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Simulation of Runoff in Air Putih, Terengganu Based on Hydrologic Modelling System (HEC-HMS)

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Abstract

Flooding is a serious global risk that is becoming more common in Malaysia. It has resulted in property destruction and fatalities. It is one of the tragedies of nature that hinders the development of Air Putih, Terengganu. Hence, the aims of this investigation were to develop the hydrologic model for Kemaman River Sub—basin and evaluate the runoff with make the calibration, validation and simulation by using Quantum Geographic Information System (QGIS) and Hydrologic Engineering Centre – Hydrologic Modelling System (HEC-HMS). Following the development of the hydrologic model for Air Putih, the model was calibrated and validated using the coefficient of determination, R^2, which yielded values of 0.84 and 0.72 respectively, the R^2 value is close to 1, therefore it is proved that the data is trustable. Subsequently, the model was employed to simulate the runoff by using HEC-HMS. By using the rainfall and discharge data from 2000 to 2024 prepared by National Hydrological Network Management System (SPRHiN), the results of run-off simulation process, it showed that the process is verified and reliable because the simulated flow in HEC-HMS is closely fit to the observed flow, which the R^2 is 0.81. Therefore, the implementation of HEC-HMS is effectively simulates the overall runoff pattern and provides a framework for understanding hydrological responses in Air Putih, Terengganu and the R^2 value demonstrates that the model aligns well with observed flow trends, indicating its utility for initial assessments.

1. Introduction

Floods are natural disasters that carry out major damage to ecosystems, infrastructure, and human lives when water overflows into typically dry ground. It is one of the tragedies of nature that hinders the development of a country [7]. Climate change, land use, urbanization, and human activities like deforestation and infrastructure development along watercourses are all contributing factors to shifting flood patterns [1]. In actuality, forty percent to fifty percent of all natural disasters that cause fatalities worldwide also occur due to flooding. Significant flooding occurred in Malaysia in 2010, which had a negative impact on several states, particularly the economy and society in general. With an average of 2,500 mm of precipitation per year across all states, Malaysia is among the nations with the highest precipitation levels worldwide. Over 200,000 Malaysians were impacted by the floods, and tragically, 21 people lost their lives as a result [3].

Near the end of the 20th century, there are estimates that the flood disaster killed roughly 100,000 people and impacted 1.4 billion people globally [9]. Almost 29,800 km^2 and 4.82 million people are affected by floods, which occur frequently in Malaysia and cause an average of 915 million in physical damage annually [16]. Floods impacted a larger population and cause more socioeconomic and environmental losses if a sustainable flood management plan is not in place. Furthermore, widespread land development and increased rainfall intensity tend to cause more abrupt flood events. The critical importance of timely simulates for many stakeholders generates considerable excitement in the development of operational run-off simulation services globally in order to reduce or mitigate the impacts of flooding.

Among the most destructive natural disasters are floods, which extensively harm ecosystems, infrastructure, and property. Effective flood risk management and mitigation require an understanding of the factors that contribute to flooding. A variety of natural and man-made factors, such as topography, deforestation, heavy rainfall, storm surges, rivers overflow and infrastructure problems can cause floods [17]. This examined each of these elements in-depth in order to acquire an adequate understanding of the mechanisms and causes underlying flooding. By comprehending these elements, people can create plans to lessen the likelihood of flooding, safeguard local communities and lessen the effects of flooding on both natural and human systems.

Numerous software programmes have been created to simulate run-off, and Hydrologic Engineering Center's Hydrologic Modelling System (HEC-HMS) is one of them that is frequently used by other researchers. Hydrographs (the timing and volume of flood flows) and an estimated peak flow of a river basin can be obtained by utilising HEC-HMS. The United States Army Corps of Engineers [18] states that run-off simulation, which provide estimates of the timing and extent of expected hazardous or damaging flood conditions, can support emergency operations. The United States Army Corps of Engineers states that run-off simulation, which provide estimates of the timing and extent of expected hazardous or damaging flood conditions, can support emergency operations. It is essential to flood control reservoirs' efficient operation.

Beginning in 2013, floods affected Kemaman for three years in a row. Residents in the contemporary satellite townships at Air Putih pack up their belongings and relocate to higher ground whenever the monsoon arrives. The loss of Air Putih's water catchment area due to housing development was one of the causes of the flood. The wetland at Air Putih functioned as a massive sponge, soaking up extra rain. As one of Terengganu's flood-prone areas, Air Putih was chosen as the case study for runoff simulation using HEC-HMS. This study encompassed the hydrologic modelling of the Kemaman River Sub-basin, as well as the calibration and validation of the results. The purpose was to compare the simulated flow pattern with the observed flow, as Air Putih, Terengganu was located within the Kemaman River Sub-basin. Then, the study simulated the runoff by using HEC-HMS at Air Putih, Terengganu. The aim was to analyze the overall runoff pattern and provides a framework for understanding hydrological responses in Air Putih, Terengganu.

2. Literature Review

This section discussed several runoff simulation software, including QGIS process and method that involvedthat need to be use in this study. This section also concluded with an earlier research on the use of HEC-HMS for run-off simulation.

The US Army Corps of Engineers created the HEC-HMS (Hydrologic Engineering Centre – Hydrologic Modelling System) model, which was applicable to numerous hydrological simulations [14]. Urban flooding, flood frequency, planning for flood warning systems, reservoir spillway capacity, stream restoration, and other issues can all be examined using the HEC-HMS model. There are four primary parts to the HEC-HMS. An advanced graphical user interface showing hydrologic system elements with interactive capabilities, an analytical model for determining overland flow runoff and channel routing, a system for storing and managing data, particularly large, time variable data sets, and a way to display and report model outputs. The viability of the model for this research's location and purpose must be verified, as it has not been calibrated and validated for the watersheds in Sri Lanka. Model predictability is increased by calibrating rainfall runoff models in relation to local observational data. Users are more confident in the model's reliability when the results match the observed values from the stream-flow measurement.

HEC-GeoHMS, an ArcView GIS tool was used to process the Digital Elevation Models (DEMs) of the research regions in Pakistan. This included basin processing, catchment delineation, and terrain pre-processing. With the use of observed data, the model was verified and calibrated. The suggested approach for risk reduction and flood prediction is non-structural. The core of the flood warning application is the Hydrologic Modelling System (HEC-HMS), which calculates the runoff or stage threshold conditions and offers a sufficient lead time forecast. Data from the Pakistan Meteorological Department (PMD) is inserted into a hydro-meteorological database and subsequently into the HEC-HMS for the purpose of assessing flood risk. An early warning message and a real-time flood scenario were visualised using a server-client application [12].

There are three type of software program were capable of runoff simulation which were HEC-HMS, SWAT and SVR based on their strengths and limitations [5]. All of the three software can be considered as a very good runoff simulation software. 29 Each of the software respectively good software with their own strength. After all the consideration, this study choose to use HEC-HMS because its strength appeared better that the other two software. Firstly, the ability to predict various watershed conditions and sizes. Other than that, a thorough user interface with built-in utilities. Lastly, generally performs well in simulating runoff, often surpassing other models like SWAT in specific conditions.

The runoff curve number, or simply CN, is an empirical parameter used in hydrology to forecast direct runoff or infiltration from excess rainfall. The USDA Natural Resources Conservation Service, formerly known as the Soil Conservation Service, or SCS, created the number, which is still commonly referred to as a "SCS runoff curve number" in the literature. The runoff curve number was ascertained through an empirical analysis of small catchment runoff and hill slope plots provided by the USDA. It is a well-liked and useful method for calculating how much direct runoff a rainfall event will produce at a given spot [13].

QGIS is a cross-platform, open-source geographic information system that allows users to view, edit, and analyse geospatial data. This platform is free to use and supports many different database formats and features. Its growing feature set is made possible by its necessary plugins. With this GIS application, it is possible to view data and overlay vector and raster data in different formats. Google Earth Pro is software that integrates a vast amount of satellite data into a single system, enabling users to visualise the earth and investigate a variety of geographic topics. With Google Earth Pro, users can download geospatial data in the KML format, look at the planet in high resolution, and search for specific coordinates.

3. Methodology

The methodology in research refers to the systematic and structured approach used to conduct a study, encompassing the procedures and techniques employed to analyze and interpret data. This section offers details on the study area. A flowchart analysis established in order to meet the goals of this study and finish it on time frame. Data collection also included with rainfall and stream flow data that requested from National Hydrological Network Management System (SPHRiN). Then, topography map extraction using data analysis by using Google Earth Pro and GIS database establishment for the Kemaman River Sub-basin are all included in the methodology. This section also covers the HEC-HMS model setup, model calibration, validation, and simulation techniques. HEC-HMS is a watershed models that feasible for parameter estimation on a regional scale and benefit from faster computer programmes than spreadsheet exercises [10].

3.1 Data Collection

Data collection included with satellite image for Kemaman River Sub-basin, rainfall and stream flow data from nearest station in Air Putih, Terengganu. A satellite image of the Kemaman River Sub-Basin that was obtained from Google Earth Pro, which was taken for comparison with a topography map, shows the changes in land use. Data that on rainfall gathered from Malaysia's Department of Irrigation and Drainage (DID). Data on desired rainfall and stream flow are available for the years 2000 through 2024. The Kemaman Sub-basin has a rainfall measuring station. JPS Kemaman Station was selected for rainfall data while Kemaman River at Rantau Panjang Terengganu Station was selected for stream flow data. Every day rainfall and stream flow was recorded at the station.

3.2 Establish a GIS database for Kemaman River Sub-basin

A Geographic Information System (GIS) database needs to be set up in order for the Kemaman River Sub-basin to generate spatial data about land use, rivers, contours, and other features. Quantum Geographic Information System (QGIS) as an open-source software option that integrates GIS and remote sensing data to facilitate workflow programming to earn spatially distributed modelling on a watershed scale [2]. QGIS supports processing of both vector and raster data, and Python scripting is accessible for automated modelling. The HEC-HMS models must be constructed using these spatial data. Topography maps were used to create a GIS database for the Kemaman River Sub-basin using QGIS. After being extracted, relevant layers were found to include sand, rubber, oil palm, and others. Every land use layer has a polygonal theme and is made up of polylines. These processes include, among other things, editing, merging, interpolating, and converting polylines into polygons.

3.3 Hydrological Modelling System (HEC-HMS) Model Setup

The Hydrologic Modelling System (HEC-HMS) and Geographic Information System (GIS) software from the Hydrological Engineering Centre are combined in this study to create a framework for hydrological modelling. It accomplishes this by estimating the hydrologic parameter based on the Digital Elevation Model and using Quantum Geographic InforQGIS to generate the input of the HEC-HMS parameter. Users are more confident in the model's reliability when the results match the observed values from the stream-flow measurement [11]. It is expected that these advancements provide a more precise and efficient substitute for the methods currently used to study watersheds. Creating a watershed data structure on the GIS platform that can be imported straight into HEC-HMS is the main purpose of QGIS. The model was set up in QGIS, and then the layout was transferred to the

HEC-HMS model. Files for background maps, lumped basin schematic models, distributed basin schematic models, and grid-cell parameter files [8].

The sub-basin functions as a model for the actual watershed. The preparation of make up the sub-basin element involves 3 methods. First, the Loss Method employed was SCS Curve Number Loss. The curve number approach is used in the Soil Conservation Service Curve Number method to compute incremental losses. Three parameters are needed for the SCS CN method: the percentage of impervious area, the curve number, and the initial abstraction. The bare minimum of precipitation necessary for surface excess to occur is referred to as the initial abstraction.

$$CNw = \frac{Percentage\ Area\ (\%)}{Total\ Percentage\ Area\ (\%)} \times CN\ Value \tag{1}$$

The curve number (CN) can determine by using hydrologic soil group and ground cover. There was an example of Sub-basin 1 calculation from Air Putih study area. The Curve Number includes the collective soil group and land use combinations within the sub-basin and allows for the specification of the percentage of the sub-basin that is directly connected to impervious areas.

Table 1: Example *Curve Number calculation for sub-basin 1*

Land Use	Area (km^2)	Percentage Area (%)	CN Value	Weightage CN Value (CNw)
Development area	3.56	10.46	85	8.891
Water Bodies	1.19	3.49	100	3.490
Oil Palm	3.23	9.49	87	8.300
Bare Land	1.09	3.2	79	2.500
Forest Land	24.98	73.36	60	44.02
Total	34.05	100		67.2

Second, a Transform Method for the SCS Unit hydrograph cause QGIS produced the necessary input data for HEC-HMS, namely the lag time. Based on empirical data collected from a small agricultural watershed, the SCS UH method was developed. Dimensionless hydrographs were created by generalizing the data, and a highly accurate hydrograph was produced for widespread use. The general hydrograph is produced by scaling the hydrograph by the time lag. The time interval between the centroid of the precipitation mass and the peak flow of the resulting hydrograph is referred to as the standard lag.

$$T_c = \frac{l^{0.8}(S+1)^{0.7}}{1140Y^{0.5}} \tag{2}$$

Table 2: *Time of Concentration data for Air Putih*

Sub-Basin	L (km)	Y	L (ft)	Y (%)	S	Tc	Lag(hr)	Lag(min)
Sub-Basin 1	14.47705	0.10454	47496.88	10.454	4.8810	5.169	3.1014	186.084
Sub-Basin 2	17.85299	0.05141	58572.80	5.141	4.5921	8.415	5.0490	302.940
Sub-Basin 3	15.93145	0.06494	52268.54	6.494	3.9353	6.263	3.7578	225.468

Third, Base flow method was modelled in this study using recession modelling. The recession base flow approach is specifically meant to pinpoint the distinctive pattern that emerges in watersheds after an event causes channel flow to drop exponentially. There are two approaches that can be used. The initial discharge and initial discharge per area must be provided in order to define the initial condition. Estimating the initial flow is better done using the initial discharge method. The recession constant measures how quickly base flow falls following storm occurrences. The base flow recorded one day ago is divided by the base flow at this moment to compute it.

In the basin model, the water flow is transmitted via the reach. One or more upstream components is the source of the inflow into the reach. Because it uses both mass conservation and diffusion representation to modify momentum conservation, the Muskingum-Cunge Routing Method was selected for this model. The overall reach should be in line with the length. Over the whole reach, the element's average slope should be present. The mean value for the entire reach should be used to compute the Manning's roughness coefficient.

3.4 Data Calibration, Validation and Simulation

The process of figuring out the characteristics or parameters that define a system is called calibration. Initial abstraction, curve number, imperviousness, lag time, initial discharge, recession constant, and ratio are among the parameters that are calibrated and then tweaked until the simulated and observed hydrographs are nearly exactly fitted. Calibration process used 8 December 2022 until 21 December 2022 for rainfall and stream flow data. Topographic maps and the QGIS procedure can be used to determine various river parameters, including its length, shape, slope, and Manning's n. Every process event makes use of a different basin model (each basin model has a unique set of parameters) [18].

The validation process involves using different sets of data to test the model's applicability. During the validation process, the model parameters that were employed during the calibration process are kept. Then, validation process used 15 November 2023 until 28 November 2023 for rainfall and stream flow data. The degree of agreement between the simulated and observed hydrographs will be shown through comparisons. If the validation result is not successful, the calibration process will be carried out again. There is some iterative trial and error involved in both the calibration and validation processes. The coefficient of determination (R^2) value is used to assess the accuracy of the hydrologic model. A closer R^2 value to 1 indicates a more accurate model; conversely, a closer R^2 value to 0 indicates a less accurate model.

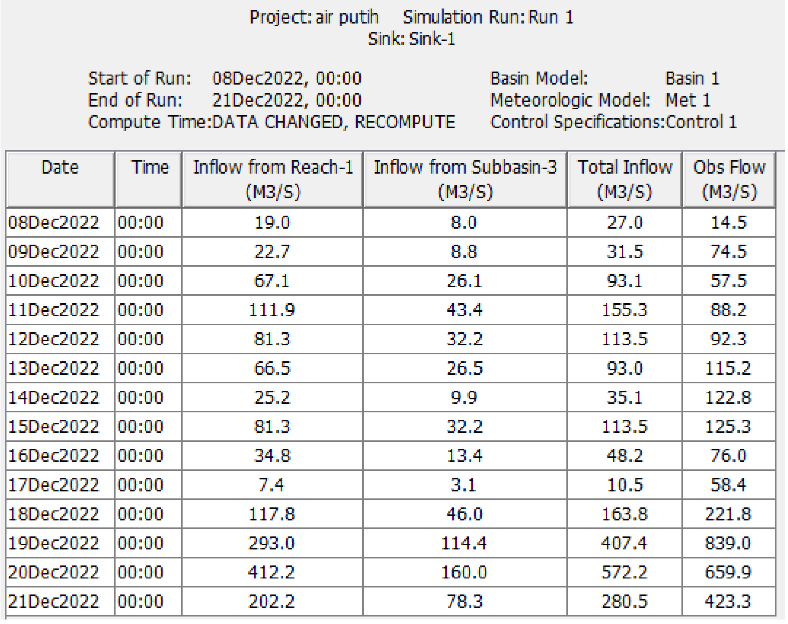
Runoff simulation refers to the process of modeling how rainfall is converted into surface runoff in a watershed or drainage basin These simulations have the ability to reproduce historical water surface elevations and generate hypothetical scenarios for flood zoning maps [6]. This involves creating mathematical by using 5 December 2019 until 18 December 2019 for rainfall and stream flow data. Runoff simulation is crucial for understanding and predicting water flow patterns, which aids in flood management, water resource planning, and environmental assessments.

4. Result and Discussion

Results of the calibration and validation have been laid out and discussed in this section. Additionally, runoff simulation's result also have been clarified by using rainfall data anticipated by National Hydrological Network Management System (SPRHiN).

4.1 Result of calibration and validation process

The data of the calibration and validation process to Air Putih, Terengganu is showed in Fig. 1 and Fig. 3. The graphs of the total in flow and observe flow for calibration and validation process are showed in Fig. 2 and Fig. 4 respectively. The results of R^2 for each sub-basins for the calibration and validation process showed in Table 4 and Table 5.



Project: air putih Simulation Run: Run 1
Sink: Sink-1

Start of Run: 08Dec2022, 00:00
End of Run: 21Dec2022, 00:00
Compute Time: DATA CHANGED, RECOMPUTE

Basin Model: Basin 1
Meteorologic Model: Met 1
Control Specifications: Control 1

Date	Time	Inflow from Reach-1 (M3/S)	Inflow from Subbasin-3 (M3/S)	Total Inflow (M3/S)	Obs Flow (M3/S)
08Dec2022	00:00	19.0	8.0	27.0	14.5
09Dec2022	00:00	22.7	8.8	31.5	74.5
10Dec2022	00:00	67.1	26.1	93.1	57.5
11Dec2022	00:00	111.9	43.4	155.3	88.2
12Dec2022	00:00	81.3	32.2	113.5	92.3
13Dec2022	00:00	66.5	26.5	93.0	115.2
14Dec2022	00:00	25.2	9.9	35.1	122.8
15Dec2022	00:00	81.3	32.2	113.5	125.3
16Dec2022	00:00	34.8	13.4	48.2	76.0
17Dec2022	00:00	7.4	3.1	10.5	58.4
18Dec2022	00:00	117.8	46.0	163.8	221.8
19Dec2022	00:00	293.0	114.4	407.4	839.0
20Dec2022	00:00	412.2	160.0	572.2	659.9
21Dec2022	00:00	202.2	78.3	280.5	423.3

Fig. 1: Calibration data of Sink 1 from 8 December until 21 December 2022

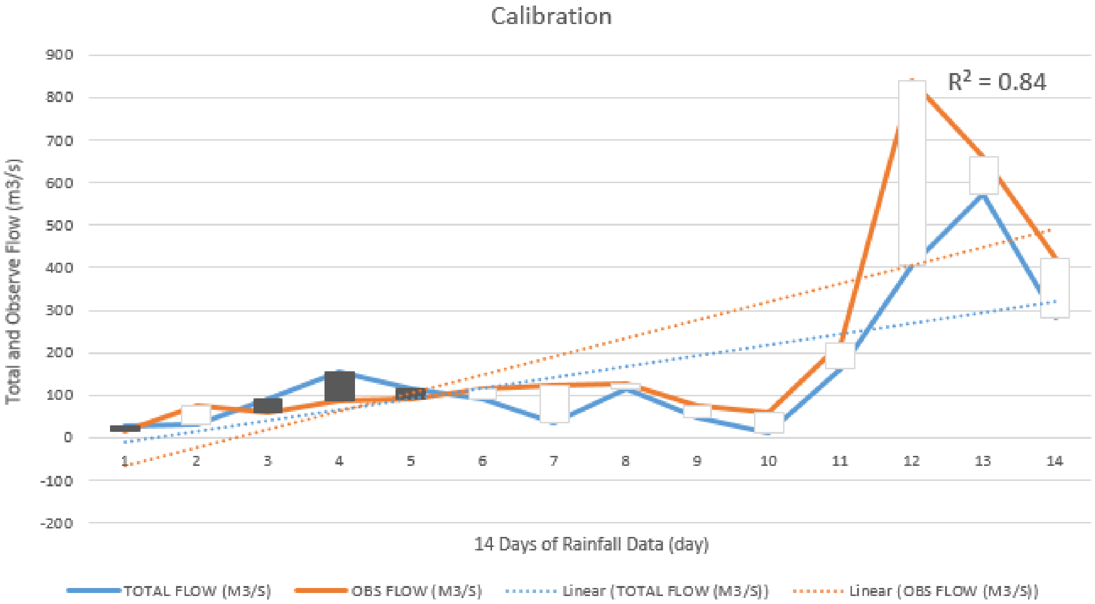
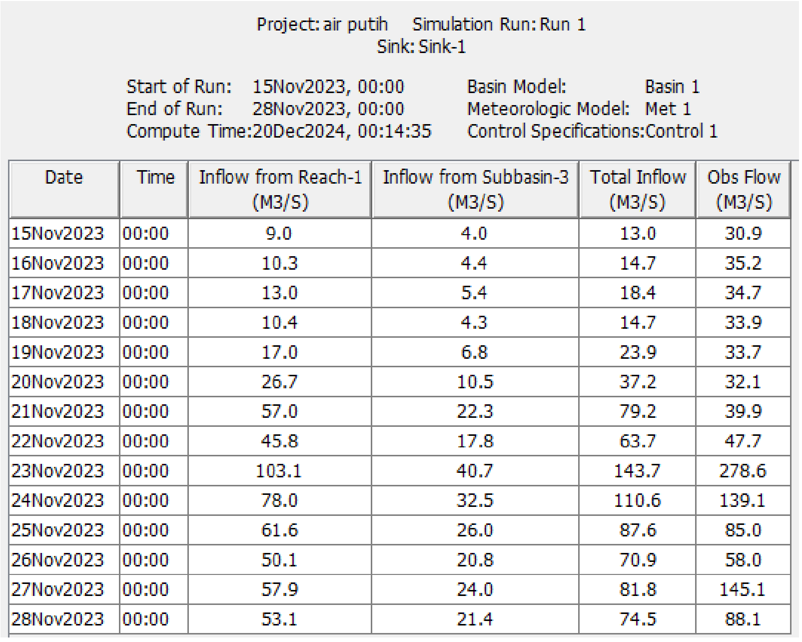


Fig. 2: Total and Observe Flow (m^3/s) against 14 Days of Rainfall (day) for calibration

Table 4: Result of coefficient determination for calibration process

Computation Point	RMSE Stdev	Coefficient determination (R^2)
Subbasin-2	1.0	0.84
Subbasin-1	1.1	0.84
Subbasin-3	1.1	0.84

Based on the results of calibration process, it showed that the process is verified and reliable because the simulated flow in HEC-HMS is closely fit to the observed flow. Besides, the R^2 value is close to 1, therefore it is proved that the data is trustable and can be used for run-off simulation.



Project: air putih Simulation Run: Run 1
Sink: Sink-1

Start of Run: 15Nov2023, 00:00
End of Run: 28Nov2023, 00:00
Compute Time: 20Dec2024, 00:14:35

Basin Model: Basin 1
Meteorologic Model: Met 1
Control Specifications: Control 1

Date	Time	Inflow from Reach-1 (M3/S)	Inflow from Subbasin-3 (M3/S)	Total Inflow (M3/S)	Obs Flow (M3/S)
15Nov2023	00:00	9.0	4.0	13.0	30.9
16Nov2023	00:00	10.3	4.4	14.7	35.2
17Nov2023	00:00	13.0	5.4	18.4	34.7
18Nov2023	00:00	10.4	4.3	14.7	33.9
19Nov2023	00:00	17.0	6.8	23.9	33.7
20Nov2023	00:00	26.7	10.5	37.2	32.1
21Nov2023	00:00	57.0	22.3	79.2	39.9
22Nov2023	00:00	45.8	17.8	63.7	47.7
23Nov2023	00:00	103.1	40.7	143.7	278.6
24Nov2023	00:00	78.0	32.5	110.6	139.1
25Nov2023	00:00	61.6	26.0	87.6	85.0
26Nov2023	00:00	50.1	20.8	70.9	58.0
27Nov2023	00:00	57.9	24.0	81.8	145.1
28Nov2023	00:00	53.1	21.4	74.5	88.1

Fig. 3: Validation data of Sink 1 from 15 November until 28 November 2023

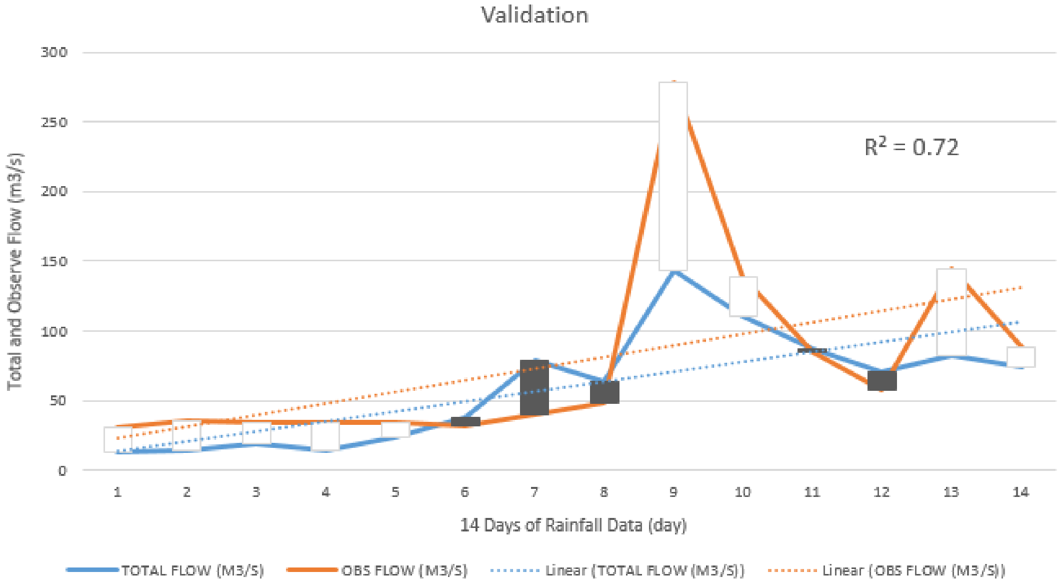


Fig. 4: Total and Observe Flow (m^3/s) against 14 Days of Rainfall (day) for validation

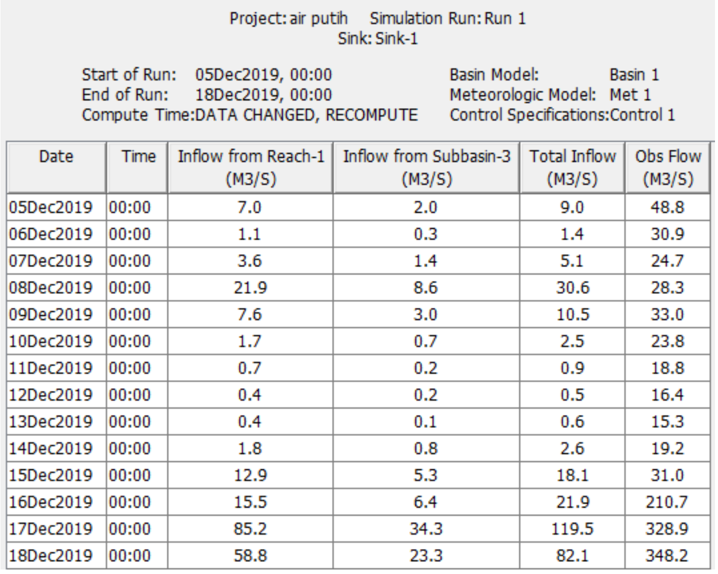
Table 5: Result of coefficient determination for validation process

Computation Point	RMSE Stdev	Coefficient determination (R^2)
Subbasin-2	1.1	0.73
Subbasin-1	1.2	0.71
Subbasin-3	1.1	0.72

Based on the results of validation process, it showed that the process is verified and reliable because the simulated flow in HEC-HMS is closely fit to the observed flow. Besides, the R^2 value is close to 1, therefore it is proved that the data is trustable and can be used for run-off simulation.

4.2 Result of runoff simulation process

The data of the run-off simulation process to Kemaman Sub-basin (outlet) is showed in Fig. 5. The graphs of the total inflow and observe flow for runoff simulation process are showed in Fig. 6 respectively. The results of R² for each sub-basins for the run-off simulation process showed in Table 6.



Project: air putih Simulation Run: Run 1
Sink: Sink-1

Start of Run: 05Dec2019, 00:00
End of Run: 18Dec2019, 00:00
Compute Time: DATA CHANGED, RECOMPUTE

Basin Model: Basin 1
Meteorologic Model: Met 1
Control Specifications: Control 1

Date	Time	Inflow from Reach-1 (M3/S)	Inflow from Subbasin-3 (M3/S)	Total Inflow (M3/S)	Obs Flow (M3/S)
05Dec2019	00:00	7.0	2.0	9.0	48.8
06Dec2019	00:00	1.1	0.3	1.4	30.9
07Dec2019	00:00	3.6	1.4	5.1	24.7
08Dec2019	00:00	21.9	8.6	30.6	28.3
09Dec2019	00:00	7.6	3.0	10.5	33.0
10Dec2019	00:00	1.7	0.7	2.5	23.8
11Dec2019	00:00	0.7	0.2	0.9	18.8
12Dec2019	00:00	0.4	0.2	0.5	16.4
13Dec2019	00:00	0.4	0.1	0.6	15.3
14Dec2019	00:00	1.8	0.8	2.6	19.2
15Dec2019	00:00	12.9	5.3	18.1	31.0
16Dec2019	00:00	15.5	6.4	21.9	210.7
17Dec2019	00:00	85.2	34.3	119.5	328.9
18Dec2019	00:00	58.8	23.3	82.1	348.2

Fig. 5: Simulation data of Sink 1 from 5 December until 18 December 2019

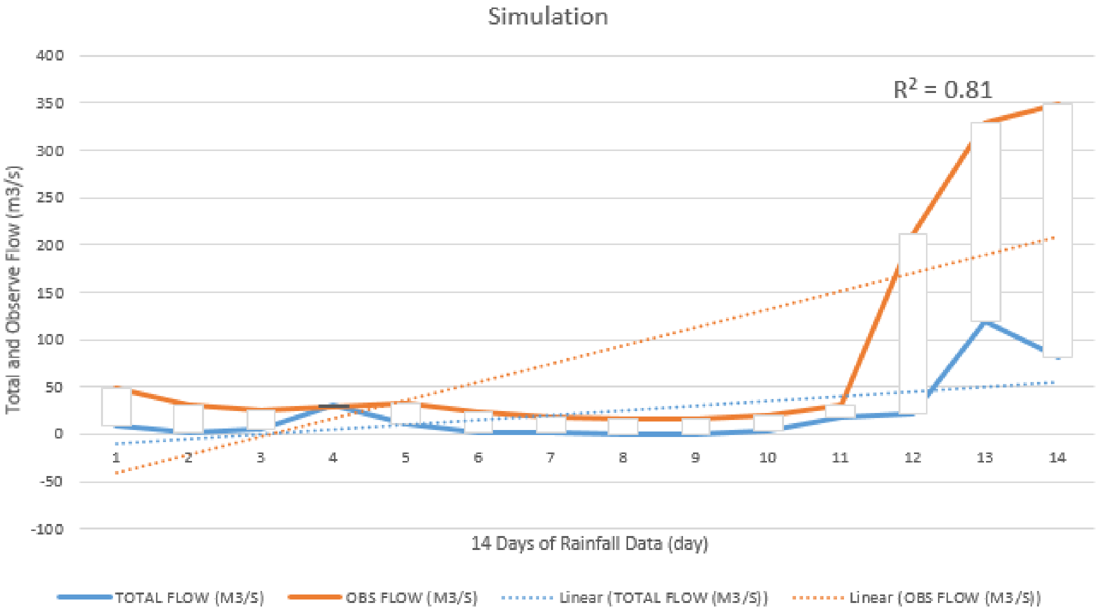


Fig. 6: Total and Observe Flow (m³/s) against 14 Days of Rainfall (day) for runoff simulation

Table 6: Result of coefficient determination for runoff simulation process

Computation Point	RMSE Stdev	Coefficient determination (R²)
Subbasin-2	1.1	0.81
Subbasin-1	1.2	0.81
Subbasin-3	1.1	0.81

Follow by the graph displays the simulation results comparing total inflow (simulated by HEC-HMS) and observed flow over time, along with their respective linear trend lines. The observed flow (orange line) shows significantly higher peak values compared to the total inflow (blue line) simulated by the model, particularly at day 13, where the observed flow sharply rises to approximately 348.2 m^3/s, while the simulated total inflow reaches a much lower value. The R^2 value of 0.81, have been lay out in the graph, indicates a reasonably good correlation between the observed and simulated data trends. The linear trend lines for both datasets illustrate the overall flow pattern over time, with the observed flow exhibiting a steeper slope compared to the simulated inflow.

Therefore, the implementation of HEC-HMS is effectively simulates the overall runoff pattern and provides a framework for understanding hydrological responses in Air Putih, Terengganu and the R^2 value demonstrates that the model aligns well with observed flow trends, indicating its utility for initial assessments.

5. Conclusion

In conclusion, the flood is one of Malaysia's most destructive natural disasters, and it has long impacted the community of Air Putih. In addition the cause of rapid and intense flooding in a short amount of time, heavy rainfall cause flash floods, which are most common in steep terrain and urban areas with high runoff [7]. At the moment, the impact of flooding has risen due to land use changes and climate change. Consequently, runoff simulations with HEC-HMS software would be one of the options. The hydrologic model of Air Putih has been effectively created in this study. The study successfully established a framework for simulating runoff processes, as evidenced by an R^2 value of 0.81, indicating a reasonable correlation between observed and simulated data. Calibration ensures the model accurately represents local conditions, while validation confirms its reliability for future applications. Based on this information, the relevant organisations in charge of flood control in Terengganu, particularly in Air Putih, may create a proactive plan for the future of Air Putih to mitigate the possibility of floods that might have an impact on the local populations.

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