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MODELING RAINFALL-RUNOFF RELATIONS USING HEC-HMS IN AN OIL PALM CATCHMENT FOR DOUBLE RAIN EVENTS IN LABU RIVER BASIN OF PENINSULAR MALAYSIA

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ABSTRACT

In order to simulate a single rainfall event that occurred in the Labu catchment on April 7 and August 13, 2015, the HEC-HMS and soil moisture balance models were used. Based on the years that the peat swamp forest was converted into an oil palm plantation, the study plots within the watershed were divided into four plots: 2000, 2002, 2006, and 2010. In this study, two different hydrological models were employed such as the Soil moisture balance model and the Hydrologic Modeling System (HEC-HMS). A rainfall-runoff relationship for the sub-catchment was established using the Hydrologic Modeling System, HEC-HMS, coupled with recorded flow and rainfall data. This relationship was calibrated and then validated before being utilized for runoff estimation. The calibrated streamflow from the soil moisture balance model was compared with the HEC-HMS discharge values, which were used as the observed flow. The results show that the calibrated streamflow in the soil moisture balance model agrees with the observed streamflow data in the HEC-HMS. Following the two rainfall occurrences, the two models' respective Nash-Sutcliffe Efficiency (Ef) values were 0.82 and 0.90 which implies that the observed flow and the predicted flow by the models are correlated and this shows a strong acceptable model performance for model simulation. This also means that the application of the HEC-HMS along with a recorded streamflow data shows the ability of the HEC-HMS model to calculate the streamflow volume in a double storm event at Labu basin

1.0 Introduction

For the Labu sub-basin in the southwest of the Malaysian Peninsula, there have been insufficient hydrologic studies leading to insufficient planning and management of the sub-region's water resources (Hughes, 2019; Tarpanelli *et al*., 2023). Major construction projects have been hampered as a result in Peninsular Malaysia's Langat river basin as well as the catchment. This explains why there have been very few or no returns on investment for the oil palm business in the region despite significant investment (Andrianto *et al*., 2019; Prananta and Kubiszewski, 2021). According to Ziaei and Ali (2021), 74.1% of the palm goods supplied to Southeast Asia in 2011 were made up of palm oil. Palm oil and other products made from palm were exported annually for a value of $27 billion in 2011, up from $21 billion (a 28.6 % rise) in 2010. The oil palm is Malaysia's most valuable agricultural crop. Despite all these advantages, maintaining these economic gains is in jeopardy due to insufficient soil water availability for enhanced oil palm production and a lack of application of some other best management practices (BMPs) that would increase sustainability (Duguma *et al*., 2020; Lintern *et al*., 2020). The management of soil water, especially for oil palms grown on peat, is the most important of these BMPs in oil palm plantations.

However, complicated hydrological processes that are primarily about comprehending rainfall patterns and watershed qualities of the basin must be understood in order to improve the sustainability of the region's water management. Applying rainfall-runoff models, especially in terms of rainfall spatial distribution over the catchment area (Saha *et al*., 2022), is currently the region's biggest problem when studying its water resources (Tsakiris and Loucks, 2023). This is due to the fact that rainfall is the main input of any hydrological model. The generation of runoff from catchments that are mostly ungauged or badly gauged, as we have in many developing nations like Malaysia, is another significant challenge. This has led to uncertainty in the flow generation from such catchments, which would have serious negative effects on the region's hydrological processes and modeling. This has also had a significant impact on the oil palm output because the catchment's available water resources are not properly accounted for due to a lack of fundamental knowledge of rainfall-runoff interactions.

Some of these hydrological issues have been resolved by the use of data- or knowledge-driven hydrological models, such as the Hydrologic Modeling System (HEC-HMS) from the Hydrologic Engineering Center which was created to overcome modeling difficulties (Lin *et al*., 2020). This watershed model is built on a conceptual depiction of the actual physical water flow process over the full basin region to mimic the mechanisms involved in precipitation (Wilby *et al*., 2003). For humid, tropical, subtropical, and desert watersheds to simulate and forecast streamflow, the HEC-HMS offers both lumped parameter-based modeling and distributed parameter approaches (Gessessew *et al*., 2020; Ismail *et al*., 2020). According to various datasets and catchment types (Gunathilake *et al*., 2021; Shakarneh *et al*., 2022; Tibangayuka *et al*., 2022) it has been demonstrated that HEC-HMS can reliably simulate and predict streamflow. In order to determine the rainfall-runoff information for the basin, the Labu catchment's runoff hydrograph will be derived using HEC-HMS in this study.

2. Materials and Methods

2.1 Study Area

The study area is the Labu catchment which lies between longitude 101° 40′ 07” E to 101°50′.71″E and latitude 02°49′14.43″N to 02°44′.76 ″N in Western Malaysia (Figure 1). The Labu catchment is bounded by Lower Langat Catchment to the west and Beranang Catchment to the north (Figure 2). The total area extent of the catchment is about 167 km^2 and the tributaries consist of Batang Labu (about 17.9 km), Batang Nilai (6.4 km), and the main Labu River (31.1 km). The Labu River flows are from the territorial divisions of Labu, Seremban and flow through the town of Nilai, and finally meets Langat River at about 3 km south of Dengkil town (Figure 2). The location of the Labu catchment allows it to enjoy an equatorial climate with annual average temperatures between 20.5 and 36°C with two distinctive rainfall patterns that is moderately dry and moist and receive the lowest yearly rainfall for Peninsular Malaysia. Labu River basin soil is covered mostly by quarternary alluvium which are made up of unconsolidated to semi-consolidated peat, clay, silt, sand, and gravel (Mohd Adnan *et al*., 2013). The land use patterns of the study area are agricultural land, settlements, forests, industries, development projects, water bodies, and post-landfill practices. Table 1 shows the GPS position of the selected riverbed sampling locations and a description of the study area in the Labu River Basin.

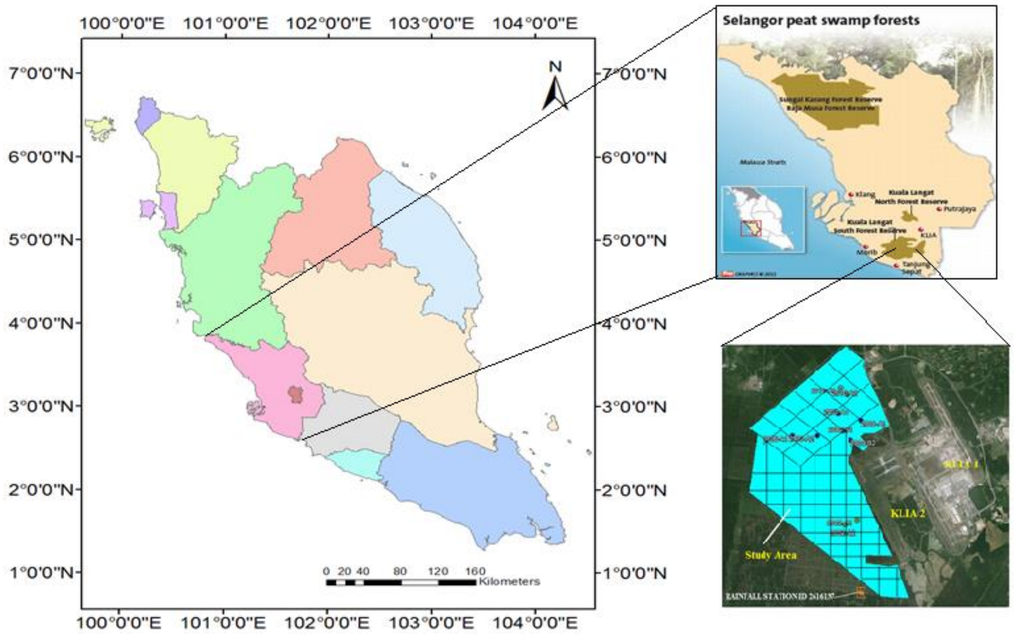

Figure 1: Location of the study area

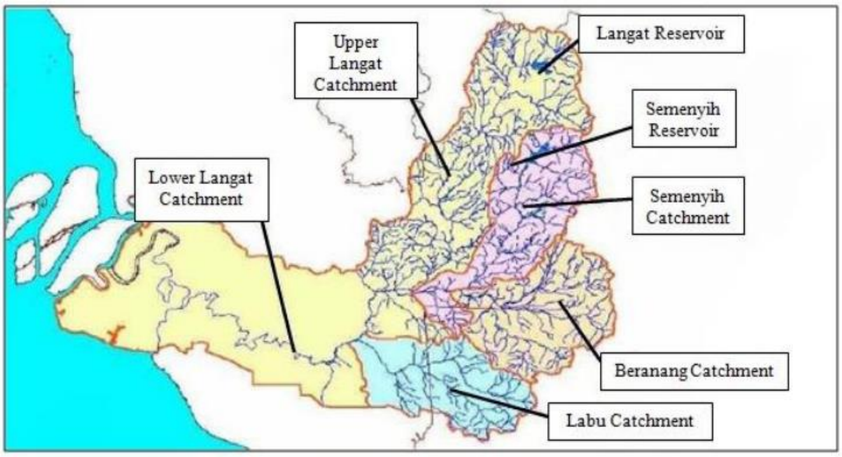

Figure 2: Location of Labu River Basin within Langat River Basin
Source: Zakaria (2008)

2.2 Site selection

The study area located in Sepang with a total area of 4,950 ha (49.5 km^2) was divided into four different sub-basins, each sub-basin named according to the years the peat swamp forests were converted to oil palm plantations, such as; 2000, 2002, 2006, and 1978/2010. The latter was first converted to oil palm plantation in 1978 before it was re-cleared for cultivation in the year 2010. All the sub-basins have the same hydrologic soil type and same vegetation but with different catchment areas. Their respective geo-locations, elevations, areas, and land cover are presented in Table 1.

Table 1: Location of study areas with their features and land cover

No	Plot	Latitude S	Longitude E	Elev. (m)	Land use	Area (km^2)
1	2000-Year	02 43.816	101 39.576	19	OP Plantation	19.31
2	2002-Year	02 43.074	101 40.368	8	OP Plantation	12.34
3	2006-Year	02 44.552	101 38.932	13	OP Plantation	8.925
4	2010-Year	02 45.950	101 39.877	19	OP Plantation	8.925

Due to a lack of real-time runoff data in the research area, the 35.38 km^2 Semenyih watershed (Figure 2) was chosen as a proxy site for runoff estimation using the HEC-HMS model. Daily and hourly flow and rainfall data from gaging stations along the Semenyih River have been recorded for the Semenyih Catchment which lies within latitudes of 2° 40' 152" N to 3° 16' 15" N and longitudes of 101° 19' 20" E to 102° 1' 10" E. Semenyih basin was selected because it has Sepang basin's plant and soil characteristics. Although the Semenyih Basin contains a mixture of peat and mineral soils, the Sepang Basin is primarily composed of peat. However, the Sepang Basin system is heavily drained, which will significantly shorten the catchment's retention time and prevent the peat soil from acting as a sponge. In order to estimate runoff, Semenyih Basin, a primarily mineral soil deposit, was used as a proxy. Therefore, a flow pattern was established for the study region, which is located Southwest of the Semenyih basin, using runoff data output from the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) and recorded streamflow and rainfall data from the Semenyih basin.

2.3 Runoff estimation from HEC-HMS using observed streamflow data

In this study, the runoff hydrographs from a design storm on the Sepang oil palm plantation basin were simulated using the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS). A hydrologic model for the Semenyih basin with a catchment size of 35.38 km^2 was established using the HEC-HMS version 4.1. According to USACE (2000), the HEC-HMS is a numerical model that simulates the behavior of watersheds, channels, and water-control structures in order to forecast flow, stage, and timing. According to Chen *et al.* (2009), the model divides a watershed into sub-catchments that are treated as homogenous in terms of land-use, soil type, etc. in order to address the spatial distribution of catchment features.

Figure 3 shows the model schematic that was set up in HEC-HMS for the study area. It comprises of subbasins which represent a drainage area within the Basin Model for each study plot and the 'junctions' which serve as points of interest where reaches in each sub-basin are connected, in this case, a drainage system.

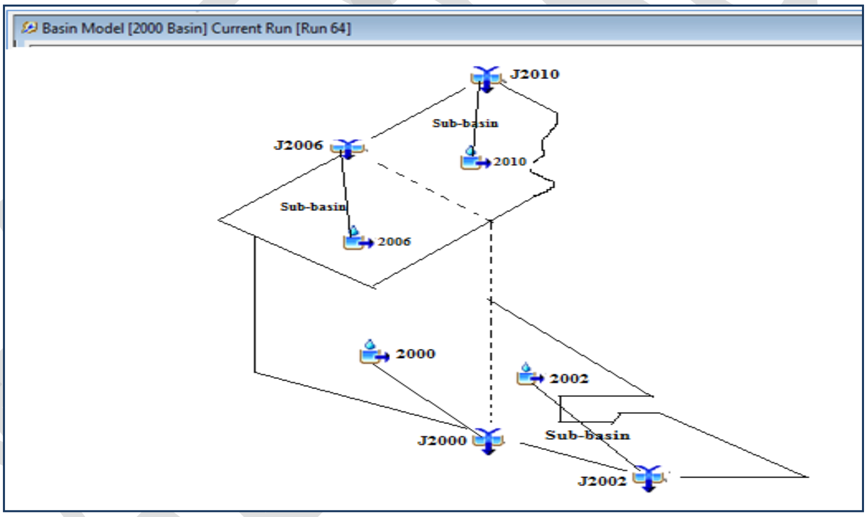

Figure 3: HEC-HMS Model Schematic Diagram for Study Area

2.4 Model Calibration Using HEC-HMS and observed streamflow

The resulting runoff from the HEC-HMS was statistically compared with the recorded streamflow data obtained from soil moisture balance model by adjusting the model parameter values of HEC-HMS until the model results match the observed streamflow data. In the use of HEC-HMS, a basin file is needed to specify the physical parameters of the basin such as the catchment area, and sub-basin data. In addition to the basin model, meteorological data that describes the meteorology (rainfall) of the catchment was also established for the study area. A Control Specification file containing information pertinent to model timing like when a storm occurred and the time interval for the model use is also included in the HEC-HMS. These three models are referred to as Components in the HEC-HMS model and are the basis for the rainfall-runoff modeling in the HEC-HMS. The basin file in the HEC-HMS contains different hydrologic elements. Among all the hydrologic elements in the model is the 'sub-basin' hydrologic element which is used in the computation of rainfall-runoff in a watershed. Having selected the sub-basin as the hydrologic element in converting rainfall to runoff in the watershed, the information on methods needed in computing loss rates, hydrograph transformation, and baseflow is required. Different loss methods are available in HEC-HMS. They are; SCS Curve Number method, Initial and Constant method, Soil Moisture Accounting method, Green and Ampt method, Deficit and constant method and exponential loss method. For the Transfrom Method, SCS Unit hydrograph was used in the runoff estimation. Transfrom methods helps in specifying how to convert excess rainfall to direct runoff. The Soil Conservation Service Curve Number method (SCS-CN) is essentially an empirical, one-parameter (CN), event rainfall-runoff model. For the use of SCS Curve Number method in HEC-HMS, each sub-basin requires a value for the Curve Number (CN), Lag-time (which is the time difference between the peak precipitation and peak discharge) and percent imperviousness. The percent imperviousness is a function of the landuse of the study area and is the ratio of the impervious areas of the study area to the total areas of the basin in question. Hence the percent imperviousness is obtained by dividing the entire basin into groups based on their present land use like; Open space, Estate-Residential, Industrial, Water, Low-Intensity Commercial, Institutional, Transportation etc. The detailed estimation of the Percent Imperviousness of the Semenyih basin is explained in the preceding section. The dimensionless CN accounts for the effects of land use/land cover, soil types, and hydrologic conditions on surface runoff, and relates direct surface runoff to rainfall.

Having obtained the values of percent imperviousness, the values of CN and Lag-time were both inserted as input parameters in the HEC-HMS to obtain direct runoff which was then compared with the recorded flow. A statistical relationship was established between the flow data from HEC-HMS and recorded flow data from the Semenyih basin. Both hourly and daily flow and rainfall data covering 2013 to 2015 were obtained from Department of Irrigation and Drainages (DID) and used in the runoff estimation. Two highest rainfall depths with simple hydrographs were chosen for the calibration of the HEC-HMS model. Hourly rainfall depths of April 7th and November 23rd, 2014 water year were chosen for the calibration of the model while the months of September and December were used for model validation. Having established the flow data for April 7th and November 23rd, the flow data from HEC-HMS and the recorded flow data from the Semenyih basin were tested for model performance using both the coefficient of determination R^2 and Nash–Sutcliffe model efficiency coefficient (E_{NS}) (Dongguan *et al.* 2009; Karthikeyan *et al.* 2013). The R^2 value represents an indicator of strength of the relationship between the observed and simulated values while Nash-Suttcliffe simulation efficiency (E_{NS}) indicates how well the plot of observed versus simulated values fit into the 1:1 line.

The Nash–Sutcliffe model efficiency coefficient is used in assessing the predictive power of hydrological models, and it is defined as equation 1

$$E = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_o^t - \bar{Q}_o)^2} \quad (1)$$

Where;
Q_o = mean of observed discharges (m^3/s), and
Q_m = modeled discharge (m^3/s), and
Q_o^t = observed discharge (m^3/s) at time *t*.

Nash–Sutcliffe efficiency ranges from infinity to 1. The value of efficiency of 1 (when $E = 1$) means there is a perfect match of modeled discharge relative to the observed data. The value of efficiency equal to (when $E = 0$) shows that the predictions of model are as accurate as the mean of the observed data, whereas an efficiency below zero ($E < 0$) occurs when the observed mean is a better predictor than the model or, in other words, when the residual variance (numerator in equation 6.1), is larger than the data variance (the denominator). Therefore, the closer the model efficiency is to 1, the more accurate the model is (Karthikeyan *et al.* 2013). And according to Dongquan *et al.* (2009), an E_{NS} greater than 0.5 indicates acceptable model performance for model simulation.

3. Results and Discussion

3.1 HEC-HMS Model Calibration for Semenyih Basin

Rainfall depths of April 7th and August 23rd in Labu basin were used in the calibration process of runoff estimation using hourly time-step. With the assumed base flow values for each month (3.6 m^3/s for April and 4.0 m^3/s for August), initial runoff estimation was carried out using the varied CN and Lag-time values with the value of percent imperviousness which was estimated as 17.64 %. Table 2 shows the various adjustments made in the HEC-HMS and the output results of Nash–Sutcliffe model efficiency coefficient ($\mathbf{E_{NS}}$) and Coefficient of Correlation (R^2) for various trials. Curve number value of 40 and Lag-time of 60 minutes, with estimated impervious value of 17.64 % were chosen after series of trials and these were further used in the validation processes. CN value of 40 and Lag-time of 60 minutes gave the $\mathbf{E_{NS}}$ of 0.794 and R^2 value of 0.853 for April 23rd calibration which showed a good fit and well above 0.5 thresholds. This also showed that the two-flow data were not significantly different and that the model predictions are as accurate as the mean of the observed data (Dongquan *et al.* 2009). Figures 4 and 5 show the hydrographs of the calibrations carried out from the two flood events of April 7th and August 23rd 2014 water year. The two hydrographs indicate that the simulated flows reasonably predicted the recorded flow. This was further supported by Nash-Sutcliffe results of Figures 6 and 7 for the same flood events of April 7th and August 23rd which showed that the values were higher than the minimum recommended in hydrological simulation, according to Dongquan *et al.* (2009) and Karthikeyan *et al.* (2013).

Table 2: HEC-HMS adjustment of CN and Lag-Time using Percent Imperviousness of 17.64 % for Calibration

Month	Trials	Curve Number	Lag-Time (Mins)	E_{NS}	R^2
APRIL	1	40	60	0.820	0.860
	2	45	60	0.794	0.853
	3	50	100	0.70	0.70
	4	65	100	-0.26	0.699
	5	70	100	-1.10	0.699
AUGUST	1	40	60	0.904	0.941
	2	45	60	0.897	0.941
	3	50	100	0.894	0.931
	4	65	100	0.115	0.799
	5	70	100	-0.602	0.789

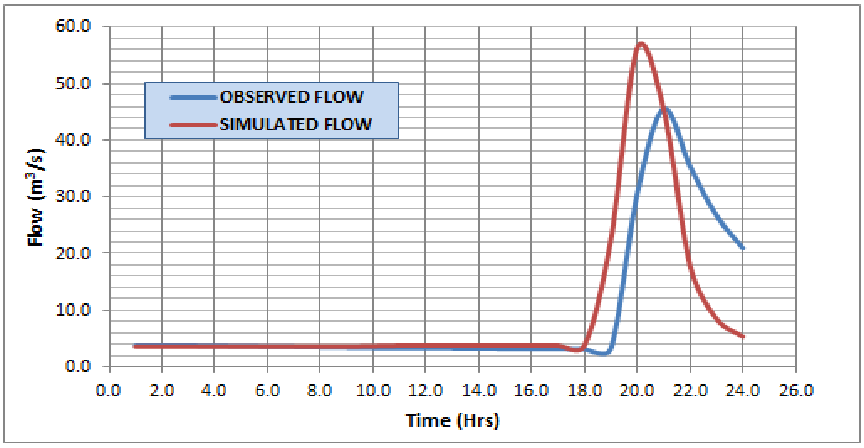

Figure 4: Comparison of Simulated and Observed Hydrographs for April 7th 2014 Flood Event of Semenyih Basin

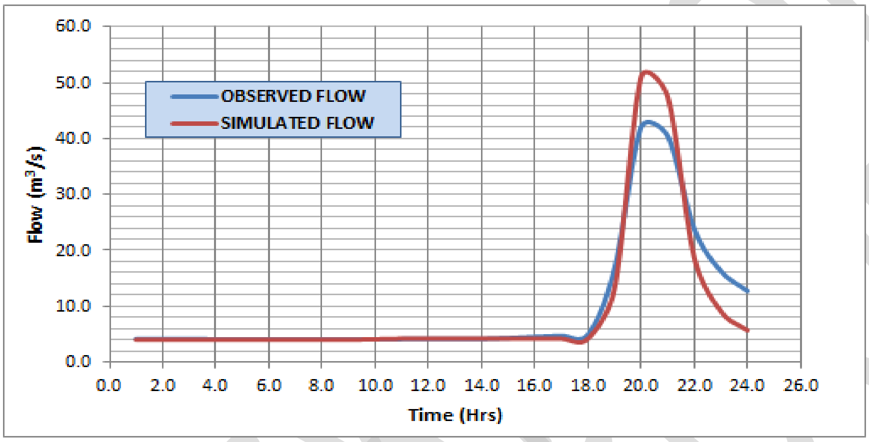

Figure 5: Comparison of Simulated and Observed Hydrographs for August 23rd 2014 Flood Event of Semenyih Basin

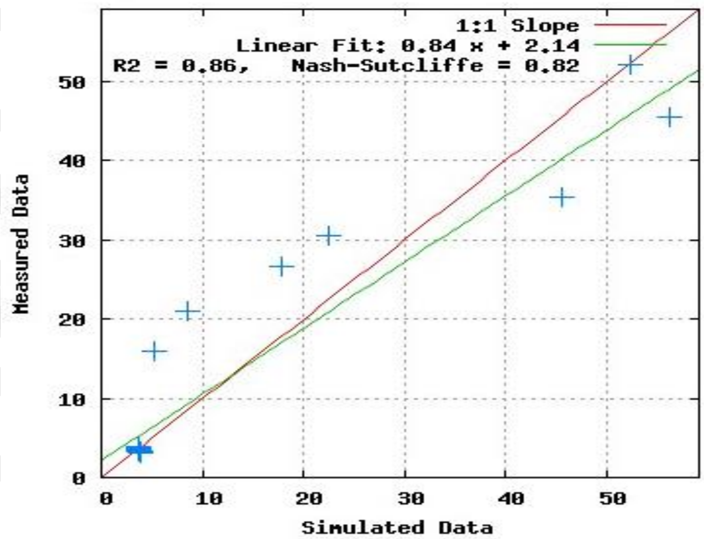

Figure 6: Values of R^2 and E_{NS} For April 2014 Simulated Flow during Calibration at CN = 40, Lag-time = 60mins and Percent Imperv = 17.64%

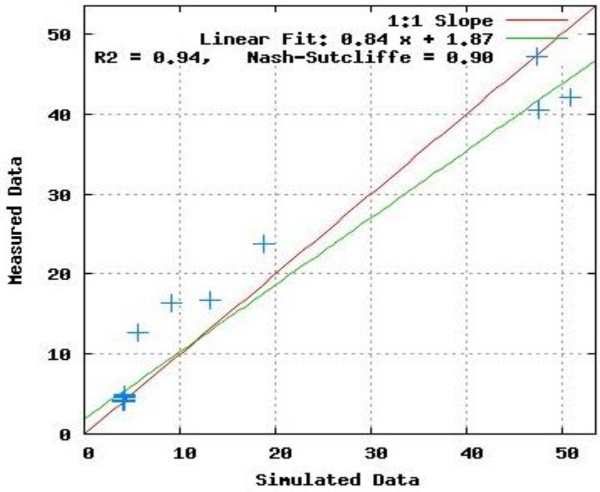

Figure 7: Values of R^2 and E_{NS} For August 2014 Simulated Flow during Calibration

3.2 HEC-HMS model validation for Semenyih Basin

Validation of the HEC-HMS model for Semenyih Basin was done using the daily rainfall data from September to December 2014. The daily rainfall data was used in the HEC-HMS model with input parameters of CN of 40 and Lag-time, 60 minutes and estimated percent impervious values 17.64 %. Figure 8 shows that the simulated flows gave a moderate prediction of the observed flow, though there seemed to be overpredictions in some cases. Figure 9 shows the statistical results of $\boldsymbol{E_{NS}}$ and R^2 values which shows a good prediction as the values of $\boldsymbol{E_{NS}}$ and R^2 were greater than 0.5.

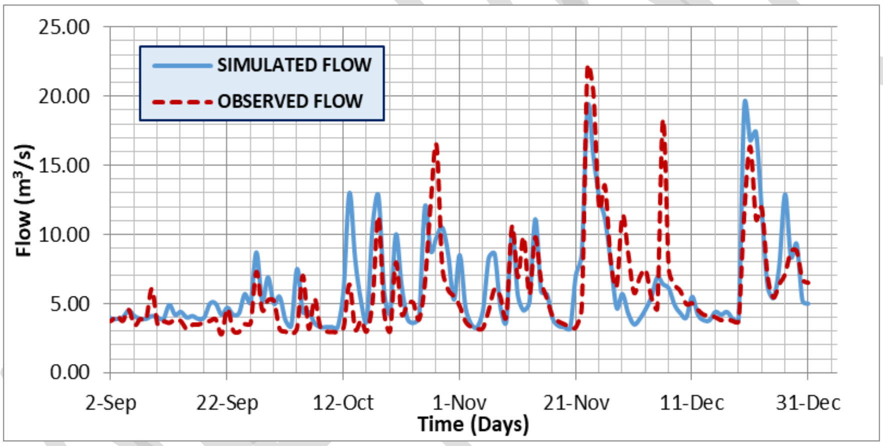

Figure 8: Simulated and Observed Flows for September to December 2014 during the validation process.

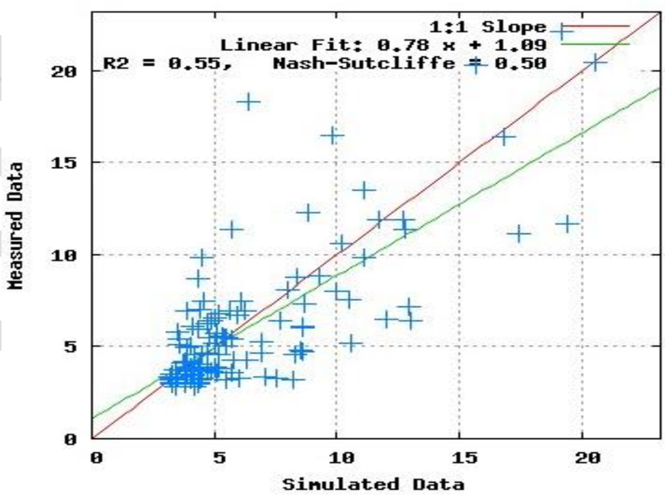

Figure 9: Values of E_{NS} and R^2 for Sept-December 2014 simulated Daily Flow for Validation Process

The adopted HEC-HMS input parameters such as CN value of 40 and Lag-Time of 60 minutes were used in establishing a runoff estimate for the study area of Sepang with the catchment area of 49.5 km^2. The percent impervious value for Sepang area was estimated using the same procedure used for Semenyih basin.

4. Conclusion

HEC-HMS model has been used to simulate a single rainfall event that occurred in the Labu catchment in Peninsular Malaysia. To fully comprehend the characteristics of the watershed, geological, soil, and land use data were used along with HEC-HMS model. In order to forecast the surface runoff, the HEC-HMS hydrologic modeling program was applied to the Labu watershed in southwest Malaysia. The hydrologic losses from the study area were calculated using the SCS curve number loss method, and the effective transformation of rainfall was achieved using the SCS unit hydrograph method. The measured runoff events of April 7 and August 13, 2015, served as a calibration point for the model parameters. The daily Nash and Sutcliffe efficiency (NSE) was utilized to calculate the degree of agreement between the predicted and observed stream flow. As a result, the runoffs produced by the frequency storm approach will be crucial for the assessment of the flood risk in the neighbouring cities. The observed streamflow obtained from the meteorological agency was compared with the HEC-HMS discharge values, which were used as the observed flow. The observed streamflow obtained from the meteorological agency agrees with the observed streamflow data in the HEC-HMS with good agreement.

In conclusion, the application of the HEC-HMS along with a recorded streamflow data shows the ability of the HEC-HMS model to calculate the streamflow volume in a double storm events at Labu basin. Recommendation on the use of a GIS-based approach in rainfall-runoff modeling coupled with the use of different land use patterns, especially in regions with a complex mix of land use features and different soil types will be a major breakthrough hydrological modeling.

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