Application of HEC-GeoHMS and HEC-HMS as Rainfall–Runoff Model for Flood Simulation

Salwa Ramly and Wardah Tahir

Abstract Flood modeling and simulation assist in the prediction of the hazard for better flood preparedness and thus reduce flood damages. The study had simulated flood occurrence at the upper Klang–Ampang River Basin which is a flood-prone area near the capital city of Malaysia. Digital elevation model (DEM) for this area was processed in the ArcGIS 10.2 environment using terrain preprocessing tools to delineate the basin, sub-basin, and stream network. Results from the terrain preprocessing were used in the HEC-GeoHMS to extract the hydrologic parameters of the river basin. These hydrologic parameters were used in the estimation of streamflow runoff in HEC-HMS. The study had produced an illustrative and comprehensive representation of the sub-basin with reasonable accuracy indicated by the Nash–Sutcliffe coefficient of 0.86.

Keywords Rainfall–runoff model · HEC-GeoHMS · HEC-HMS

1 Introduction

Flooding is a natural phenomenon caused by various factors. Flooding also varies in terms of size of the affected area, flood duration, and depth of flood. Flooding happens when the normally dry areas have been inundated with water. Among the factors that could cause flood are excessively heavy and prolonged rainfall, urbanization, river erosion, deforestation, and poor drainage systems. Therefore, analysis on flood event is important to understand the response of the catchment to the heavy rainfall and the change of the land use. Nowadays, with the advance of the geographic information system (GIS), analysis of the flood using rainfall–runoff model has been enhanced to get better simulation and result.

Application of GIS in rainfall–runoff model is widely used to estimate the catchment characteristics based on the digital elevation data. Digital elevation

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model (DEM) is a digital model with 3D view representing the terrain of surface catchment or area. DEM is in raster format, and each pixel value of the raster data represents an elevation of the point. There are many techniques to produce the DEM data, and it depends on the resolution needed for the study. Remote sensing is the most common technique used for data collection of digital terrain model (DTM) before its conversion to DEM. However, DEM can also be generated from land surveying techniques or topographic map using GIS program. Most common GIS program is ArcGIS from ESRI. ArcGIS could convert vector data from terrain line in topographic map and produce the DEM as a raster format file. This DEM could be used to determine the catchment characteristics such as streamline and drainage network and delineate the basin and sub-basin [1]. This information could be used as hydrologic parameter value for rainfall–runoff modeling. DEM also has been widely used for flood and drainage modeling, land use studies, and other applications [2–4].

Rainfall–runoff model describes the relationship between rainfall and runoff of a catchment area. The model will estimate the surface runoff in the channel or river system as a response to rainfall input data for the target catchment. There are numerous rainfall–runoff model software programs available, and each has its own advantages and disadvantages. One of the widely used rainfall–runoff model software programs is the HEC Hydrologic Modelling System (HEC-HMS).

The HEC-HMS mathematical model is designed to simulate the complete hydrologic processes of dendritic catchment [5]. The model will simulate rainfall–runoff and routing processes in natural or controlled watershed. It shall predict flow, stage, and timing for giving rainfall input into the basin. Hydrographs from the program are useful for water resources studies such as for flood forecasting, water availability, urban drainage design, or reservoir design. Combination between HEC-HMS and GIS, impact of the land use change in the catchment could be analyzed based on the increment of the stream flow in the river system.

Application of HEC-HMS in the rainfall–runoff model has been used in various objectives of the study. One important objective of the study using HEC-HMS is for flood forecasting. [6] conducted a study on regional-scale flood modeling using radar, GIS, and HEC-HMS/HRAS for the San Antonio River Basin, USA. The study found that the model has the capability to perform hydrologic studies on a regional scale for a large watershed. The other study by Oleyiblo [7] also conducted a study on flood forecasting by using HEC-HMS in Misai an Wan'an catchments in China. From the study, the model predicted peak discharge accurately and the author concluded the HEC-HMS is suitable for flood forecasting at the studied catchments. Besides flood forecasting purposes, HEC-HMS is also suitable to be used in the analysis of the land use change. A study was conducted by Ali et al. [8] on the impacts of land use change on surface runoff of Lai Nullah Basin in Islamabad, Pakistan, using HEC-HMS and GIS data. The simulation of the model shows the effects of land use for future development and suggested the future planning for this catchment should take into account the water management and planning. As a program for rainfall–runoff model, many researchers used

HEC-HMS for streamflow analysis. Other studies by [9–13] used HEC-HMS for streamflow analysis with different approaches based on their research objectives.

The main objective of this work is to develop a framework for rainfall–runoff model by using HEC-HMS program and utilize a GIS input in HEC-GeoHMS to extract the hydrologic parameters at upper Klang–Ampang catchment.

2 Background

2.1 Study Site and Data

Klang River Basin is an important basin in Malaysia located at Kuala Lumpur, the capital and the largest city in Malaysia. This river basin is placed between 101°30′ and 101°55′ E longitudes and 3–3°30′ N latitude. Klang River Basin is highly dense with 1.7 million populations. The main rivers in Klang River Basin are Sungai Klang, Sungai Ampang, and Sungai Gombak. The area of interest of the study is the upper Klang River Basin, which consists of Sungai Klang and Sungai Ampang. Total catchment for this study area is 159.7 km^2. The altitude ranges from 1430 masl at the upper part of the catchment and low-lying area in the downstream of the river near the city center. Mean annual rainfall for the upper part of Klang catchment is 2600 mm. Figure 1 shows the upper Klang–Ampang catchment with the topographic map of Kuala Lumpur.

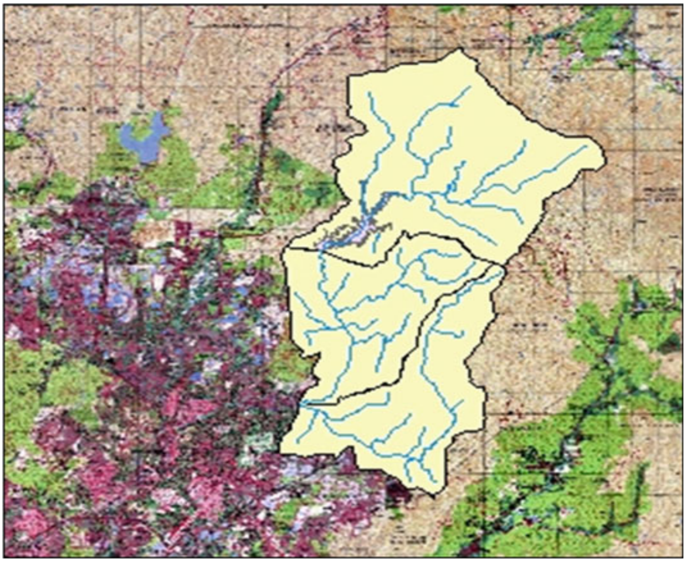

Fig. 1 Study area: Upper Klang–Ampang river basin

There is a dam located at the upstream of the Klang River approximately 10 km from the confluence of Klang–Ampang River. This dam is situated in the forest as its watershed. The concrete arch dam with a spillway in the center is used for water supply purposes and also as flood mitigation for Klang Valley. Downstream areas of the dam are rapidly developing for residential and commercial purposes. The upper Klang–Ampang catchment is selected since it is prone to flood and a large part of the catchment at low-lying area has been well developed with residential and commercial properties.

Land use, soil, rainfall, and streamflow data were obtained from the Department of Irrigation and Drainage (DID). In order to use HEC-GeoHMS, DEM is needed to delineate the watershed. These DEM data were derived from 20-m contour line map produced by JUPEM using ArcGIS program.

2.2 HEC-GeoHMS

HEC-GeoHMS is an extension for ArcGIS (ESRI) released by the US Army Corps of Engineers, Hydrologic Engineering Center (HEC). It is a geospatial hydrology toolkit which allows user to create basin parameters based on topographic data for the use of hydrologic model [14]. Overview of GIS and HEC-HMS is shown in Fig. 2. HEC-GeoHMS is used to derive a river network of basin from the DEM data. It also can delineate basin and sub-basin of the watershed. HEC-GeoHMS creates the drainage network by analyzing the digital terrain data and transforming the drainage paths and watershed boundaries into a hydrologic data structure to represent the drainage network.

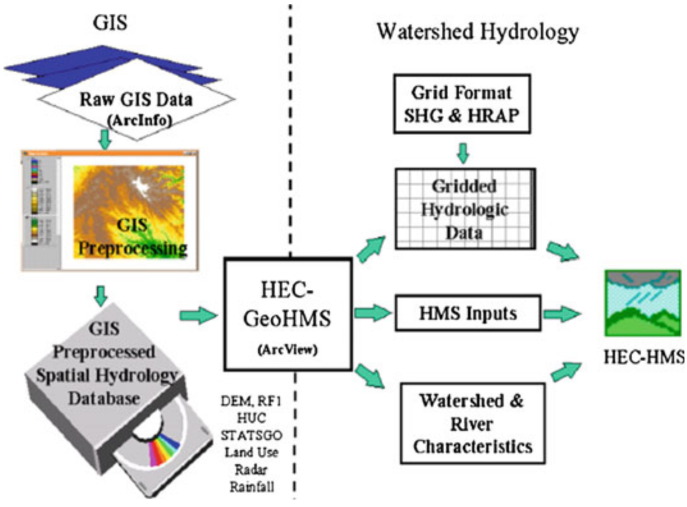

Fig. 2 Overview of GIS and hydrology program [14]

2.3 HEC-HMS

The HEC Hydrologic Modelling System (HEC-HMS) is a hydrologic model designed to simulate hydrologic processes of the dendritic watershed systems [15]. This mathematical model will simulate precipitation–runoff and routing processes in natural or controlled watershed. The spatial data from HEC-GeoHMS could be imported to the HEC-HMS, and the model shall predict flow, stage, and timing for the basin based on the given meteorological dataset and land use information. HEC-HMS uses various hydrologic analysis procedures for continuous or event-based analysis for hydrologic analysis. There are three main components in the HEC-HMS model: basin model, meteorological model, and control specification. The basin model consists of the elements of the basin and sub-basin, the connectivity, and runoff parameter. The meteorological model contains the rainfall and evaporation data, while control specifications consist of the start/stop timing and calculation intervals for run.

3 Methodology

The use of GIS in rainfall–runoff model is useful because it facilitates the development of the basin model. HEC-GeoHMS is integrated with ArcGIS software. It uses ArcGIS and the spatial analyst extension to develop hydrologic parameters as input data for HEC-HMS. The spatial analyst extension will process the terrain based on DEM and stream data. This process is called terrain preprocessing, where the stream network and watershed are created.

3.1 Terrain Preprocessing

Delineation of the catchment and stream network could be done with terrain preprocessing tools. It is one of the many useful tools in the ArcGIS application. There are 10 steps in terrain preprocessing as shown in Fig. 2 to generate the drainage or river network and watershed and sub-basin boundaries. Terrain preprocessing results consist of raster and vector data. These data will be the input for HEC-GeoHMS project setup. Terrain preprocessing also could be done by using Arc-Hydro tools. Reference [14] gives detailed description of the terrain preprocessing steps to create the stream network and delineation of the catchment (Fig. 3).

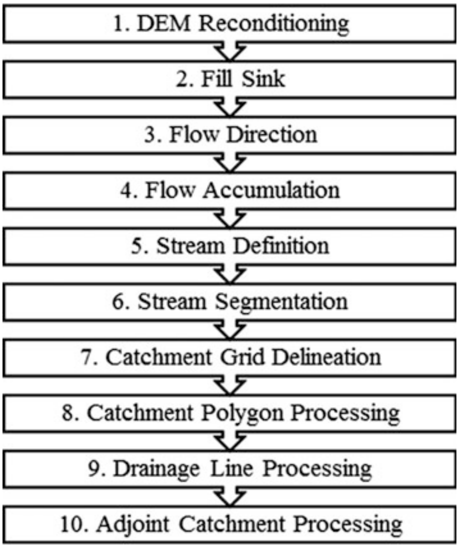

Fig. 3 Steps for terrain preprocessing

3.2 HEC-GeoHMS

HEC-GeoHMS computes dataset from terrain preprocessing to produce the hydrologic parameters. Hydrologic parameters that could be computed are river length, river slope, basin centroid, longest flow path, and centroid flow path. There are three main steps in HEC-GeoHMS to calculate the hydrologic parameters in the basin (Fig. 4).

Results or datasets in raster and vector formats from terrain preprocessing were used in the HEC-GeoHMS project setup. Raster data are raw DEM, filled DEM, flow direction grid, flow accumulation grid, stream network, stream link grid, catchment grid, and slope grid, while vector data are catchment, drainage line, and adjoint catchment. Once defined the project for HEC-GeoHMS, a new data frame is created and all the terrain preprocessing data were extracted and imported to a new project.

After the new project had been created, the basin processing menu was used to revise or customize the sub-basin delineation, dividing sub-basins, and merging streams. The outlet point of the target study area was defined with located batch

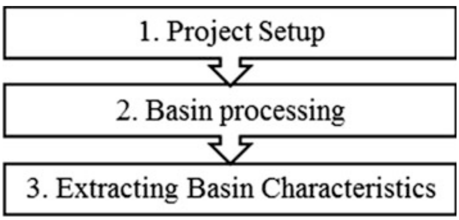

Fig. 4 Steps for HEC-GeoHMS

point at the basin. Then, the program defined and generated a new basin based on the defined outlet point.

Extracting the basin characteristics was done using the tools provided. Physical characteristics are extracted river length, river slope, basin slope, longest flow path, basin centroid, centroid elevation, and centroid flow path. These physical characteristics of sub-basins and rivers were used to estimate hydrologic parameters of the basin.

3.3 HEC-HMS

HEC-HMS is designed to simulate the complete hydrologic processes of the watershed. In order to simulate the hydrologic processes, the program needs data on hydrologic parameters of the basin as input data. Hydrologic parameters from the HEC-GeoHMS are essential to be used in this program.

HEC-HMS uses hydrologic parameters from HEC-GeoHMS to develop the rainfall–runoff model. To set up a hydrologic model using this program, there are three main components/models need to be created: basin model, meteorological model, and control specification. Sub-basin and stream data which were derived from HEC-GeoHMS were imported to the basin model as a background map.

In the basin model, elements of the basin such as sub-basins, reaches, junctions, and reservoir were created. This model has three sub-basins, and schematic diagram of the basin model is shown in Fig. 5. SCS curve number was selected as loss method, while transform method used was SCS unit hydrograph.

SCS curve number (CN) estimates precipitation excess as a function of cumulative precipitation, soil cover, land use, and antecedent moisture. Precipitation excess could be calculated by using Eq. (1).

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \tag{1}$$

P_e accumulated precipitation excess at time t;
P accumulated rainfall depth at time t;
I_a the initial abstraction (initial loss);
S potential maximum retention.

Potential maximum retention, S, is a measurement of the ability of a catchment to abstract and store storm precipitation. There will be no precipitation excess until the accumulated rainfall exceeds the initial abstraction.

According to Ref. [5], the SCS developed a relationship of I_a and S as in Eq. (2):

$$I_a = 0.2S \tag{2}$$

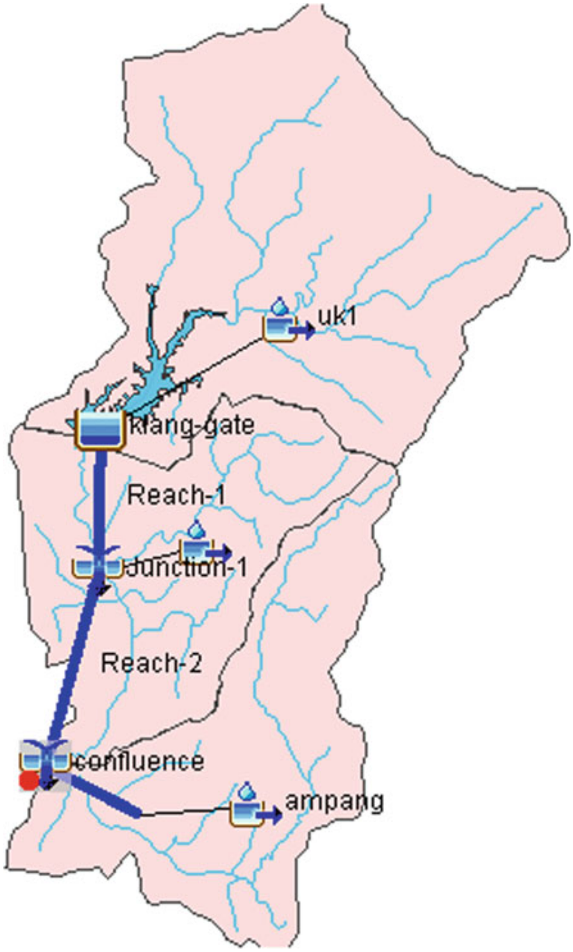

Fig. 5 Schematic of HEC-HMS model for upper Klang–Ampang catchment

The cumulative excess at time t could be calculated with the Eq. (3):

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (3)$$

The difference between the accumulated excess at the end of and the beginning of the period called as incremental excess for a time interval. The maximum retention, S, and watershed characteristics are related through an intermediate parameter, called as curve number (CN). The relationship between S and CN is shown in Eq. (4):

$$S = \frac{25{,}400 - 254\mathrm{CN}}{\mathrm{CN}} \quad (4)$$

CN values range are 100–30 where value for 100 for water bodies and 30 for permeable soils with high infiltration rates. CV values could be estimated based on appendix A, CN Table in [5] which it was reproduced from the SCS report, Urban hydrology for small watersheds.

Meteorological model was created using observed rainfall and discharge data. The observed historical data of three precipitation stations representing each sub-catchment, and one stream discharge gauge station at the confluence of Klang River and Ampang River was used for model calibration and verification. Five-minute time step was used for the simulation based on the time interval of the available observed data. Observed rainfall and discharge data were added in the time series data manager component as precipitation gage and discharge gage. The meteorological model was set as specified hyetograph method. The control specifications were used to set the time step for the simulation, starting and ending for date and time. Basin model, meteorological model, and control specification were combined before running the program.

4 Results and Discussion

4.1 Terrain Preprocessing and HEC-GeoHMS

Catchment of the upper Klang–Ampang River Basin was delineated by using terrain preprocessing tools in ArcGIS program. The results of each step in the terrain preprocessing are shown in Fig. 6. Output data from terrain preprocessing were used in HEC-GeoHMS for project setup. From the HEC-GeoHMS results, sub-basin areas were extracted and the data are shown in Table 1. These data were used to set up the rainfall–runoff model in HEC-HMS.

4.2 Rainfall–Runoff Model with HEC-HMS

For this study, sub-basins generated in HEC-GeoHMS were combined or merged to make 3 sub-basins: UK1, UK2, and Ampang. The purpose of this combination is to simplify the rainfall–runoff model setup for the beginning of the analysis on the streamflow at the confluence of Klang–Ampang River.

Analysis of the streamflow at the confluence of Klang–Ampang River was done for selected event on May 3, 2011. The model was calibrated and validated with the observed discharge data at the confluence of upper Klang–Ampang catchment. Figure 7 shows the result of simulation run for an event on May 3, 2011. Simulation

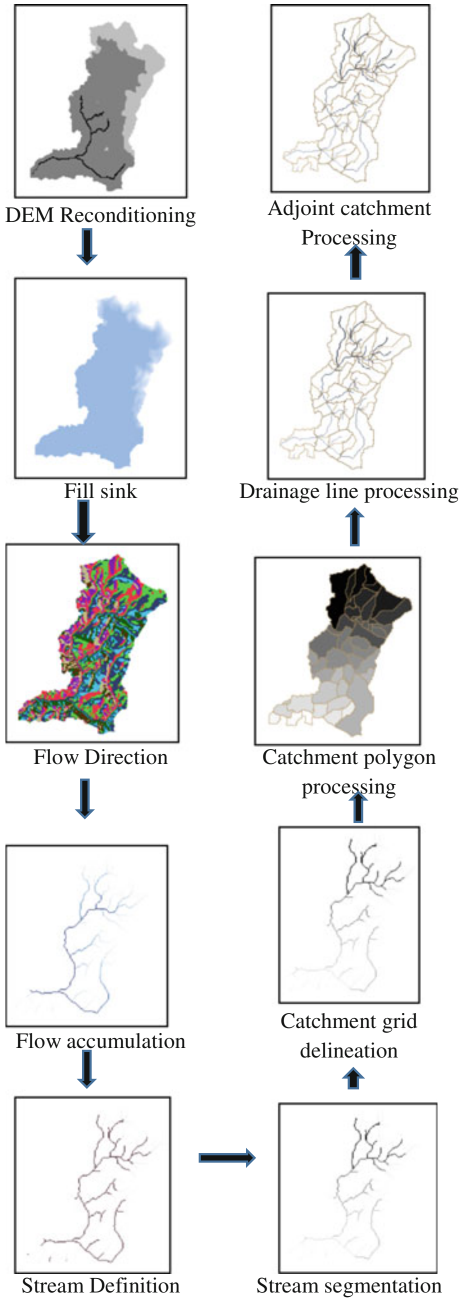

Fig. 6 Terrain preprocessing results for each step

Table 1 Catchment parameter

Sub-basin area	Km^2
UK1	76.94
UK2	41.14
Ampang	41.64
Total	159.72

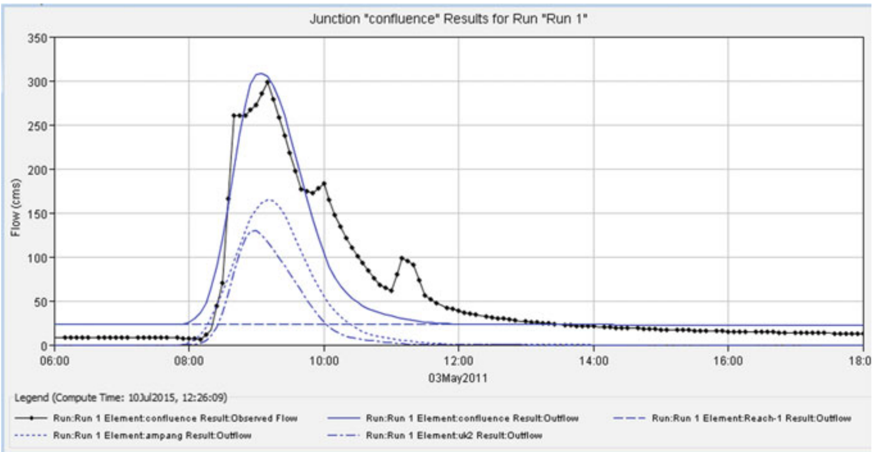

Fig. 7 Simulation result for event May 3, 2011

discharge of 308.7 m^3/s was compared with the observed discharge 298.8 m^3/s. The Nash–Sutcliffe coefficient for this simulation was 0.86, mean absolute error 17.9 m^3/s, and RMS error 25.3 m^3/s. Percentage error between simulation and observed discharge is 3.2 %. This result shows the model gives good simulation on event-based rainfall–runoff analysis study. However, further calibration and verification for other events should be done to this model.

5 Conclusion

This paper presents a methodology and development of rainfall–runoff model by using HEC-HMS program integrated with DEM data as an input for basin model. This model will have the capabilities to perform the hydrologic studies with different objectives and may expand to be a flood forecasting model by providing the further advanced computation in HEC-HMS. As conclusion, HEC-HMS is a useful program and compatible with other programs such as ArcGIS program for rainfall–runoff modeling.

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