Hydrodynamic modelling of historical flood event using one dimensional HEC-RAS in Kelantan basin, Malaysia

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Abstract. Hydraulic simulation models are critical tools for analysing the hydraulic properties of a river’s system flow. The work focuses on the simulation of a river flow in a Kelantan basin using the one-dimensional (1D) Hydrologic Engineering Center - River Analysis System (HECRAS). In the present study, cross-sections from survey data were utilised into the RAS Mapper provided in HEC-RAS 5.0 to simulate the river flow in the region. This study highlights the modelling methodology with a focus on data collection and its importance during the calibration and validation process. The model was used to discover the expected peak flood levels based on historical flood events. Simulated flows were utilised to examine the potential of the model during the model development procedure. The simulation outcomes reveal that the simulated flows are in excellent agreement during the model development as the obtained R² value was between 0.95 to 1.0 during both model calibration and validation. This demonstrates the applicability of the HEC-RAS 1D model in simulating precise river flow, especially for flood events.

1. Introduction

Computer software is employed every day to investigate the characteristics of river systems for a large variety of reasons related to the public interest. For many years, most hydraulic engineers faced constraints of needing to use more than one software to analyse the river systems [1]. The Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers developed a model known as the River Analysis System (HEC-RAS), which is now the most widely used flood modelling software in hydrodynamic simulation. It is a well-tested model that is occasionally benchmarked to compare the performance of other hydrodynamic model simulation software [2].

This software primarily intends to conduct river flow analysis in 1D steady flow and 2D unsteady flow simulations, as well as in water temperature/quality modelling and sediment transport. HEC-RAS employs hydraulic computing techniques with geometric and geometric data representation to perform the simulation for a network of manmade or natural river channels. While this model has a wide range of capabilities, the study will concentrate on the potential of HEC-RAS to run 1D river flow, especially
for flows based on flood events reported by the Department of Irrigation and Drainage Malaysia (DID) that happened along the Kelantan River catchment in Malaysia, such as in December 2010/January 2011 and January 2012. Hence, the objective of this study is to examine the potential of 1D HEC-RAS to simulate river flow based on the historical flood event by using survey cross-section data.

2. One Dimensional (1D) River Flow Modelling

The 1D model is extensively employed to simulate flow in main river channels and may be highly useful to predict flood extent in some circumstances. In dealing with flows in complicated and large networks, 1D modelling also demonstrates computational efficiency and easy parameterisation [3]. The assumption behind the 1D HEC-RAS model is that all flows across any cross-section is normal to the cross-section. There is no flow in the lateral or vertical directions, thus, all flow is considered to move in one direction (longitudinal) [4]. In a 1D model, the terrain is represented as a series of cross-sections. The average velocity and water depth at each cross-section are the results of the 1D river flow simulation.

The HEC-RAS unsteady flow simulation component can simulate 1D unsteady flow across an entire network of open channels. Numerous studies such as Hashim et al. (2021) [5] and Ahmad (2016) [6] have examined the performance of 1D modelling in hydraulic simulations, concluding that it is capable of providing a good estimate of flood level and travel time and can be used to predict flood extent. The routing for the 1D HEC-RAS model is based on the Saint-Venant equations of dynamic wave theory, as well as the continuity and momentum equations. In the same way, the energy balance equation is used to calculate the water surface profile as

\[ Z_2 + Y_2 + 2g = Z_1 + Y_1 + 2g + h_e \]  

where \( Z_1 \) and \( Z_2 \) represents the height of the main channel inverts; \( V_1 \) and \( V_2 \) represents the average velocities; \( Y_1 \) and \( Y_2 \) represents the depth of water at cross-sections; \( a_1 \) and \( a_2 \) represents the velocity weighting coefficients; \( g \) is the gravitational acceleration and \( h_e \) is the energy head loss.

3. 1D Model Development Within Kelantan Basin

Data required to develop the 1D HEC-RAS model include the Digital Elevation Model (DEM) of the study area, streamflow data, cross-section river geometry and Manning’s roughness coefficient for channel and floodplain surface roughness. The data gathered in the present study were from secondary sources. The United States Geological Survey (USGS) website has provided DEM with a 30-metre resolution for Kelantan. The 2010/2011 and 2012 flood events flow data in Kelantan for the streamflow stations (Nenggiri, Lebir, Galas and Guillemard Bridge) were obtained from the DID. The survey cross-sections for the river network of the study region were obtained from DID. The Kelantan basin as seen in Figure 1 was selected as the study region due to its near-yearly flood events. Thus, these extreme events showed the needs for river flow investigation in this region.

With the obtained data, geographic characteristics in the actual world can be represented in the model using GIS spatial registration and georeferencing techniques. At present, all GIS operations can be completed within the RAS Mapper provided in the latest HEC-RAS 5.0. The DEM was added into RAS Mapper to illustrate the terrain of the study area as shown in Figure 2. The river centreline is generated by digitising the Kelantan River flowing from the upstream of the Nenggiri River and Lebir River to the end of Kelantan River (downstream). Then, the riverbanks and flow paths were digitised for the left path of the river first, then right from upstream to downstream and their associated attribute information was allocated. To extract the elevation data from the DEM, cross-sectional lines were created (terrain
data). The intersection of cross-sectional lines with the river centre-line and flow paths provides essential information such as the downstream reach lengths, position of bank stations and manning values to the HEC-RAS simulations. The cross-sectional lines were drawn perpendicular to the river centre-line (viewing downstream from left to right) with an interval of around 1000 metres between them. Reach lengths, river profile, bank stations, and elevations were all generated into the attributes of the cross-sectional lines by employing in the RAS Mapper.

In the geometric file, the cross-section of the river geometry data cut from the DEM needs to be replaced with the survey geometry cross-section. Then, Manning's roughness coefficients ‘n’ was applied to the river profiles. Each cross-sectional line must have three (3) manning ‘n’ values: one value for channel, and two values for overbank. The ‘n’ value was assigned based on a standard reference proposed by Abbas et al. [7], and it indicates the resistance to flow. Also, another data which is the boundary conditions needed to be fed into the model to model the true historical flood event. The boundary conditions of the simulation can be set by populating the model with the stream flows data for the flood event especially at the upstream river, and at all ends of the river nodes by entering the normal depth value.

In HEC-RAS, the simulation time must be synced with the flow data. At this point, HEC-RAS had gathered all the data required for hydrodynamic modelling. The unsteady flow model was computed in the ‘Run’ windows as the final simulation step. During the simulation, the 1D model HEC-RAS classified the flow as unsteady, with the flow travelling downstream (1D) and the given cross-section serving as the entire characterisation of the river system. For the calibration process in this study, one high flood event model was run which was on 28 Dec 2010 - 03 Jan 2011 and the results were analysed. To validate the simulation, another high flood event model on 12 Jan 2012 - 18 Jan 2012 was chosen and the computed graph of flows at the upstream and downstream boundary for both events was compared to the observed flow. The coefficient of determination ($R^2$) was used to evaluate the performance of the model and it can be written as follows:
in which, \( \text{obs} \) is observed flow, \( \text{pred} \) is the predicted flow, \( \bar{\text{obs}} \) is the mean observed flow, and \( \bar{\text{pred}} \) is the predicted mean observed flow. The closer the \( R^2 \) value to 1, the better the predictions.

4. Model Results and Discussion

In HEC-RAS, the flood simulation was performed using an unsteady flow simulation. The 2010/2011 and 2012 flood events were simulated for the period of 28 Dec 2010 to 03 Jan 2011 and 12 Jan 2012 to 18 Jan 2012, respectively. The model was run for a total duration of 1 hr. The water surface elevation, flood depth, velocity and flood inundation for the Kelantan region was simulated.

4.1 Manning’s n value

Manning’s ‘n’ values for both the channel and the over banks were the significant parameters to be adjusted during calibration and validation of the 1D HEC-RAS model. Manning's coefficient ‘n’ was changed repeatedly during the calibration until the variations between the simulated and observed water levels were in good agreement. The range of ‘n’ values utilised in model calibration was between 0.01 - 0.13.

4.2 Calibration and validation of the 1D HEC-RAS models

Observed flows were used to validate the flood event simulations from 2010/2011 and 2012. The degree of agreement between the two sets of data was assessed. Figure 3 exhibits the output flow hydrographs obtained from the simulated river flows at four (4) stations in comparison to the observed flows during
the 2010/2011 flood for 1D flow calibration. The calibrated model performed well at each of the station as displayed in the figures. The simulated flow hydrographs at Nenggiri, Lebir and Galas managed to accurately capture the pattern of observed flow with obtained $R^2$ value of 1.0 for each station. Meanwhile, the simulated flow at Guillemard Bridge also gave a good agreement in capturing the pattern of observed flow and in terms of $R^2$, which obtained 0.95. The highest simulated peak flow recorded was 2393.3 m$^3$/s, which occurred at the station at Guillemard Bridge on 31 Dec 2010 at 14:00. The river flow at Guillemard Bridge is significant to be analysed as it received a high amount of river flows, which caused the occurrence of the flood. Since the calibrated model already achieved the best hydrograph results, the model was then validated using the same parameters for model validation using another extreme flood event which is in the year 2012. The agreement of the simulated flow model with observed flow data at Guillemard Bridge was examined.

**Figure 3.** Performance of the HEC-RAS 1D model during the calibration period.

The validated results by employing the January 2012 flood event can be seen in Figure 4. Similar output was likely in model calibration as the simulated flow hydrographs managed to exactly match the pattern of observed flow hydrographs, which is also shown in the model validation at station Nenggiri,
Lebir and Galas. Each station obtained $R^2$ of 1.0. This exhibits that HEC-RAS model is superior in simulating the flow hydrograph, especially when given flow hydrograph as a boundary condition at the upstream of the studied basin.

**Figure 4.** Performance of the HEC-RAS One-Dimensional (1D) model during the validation period at a) Nenggiri b) Lebir c) Galas and d) Guillemard Bridge.

For the station at Guillemard Bridge at the downstream of the Kelantan basin, an appropriate shape of flow hydrograph was achieved. The simulated and observed hydrographs for the ascending and receding limbs were in good agreement. However, the simulated flow showed under-estimation for the peak flow compared to the observed flow. The simulated hydrograph shows a peak flow at 3909.57 m$^3$/s while the observed peak flow is at 4494.2 m$^3$/s. The simulated peak flow occurred 8 hours earlier than the observed hydrograph. The value of $R^2$ at Guillemard Bridge is 0.98, which means the percentage of matching between the two hydrograph is 98%. Overall, the validation performance of the developed one-dimensional model was on good terms.
The model can reliably estimate the hydrodynamic properties of flood flow in the four (4) main rivers of Kelantan based on the calibration and validation results. The achieved outputs from this study prove that simulations by utilising the features provided in HEC-RAS such as during the previous model development chapter managed to simulate river flow efficiently.

5. Conclusion

The developed 1D model can be utilised to estimate water levels along the river reach from Nenggiri and Lebir (upstream) to Guillemard Bridge (downstream) for different flows in the river. Flood events of the year 2010/2011 and 2012 have been simulated by the model to assess the hydrographs. The flow simulation outcomes showed an excellent agreement compared to the observed flow. This demonstrates that the study, which only utilised the HEC-RAS model, managed to model 1D hydrodynamic on a big scale river such as the Kelantan basin. A deep understanding of Manning’s ‘n’ values determination should be considered in further studies corresponding to HEC-RAS modelling since this ‘n’ value is the most significant parameter to be adjusted. Also, a further HEC-RAS two-dimensional (2D) analysis is needed to model the flood inundation mapping for the downstream of Kelantan basin.

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