al., 2016) developed HEC-HMS Model in watershed of wadi Cheliff-Ghrib, Algeria in order to forecast the response of the basin to the impact of climate changes scenarios and land use and it is concluded that with extreme rain storms, the power of land use reduces. (Skhakhfa and Ouerdachi, 2016) were estimated the flood for Wadi Ressoul Watershed, Algeria using HEC-HMS Model relying on several events. Results of Model validation showed very high correlation between the observed and simulated values. Another study performed by (Sahu, et.al., 2020) which utilized the hydrological model (HEC-HMS) for modelling the rainfall-runoff in Shipra basin, India in which it shows a very good results after the calibration. (Jabbar , et.al.,2021; Sidek , et.al.,2022) had applied the HEC-HMS to predict the peak flood in different watersheds in Malaysia in which the results of calibration and validation showed a very good fit between the observed and predicted hydrographs.

There are many other studies which adopted the HEC-HMS model for flood forecasting in many countries (Yusop , et.al.,2007; Lincoln, 2009; Razi, et.al.,2010; Malek, et al., 2013; Halwatura & Najim, 2013; Gumindooga, et.al.,2017; Romali, et.al.,2018; Cheah, et.al.,2019; Niyazi, et.al.,2020; Castro & Maidment, 2020; Jabbar, et.al.,2021) in which the model proved it's accurate results in terms of basin response in time and space at event scale and for a long and continuous period as well as simulating different scenarios in forecasting the flood and the early detection. The objective of the current study is to estimate the Probable Maximum Precipitation (PMP) based on the updated rainfall and other meteorological data and predict the Probable Maximum Flood (PMF) using the Hydrological Model HEC-HMS version 4.8.

2.0 Methodology

As mentioned earlier, the main objective of the current research is to estimate the maximum flood obtained from the Sungai Perak Watershed. Based on that, hydrological analysis need to be perfoemed in order to establish the PMP and PMF values. In Sungai Perak Hydroelectric Scheme, five Dams included (i.e. Temengor Dam, Kenering Dam, Bersia Dam, Chenderoh Dam and Pergau Dam) in which the hydrological analysis fulfilled based on the latest hydrological data until 2020.

2.1 Study Area

The Perak Hydroelectric Scheme consists of four (4) dams on Sungai Perak, spanning approximately 115 km. It starts with the Temengor Dam at the uppermost, followed by Bersia Dam, Kenering Dam and Chenderoh Dam, which is 210 km from the river mouth. The dams were constructed between 1930 and 1983 with different designs and sizes. The overview of the Sg Perak Hydroelectric Scheme is shown in Figure (1) . Table (1) illustrates some details for Sungai Perak Dams.

Table (1): Details of Dams in Sungai Perak Hydroelectric Scheme

MAIN DAM	**TEMENGOR**	**BERSIA**	**KENERING**	**CHENDEROH**
Type	Rock-fill	Concrete Gravity	Concrete Gravity/Earth & Rockfill	Concrete Hollow, Buttress
Dam Height –Max (m)	127	33	48	32
Dam Crest Elevation (m)	257.6	143.3	113.7	60.4
Crest Length (m)	537	252	503	390
Gross Storage (FSL) (m^3)	6.05×10^9	577×10^6	352×10^6	95.4×10^6
Flood Storage (m^3)	0.85×10^9	7.4×10^6	56×10^6	390×10^6
Reservoir Area (Ha)	15,000	570	4,050	2,050
IDF (1:1,000 Year) (m^3/s)	13,700	5,700	12,780	13,300
Main Dam Height (m)	127	37	47	20.1
SPILLWAY	**TEMENGOR**	**BERSIA**	**KENERING**	**CHENDEROH**

MAIN DAM	TEMENGOR	BERSIA	KENERING	CHENDEROH
Type	Free-Overflow, Chute and Flip Bucket	4 Gates Ogee	Gated Ogee Overflow with Bucket & Apron	Controlled
Crest Elev. (Free Overflow) (m)	248.4	-	-	59.74
Discharge Capacity (Gates) (m^3/s)	-	5,280	9,360	3,400
Discharge Capacity (Overflow) (m^3/s)	3,700	-	-	11,300

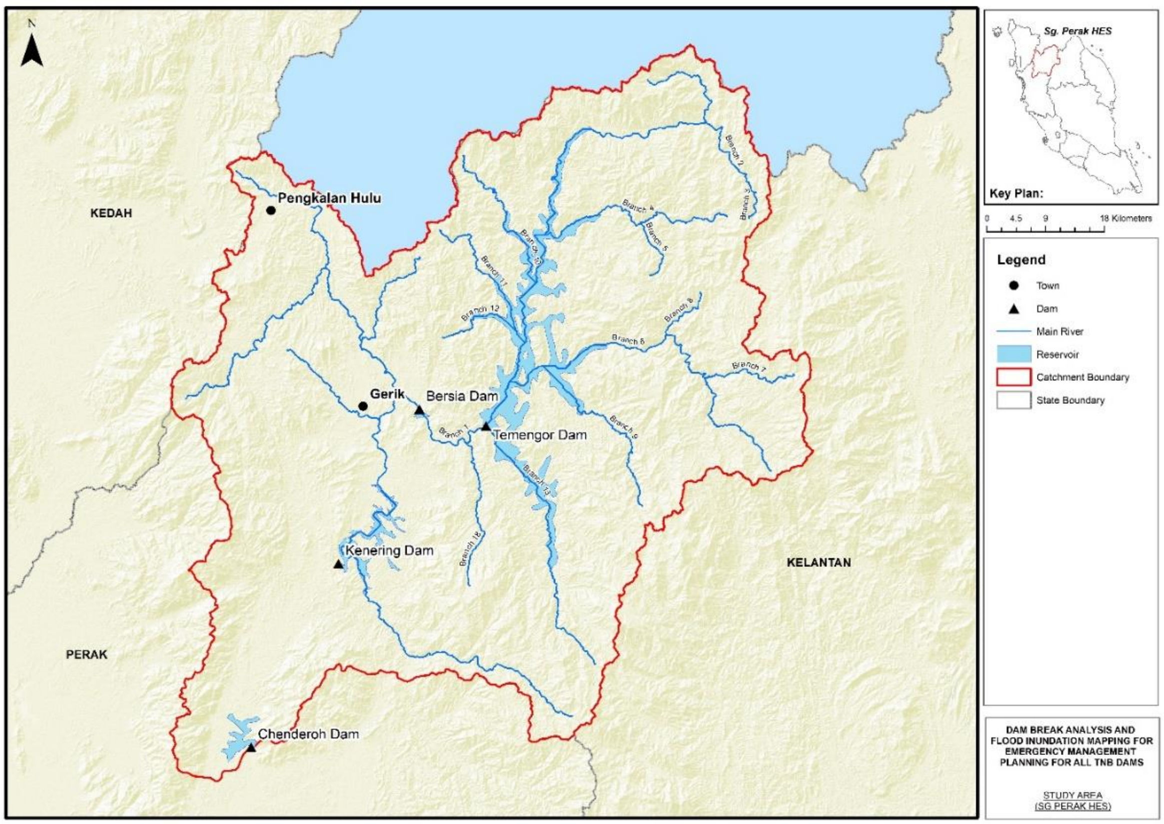

Figure (1): Overview of Sg Perak Hydroelectric Scheme

2.2 Hydrological Analysis

The total number of rainfall stations available around the study area is 37 stations. Out of 37 stations, nine (9) DID rainfall stations are located in Sungai Perak Hydroelectric Scheme, and TNB owns the remaining 28. Figure (2) shows the locations of rainfall stations for the scheme.

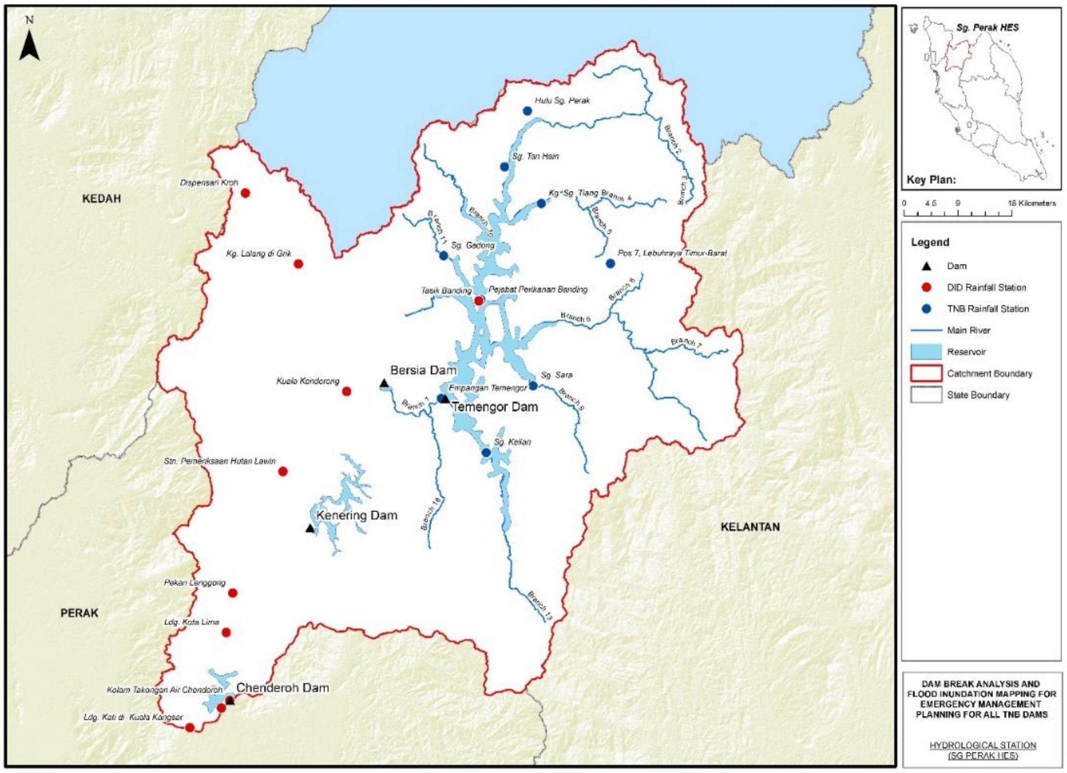

Figure (2) : Location of Rainfall Stations for Sg. Perak Hydroelectric Scheme

The selection of appropriate rainfall stations in this study was made based on Sg Perak's review of the collected rainfall data collection. The rainfall station should function automatically like a recorder and HS–logger, not manually, as the requirement is for continuous rainfall data. The longest available record should be at least 10 years. Hence, out of 37 rainfall stations available in the study area, only 25 are still operating, while only 16 stations have a good historical record (rainfall data record exceeding 10 years). The duration of the rainfall data stations has exceeded 40 years. The basic data required for this study are a series of annual maximum rainfall values for daily rainfall and hourly rainfall. The annual maximum rainfall series for a station is the sequence of rainfalls formed by extracting the highest value for each year of record.

The rainfall data for Sungai Perak has some missing values. In this study, the researchers implemented a machine learning method for filling the data.

The cumulative rainfall of a station is plotted against the average cumulative rainfall of several other nearby stations influenced by the same meteorological conditions. For each station, the cumulative rainfall of the station and the average cumulative rainfall of the other stations are plotted. It has been observed that the double mass curve method indicated consistency in their rainfall records. Thus, the annual maximum rainfall series used in the analysis for all the stations were treated as homogenous.

The highest recorded rainfall values of 1, 3 and 5-day duration for each of the 16 stations during their records are given in Table 2. This Table shows that the stations in Sg Perak have recorded the highest rainfall from 131 to 258 mm in 1-day, 162 to 312 mm in 3-day and 182 to 450 mm in a 5-day duration. Station 5411066 Kuala Kenderong recorded the highest rainfall of 258 mm for one 1-day. Meanwhile, the highest rainfall for 3-days (312 mm) and 5-days (450 mm) was recorded by Station 9132 Pos 7, Lebuhraya Timur/Barat. The highest recorded values for 1 day, 3 days and 5-day rainfall for all 16 stations were plotted, and isohyet lines were drawn to overview their spatial distribution as shown in Figure (3).

Table (2): Highest Recorded Rainfall (mm) for 1, 3 and 5 days Duration for Sungai Perak

No.	Station No.	Station Name	1-day (mm)	3-day (mm)	5-day (mm)
1.	9030	Rahman Hydraulics at Klian Intan	131.3	234.2	252.7
2.	9061	Empangan Temengor	201.6	255.0	364.7
3.	9069	Empangan Kenering	150.4	186.5	241.7
4.	9071	Kajiklim Bersia	160.0	221.5	257.1
5.	9119	Sg. Tan Hain(shifted from Kem Marker November)	196.5	263.0	355.0
6.	9120	Kg. Sungai Tiang	166.5	219.0	276.0
7.	9132	Pos 7, Lebuhraya Timur/Barat	250.5	312.0	450.0
8.	9136	Alurmasuk Sg. Toor	148.0	237.5	324.0
9.	9137	Empangan Chenderoh	149.3	203.0	298.5
10.	9138	Sg. Sara	198.0	200.5	208.5
11.	9139	Sg. Kelian (shifted from Sg. Tesau)	154.5	162.0	182.5
12.	5109070	Pekan Lenggong	160.5	290.5	330.0

No.	Station No.	Station Name	1-day (mm)	3-day (mm)	5-day (mm)
13.	5210069	Station Pemeriksaan Hutan Lawin	154.0	238.5	250.0
14.	5411066	Kuala Kenderong	258.0	285.0	306.0
15.	5610063	Kg. Lalang di Grik	186.0	220.0	265.0
16.	5710061	Dispensari Kroh	186.2	269.0	344.0

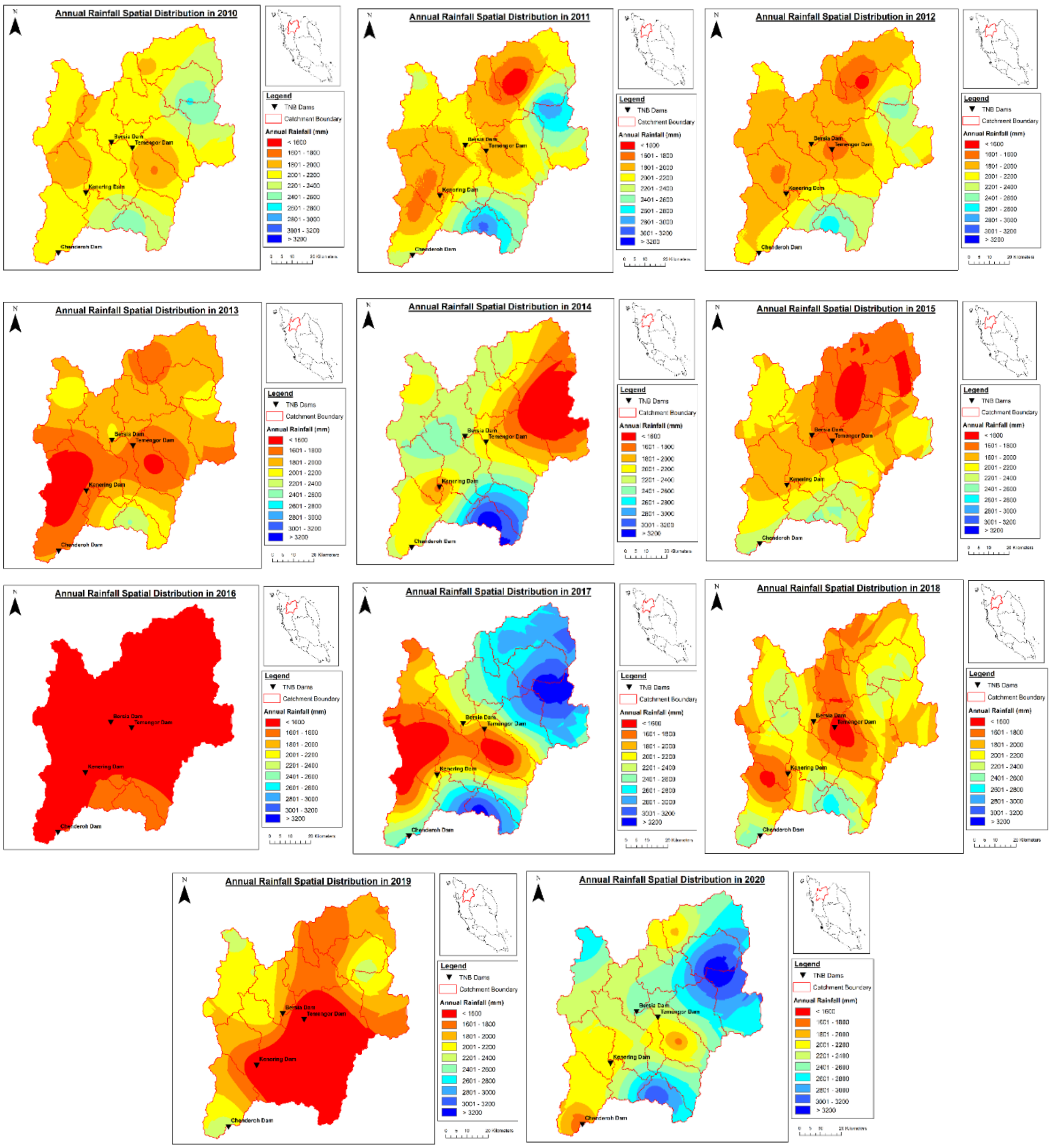

Figure (3): Annual Rainfall Distribution in 2010 - 2020 for Sg Perak Hydroelectric Scheme

2.3 Probable Maximum Precipitation (PMP)

The calculated PMP values for all durations for Temengor Dam, Bersia Dam, Kenering Dam and Chenderoh Dam were compared to the PMP values calculated in 2017 as explained in Table 3. In the current study, the Statistical Hershfield method, a common practice in Malaysia, to develop the PMP was used. This method is more commonly used and can be applied if long-term rainfall data are available. It is noticed that the revised maximum PMP value is different from the previous study done by the National University of power (UNITEN) in 2017. The difference may be due to the longer data period used in this revised study (results in different mean value) and there were no significant extreme rainfall events observed between 2017 to 2020.

Table (3): Comparison of maximum PMP value in Sg. Perak with previous studies

Duration (hour)	PMP (mm)	
	UNITEN (2017)	Current Study (2021)
1	202	299
3	262	351
6	336	457
12	477	504
24	635	629
72	892	863
120	1144	1081

2.4 PROBABLE MAXIMUM FLOOD (PMF)

In this study, the probable maximum flood (PMF) in Sungai Perak will be simulated using HEC-HMS 4.8, the estimated probable maximum precipitation (PMP) as the design rainfall input. In the deterministic methodology, the PMF hydrograph is generated by modelling the study area's physical atmospheric and drainage basin hydrologic and hydraulic processes.

2.5 Hydrological Model Set-Up for Sg. Perak

Sg. Perak consists of a unique, complex system of four (4) cascade dams with a different design, age and dam height on Sungai Perak. At the uppermost is the largest rock-filled dam, Temengor Dam. Bersia Dam is a concrete dam located about 20 km downstream of Temengor Dam and about 50 km upstream of Kenering Dam. Kenering Dam is a concrete dam, and about 45 km downstream of Kenering Dam is the Chenderoh Dam, a concrete hollow buttress dam. Figure (4) shows the delineated sub-basins in Sg. Perak. Temengor Dam catchment consists of eight (8) sub-basins (S1-S8), while Bersia Dam catchment consists of one (1) sub-basin (S9). Kenering Dam catchment consists of five (5) sub-basins (S10-S14) and Chenderoh Dam catchment consists of two (2) sub-basins (S15-S16).

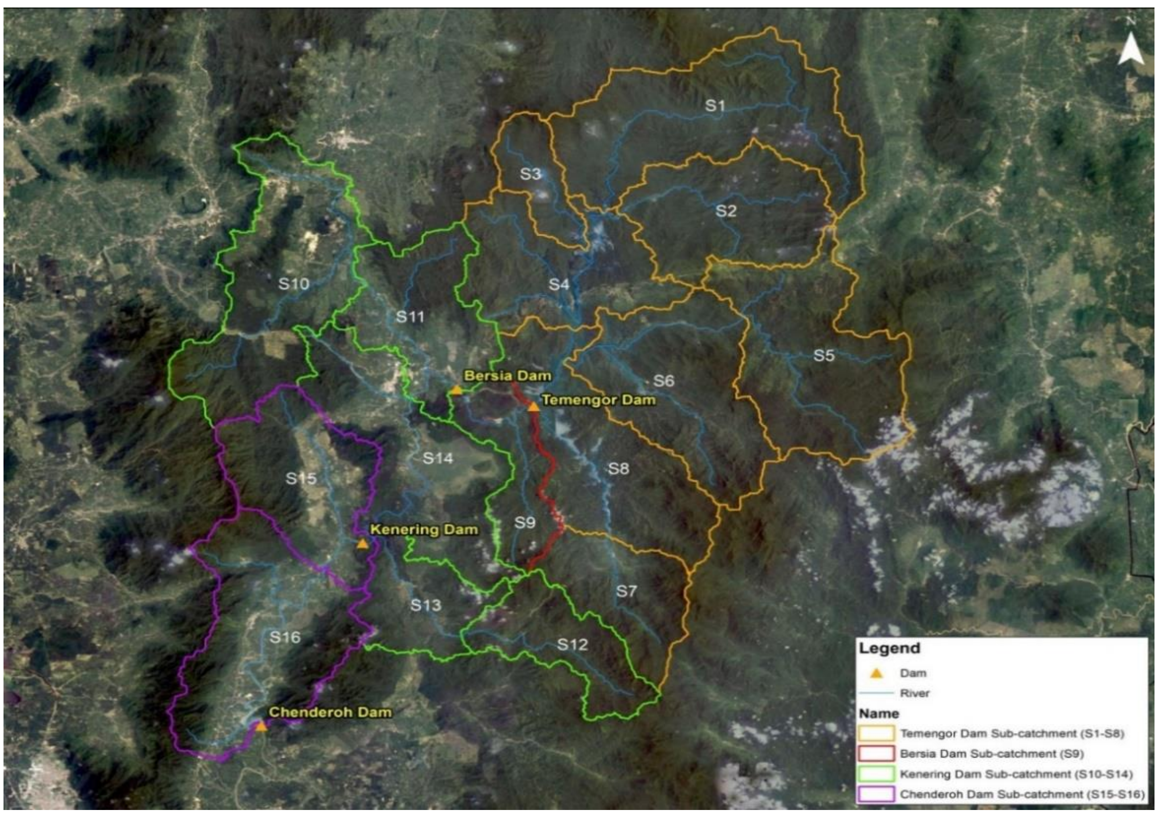

Figure (4) : The delineated sub-basins in Sg.Perak HES

2.6 Catchment Characteristics for Sub-basins in Sg.Perak

Each sub-basin is considered a lumped unit with uniform runoff characteristics in hydrological modelling and analysis. The catchment areas have been delineated according to stream network and land use homogeneity using GIS tools such as Global Mapper and the new GIS features in HEC-HMS 4.8. Figure (5) illustrates the hydrological basin characteristics that have been identified for the respective sub-basin.

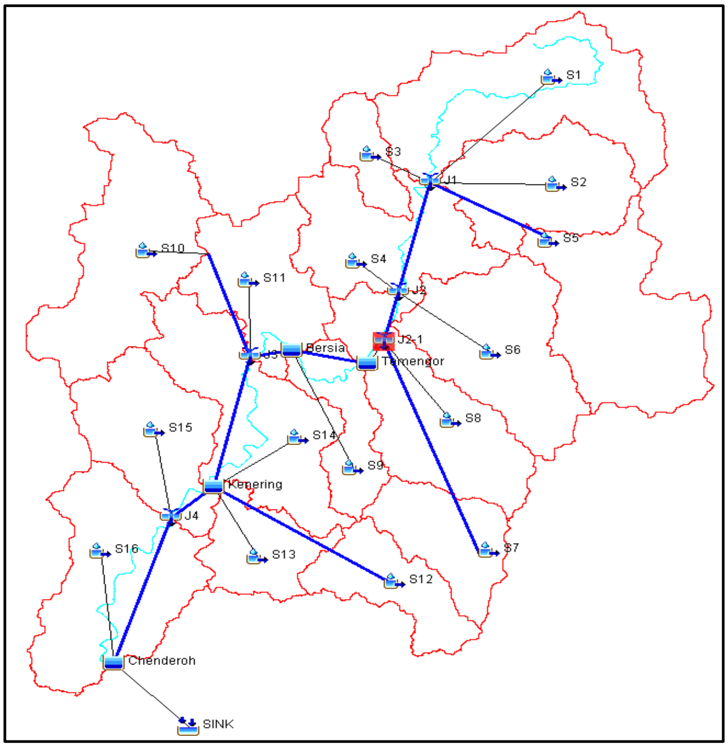

Figure (5) 1: Basin Model Set-Up for Sg. Perak

2.7 Calibration and Validation of Hydrological Model

The simulated results computed from the hydrological model need to be calibrated and validated with the observed flow data to verify the model's credibility in imitating the study area's flow generating process. Calibration utilizes the observed hydrometeorological data in a systematic search for parameters that yield the computed results best fit to the observed runoff. As no streamflow gauges are established along with the cascading dams, an alternative has been adopted to verify the simulation results in this study. The simulated inflow into the Temengor reservoir for the events in December 2014 and January 2012 was calibrated and validated to the observed inflow into the Temengor reservoir. The so-called observed inflow is a simulated flow obtained from a GR4H model that was set up for flow forecasting purposes in Temengor Dam, which has been calibrated to the derived back-calculated inflow. Furthermore, the simulated reservoir pool elevation has also been compared to the observed pool elevation recorded at the station during the selected storms for further verification of the simulated results. The calibration and validation results are evaluated by the performance parameters of Nash-Sutcliffe Efficiency (NSE) and Percent Bias (PBIAS).

Figures (6 and 7) show the calibration and validation for the storm event in December 2014 and January 2012 respectively. It is noticed that the performance parameters for both events are considered very good and good whereby for calibration, NSE and PBIAS of 0.873 and -1.76% are obtained while NSE and PBIAS of 0.679 and -8.78% are obtained for validation. Moreover, the simulated reservoir pool elevations are closely correlated to the observed pool elevations during both storm events. Although slight differences are observed from the comparison, the differences are considered acceptable as the general trend is similar for those simulations. The differences are inevitable due to inherent limitations on the inaccuracy which arose from the back-calculated inflow. Table (4) summarizes the results of the developed model for the Sungai Perak in terms of the peak flow and volume.

Table (4) : Peak inflow and volumes for Sungai Perak Dams

Duration (hr)	**Parameters**	**Temengor**	**Bersia**	**Kenering**	**Chenderoh**
1	Peak Inflow (m^3/s)	8,507	783	5,019	3,273
	Volume (Mm^3)	1,140	71	648	317
3	Peak Inflow (m^3/s)	9,929	892	5,850	3,787
	Volume (Mm^3)	1,317	82	749	366
6	Peak Inflow (m^3/s)	12,771	**1,111**	7,507	4,789
	Volume (Mm^3)	1,680	104	955	467
12	Peak Inflow (m^3/s)	13,529	1,091	7,868	4,833
	Volume (Mm^3)	1,827	113	1,038	508
24	Peak Inflow (m^3/s)	**14,902**	1,072	**8,654**	**4,879**

Duration (hr)	Parameters	Temengor	Bersia	Kenering	Chenderoh
	Volume (Mm³)	2,229	138	1,266	620
48	Peak Inflow (m³/s)	13,505	924	7,999	4,203
	Volume (Mm³)	2,732	169	1,551	760
72	Peak Inflow (m³/s)	11,583	785	6,823	3,557
	Volume (Mm³)	2,906	180	1,650	808
120	Peak Inflow (m³/s)	10,334	688	6,019	3,110
	Volume (Mm³)	3,516	219	1,998	980

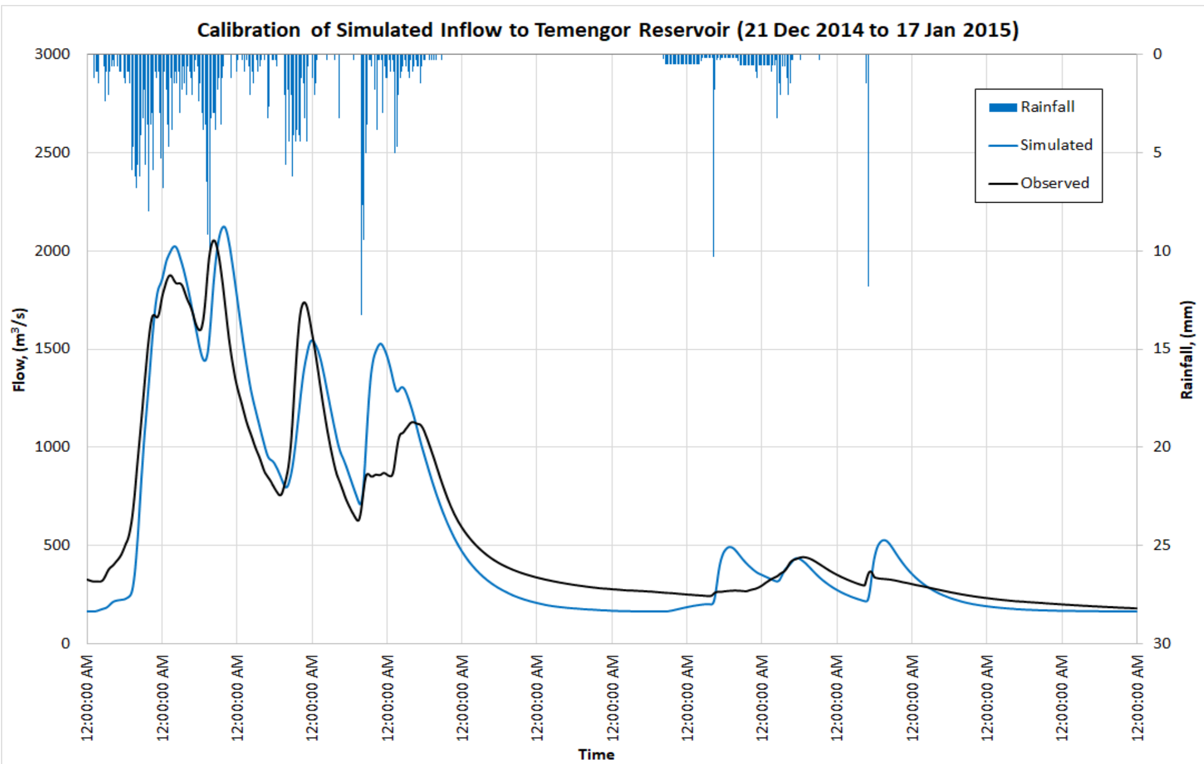

Figure (6): Calibration of simulated inflows for storm event in Dec 2014

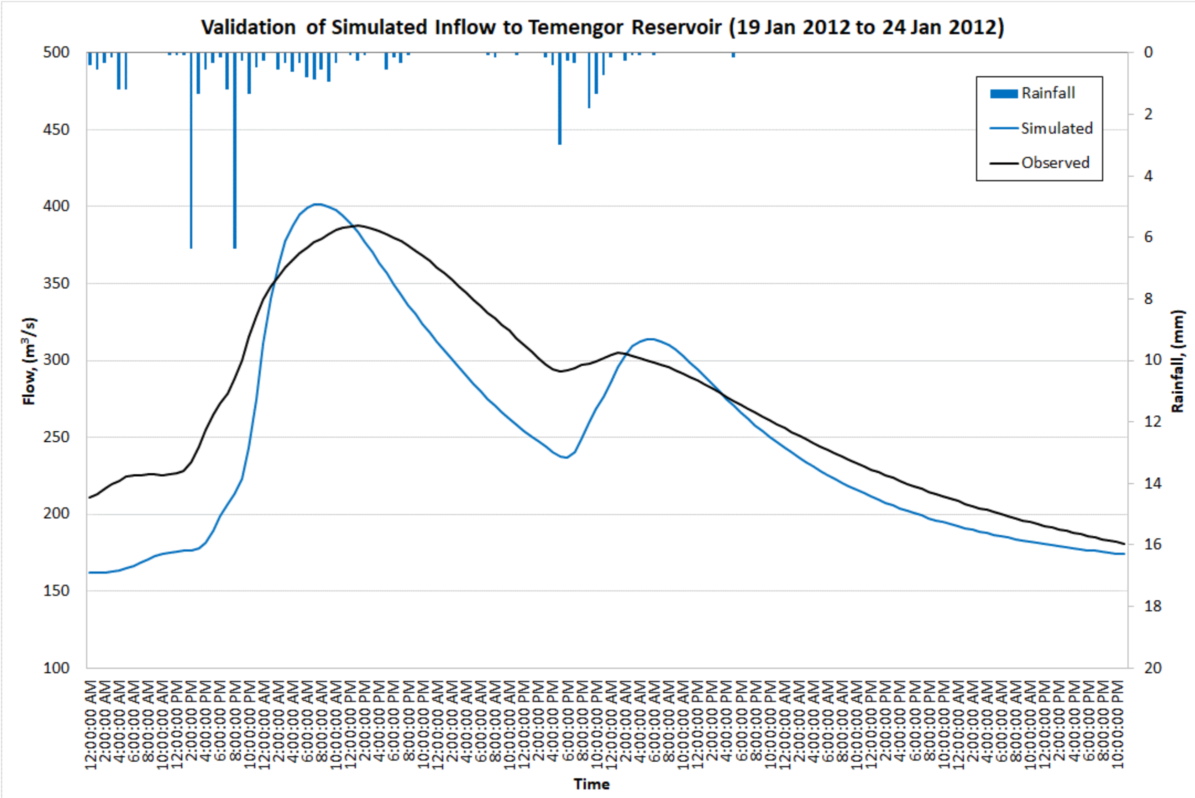

Figure (7): Validation of simulated inflows for storm event in Jan 2012

4.0 Conclusions and Recommendations

PMF simulations have been conducted in Sg. Perak HES based on the revised PMP by considering the inflow produced from intermediate catchments for each dam. It is noticed that the performance parameters for both events are considered very good and good whereby for calibration, NSE and PBIAS of 0.873 and -1.76% are obtained while NSE and PBIAS of 0.679 and -8.78% are obtained for validation. Moreover, the simulated reservoir pool elevations are closely correlated to the observed pool elevations during both storm events. Although slight differences are observed from the comparison, the differences are considered acceptable as the general trend is similar for those simulations. The differences are inevitable due to inherent limitations on the inaccuracy which arose from the back-calculated inflow. In conclusion, the hydrological model in this study has been adequately calibrated for probable maximum flood as it is credible and applicable to describe the hydrological process in Sg. Perak. It is recommended that next studies estimate the Areal Reduction factor (ARF) and perform the Probable Maximum Flood simulation for the mentioned dams in the current study by considering reservoir operations (reservoir routing). Furthermore, comparing the simulated maximum spillway discharge and the design spillway discharge capacity.

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