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Flood Mitigation for Sungai Pinji, Ulu Kinta, Perak Using HEC-HMS and HEC-RAS Model

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ABSTRACT

This paper presents a simulation of flood in Sungai Pinji, Ulu Kinta, Perak using hydrologic and hydraulic model. The study utilizes two software from Hydrologic Engineering Centre: Hydrologic Modelling System (HEC-HMS) and the River Analysis System (HEC-RAS). The HEC-HMS program was used for hydrologic modelling, which involves determining rainfall-runoff relationships based on watershed characteristics, while the HEC-RAS program was used for hydraulic modelling, which involves the modelling of water level and velocity of the river. HEC-HMS was used to produce the design hydrograph, which serves as a boundary condition for the HEC-RAS hydraulic model. Two-dimensional (2D) unsteady flow was modelled using HEC-RAS, and detention pond approach was employed as the flood mitigation strategy in the simulation. In order to evaluate the accuracy and reliability of the pond approach as a flood mitigation measure, parametric study was carried out, and the obtained results were compared against the existing conditions. Overall, the computed results show that the mitigation approach is a better solution compared to the existing conditions.

1. Introduction

In recent years, climate change contributes to global warming and affects life on earth. The consequences of climate change and global warming are now in the form of high temperatures and weather patterns that are unpredictable [2,8]. Droughts and extreme flooding can be triggered by weather instability. In most cases, improper land use planning and inadequate soil management practices can adversely affect the amount and quality of surface runoff by decreasing the covering of the soil, resulting in less water absorption and consequently increasing the amount of surface runoff.

As the amount of surface runoff increases, the severity of flooding event also increases. Floods occur when a large volume of water exceeds the carrying capacity of a river, resulting in overflow and inundation of nearby land. Floods are one of the deadliest natural disasters on the planet, with the highest projected death tolls as compared to other natural disasters. Flood is a global threat, with East Asia and South Asia being significantly affected every year [3]. Lately, there has been an increase

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in the frequency and severity of flood related event, especially in Malaysia [9]. Due to this increase, existing flood mitigation project need to be assessed and new mitigation proposed.

The Sungai Pinji catchment in Perak, Malaysia has been severely affected by recurring floods each year. With climate change, the condition is expected to become increasingly worst in the near future. These floods have imposed substantial financial burdens on the government due to the need for repair and restoration efforts. Furthermore, significant property damage and loss of lives due to the flood have been reported over the past decades. Given the projected increase in the frequency and intensity of flood events globally, effective flood mitigation strategies are crucial. One such strategy is the implementation of a detention pond approach, which reduces the peak of the incoming flow. Utilizing the HEC-HMS and HEC-RAS models, this study aims to simulate the impact of implementing detention ponds as a flood mitigation plan in the Sungai Pinji catchment.

The objectives of this study are to develop a hydrologic and hydraulic model for the Sungai Pinji catchment as well as to assess the effectiveness of the detention pond approach in reducing flood events in Sungai Pinji.

2. Literature Review

Sungai Kinta is a river located in Perak, Malaysia which ran through the busy city of Ipoh. With a 2,540 km^2 catchment area, the Sungai Kinta spans over 100 km from Gunung Korbu in Ulu Kinta, Tanjung Rambutan, to Sungai Perak. The river basin of Sungai Kinta contains seven tributaries, one of which is Sungai Pinji. Sungai Pinji is 17 km long and has a catchment area of 120 km^2. The catchment of the study area is as shown in Figure 1. The catchment area is located near Tanjung Rambutan town at Batu 8, Hulu Kinta. Figure 2 shows the Digital Elevation Model (DEM) of the study area. The upstream of Sungai Pinji is hilly and the rest of the area is flat. When heavy storm occurs, water flows rapidly from upstream and inundates the downstream area. Most of Sungai Pinji catchment, especially along the river, is almost fully developed. The most upstream part is the only undeveloped area of the catchment. Figure 3 shows the land use of the catchment, extracted from Open Street Map (OSM).

There were numerous floods that occurred in Ipoh city between 2001 to 2004, the most devastating of which saw flood water rise to waist height. To solve the issue, the Sungai Kinta flood mitigation project was undertaken by Drainage and Irrigation Department (DID) Malaysia. The project is divided into two phases. Phase 1 of the project, which cost RM30 million, was completed in September 2015 [7]. The flood control reservoirs for Sungai Pinji and Sungai Pari are part of the first phase. Phase 1 of the project was successful in reducing flood occurrence by 30 to 40%. Floods now only happen when there is extremely heavy precipitation. Phase 2 of the project was undertaken in 2019, with bunds along all Kinta River tributaries such as Sungai Klebang, Sungai Pinji, Sungai Tapah, and Sungai Buntong. Although the flood mitigation method has been put in place, there is a growing concern regarding the effects of climate change on increased storm severity and subsequently impact of flood on the mitigation project. There is a need to access the existing flood mitigation scheme and proposed new mitigation measures to ensure sufficient level of protection.

Flood events can be simulated using hydrologic and hydraulic models, giving better understanding of the flood threat and allowing for better management strategies for the hazard. Several hydraulic modelling software are available in the market such as TUFLOW, Storm Water Management Model (SWMM), OpenFlows FLOOD, and HEC-RAS. Flood mitigation measures such as bunds, detention pond, river improvement, river diversions and floodwalls can be simulated with a high level of accuracy using the modelling software. The result of the simulation can be used to determine the effectiveness of each flood mitigation measure and provide crucial information to the stakeholders.

3. Methodology

This research consisted of three key activities: development of hydrological model, development of hydraulic model and parametric study of the selected mitigation approach.

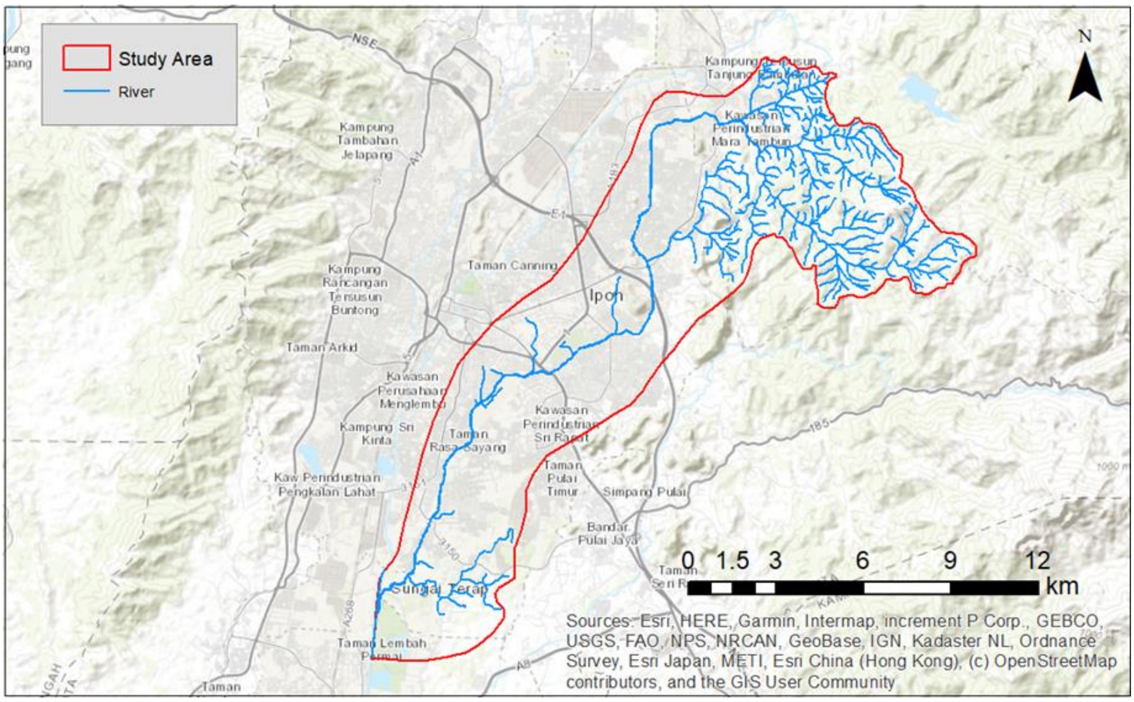

Fig. 1. Catchment of the study area

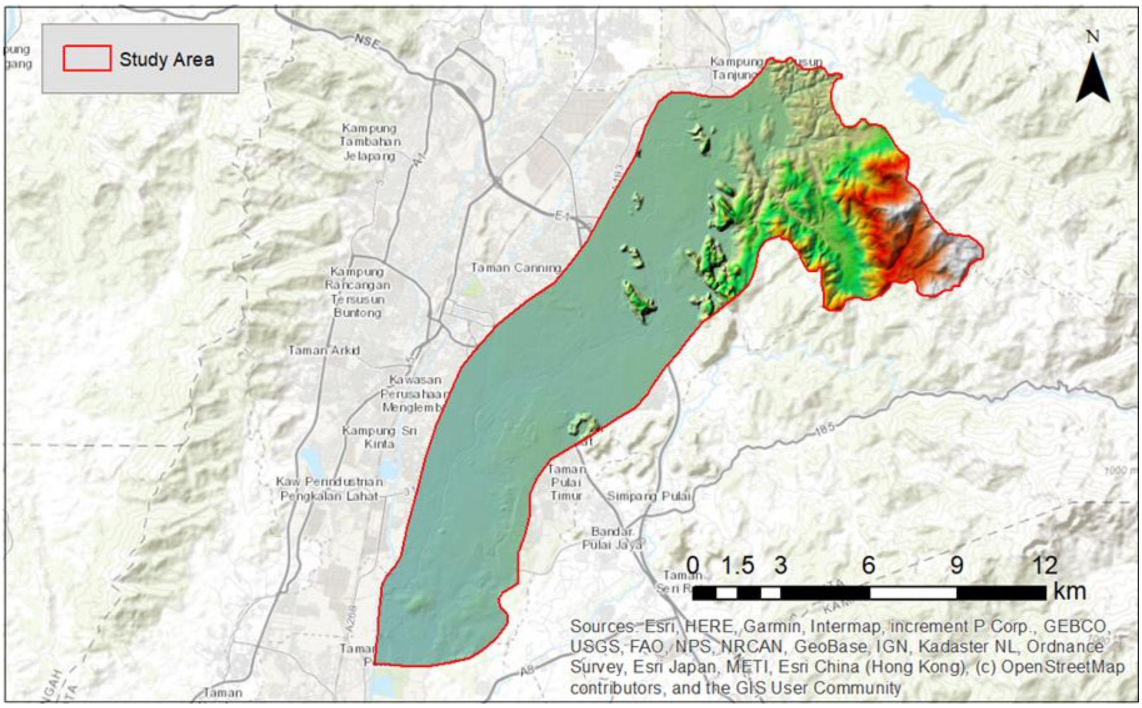

Fig. 2. Digital elevation model of the study area

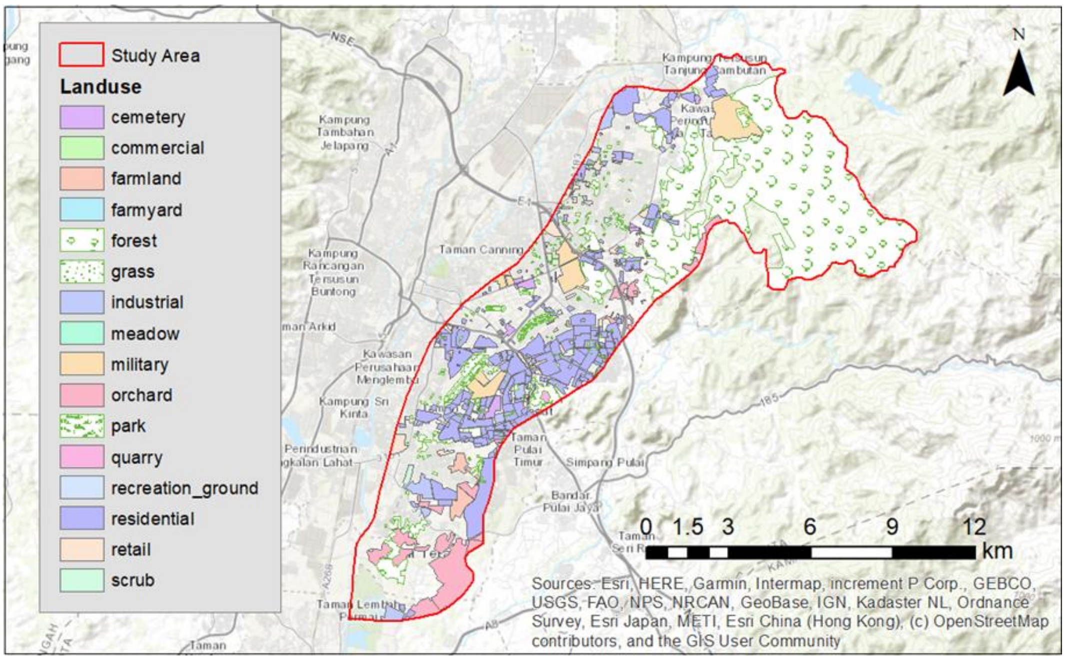

Fig. 3. Landuse of the study area extracted from Open Street Map

3.1 Hydrologic Modelling

In this study, the hydrologic model was developed using HEC-HMS software, involving eight processes which are sub-basin delineation, loss calculation, transform computation, baseflow calculation, routing calculation, model calibration and validation, and calculation of design rainfall [10]. The simplified hydrologic modelling methodology is presented in Figure 4.

3.1.1 Sub-basin delineation

Sub-basin delineation is the process of dividing the study area to few sub-areas. For this study, the sub-basin was automatically generated by HEC-HMS into nine parts, from Sub-basin A to I as shown in Figure 5. Characteristics of the sub-basin is generated using HEC-HMS function. The sub-basin characteristics were used for storm transformation, baseflow determination and routing calculation.

3.1.2 Loss method

In HEC-HMS models, the amount of surface runoff is commonly determined by subtracting the volume of water lost by infiltration, evaporation, and transpiration from the rainfall event. This study considers loss due to infiltration using the Initial and Constant method. The constant loss rate can be observed as the ultimate infiltration capacity of the soil. The infiltration rate is higher at the upstream of the catchment area which is the forest area. The starting loss and constant rate were set to zero in this study based on the HP-27 [4]. The initial estimate for the initial loss and constant rate coefficients is as given in Table 1.

Table 1
Initial and loss constant for the sub-basins

Sub-basin	Initial loss (mm)	Constant Rate (mm/hr)
A	10	5
B	10	5
C	10	5
D to I	0	0

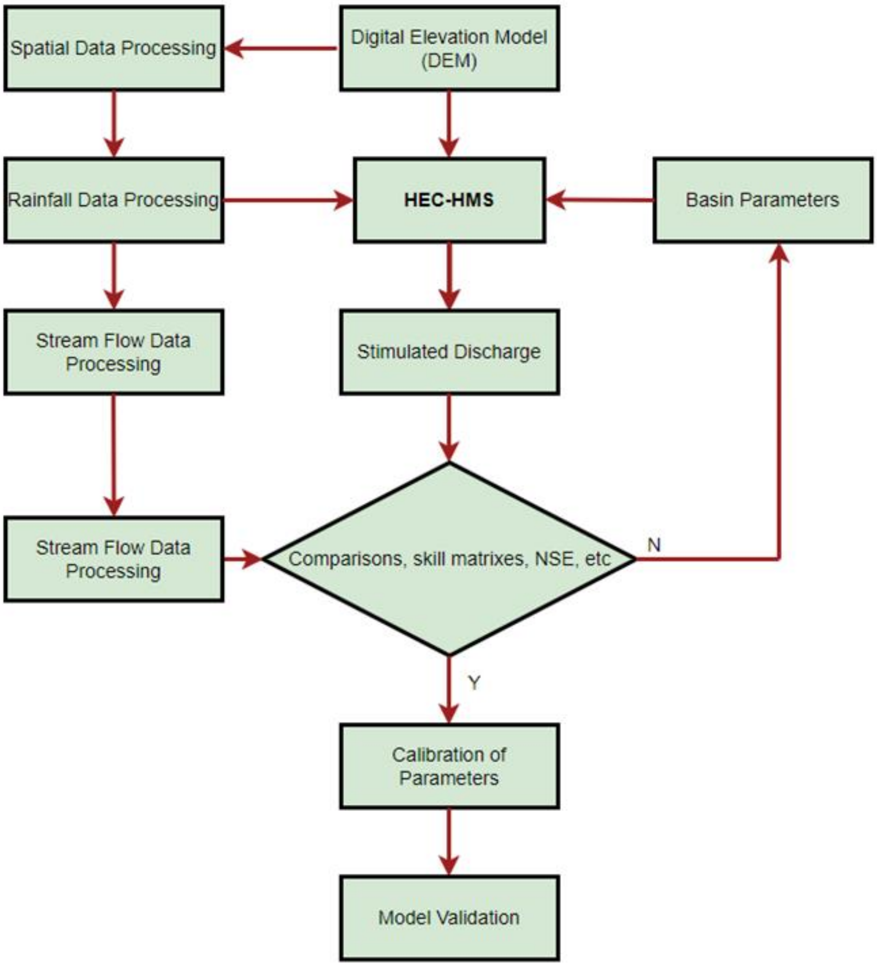

Fig. 4. Flowchart of hydrologic modelling in HEC-HMS

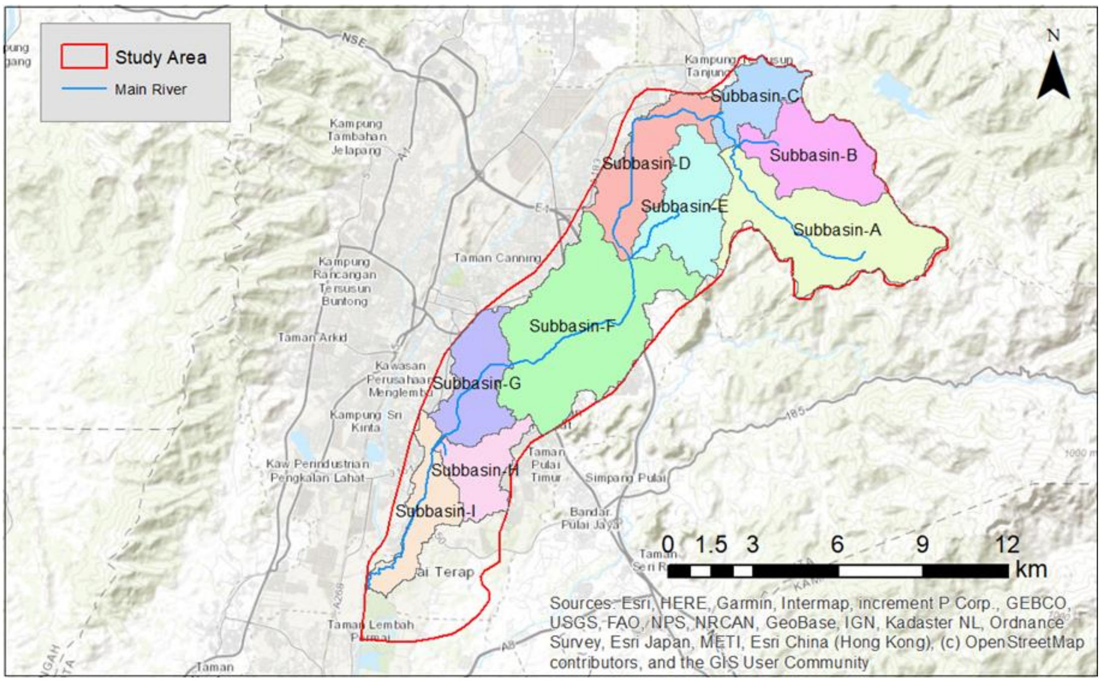

Fig. 5. Sub-basin delineation of the catchment

3.1.3 Transform method

The Clark Unit Hydrograph is used as the transform method to transform the rainfall to flowrate. The method requires the calculation of the time of concentration, T_c and storage coefficient, R. For ungauged catchment in Malaysia, these values can be obtained from HP-27 [4]. T_c and R are linked with stream length, catchment size, and stream slope as follows

$$T_c = 2.32\, A^{-0.118} L^{0.9573} S^{-0.5074} \quad (1)$$

$$R = 2.976\, A^{-0.1943} L^{0.9995} S^{-0.4588} \quad (2)$$

where A is the catchment area in km2, L is the stream length in km and S is the weighted slope of the main stream in m/km. The calculated time of concentration and storage coefficient for all the sub-basin is given in Table 1.

Table 1
Sub-basin characteristics and the initial parameters for Clark Unit Hydrograph

Sub-basin	Area (km^2)	Flow path length (km)	Flow path slope (m/m)	Time of concentration, Tc (hr)	Storage Coefficient, R (hr)
A	20.3	11.7	0.075	1.91	2.67
B	11.2	6.5	0.120	0.92	1.34
C	6.1	4.5	0.026	1.49	2.09
D	11.0	9.9	0.011	4.55	6.04
E	10.8	7.9	0.028	2.32	3.20
F	27.3	10.0	0.006	5.68	6.83
G	8.6	7.4	0.003	7.41	9.22
H	6.0	5.7	0.007	3.80	5.03
I	7.1	9.3	0.002	10.78	13.55

3.1.4 Baseflow

The constant monthly method was used to obtain the baseflow for Sungai Pinji. The design baseflow was calculated based HP-27 [4], using a best fit equation derived for general use as follows

$$Q_B = 0.11 A^{0.85889} \quad (3)$$

where is QB is the baseflow in m3/s and A is the catchment area in km2. The initial base flow for the sub-basins is presented in Table 2.

Table 2
Baseflow for the sub-basins

Sub-basin	Area (km^2)	Baseflow (m^3/s)
A	20.3	1.46
B	11.2	0.88
C	6.1	0.52
D	11.0	0.86
E	10.8	0.85
F	27.3	1.88
G	8.6	0.70
H	6.0	0.52
I	7.1	0.60

3.1.5 Routing method

To route an inflow hydrograph, the Muskingum routing method is employed. Time travel of the flood wave through the reach, K and rate of outflow from the routing reach, O are parameters that required for the routing method. X parameter is a one-dimensional coefficient with no physical significance which value must be between 0.0 (highest attenuation) and 0.5 (minimum attenuation: no attenuation). When this option is set to zero, storage inside the reach is calculated purely based on outflow. This is equivalent to level pool routing and results in the most attenuation feasible. For value of 0.5, both inflow and outflow are given equal weight when determining storage within the reach. As a result, the inflow hydrograph has no attenuation as it moves through the reach. For this study, a 0.25 initial estimate was used as initial estimate and further adjusted during model calibration. The calibration value for the Muskingum method for all reaches are given in Table 3.

Table 3
Baseflow for the sub-basins

Reach	K (hr)	X
A	6.05	0.25
B	11.01	0.25
C	20.28	0.25
D	15.63	0.25
E	7.42	0.25

3.1.6 Model calibration and validation

Model calibration and validation is an important process in hydrologic modeling where the simulated result is compared to the observed result. For this study, the rainfall and flow rate dated 13th October 2019 to 23rd October 2019, from gauging station at Jambatan Sungai Pinji were used for calibration. The data for the calibration is shown in Figure 6. Parameters for infiltration, transformation, baseflow and routing were adjusted to fit the simulated flow rate with the observed one. To ensure that the parameter is valid for other events, validation of the calibrated parameters is carried out for other historical storm events.

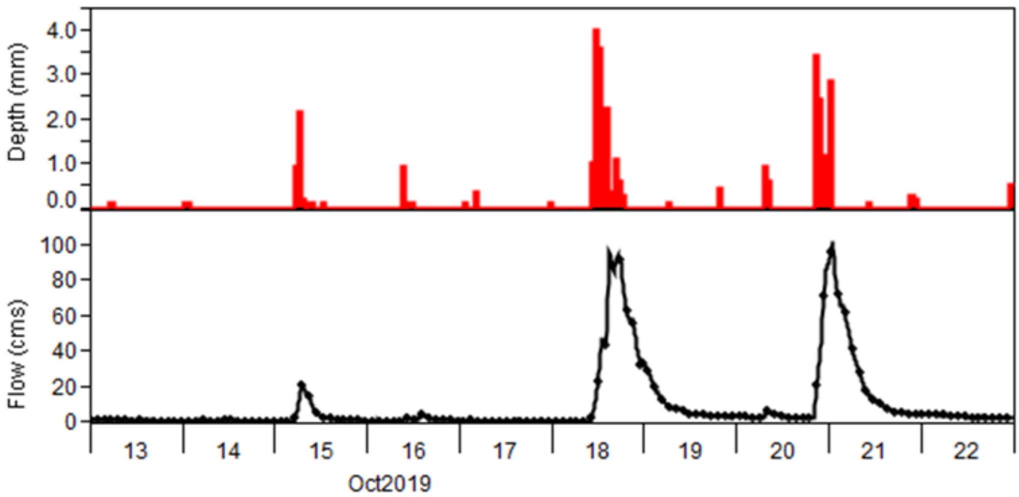

Fig. 6. Historical rainfall (top) and flowrate (bottom) between 13 October 2019 to 23 October 2019

3.1.7 Design rainfall

The design rainfall is calculated for 5-years, 20-years and 100-years average recurrence interval (ARI), based on HP-1 [6]. Intensity-Duration-Frequency (IDF) parameter, λ, κ, θ and η, obtained from HP-1 for gauging station within the study area were used to calculate the rainfall intensity. This data is required for the hydrologic model using HEC-HMS. The rainfall was assumed to be constant over the whole catchment. The storm event was simulated for three days, with time interval 10 minutes in order to obtain the rising limb, peak and recession limb of the flowrate.

3.2 Hydraulic Modelling

A 2D unsteady hydraulic model was developed using HEC-RAS software, involving five processes which are geometry generation, imposition of boundary condition, simulation and post-processing [1]. The flowchart of hydraulic modelling in HEC-RAS is presented in Figure 7.

3.2.1 Geometry generation

Interferometric Synthetic Aperture Radar (IFSAR) data from Department of Survey and Mapping Malaysia (JUPEM) was used as Digital Elevation Model (DEM) to represent the topography of the catchment. The DEM has a resolution of 5m x 5m per pixel. The DEM data is as shown in Figure 2. River bathymetry is required to allow correct flow prediction. River bathymetry is usually obtained from survey cross section, carry out at certain interval. However, as the cross-section data is not available, assumed cross sections was used instead. This is done to prevent underestimation of the flow carrying capacity which could over-estimate the flood extent. Two-dimensional (2D) model is adopted for this study. The 2D model requires generation of mesh for the computational domain. Mesh grids were created along the Sungai Pinji and finer mesh were created near the river to capture the detail of the flow. The mesh and plot of assumed cross section are as shown in Figure 8.

3.2.2 Boundary condition

In this study, four inlet boundary conditions were applied from the outlet flowrate of sub-basin C, sub-basin E, sub-basin F and sub-basin G. These outlet flowrates are obtained from the HEC-HMS model. Outlet boundary condition was specified at the downstream of the river reach. At the outlet boundary, free flow condition was prescribed using normal water depth, allowing water to escape freely from the domain. The location of the boundary conditions is shown in Figure 9.

3.2.3 Simulation parameters

The simulation period for the model is set to five days. A dynamic wave model was used instead of the full Shallow Water Equation model to reduce computational effort. The use of dynamic model is appropriate since the flow involving flood is usually quite slow where the advective terms does not affect the overall result. In order to reduce computational time, adaptive time stepping with maximum Courant number of 1 was used. Both existing condition of Sungai Pinji and mitigation plan which is pond approach simulation were carried out.

3.2.4 Post processing

In this process, flood inundation mapping was computed to understand better the effects of flooding in Sungai Pinji area. The inundation area due to the flood can be calculated as part of the processing step.

3.2.5 Proposed flood mitigation

Detention pond approach was proposed as mitigation for Sungai Pinji to reduce the severity of the flood. In this study, pond was not modelled directly in the hydraulic model. Instead, the pond is considered in the hydrologic model. An off-line pond approach was adopted using conditions in which the resulting flow rate from the hydrologic model to the hydraulic model has a reduction in the peak flow rate by 10%, 20%, 30% and 40% from the original condition. The resulting inundated area for each case was then compared to the existing case to determine the effectiveness of each proposal.

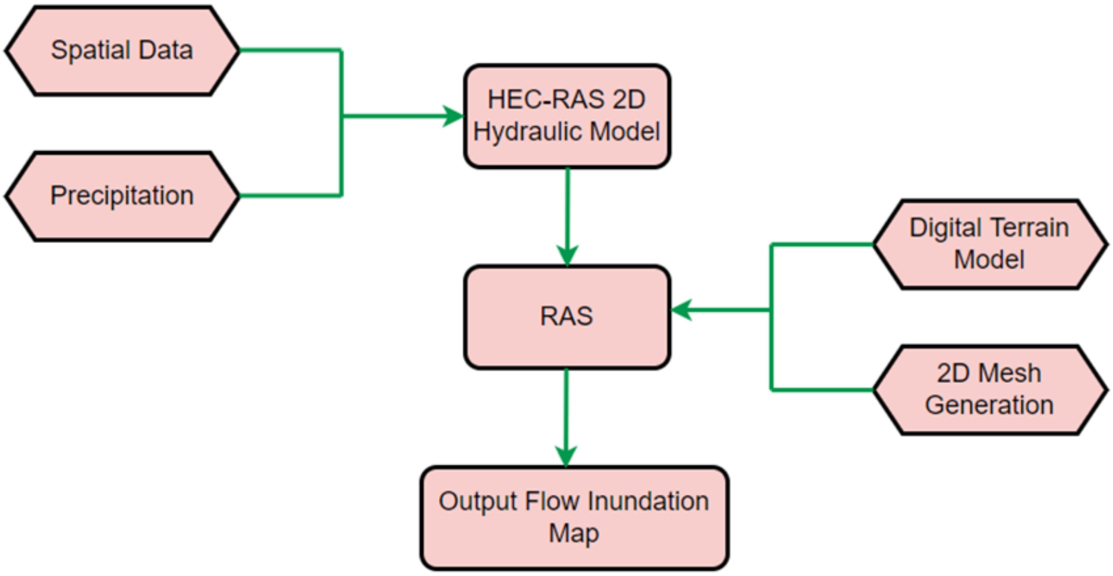

Fig. 7. Flowchart of hydraulic modelling in HEC-RAS

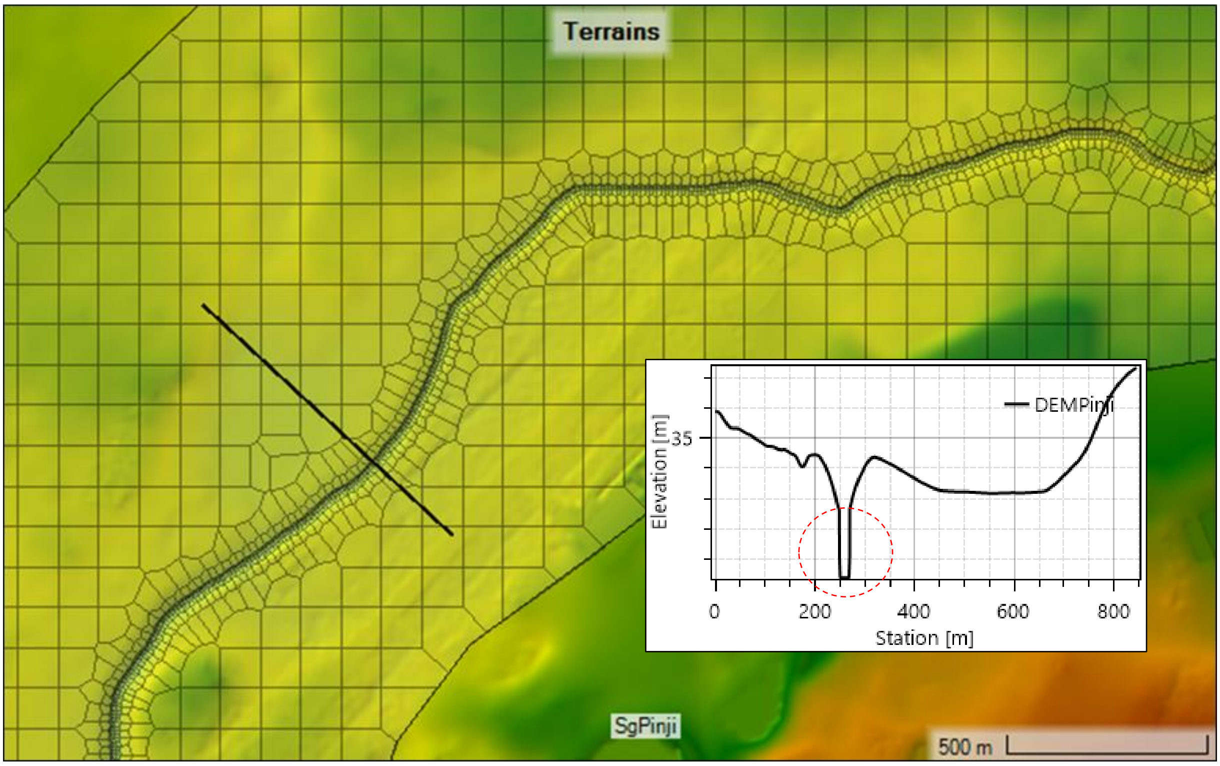

Fig. 8. Meshing for the computational domain and plot of assumed cross section (red circle)

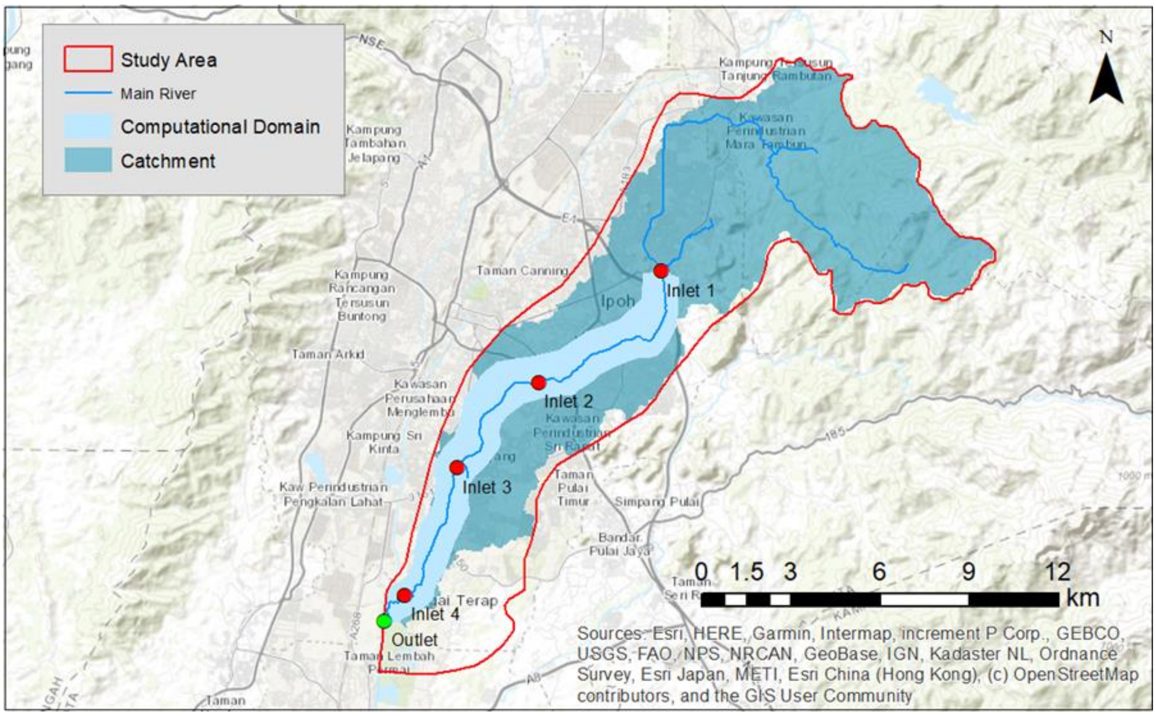

Fig. 9. Inlet (red circle) and outlet (green circle) boundary conditions for the HEC-RAS model

4. Results and Discussion

4.1 Hydrologic Modelling

The hydrologic model was calibrated to produce a model similar to the actual storm event at Sungai Pinji. Before calibration, the peak discharge for model is 60.9m^3/s while observed flow gage at Jabatan Sungai Pinji is 102.2m^3/s After calibration, the peak discharge for the model increased to 112.6m^3/s, reducing the maximum error of the peak discharge from 40.4% down to just 10.1% as shown in Figure 10. The Nash-Sutcliffe efficiency (NSE) coefficient increased from 0.619 to 0.853 after the model is calibrated. As the Nash-Sutcliffe value approaches 1, the agreement with observed data is considered as excellent. The calibrated model was then validated against Nov 2019 storm event. The validation for the flow rate is shown in Figure 11. The NSE coefficient for the validation is 0.789, again showing that the calibrated model has excellent agreement with observed data.

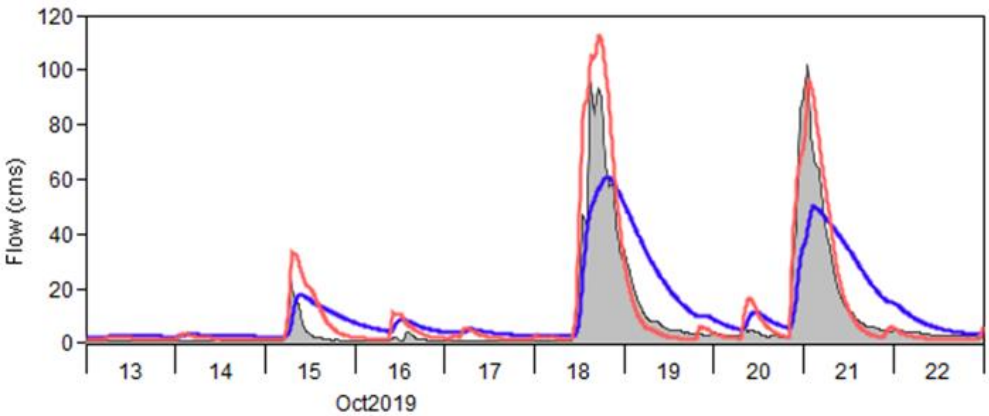

Fig. 10. Flow rate comparison between observed (grey area), and initial (blue line) and calibrated (red line) models.

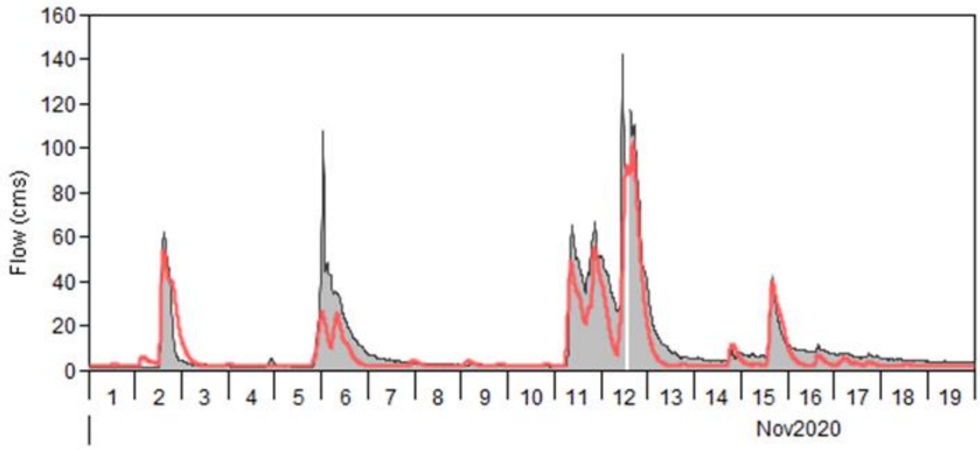

Fig. 11. Flow rate validation between observed (grey area), and calibrated models (—)

Next, the critical storm for the model is determined by comparing the peak flow rate for different storm duration [5]. The critical storm duration is determined from the storm duration that gives the maximum peak. Figure 12 shows the outlet hydrograph for different storm duration. From the figure, the maximum peak occurs for the 24-hours storm duration. Therefore, this duration was selected as the critical storm for the design rainfall.

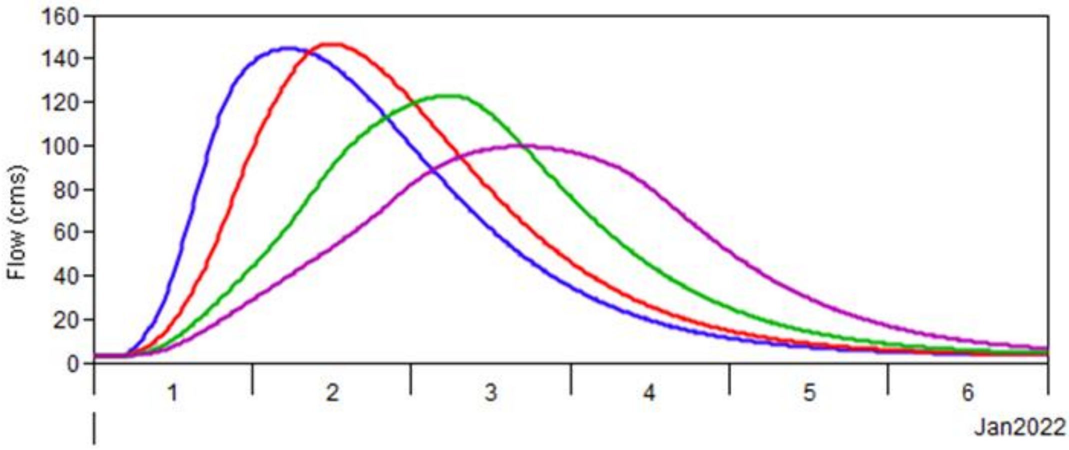

Fig. 12. Outlet hydrograph for different storm duration. Legend: 12-hours (—), 24-hours (—), 48-hours (—), 72-hours (—)

The design rainfall based on 5-years, 20-years and 100-years ARIs were calculated based on HP-1. Politeknik Ungku Omar rainfall station was selected, as this station is located within the catchment area. The design rainfall is calculated based on the IDF parameter, critical storm duration and temporal pattern. The rainfall hyetograph for different ARIs is given in Figure 13.

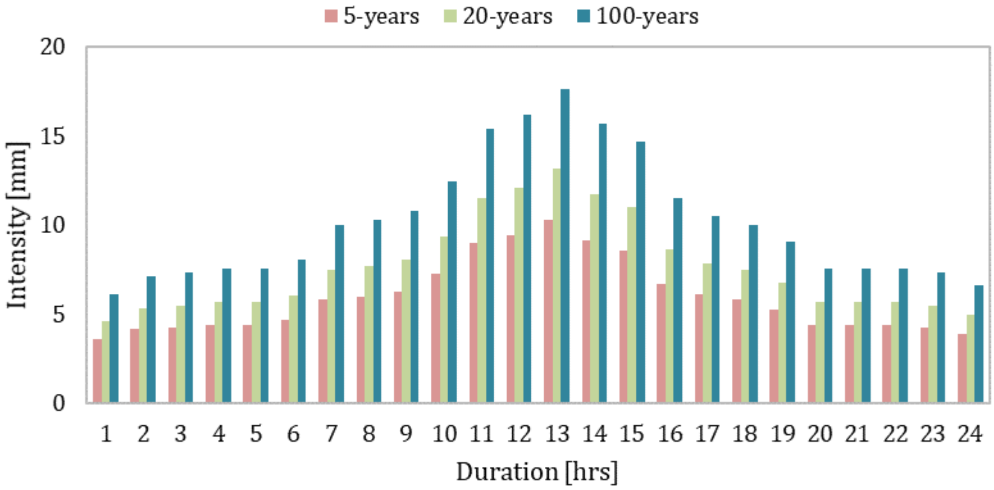

Fig. 12. Design rainfall for 5-years (—), 20-years (—) and 100-years (—) ARIs

The flow hydrograph for the design rainfall was computed at four locations: outlets of reach-B, reach-C, reach-D and reach-E. Figure 12 shows the design hydrograph at reach-B for 5-years, 20-years and 100-years ARIs design rainfall. The peak of the hydrograph increases with increase in storm severity.

4.2 Hydraulic Modelling

The Sungai Pinji hydraulic model was used to generate flood inundation map and plots of water surface elevation (WSE) for both existing condition and post mitigation condition, for 5, 20 and 100 ARIs. The flood inundation map for 5, 20 and 100 years return period are presented in Figure 13 to 15. The inundation area for 100 years return period is 3.9km2. There is an increase of 143% in the flood inundation area from 5-years ARI to 100-years ARI. The inundation area for the design storm events is presented in Table 4.

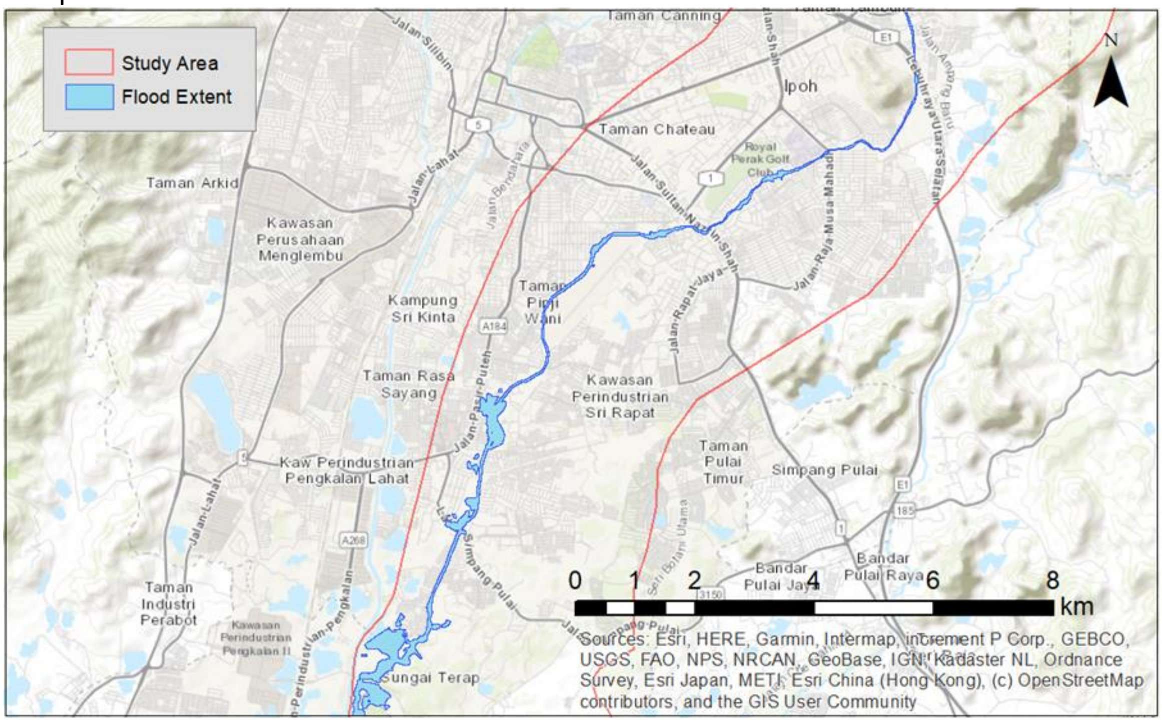

Fig. 13. Flood inundation without mitigation for 5-years ARI

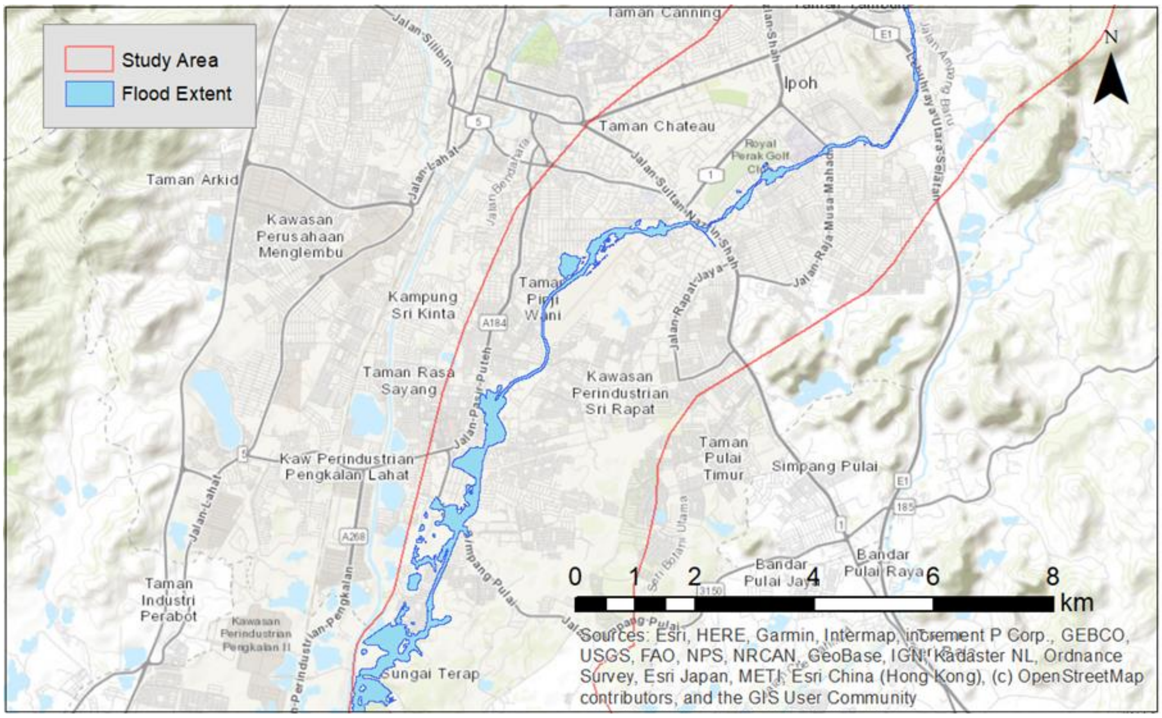

Fig. 14. Flood inundation without mitigation for 20-years ARI

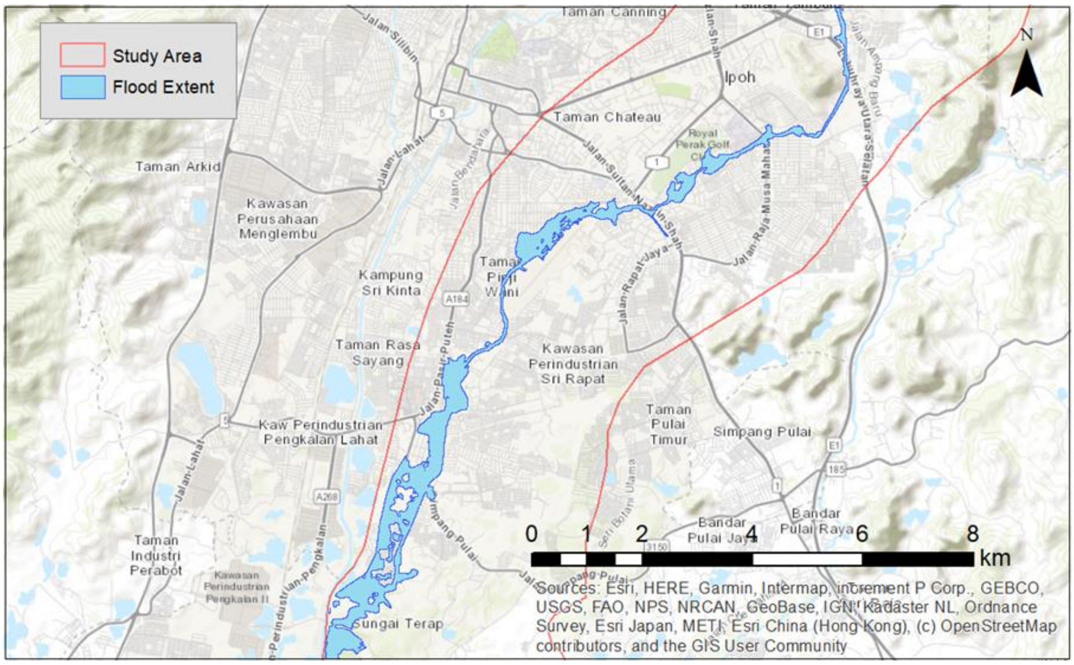

Fig. 15. Flood inundation without mitigation for 100-years ARI

Table 4
Inundation area for different design storm events

ARI	Inundation area (km^2)
5-years	1.6
20-years	2.6
100-years	3.9

The detention pond approach is adopted as a mitigation method in this study. As the catchment area is predominantly urban, with important residential, industrial and commercial areas, the 100-years ARI of protection level is considered. Since the pond reduces the peak of the incoming flow, the flow at Inlet 1 (upstream) received much reduced flow. This resulted in the reduction in the overall flood inundation. The flood inundation map for the four cases considered, 10%, 20%, 30% and 40% reduction in peak flow rate is shown in Figure 16 to Figure 19.

A gradual decrease in the inundation area and flood volume is observed as shown in Table 5. For pond with the smallest peak reduction (10%), the inundation area reduces by 7.7%. This reduction in inundation area increases by 17.9% to 30.8%for peak reduction of 20% and 30%. For the maximum peak flow reduction considered here, at 40%, the inundation area is reduced by a whopping 46.2%. The result shows that by reducing the peak flows that enter the catchment, huge reduction in the inundation area due to flood can be achieved.

Table 5
Reduction in inundation area for various peak flow reduction

Peak reduction (%)	Inundation area (km^2)	Inundation area reduction (%)
0 (no mitigation)	3.9	0
10	3.6	7.7
20	3.2	17.9
30	2.7	30.8
40	2.1	46.2

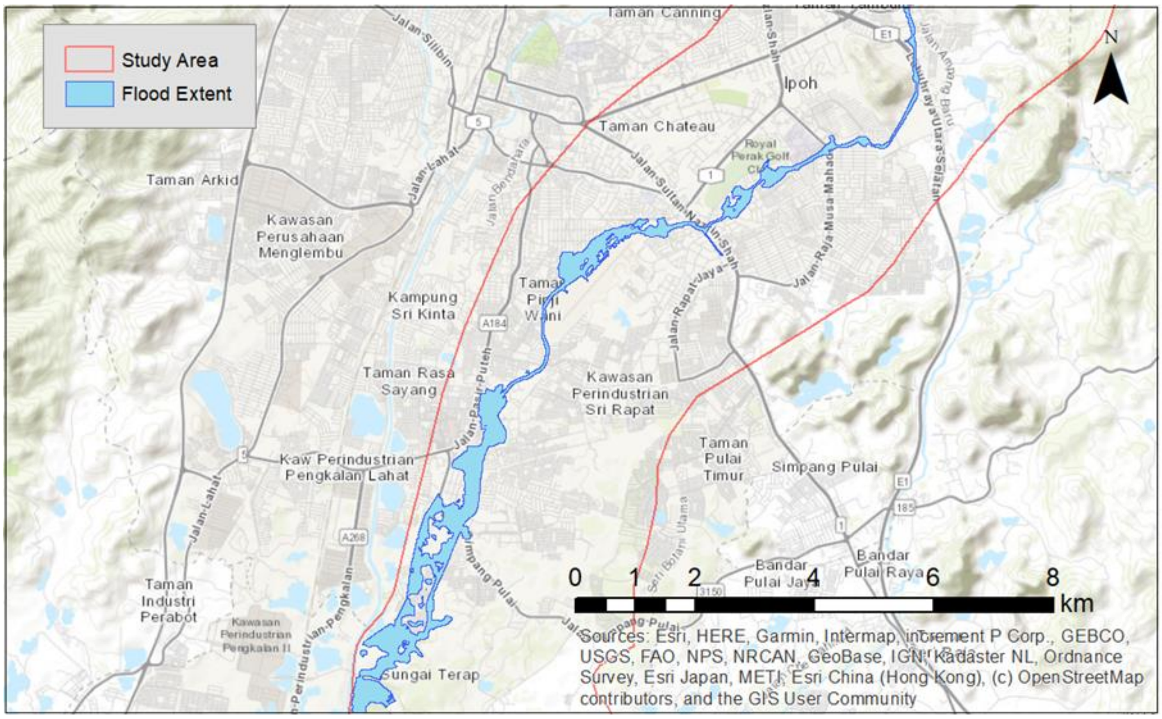

Fig. 16. Flood inundation for 100-years ARI with 10% peak reduction

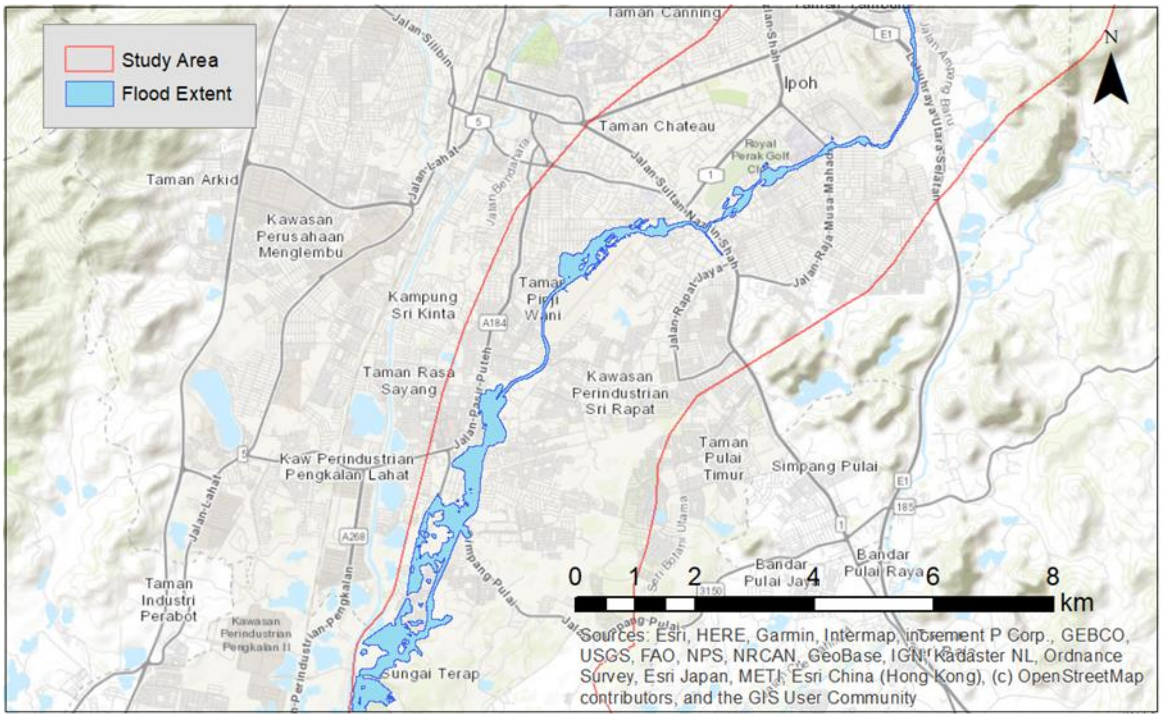

Fig. 17. Flood inundation for 100-years ARI with 20% peak reduction

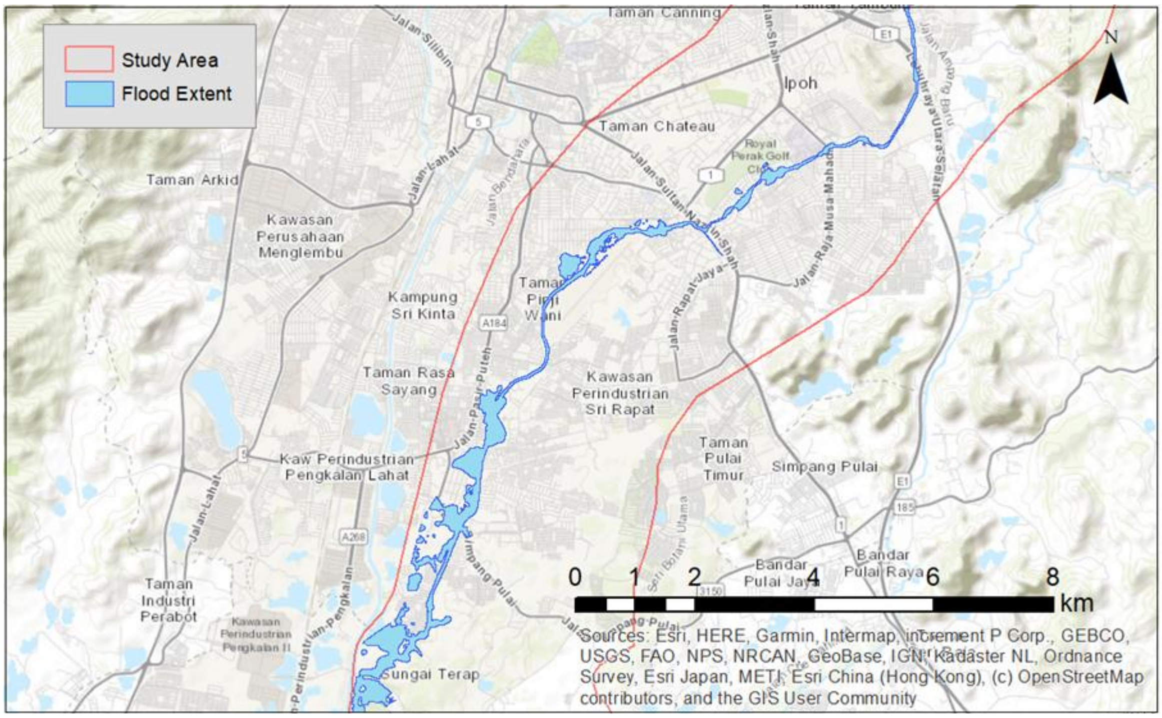

Fig. 18. Flood inundation for 100-years ARI with 30% peak reduction

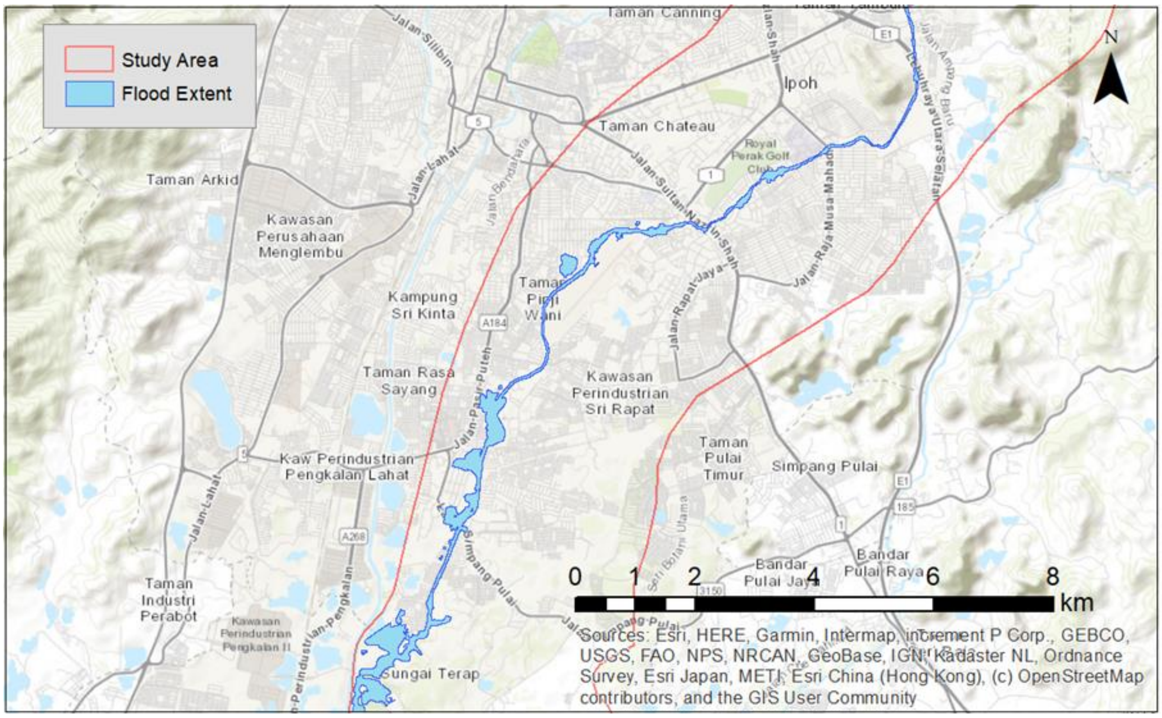

Fig. 19. Flood inundation for 100-years ARI with 40% peak reduction

4. Conclusions

In this paper, hydrologic and hydraulic models based on HEC-HMS and HEC-RAS was successfully developed to simulate the flood event at Sungai Pinji, Ipoh, Perak. The calibrated hydrologic model together with a two-dimensional (2D) hydraulic model were used to simulate design storm event for 5-years, 20-years and 100-years ARI. The inundation maps were produced to show the area affected by the flood. Detention pond that reduces the incoming peak flow were considered as mitigation for the study area. A reduction of 46.2% in inundation area is achieved with the pond design that can reduce the peak flow by 40%. The result of the study can provide some guidance on the mitigation option possible to help reduce flood problem for the study area.

Acknowledgement

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