APPLICATION OF GEOSPATIAL AND HYDROLOGICAL MODELING FOR RUNOFF ESTIMATION IN LEBIR RIVER BASIN, MALAYSIA

Suhaini Mohamad Sukairi[1], Sobri Harun[1], Kamarul Azlan Mohd Nasir[1], Ponselvi Jeevaragagam[2], Mohd Radhie Mohd Salleh[3]

[1] Department of Hydraulics and Hydrology, School of Civil Engineering,
Universiti Teknologi Malaysia, Johor Bahru, Malaysia
[2] Department of Environmental and Water Engineering, School of Civil Engineering,
Universiti Teknologi Malaysia, Johor Bahru, Malaysia
[3] Department of Geoinformation, Faculty of Built Environment and Surveying,
Universiti Teknologi Malaysia, Johor Bahru, Malaysia
suhaini4@graduate.utm.my, (sobriharun, kamarulazlan, ponselvi)@utm.my, mohdradhie.gis@gmail.com

Commission IV, WG7

KEY WORDS: Flood, GIS, Remote Sensing, Disaster, HEC-HMS, RRI.

ABSTRACT:

Non-stop heavy rain had happened on 15th December of 2014, causing flood in Kelantan districts. Approximately 250 of flood victims in three districts were involved and relocated to six temporary relief centres. A hydrological model is designed to simulate the runoff process for a catchment area. In this study, Hydrologic Engineering Center Modelling System (HEC-HMS) and Rainfall-Runoff-Inundation (RRI) modeling method were used in the simulation of flow hydrograph for the Sungai Lebir catchment. Establishing the simulation at Sungai Lebir using the both models may help in analysing large-scale flooding in the future. The use of HEC-HMS and RRI require data of precipitation and flow rates obtained from the Department of Irrigation and Drainage (DID) centre. There are two main processes in the modelling stage namely calibration and validation. A total of two dates of rainfall events used for the calibration process; the events on December 5, 2014 to December 11, 2014 (Calibration 1) and December 15, 2014 to December 20, 2014 (Calibration 2) which resulting low NSE value for Calibration 1 with -9.806 and -0.312 for HEC-HMS and RRI, respectively. Whereas for the validation process, two sets of events on December 1, 2001 to January 7, 2002 (Validation 1) and November 16, 2013 to December 23, 2013 (Validation 2) have been used, resulting that HEC-HMS outperformed RRI with the recorded value of 0.817 and 0.821, for Validation 1 and Validation 2, respectively. The results indicate that the flow rate computed using the HEC-HMS software is not significantly different from the actual flow rate, and it also demonstrates the suitability of the HEC-HMS software for use in flow rate estimation.

1. INTRODUCTION

One of Malaysia's most regular natural calamities is flooding. Flash flooding and monsoon flooding are the two main types of flooding that have a significant negative influence on both human life and the environment (DID, 2017). Flash floods are sudden and caused by unexpectedly strong rain, while monsoonal floods occur throughout the monsoon seasons (Shah et. al, 2017). In Malaysia, 5.7 million people (20%) live in areas at danger of flooding, which accounts for 9% of the nation's total land area. According to statistics, these destructive floods occur virtually yearly, particularly in Peninsular Malaysia's East Coast states of Sarawak, Kelantan, Terengganu, Pahang, and east Johor (Saimi F.M et. al, 2020).

Flood tragedies frequently result in significant losses for both the nation and the individual. Millions of ringgit in losses must be endured by Malaysia each year. It is well known that flood disasters will result in structural and non-structural damage, such as harm to buildings and drainage systems, destruction of property and loss of life, contamination of food and water, harm to agricultural land, and disruption of socioeconomic activities like communication and transportation. In order to lessen the effects of floods, structural and non-structural measures will be used in flood protection and mitigation. The Department of Irrigation and Drainage Malaysia (DID) has suggested a number of initiatives in response to the negative consequences of previous significant floods.

Floods bring many effects to most of the engineering structure such as bridges, embankments, tanks and reservoirs, etc. Therefore, with implementing the structural and non-structural measures in flood protection and mitigation will help to reduce the impacts of floods. Seeing the adverse effects of the past major floods, the Department of Irrigation and Drainage Malaysia (DID) has proposed several projects. The main components of the DID flood mitigation strategy and policy are structural measures (such as building dams and embankments to control flood flows), non-structural measures (such as flood risk assessment and mapping, land use planning and flood forecasting, and warning systems to mitigate flood impacts), and flood disaster relief and preparedness equipment (DID, 2021). To establish an effective long-term flood risk management strategy, the study of Romali (2021) underlined the need for a balance between structural flood measures and non-structural flood measures.

The flood disaster, especially the major floods that hit the State of Kelantan in 2014 which caused the water to overflow to the surrounding areas and rose more than one metre high; producing damage to houses, buildings and infrastructure including roads and bridges. The effects of major floods in Kelantan are felt especially in the Kuala Krai, Tumpat, Tanah Merah, Gua Musang and Kota Bharu. The flood was due to the rising levels of three major rivers in Kelantan; Sungai Galas in Dabong, Gua Musang (46.47 meters). Sungai Lebir in Tualang, Kuala Krai (42.17 meters) and Sungai Kelantan (22.74-34.17 meters). Flood forecasting is important in enhancing the effectiveness, safety and maintenance of the existing flood control system. Flood control measures and stormwater management can also be identified and implemented despite the existence of flood mitigation plans by the Department of Irrigation and Drainage (DID) Kelantan. Among the flood control methods implemented by JPS Kelantan is the Kelantan River Flood Mitigation Project. This in turn protects all developments that are taking place in the river basin area.

For the purpose of this research, the estimation of the amount of surface runoff and flow levels in the river were used in predicting the future flood. In addition, the input from geospatial data such as land use and land cover, soil map, and Digital Elevation Model (DEM) is very helpful in improving the hydrological modelling process. These data can be used in the preparation of hydrological modelling parameters such as river slope, Manning’s roughness, soil depths, and lateral saturated hydraulic conductivity.

In conclusion, it is critical to accurately predict surface runoff and flow rates in Sungai Lebir in order to predict upcoming floods. The accuracy with which the two models—Rainfall-Runoff-Inundation (RRI) and the Hydrologic Engineering Centre-Hydrological Modeling System (HEC-HMS)—simulate the runoff of the chosen river basin will be evaluated in this study.

2. STUDY AREA

2.1 Description of Study Area

The Sungai Kelantan catchment, in Peninsular Malaysia's north-western region, is one of the most important catchments in the country as shown in Figure 1. The greatest length and breadth of the catchment are 150 and 140 kilometres, respectively. From Banjaran Titiwangsa to the South China Sea, Sungai Kelantan extends for around 248 kilometres. It covers more than 88 percent of Kelantan and has a drainage area of 13,088. Sungai Kelantan is divided into five sub-catchments: Galas, Nenggiri, Pergau, Kuala Krai, and Lebir. Throughout the catchment, there are large areas of forest and agricultural land cover.

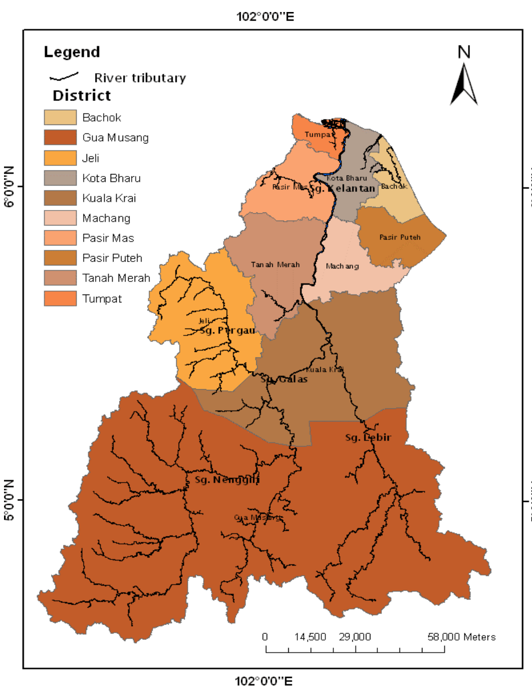


Figure 1. Sungai Kelantan tributaries and Kelantan district map

The Sungai Kelantan was used in this study to simulate the influence of a diffusion wave and an inundation map for many return intervals. Sungai Kelantan was also used to conduct the time series study. The Sungai Kelantan is located in northeast Peninsular Malaysia and is one of the country's major rivers. It is frequently flooded by monsoons (Chan, 2002; DID, 2004). The Kelantan River Catchment is characterised by relative humidity, mild winds, and heavy monsoonal rainfall during the NE monsoon season, when high velocity NE winds give significant rain to this area. Kelantan receives roughly 40% of its annual rainfall during the NE monsoon. On a broad scale, the Kelantan catchment can be divided into two climate areas based on land elevation surface and rainfall influence. The first is the climate in the North, while the second is the climate in the Middle Highlands. The climate in the north is typically associated with moderately mild temperatures and predictable weather patterns (i.e. dry and wet conditions through the year). The Middle Highlands, on the other hand, has a colder climate and receives less rainfall than the North Highland region.

The Sungai Kelantan catchment's precipitation is not evenly distributed throughout the year. The wet period and the dry period are two meteorological conditions that occur in this location. Wet weather coincides with the NE monsoon, as previously stated. Rainfall of 100 to 300 mm per day has been observed during the intense NE monsoon season (DID, 2004). Weak winds or quiet air conditions describe the dry season. The mean annual rainfall for the Sungai Kelantan catchment was 3242 mm in 2014, with the highest total of 1267.5 mm in December (during the NE monsoon) and the lowest totals of 5.5 mm and 121.7 mm in February and March. In this study, Sungai Lebir catchment was selected for the modelling process.

3. METHODOLOGY

In general, the implemented methodology in this study contains four (4) main stages. The first stage concentrates on the data collection, which consists of gathering of hydrological rainfall data and remotely sensed data i.e. DEM and satellite images. The second stage emphasizes on the data pre-processing while the third phase focuses on model calibration. In the fourth phase, the results were validated by calculating the Nash-Sutcliffe efficiency (NSE) and Root Mean Square Error (RMSE).

3.1 Data Collection

Overall, three types of data were collected i.e. hydrological data, remotely sensed data, and geological data. The study employed hydrological data from 1978 to 2015, which included precipitation and stream flow records. The historical data came from the Malaysian Department of Irrigation and Drainage's hydrological data network (DID). Precipitation data for the entire Sungai Kelantan catchment was separated into yearly, seasonal, and monthly time-series. The year was divided into two primary seasons for seasonal trend analysis: wet season (October to March) and dry season (April to September) (April to September). Total precipitation was calculated for each rain gauge station every six months, and trends were fitted to the data.

For remotely sensed data, Landsat-8 OLI images were obtained through the US Geological Survey Earth Resources Observation and Science Center (http://earthexplorer.usgs.gov). The image data and was acquired on 2014 (before flooding event) with low cloud cover. For the topographical data, Shuttle Radar Topography Mission (SRTM) 30M Global DEM (Figure 2) was downloaded from USGS website which cover the whole Sungai Lebir catchment area. Meanwhile, geological data was collected from Department of Mineral and Geosciences Malaysia in GIS format (Figure 3).

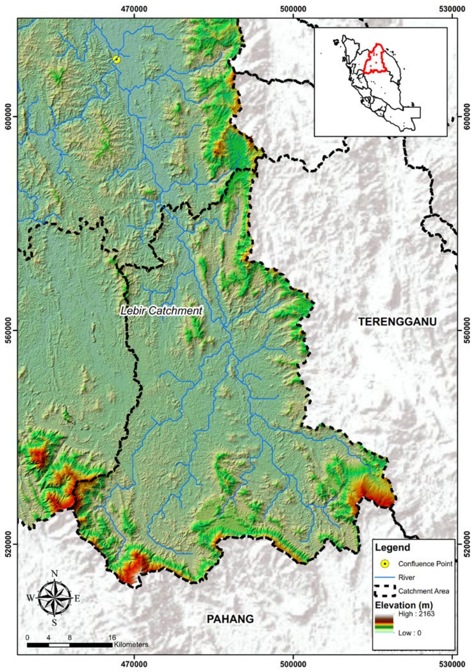


Figure 2. DEM map of Sungai Lebir catchment area

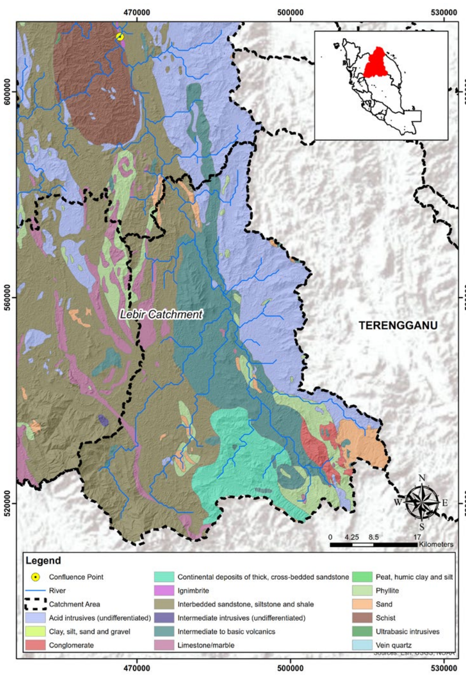


Figure 3. Geological map of Sungai Lebir catchment area

3.2 Data Pre-Processing

Three stations' worth of rainfall data were combined into one Comma Separated Value File (.csv) in Microsoft Excel before being imported into the RRI and HEC-HMS models. The historical data were provided by the Department of Irrigation and Drainage (DID) of Malaysia's hydrological data network. The year was divided into the wet (October to March) and dry (April to September) seasons in order to analyse seasonal changes. Every six months, total precipitation was determined for each rain gauge station, and trends were fitted to the data. The data was chosen because it had good continuity and minimal missing data records.

Data pre-processing at this stage aimed to include all relevant GIS data sources and provide a full set of input data for hydrological modelling. In general, numerous types of GIS data were used, including geology, land use, and digital elevation model (DEM) data. Within the Sungai Lebir catchment, 30-meter spatial resolution DEM data was acquired from USGS Earth Explorer. DEM is the most important piece of information for locating a watershed. The topography or geographic distribution of heights in a terrain above a random datum is represented by a square grid matrix with the mean cell elevation kept in a two-dimensional array of numbers (Garbrecht and Martz, 2000).

Data in shapefile format was collected from Plan Malaysia for information on land use and land cover. For each lot parcel, the data includes detailed attribute information, including three levels of land use class and district. The sole level of land use that has been used is the first level in order to simplify the hydrological modelling. Additionally, this data was used to generate the CN number gridding method. The geological data or the hydrological soil group that was downloaded from the Distributed Active Archive Center of Oak Ridge National Laboratory (ORNL DAAC).

3.3 Model Calibration

3.3.1 HEC-HMS Model

The technical ability of the hydrological model as well as the quality of the input data are both necessary for a well-calibrated model. For the period of 2007–2010, the HEC–HMS model for the Sungai Lebir basin was manually calibrated by comparing the observed streamflow for the peaks, timing, and runoff volumes.

A sensitivity analysis was conducted to identify the crucial variables influencing the calibration of the rainfall-runoff model. A single parameter was changed at a time in increments of 10%, ranging from 50% to 50% (Gunathilake M. B. *et. al.*, 2019). Up until the best agreement between observed streamflow and simulated streamflow was attained, this was done while maintaining other hydrological parameters constant. The most critical factors are shown to be groundwater 1 storage (mm), impervious percentage (%), soil storage (mm), and soil percolation (mm/hr).

3.3.2 RRI Model

The model is calibrated using the initial parameter value ranges. The ranges are manually established based on hydrological knowledge and geospatial based data. The calibration was done using different parameters based on a 2014 event. RRI Builder uses three types of land use: urban, farm, and forest. Clay type is the soil type for agriculture land, according to the Department of Geology and Mineral Resources. As a result, numerous types of soil texture were simulated to achieve the most accurate parameter value for agricultural land. As a calibrated parameter set, the sample with the best performance is chosen. The best performance was showed as clay. Table 1 lists the model parameters that were used in the simulation.

Table 1. RRI Builder parameters

Parameters	Forest	Urban	Agriculture
Manning's roughness on slope cells, n_S (in $m^{-1/3}$)	0.400	0.400	0.400
Soil depths, d (in m)	1.000	1.000	1.000
Effective porosity, ϕ (-)	0.475	0.475	0.475
Green Ampt Infiltration Model Parameters			
Vertical saturated hydraulic conductivity, k_V (in m/s)	0.000	0.000	1.67×10^{-7}
Suction at the wetting front, S_f (m/s)	3.163	3.163	3.163
Lateral sub-surface and surface model parameters			
Lateral saturated hydraulic conductivity, k_a (m/s)	0.100	0.000	0.000

3.4 Model Validation

Nash-Sutcliffe efficiency (NSE) is a metric that quantifies a model's efficiency by linking the errors to the variance in the data. The NSE is a composite measure of bias and random errors; the value is 1 for perfect prediction, 0 for average prediction, and negative for worse than average prediction.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{i\_obs} - Q_{i\_sim})^2}{\sum_{i=1}^{n}(Q_{i\_obs} - \overline{Q_{i\_obs}})^2} \quad (1)$$

Where Qi_obs and Qi_sim are the observed and simulated data, respectively; n is the total number of data records; $Qobs$ and $Qsim$ are the mean observed and simulated data for the evaluation period.

4. RESULTS AND DISCUSSION

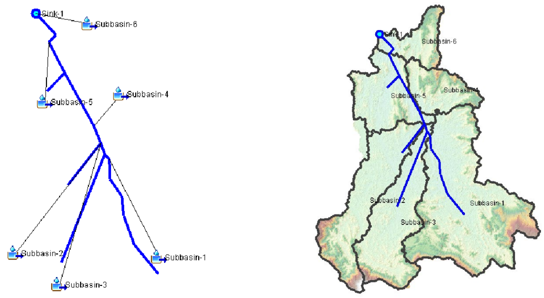
4.1 Catchment Characteristics

The catchment boundary was produced from DEM that undergoing several procedures. Overall, six sub-basins were successfully derived within Sungai Lebir basin (Figure 4). The detail of catchment characteristics can be found in the Table 2. These parameters values were used during the simulation process.

Table 2. Catchment characteristics for Sungai Lebir Basin

Sub-basin	Average CN	L (KM)	Imp (%)	Basin Slope (%)	Tc (hour)	Lag (minute)
1	76.01	63.39	5.53	27.88	18.74	674.74
2	77.48	83.45	5.83	27.53	23.21	835.49
3	78.36	83.74	5.86	25.30	24.10	867.59
4	75.66	24.91	5.38	31.61	8.36	301.04
5	78.71	36.94	6.35	24.42	12.71	457.54
6	75.73	42.82	5.52	31.18	12.98	467.23

**CN= Curve Number, L=Longest Flowpath Slope, Imp=Impervious, Tc=Time of Concentration*



(a) (b)

Figure 4. (a) Schematic diagram and (b) delineated watershed polygon of Sungai Lebir basin

4.2 Results from HEC-HMS and RRI Model

Table 3 and table 4 depicts the period of the event and the NSE value for the calibration and validation process from both HEC-HMS and RRI models..

Table 3. Result comparison between HEC-HMS and RRI for calibration

Calibration Result		
Period	**HEC-HMS**	**RRI**
Calibration 1 (5 - 11 December 2014)	1st: -15.721 2nd: -9.806	-0.312
Calibration 2 (15 - 20 December 2014)	1st: 0.373 2nd: 0.858	0.587

Table 4. Result comparison between HEC-HMS and RRI for validation

Validation Result		
Period	**HEC-HMS**	**RRI**
Validation 1 (1 December 2001 - 7 January 2002)	1st: 0.206 2nd: 0.817	0.786
Validation 2 (16 November 2013 - 23 December 2013)	1st: 0.354 2nd: 0.821	0.731

As indicated in Tables 3 and 4, the NSE value was used to evaluate the performance of both modeling methods. The NSE value for the calibration procedure varied between -15.721 and -0.312 for Calibration 1 and between 0.373 and 0.858 for Calibration 2. For Calibration 1, RRI fared better than HEC-HMS by achieving a lower negative NSE value (-0.312). NSE increases from -15.721 to -9.806 as a result of the application of the optimization procedure, whilst the HEC-HMS technique demonstrates significant improvement. For Calibration 2, HEC-HMS surpassed RRI by achieving a high NSE value of 0.858 (after optimization) compared to RRI's 0.271.

During the validation process, it was found that HEC-HMS performed better than RRI throughout the entire validation process. After utilizing parameter optimization, HEC-HMS showed steady improvement, as seen by a significantly increased NSE value. For Validation 1 and Validation 2 respectively, the values were increased by 0.611 and 0.467. This reveals that the flow rate estimated by the HEC-HMS programme does not differ by a considerable amount from the real flow rate, and it also confirms that the HEC-HMS software is suitable for use in flow rate estimation.

The NSE number is comparable to the findings of Tassew *et al.* (2019), who conducted research on the hydrological simulations in the Gilgel Abay Catchment. The researchers achieved an NSE value of 0.884 as a result of their findings. Although the discharge for the considered period was effectively simulated, the findings demonstrated that the model is adequate for hydrological simulations in the basin of the Al-Adhaim river. The results showed that the model somewhat underestimated the discharge by a little amount (Hamdan *et al*., 2021).

5. CONCLUSION

Sungai Lebir basin was selected in this research to compare the hydrologic performances of two widely used hydrologic models the HEC-HMS and the RRI models. The HEC-HMS model developed for the Sungai Lebir basin was calibrated and validated and then compared with the earlier developed RRI model. The NSE obtained during the calibration process were -9.806 and 0.858, while 0.817 and 0.821 for validation using the HEC-HMS model. For the RRI model, the calibration results were -0.312 and 0.587, whereas 0.786 and 0.731 for validation. The HEC-HMS model was able to produce more accurate stream flow results compared to RRI model for all the period. More accurate results can be found after performing optimization process whereas the NSE value increased by 0.611 and 0.467. Overall, the performance of both models is deemed to be satisfactory.

REFERENCES

Chan, N. W. (2002). Reducing flood hazards exposure and vulnerability in Peninsular Malaysia flood. London: Taylor & Francis Publisher.

DID. Drainage and Irrigation Department. (2004). Annual flood report of DID for Peninsular Malaysia. Kuala Lumpur: Unpublished report.

DID. Flood Management Approaches Structural Measures Flood Relief Machinery and Organization. Available online: https://www.water.gov.my/index.php/pages/view/370 (accessed on 24 March 2021).

Gunathilake, M. B., Panditharathne, P., Gunathilake, A. S., & Warakagoda, N. D. (2019). Application of HEC-HMS Model on Event-Based Simulations in the Seethawaka Ganga River, Sri Lanka. Sch. J. Appl. Sci. Res, 2, 32-40.

Hamdan, A.N.A.; Almuktar, S.; Scholz, M. Rainfall-Runoff Modeling Using the HEC-HMS Model for the Al-Adhaim River Catchment, Northern Iraq. Hydrology 2021, 8, 58. https://doi. org/10.3390/hydrology8020058

Romali, N. S., & Yusop, Z. (2021). Flood damage and risk assessment for urban area in Malaysia. Hydrology Research, 52(1), 142-159.

Saimi, F. M., Hamzah, F. M., Toriman, M. E., Jaafar, O., & Tajudin, H. (2020). Trend and linearity analysis of meteorological parameters in peninsular Malaysia. Sustainability, 12(22), 9533.

Shah, S. M. H., Mustaffa, Z., & Yusof, K. W. (2017). Disasters worldwide and floods in the Malaysian region: a brief review. Indian Journal of Science and Technology, 10(2), 1-9.

Tassew BG, Belete MA, Miegel K. Application of HEC-HMS Model for Flow Simulation in the Lake Tana Basin: The Case of Gilgel Abay Catchment, Upper Blue Nile Basin, Ethiopia. Hydrology. 2019; 6(1):21. https://doi.org/10.3390/hydrology6010021

US Geological Survey Earth Resources Observation and Science Center http://earthexplorer.usgs.gov