Flood Inundation Modelling in the Kuantan River Basin using 1D-2D Flood Modeller coupled with ASTER-GDEM

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Abstract. Topography dataset is an important input in performing flood inundation modelling. However, it is always difficult to obtain high resolution topography that provide accurate elevation information. Fortunately, there are some open source topography datasets available with reasonable resolution such as SRTM and ASTER-GDEM. In Malaysia particularly in Kuantan, the modelling research on the floodplain area is still lacking. This research aims to: a) to investigate the suitability of ASTER-GDEM to be applied in the 1D-2D flood inundation modelling for the Kuantan River Basin; b) to generate flood inundation map for Kuantan river basin. The topography dataset used in this study is ASTER-GDEM to generate physical characteristics of watershed in the basin. It is used to perform rainfall runoff modelling for hydrological studies and to delineate flood inundation area in the Flood Modeller. The results obtained have shown that a 30m resolution ASTER-GDEM is applicable as an input for the 1D-2D flood modelling. The simulated water level in 2013 has NSE of 0.644 and RSME of 1.259. As a conclusion, ASTER-GDEM can be used as one alternative topography datasets for flood inundation modelling. However, the flood level obtained from the hydraulic modelling shows low accuracy at flat urban areas.

1. Introduction

Flood leads to property damages, loss of life and economic crisis [1]. The main reasons causing flood to happen are such as heavy and high intensity rainfall, ineffective drainage system, and high volume of runoff due to increasing impervious ground surface [2]. In Kuantan, monsoon season largely affects the weather. During the monsoon season (the northern east monsoon), major floods occurred. Furthermore, the land use changes for urbanisation has worsened the flood condition. In 2013, there are about 14,044 people separated and major damages in terms of electricity supply, road's structure, buildings, and belongings. Due to these disasters, the Malaysian government should allocate substantial amount of money to repair and manage the damages [1]. Therefore, good flood risk management and planning must be implemented to reduce floods [3]. Since it is not possible to avoid rapid urbanisation, efficient flood management practices are advisable [2]. The objectives of this study are: a) to investigate the
suitability of ASTER-GDEM to be applied in the 1D-2D flood inundation modelling for the Kuantan River Basin; b) to generate flood inundation map for Kuantan river basin.

The Geospatial Information System (GIS) and Remote Sensing (RS) datasets have been introduced few decades ago and widely used to facilitate flood hazard modelling [4]. There are several GIS applications available such as ArcGIS and QGIS while RS datasets such as ASTER-GDEM and SRTM to be integrated in the hydrology and hydraulic studies. In hydrology studies, topography dataset is used for watershed delineation where all the sub basins are to be identified and the stream line can be defined. For hydraulic modelling, topography dataset acts as the base elevation map in the flood inundation modelling. After the hydraulic analysis, the flood level and flood extent can be identified. For better result, high resolution topography for example LiDAR, IFSAR, IKONOS and Spot DEM are recommended. However, the acquisition of these datasets is costly.

In this study, ASTER-GDEM with 30m resolution was chosen to perform flood inundation modelling in the Flood Modeller. The selected topography dataset and Flood Modeller software are available and downloadable from the NASA Land Data Products and Services, U.S. Geological Survey (USGS) and the Flood Modeller main website respectively without any charges.

1.1. Study area
The study area selected for the research is the Kuantan River Basin (KRB). KRB is one of the main river basin in the Pahang state. It has a watershed boundary of 1630 km². Sg. Kuantan is the main river in KRB begins from Mukim Ulu Kuantan and ends at the Perkampungan Tanjung Lumpur outlet point towards the South China Sea. The KRB contains several tributaries which flow along the rural, agricultural, urban, and industrial areas of Kuantan district into the Sg. Kuantan [1]. This study area has been chosen due to the frequent flood occurrence along the Sg. Kuantan in the basin. Figure 1 shows the boundary of the study area displaying the streamflow station, rainfall stations, and the main river.

1.2. Topography datasets
Topography dataset which stores elevation data serve as the main source for representing river bathymetry profile and floodplain topography. It is very common to extract river cross sections from topography dataset when there is lack of survey information. The selection of suitable Digital Elevation Model (DEM) resolution for the representation of river cross section profile is crucial for flood inundation mapping [5]. Table 1 shows some guidance on the selection of cell size [6].

![Figure 1. Boundary of KRB displaying the streamflow station, rainfall stations, and the main river.](image-url)
### Table 1. Recommended DEM cell sizes and their range of applications.

| Cell Size (m) | Watershed Area (km²) | Typical                      |
|---------------|-----------------------|------------------------------|
| 30            | 5                     | Urban watersheds             |
| 90            | 40                    | Rural watersheds             |
| 460           | 1000                  | River basins                 |
| 930           | 4000                  | Nations                      |
| 5600          | 150,000               | Continents                   |
| 9300          | 400,000               | Global                       |

ASTER is an advanced multispectral imager that has been launched on board NASA’s Terra spacecraft in December 1999 [7]. The ASTER-GDEM is a joint product developed and made available to the public by the Ministry of Economy, Trade, and Industry (METI) of Japan and the NASA. These global data are free source which are available at the NASA Land Data Products and Services, U.S. Geological Survey (USGS) website [6]. ASTER-GDEM has several merits such as low cost, high spatial resolution, good correlation over vegetated areas but it may prone to masking by clouds [7]. According to previous studies, making an accurate flood map is not easy and cheap. Hence, ASTER-GDEM can become the alternative mean to produce flood map.

### 1.3. Flood inundation modelling

Flood inundation modelling is a complex process where topography dataset, hydrological model, and hydraulic model are combined to perform final analysis. Through these processes, the potential flood water level and flow pattern can be predicted from time to time even if the river system is hindered by man-made structures or vegetation. Moreover, the flood extent area can be detected to ease the local authorities to trace and perform maintenance based on the affected zone. In time, many researchers, water authorities, and environmental state agencies have turn their focus on developing flood inundation map instead of traditional ground survey solution [3].

There are four key data items for flood inundation modelling such as topography dataset to construct the model grid; discharge flow or stage data to provide model inflow and outflow boundary conditions; an estimation of the effective friction parameter for each model cells; and a source of validation data [8]. Generally, flood modelling consists of two components which are the hydrological simulation where hydrographs of the flood event were generated, and the hydraulic simulation where the influence of flood wave across the river channel and the mapping of flood extent regions [9]. For flood routing models, there are one-dimensional (1D), two-dimensional (2D) or coupled 1D-2D (also referred as quasi-2d) numerical solutions available for steady and unsteady flow conditions [10]. 2D hydrodynamic models discuss about the variation of flow in both, the longitudinal and the transverse directions of river channel towards the floodplain [5].

### 1.4. Flood Modeller

There are many hydraulic modelling have been done using different software such as Flood Modeller, MIKE-Flood, and HEC-RAS to solve the full momentum St. Venant equations [8]. Flood Modeller has been developed to solve one-dimensional (1D) channel flow model (Saint-Venant equations) and two-dimensional (2D) shallow-water equation solver [5]. In simple term, flood routing models solve part or the full one-dimensional 1D Saint-Venant continuity and momentum depth-averaged equations in the longitudinal direction 1D model. The 1D Saint-Venant continuity Equation (1) and momentum equations Equation (2) are shown as below:
\[
\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \tag{1}
\]

\[
\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \beta Q^2 \right) + gA \frac{\partial H}{\partial x} - gAS_f = 0 \tag{2}
\]

\[
S_f = \frac{Q|Q|}{K^2} \tag{3}
\]

\[
K^2 = \frac{A^2R^4}{n^2} \tag{4}
\]

\[
R = \frac{A}{P} \tag{5}
\]

where \( Q \) [m³/s] is the discharge; \( A \) [m] is the wetted area; \( q \) [m³/s] is the lateral inflow; \( g \) [m²/s] is the gravity acceleration. \( S_f \) [-] is the friction slope; \( K \) [-] is the channel conveyance calculated according to Manning’s equation; \( R \) [m] is the hydraulic radius; \( P \) [m] is the length of the wetted perimeter; and \( n \) [-] is the Manning’s roughness coefficient.

The equations are described in mathematical terms as a pair of one-dimensional non-linear hyperbolic partial differential equations. In general, the solution of any system of differential equations depends on the existence, uniqueness, and stability conditions of the solution itself. Furthermore, the numerous assumptions for the simplification of the Navier-Stokes equations to the 1D Saint-Venant equation, the mathematical integration difficulties as well as the computational cost are still high, especially for representing the inundation of a flood wave across a longer river and bigger area. However, it could be enough to further simplify the momentum equation to the steady dynamic wave, diffusive wave, or kinematic wave [10]. Flood Modeller also incorporates an integrated Muskingum-Cunge flow routing solver and a comprehensive range of hydraulic structures, including gates, abstractions and pumps operated by logical rules. Besides that, it also provides three integrated 2D numerical solvers, tried and tested on projects throughout the world for various hydraulic and environmental studies as listed in Table 2.

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**Table 2. Three 2D solvers in Flood Modeller.**

| 2D Solvers            | Description                                                                 |
|-----------------------|----------------------------------------------------------------------------|
| Alternating Direction Implicit (ADI) solver | First developed in the 1980s, the quick, accurate and robust Alternating Direction Implicit (ADI) solver can be applied to riverine, overland, estuarine, and coastal modelling problems where the flow is not rapidly changing. |
| Total Variation Diminishing (TVD) solver | Providing accurate and stable results for complex hydraulics, the Total Variation Diminishing (TVD) solver provides accurate representation of two-dimensional ‘shocks’ (rapid changes in water surface profile). |
| FAST solver | The FAST solver enables rapid assessments of flooding, providing results up to 1,000 times quicker than traditional 2D solvers. It produces results in seconds or minutes, as opposed to hours or days |

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Flood Modeller 2D solver, and many other models of its type, represent shallow water hydraulics. These can be described by the shallow water equations as below:
\[
\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = 0 \tag{6}
\]

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + g \frac{\partial (h + z)}{\partial x} + \frac{g n^2 u \sqrt{u^2 + v^2}}{h^{4/3}} - \frac{v}{h^3} \left( \frac{\partial^2 hu}{\partial x^2} + \frac{\partial^2 hu}{\partial y^2} + \frac{\partial^2 hv}{\partial x \partial y} \right) = 0 \tag{7}
\]

\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + g \frac{\partial (h + z)}{\partial y} + \frac{g n^2 v \sqrt{u^2 + v^2}}{h^{4/3}} - \frac{u}{h^3} \left( \frac{\partial^2 hv}{\partial x^2} + \frac{\partial^2 hv}{\partial x \partial y} \right) = 0 \tag{8}
\]

where \( u \) [m/s] and \( v \) [m/s] are the two components of the horizontal velocity; \( h \) [m] is the flow depth; \( z \) [m] is the bed elevation; \( x \) [m] and \( y \) [m] are the horizontal distances in the \( x \) [m] and \( y \) [m] directions; \( t \) [s] is the time; \( g \) [m²/s] is the acceleration due to gravity; \( n \) [-] is the Manning's coefficient of roughness; and \( \nu \) [m/s] is the kinematic eddy viscosity used to parameterize horizontal turbulent momentum transport, with a value between 0 and 1.

These equations describe the motion of water in terms of a depth-averaged 2D velocity and the water depth, in response to the forces of gravity and friction. These equations typically represent situations where flow is approximately horizontal, is uniform with depth, and where vertical accelerations are small. The velocity components represent the water velocity averaged either over the depth of the water column, ignoring variations in flow direction and magnitude with depth or over time, ignoring short-term turbulent velocity variations. One important property of shallow water flows is the different behaviors of subcritical and supercritical flows. Supercritical flows tend to develop jumps (sudden changes in velocity and water level), which are difficult to represent in the model without causing instability. The difficulty of modelling these jumps is the reason 2D solver has the TVD solver as well as the more commonly used ADI solver.

2. Methods
In this study, the required primary data is ASTER-GDEM in ASCII file format as the floodplain topography and cross section survey data as the 1D schematic model. Next, the simulated discharge which were calculated by rainfall runoff modelling were used as the inflow and outflow boundaries condition in the Flood Modeller. The calibrated hydrological parameters for the flood event in the year 2010 was validated with the flood event in the year 2013.

For the hydraulic modelling, the river cross-sections derived from the ASTER-GDEM was not as accurate as the survey data. Thus, the survey data were used for cross section generation in Flood Modeller. The cross sections in the format of comma-separated values (CSV) were imported into Flood Modeller. Then, the calculated discharge for the year 2010 were added as input boundaries to simulate the 1D steady and unsteady flow. Steady flow was performed to make sure that the river profile generated was appropriate before the unsteady flow modelling was carried out. Next, the simulated water level data was calibrated with the observed water level (Kuantan bypass) which is located near the downstream part of Sg. Kuantan.

For 2D modelling, an active area was created which represents the flood prone area along the main river. Next, the 1D-2D link line was generated in Flood Modeller which connects the 1D open channel flow to the 2D floodplain topography. Finally, 2D modelling with 2D ADI solver was conducted and flood inundation map for the year 2010 was obtained.

3. Results and discussion
For the 1D unsteady flow modelling, the calibration was done using the data from 2010. The calibration parameters were obtained by fitting the simulated water level against the observed as shown in Figure 2. Then, the same parameters were applied for the validation process. The validation result for the year 2013 is displayed in Figure 3.
From the error analysis, the simulated water levels for the year 2010 has a Nash–Sutcliffe efficiency (E) of 0.802 and Root-mean-square error (RSME) of 0.227. Both results indicate high accuracy of efficiency, Meanwhile, the validated results for year 2013 applying the same parameters value obtained from the calibration process show NSE of 0.644 and RSME of 1.259. Compare to the calibration, both errors obtained for the validation result are higher, indicating that the calibration parameters may need to be improved.
Figure 4. Result from the 2D flood inundation map obtained from the calibration process for the year of 2013.

Figure 4 indicates the flood inundation map for the year 2013. The maximum flood level range was 3.276–3.636m while the minimum flood level range was 0–0.364m. The maximum flood occurred at downstream at the low land area near the river mouth while the minimum flood level occurred at the upstream. Since the observed flood studies were only available at the circled region in Figure 4, the discussion focused only at this location. The others flood zones will be discussed in future after all the information are completely obtained.

Figure 5. Simulated flood map of the focus area based on the variable flood studies.
Figure 5 displays the flood extend area (highlighted in blue) or the floodplain area simulated by the Flood Modeller for the calibration result for year 2013. From the figure, the flood level range was 0 – 1m. Based on the hatched areas, the affected region was at Perumahan Sungai Isap Tiga. Besides that, the road branches within the villages were affected. In addition, there was water spilled over the swamplike area as circled in Figure 5. The simulated flooding areas obtained were underestimated compare to the flood report in the year of 2013 from Department of Irrigation and Drainage (DID).

The cause of flood occurred along the Kuantan river was due to continuous development of the Kuantan city which leads to the increasing imperviousness of land areas. More impervious areas have reduced the infiltration of water into the ground and consequently increase the runoff volume during rainy season. Therefore, it is important to consider the land use effect in the urban area when designing flood mitigation measures in the Kuantan River Basin.

4. Conclusion

In all, the 30m resolution of ASTER-GDEM is suitable to be integrated with the Flood Modeller to create flood inundation map for the KRB. In this study, the 1D channel model and 2D floodplain model were presented well by using Flood Modeller. The study has shown that the performance of the model to simulate the flood level is adequate with NSE of 0.644 and RSME of 1.259.

However, the generated flood map does not provide sufficient extension because the open source Flood Modeler applied in this study has limitation in term of the number of nodes and the 2D cells extend. Hence, it is recommended to use full version of Flood Modeler if possible. Moreover, if higher resolution of topography dataset is available such as LiDAR, more accurate result can be obtained. Nevertheless, the adequate result obtained in this study has shown that the 30m ASTER-GDEM coupled with the open source Flood Modeller can be used as preliminary flood inundation study.

By having the flood inundation map, the flood level and flood areas can be predicted and this information are useful for the water authorities in decision making such as evacuation during flood event, and selecting flood mitigation options.

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