LOWLAND TECHNOLOGY INTERNATIONAL Vol. 13, No. 1, 27-35, June 2011
International Association of Lowland Technology (IALT), ISSN 1344-9656

FLOOD INUNDATION MODELING FOR KOTA TINGGI CATCHMENT BY COMBINATION OF 2D HYDRODYNAMIC MODEL AND FLOOD MAPPING APPROACH

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ABSTRACT: Flood inundation model in lowland catchment area plays an important role in flood management. This paper describes the development of flood inundation model where Kota Tinggi catchment has been chosen as the case study. This model is built using InfoWorks River Simulation (RS) and it is combined with flood mapping techniques. This model is calibrated using historical flood event on 12th January 2007. It is found that the water level of the river overflows due to heavy rainfall on January 12th 2007, and the highest rainfall data of 50.8mm was recorded. The outflow hydrograph from the breach was estimated to perform inundation simulation. Flood inundation simulation shows that the water spread out through the Kota Tinggi catchment and the maximum inundation depth was above 10 m. The results of this research will benefit future modeling efforts by providing a tool for hydrological forecasts of flooding on lowland areas. While designed for the Kota Tinggi catchment, this model may be used as a prototype for model applications in other areas of the country.

Keywords: Flood inundation Model, Flood mapping approach, 2D hydrodynamic modeling, Kota Tinggi Catchment

INTRODUCTION

Flooding is one of the major natural disasters that affect many parts of the world including the developed nations. Besides losing billions of dollars in infrastructure and property damages, hundreds of human lives are lost each year due to flooding. Major changes in land use that affect hydrology systems are deforestation, intensification of agriculture, drainage of wetlands, and urbanization. One of the keys in preventing and reducing losses is to provide reliable information to the public about the flood-risk through flood inundation maps. Besides identifying future flood level areas, flood inundation modelings are also useful in rescue and relief operations related to flooding.

2 Dimensional (2D) models are best employed in conjunction with a Digital Elevation Model (DEM) of the channel and floodplain surface that, in conjunction with suitable inflow and outflow boundary conditions, allows the water depth and depth-averaged velocity to be computed at each computational node at each time step.

Thus the need of flood inundation modeling has increased in line with model developments and increased computational resources, but the possibility that simpler models may provide similar levels of predictive ability has not actually been considered (Bates et al. 2000).

The 2D nature of flood maps has promoted the use of 2D models in order to promote the synergy between distributed observations and predictions, whereas point measurements of stage or discharge are more compatible with 1 Dimensional (1D) model. The high resolution of remotely sensed data has encouraged modeling at a higher spatial resolution than was previously recorded, and has also encouraged the integration of high resolution DEMs into hydraulic model (Horritt et al. 2002).

The recent advancement in the computer technology enables the computer models to be developed by

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Note: Discussion on this paper is open until December 2011

modelling the river system and perform flood simulation; prediction can be made to avoid unexpected flood and remedial action can be taken earlier.

In view of the above and severity of the damages caused by extreme events, it is therefore necessary to establish a hydrologic model to simulate flood levels. This is very much necessary for identification of possible inundated areas, so that a flood warning can be issued to the people in the affected areas. Therefore a study of river modeling for flood simulation is important to avoid any future disaster. This paper presents the results of the application of 2D hydrodynamic model combined with flood mapping approach to model a river network, simulate flood and produce a flood inundation model for Johor River, Malaysia in Kota Tinggi Catchment.

STUDY AREA

Kota Tinggi Catchment in Johor, Malaysia is the largest district with an area of approximately 3,490 km^2. Sungai Johor has a drainage length of 122.7 km that covers an area of 2,636 km^2. It originates from Mount Gemuruh that flows through the south-eastern part of Johor and finally into the Straits of Johor. About 60% of the catchment is undulating highland rising to a height of 366 m while the remainder is lowland and swampy. The highland in the north is mainly jungle. (Razi et al. 2010) With reference to the Soil Map of Malaya, Kota Tinggi catchment infiltration rate is in group A which is 0.30 to 0.45 in/hr (MASMA 2000). The catchment receives an average annual precipitation of 2,470 mm and the temperature in the basin ranges from 21°C to 32°C. Fig. 1 shows a part of Kota Tinggi catchment area.

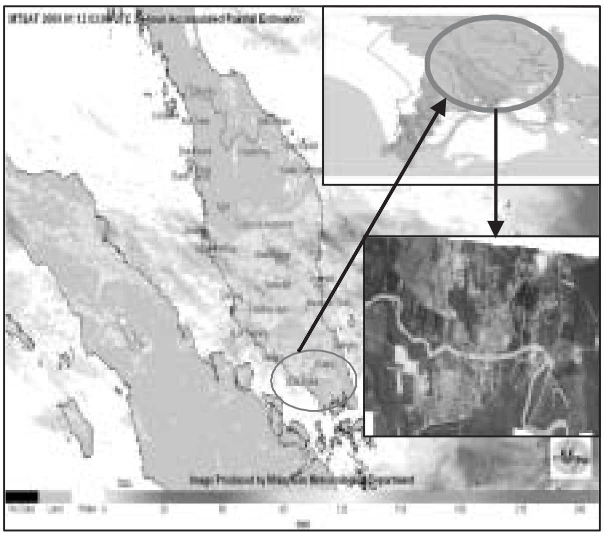

Fig. 1 Kota Tinggi Catchment Area Map

Fig. 2 Flood at Kota Tinggi town in January 2007

In January 2007, Kota Tinggi town was affected by flood and it was reported that several downstream areas along Sungai Johor were inundated and this is attributed to the reverse tidal flow. Magnitude of flooding was its maximum when heavy rainfall occurs together with the upsurge of tides. Fig. 2 shows a picture of Kota Tinggi town in January 2007 flood.

FLOOD INUNDATION MAPPING

Flood inundation mapping provides flood risk maps that represents the characteristics of a hypothetical flood graphically from a synthesis of past flood events. With sufficient long term and accurate records, flood extents drawn from the empirical results become very powerful prediction tools because the flood risk map is often a map of more than one flood event. Flood inundation maps are therefore the basic tools and starting points of regional flood intervention policy (Jeb et al. 2008). For the public, flood inundation maps can help to increase overall public awareness on flood risk and hazards.

Flood inundation mapping, when combined with reliable flood forecasts, can provide local authorities with important information for emergency flood response. The accuracy and the utility of a flood inundation map totally depend on the quality of the topographic information used as the base for the map. Where topographic information has been gathered digitally, its utility depends on its resolution. Previously, flood inundation modeling has been constrained by the limited spatial resolution of available topographic data sources or the cost of acquiring such data through ground survey. Hence, model resolution has typically been much finer that the resolution of the topography data used to drive the simulation (Bates et al. 2003). In very flat areas, where a few feet in elevation make a tremendous difference in the extent of the floodplain, high-resolution data is critical but not always available.

Collection of ground elevation data is a resource intensive task in terms of human resources, time and money (Merwade et al. 2008).

The ground elevation data known as Digital Terrain Model (DTM) can be obtained from various sources such as LIDAR, aerial photo, ground survey and satellite data. DTMs are standard products from aerial photography using analytical and digital photogrammetric techniques (Jing Li et al. 2009). However, the measuring technique is a manual process which requires skills and experience of inserting the measuring mark on the stereo model surface with every new measurement. This is a very slow operation so obtaining a DTM is usually a time consuming and very costly process. Digital photogrammetric employs image matching techniques to compute elevation measurements from stereo pairs of digital aerial photographs. Then DTM can be automatically performed which makes the process much faster and very cost effective compared to the analytical technique. Unfortunately, the quality of these automatically generated DTM may not be as high as when compared with a DTM from analytical techniques. Therefore, interpolation of historic/traditional data (typically cross sections) in conjunction with other datasets such as aerial photographs, LIDAR and digital elevation models (DEMs) is a common approach in creating flood mapping.

The spatial resolution and vertical accuracy of surrounding topographic datasets are dependent on factors such as techniques used for data collection (e.g. air borne LIDAR or contour surveys) and processing (e.g. interpolation of contour lines and filtering algorithm for LIDAR) because geometric descriptions of channel bathymetry and its surrounding topography affect hydrodynamic modeling of river channels including flood inundation mapping (Merwade et al. 2008; Cook et al. 2009). It is important to understand and address the issues associated with creating river terrain models using conventional approaches. The importance of using an accurate and high-resolution DEM for hydrologic modeling is underscored by these terrain-preprocessing steps; if the DEM used is not sufficiently accurate, simulated rivers may follow very different paths from their actual pathways, and consequently watersheds will be delineated incorrectly (Knebl et al. 2005).

However, the country's hydrology and hydraulics information is out of date. Flood inundation mapping in the Kota Tinggi Catchment, however is complicated by a number of factors. Some of these factors include inadequate topographic information, tidal effects at the mouth of the Johor River, changes in the distribution of flow in the distributaries channels and flooding resulting from high rainfall directly on the delta.

HYDRODYNAMIC MODEL

A number of researches on the applications of hydrodynamic models based on the one-dimensional Saint-Venant equations have been conducted. However, the performances of these models are not satisfactory as applied to tidal rivers. The main reason is the shortage of local flow data and many factors related to the real-time flood forecasting. It is thus valuable to improve the performance of the hydrodynamic model. (Bao et al. 2009).

River hydraulic model used for flood simulation modeling can be classified as one dimensional (1D) or two dimensional (2D) hydrodynamic models. 1D hydrodynamic model are widely used. They are based on the St. Venant equations (conservation of the mass and momentum laws for shallow water) to calculate the free surface flow for steady and unsteady flows in open channels. The following basic Saint Venant equations for the conservation of mass and momentum are used to describe the flow and water level variations in dimensional models are shown in Eqs. (1) and (2).

$$\frac{\delta Q}{\delta x} + \frac{\delta A}{\delta t} - q = 0 \qquad (1)$$

$$\frac{\delta Q}{\delta x} + \frac{\delta}{\delta x}\left(\frac{\alpha Q^2}{A}\right) + gA\frac{\delta h}{\delta x} + \frac{gQ|Q|}{C^2 AR} = 0 \qquad (2)$$

These shallow water partial differential equations are solved by numerical equations using most often the finite difference method or in some cases by the finite element method or the finite volume method in an implicit scheme; under the assumptions that the water is incompressible and homogeneous, the bottom slope is small and the water lengths are large when compared with the water depths (Mu et al. 2007). 1D hydrodynamic model require a minimum amount of data as the river cross section geometry, the river bed resistance factors and, the time series for discharges and water levels at the boundary conditions. Examples of 1D hydrodynamic modeling system are MIKE 11 (DHI Water & Environment), HEC-HMS (US Army Corps of Engineers) and Info works (HR Wallingford). Whilst these 1D hydrodynamic models compute energy-loss between successive cross-sections and either subcritical or supercritical flow regimes, they are unable to model many features of high-magnitude floods (Jonathan L. Carrivick 2006). Indeed 1D hydrodynamic model, slope area methods and other hydrological methods only provide reconstructions of peak discharge. Thus these methods do not provide information on how flow conditions varied before and after peak stage, or how long peak discharge persisted. Other features of high-magnitude floods are also excluded, such as rapidly varied flow, or specifically; simultaneous inundation of multiple channels, sheet or unconfined flow, simultaneous channel and sheet flow, flow around islands, hydraulic jumps, multi-directional flow including backwater areas and multiple points of flood initiation. Without a quantification of the hydraulics associated with these flow conditions, high-magnitude flood impacts cannot be fully understood.

Nowadays, the availability of high resolution Digital Elevation Models (DEMs) to represent the earth surface allows coupling hydraulic models to obtain the flood extent and water levels in floodplains. Many studies on flood mapping have been conducted using 1D or 2D hydrodynamic models (Horritt et al. 2002; Liu et al. 2003; Jeb et al. 2008; Bates et al. 2003; Jonathan L. Carrivick 2006; Merwade et al. 2008; Mason et al. 2009). Although 1D models are accurate in the main river channel they are not accurate for over bank flow (Bates et al. 1997) e.g. for modeling wave propagation from the river onto the floodplain. For the purpose of improving the performance of flood inundation model in the urban catchment, the integration of 2D hydrodynamic model and the flood mapping model is proposed and used in the Kota Tinggi catchment of the Johor River in Johor, Malaysia.

DEVELOPMENT OF FLOOD INUNDATION MODEL

The 2D hydrodynamic model used in this research is InfoWork RS, from HR Wallingford. The InfoWorks RS river model, namely a hydrodynamic model of the river simulation that incorporates ground models that extend across the catchments, and a hydrological model, representing the impact of wetting events on the river system by modeling run off of rain into the river system. The behavior of the river in terms of levels, rates of flow, and other parameters can then be simulated against various rainfall events.

Statistical analysis of historical rainfall patterns on January 2007 in Kota Tinggi catchment is used to determine designed rainstorms of specific return periods. These designed rainstorms are used as inputs to the model, hydrological and hydraulic analysis has been done to determine the resultant flows and levels, and finally the flood mapping results are calculated. By following this process, the model can be used to investigate the likely outcomes of specific design rainfall events. Rainfall data input to the model must be geographically specific, covering the whole catchment. The data used is usually from specific storms or extended rain events.

The basic component of the InfoWork RS model is a Digital Elevation Model of resolution and accuracy sufficient to identify both the channel (location and slope) and those elements of the floodplain topography considered necessary to flood inundation prediction. In reality this resolution and accuracy cannot be known a priori and may vary between applications, so an informed guess is needed as a starting point for model development. In time, we should be able to determine guidelines for this aspect of the model development process.

After the DEM for the Kota Tinggi catchment is available, the plan is to implement the 2D hydrodynamic model InfoWork RS. The model operates using an unstructured grid, allowing for greater detail near channels and levees, and is computationally efficient. Unsteady flow models are to be developed for a range of inflows at the upstream of the catchment and the water level at the downstream of the catchment. A library of inundation maps then are to be prepared for key locations in the catchment, with each map representing an inflow and water elevation. Subsequent development may allow the use of forecast peak flows at the upstream of the catchment to develop maximum inundation maps for a particular storm. Fig. 3 shows summaries of steps

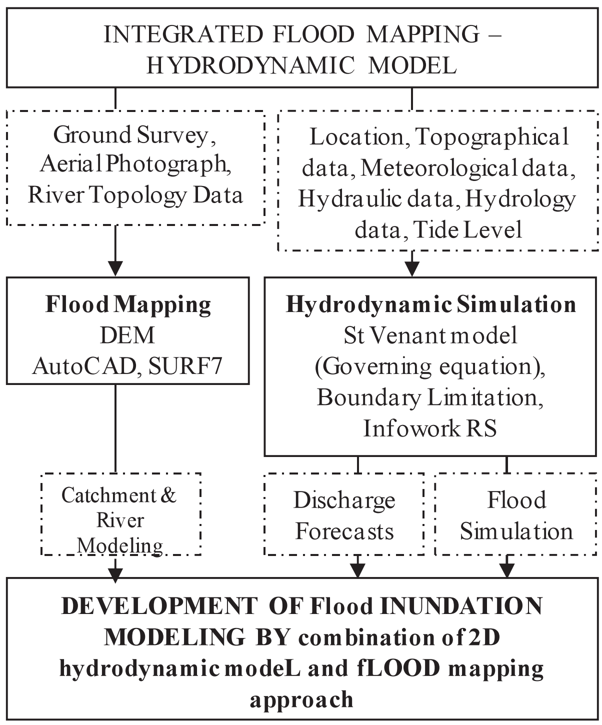

Fig. 3 Summaries of Steps in Flood Inundation Model

on development of flood inundation model for Kota Tinggi Catchment.

RESULTS AND DISCUSSION

2D Hydrodynamic Model

The cross section profiles of Johor River are collected from the Department of Irrigation and Drainage, Malaysia (DID) and compared with site survey data at Kota Tinggi Catchment done in May 2009. There are 15 river cross section profiles available in AutoCAD format which is later processed to be converted directly into InfoWorks RS model database. Fig. 4 show the river model of Johor River after input all the required data.

Hydrological data inclusive of cross section, water level data and rainfall data is imported into InfoWorks RS. From these data, a model is created and later simulated for the process of calibration and verification. The results can be obtained from InfoWorks RS.

In any hydrodynamic river simulation, the most important input would be the shape of the river which is represented by the cross section, river flow and water level (Bustami et al. 2009). Boundary conditions are the input data applied either at the upstream or downstream end points, to present the river flow on each or junction of the network. Figs. 5, 6 and 7 show the river cross section at different chainage from InfoWork RS.

Flow time Boundary is applied on Kampung Kelantan as the upstream inflow hydrographs. The flow time boundary specifies a pair set of data consisting of flows and times. Stage time boundary is used on Johor Lama as the downstream end of the network. A stage time boundary specifies a pair set of data that comprises of water levels above datum and times.

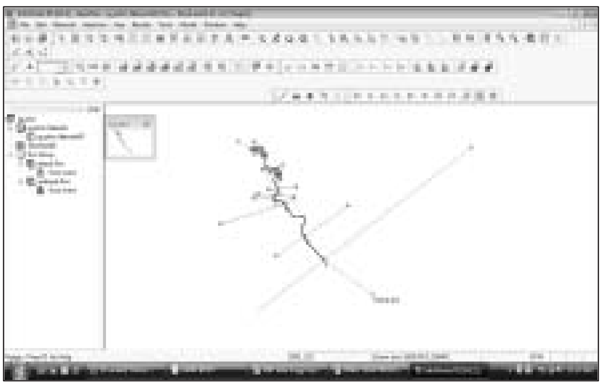

Fig. 4 Johor River Model

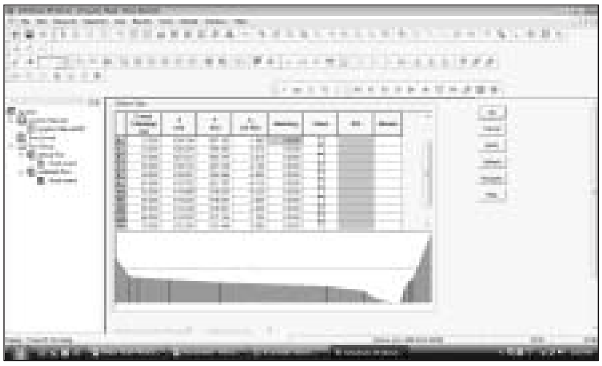

Fig. 5 River cross section at chainage A, Kampung Kelantan (Upstream)

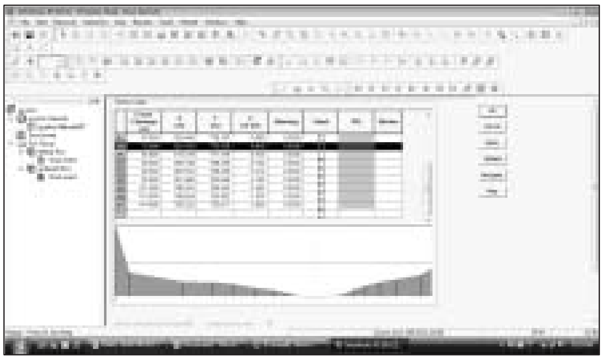

Fig. 6 River cross section at chainage H, Panti (Middle)

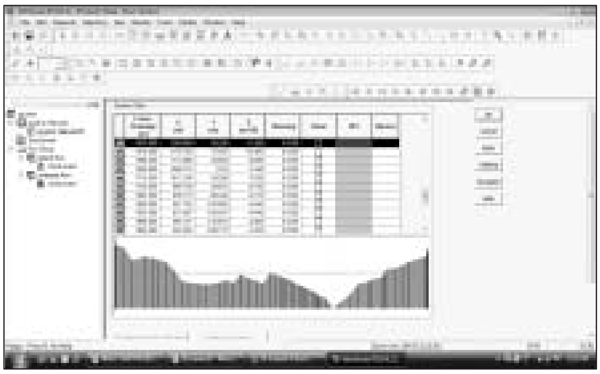

Fig. 7 River cross section at chainage O, Johor Lama (Downstream)

Simulation is the last process involving river modeling. This procedure is carried out to view the behavior of the river network under particular conditions and the effects of the input or given boundary conditions to the modeled river over a period of time. Simulations are grouped into runs, with each run applying to a single network but utilizing one or more events data sets. The time span given for simulations is dependent on the model (Siang et al. 2007).

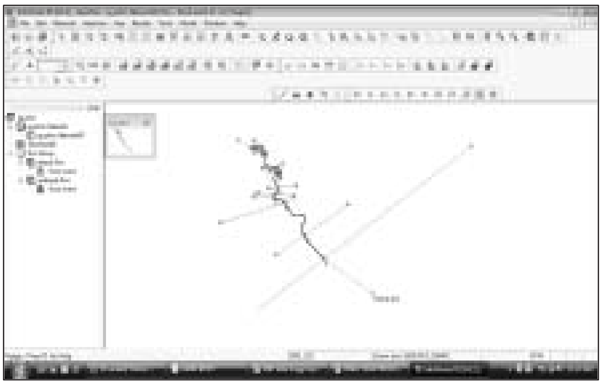

Fig. 8 Generated Direct runoff hydrograph for storm event of January 12th 2007

The information gathered from the analytical observation matched the storm events on January 2007. These storm events were selected to run simulations corresponding to the respective water level station data. Fig. 8 illustrates the derived hydrographs with the rainfall hyetograph.

Fig. 9 shows the water level record at the river mouth and it is used to define time variables of stage or water surface elevation at a downstream cross section.

Simulation for Unsteady Flow

The generated direct runoff hydrograph derived from the rating curve was used as the boundary input to simulate Johor River real time flood occurrence on January 12th 2007. For flood simulation, the result of simulation for unsteady flow is used because the maximum flow of unsteady flow is higher compare the steady flow (Bates et al. 2003).

The flood will occur when the water level of the river is over flow due to the heavy rainfall. Rainfall data on January 12th 2007 was selected when the flood is occurring during this month. Fig. 10 shows rainfall profile on 12th January 2007 and it shows that the highest rainfall data records are during 18.00 p.m. with the rainfall data record as 50.8 mm. It shows that the water level at the Johor River is over flow and flood will occur.

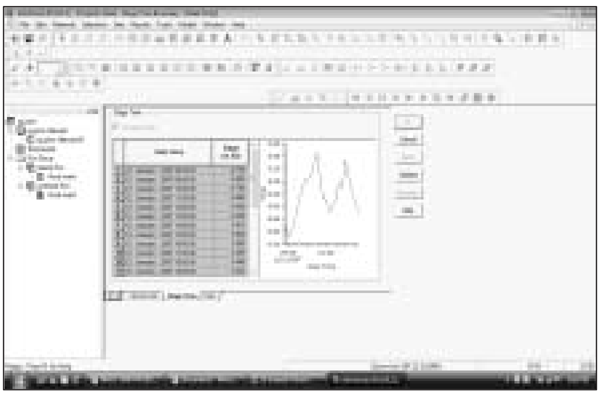

Fig. 9 The water level profile on 12 January 2007

The flood elevation profile proves that there was flood within the Johor River after 17 hours of continuous rain. The selected event on January 12th 2007 produced the flood simulation output with a rise in water level between 20.00 p.m. on January 12th 2007 to 4.00 a.m. January 13th 2007 which is 10 m increase. Fig. 11 shows

Fig. 10 Rainfall profile on 12th January 2007

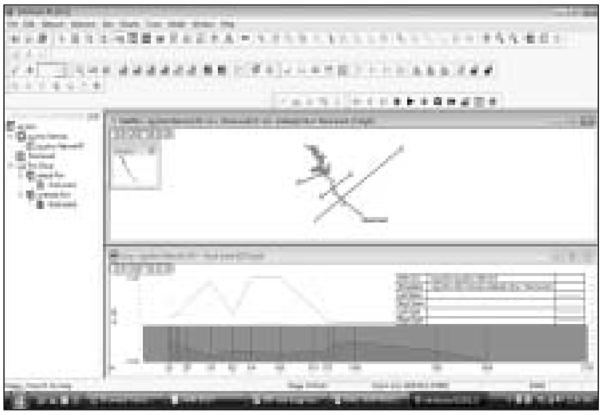

Fig. 11 Results of Simulation for Unsteady Flow

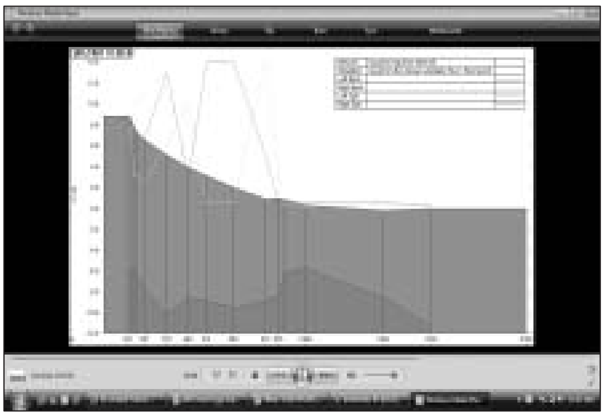

Fig. 12 River cross section at chainage O, Johor Lama (Downstream)

the simulation result of the unsteady flow and Fig. 12 show the flood simulation of the 12^{th} January 2007 storm event.

Flood Mapping Approach

Mapping is the most proper approach to describe flood pattern especially for flood mitigation. Thus, three dimensional (3D) maps are used to increase the flood speculation factors at Johor River in Kota Tinggi Catchment. Creating three dimension maps are challenging and costly. This topic describes a model that simulates flooding resulting from storm surge and waves generated by tropical rain weather. The model consists of two components implemented at three levels of nested geographic regions, namely, river, drain, and river mouth. The operation is automated through a preprocessor that prepares the computational grids and input atmospheric conditions and manages the data transfer between components. The storm surge and local tides define the water level in each nearshore region, where a prediction model uses the kriging gridding method to simulate the surf-zone processes and runup along the zone. This package is applied to hindcast the river flooding caused by tide and source from upstream.

Fieldwork data set contains position, topography height, time of observed and detail of spot. All data have to be synchronized together with the water level to comply the real time flood situation. Digital Elevation Model (DEM) set up by Surfer 7.0 to produce 3D map and used for overlapping process. Finally, water level map can be adjusted to establish the possible inundated area by entering the time of tidal period.

DEM's for Kota Tinggi Catchment has been prepared using aerial photo fine mode 10m. DEM accuracy was evaluated through comparisons of DEM derived to field surveyed value for elevations. SURF7 software was used to develop of flood map for Kota Tinggi catchment. SURF7 is a contouring and 3D surface mapping program that runs on Microsoft Windows. It will quickly and easily converts the data from DEM into outstanding contour, surface, wireframe, vector, image, shaded relief, and post maps. In this study, SURF7 wireframe maps were created to identify the possible inundated area. This wireframe maps provide an impressive three dimensional display of the data. Wireframes are created by connecting Z values along lines of constant X and Y. A wireframe map can be used to display any combination of X, Y, and Z lines. A DEM file was used to create this map and color zones were defined for the X and Y lines.

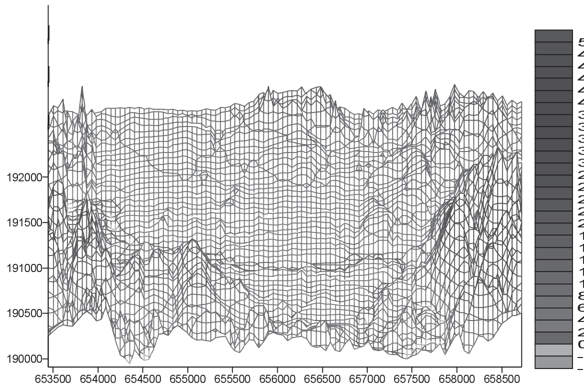

Fig. 13 Flood mapping for Kota Tinggi catchment

In the flood mapping development, the wireframe maps for Kota Tinggi Catchment was prepared after DEM conversion in AutoCAD. The wireframe processing output is illustrated in Fig. 13. The interpolation techniques used in flood mapping for Kota Tinggi catchment uses kriging gridding method to produce better results.

Flood Inundation Model

The results of the simulation of 2D hydrodynamic model can be visualized through the development of flood map using SURF7 and it is shown in Fig. 14. Flood inundation model for 12^{th} January 2007 are constructed for analysis to produce inundation planning maps. A flood inundation model is created in combination of 2D hydrodynamic model and survey model, SURF7 through a semi automated process where the topography is subtracted from the water surface to establish the inundation extent. The water surface used to map the inundation extent is created by linearly joining the water surface extent points on each cross section as shown in Fig. 14.

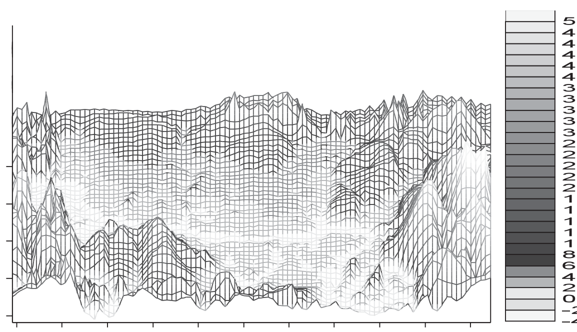

Fig. 14 Flood inundation model for January 12^{th} 2007 storm event

CONCLUSION

The integration of flood mapping with 2D hydrodynamic modeling opens up possibilities for flood control measures studies, flood forecasting, development of flood inundations model and flood evacuation plans especially for lowland area. The result shows that this model can be used as reference for identifying free land for future development in the Kota Tinggi catchment, especially in the affected lower regime of the catchment by flooding on which this research is focused. In addition, detailed visualization from flood inundation model can be important information for flood management programme in giving recommendations for future planning. This study proves that the application of combined flood mapping and 2D hydrodynamic model for development of flood inundation model integrated with changes of tidal level can be used for many programme in water resources management.

This study finds that the geomorphology of the river (or fluvial system) changes from time to time with changes in man-made artifacts such as embankments. Within 5 or 10 years, there could be changes in the geomorphologic features within one area, especially in the low land area where erosion and sedimentation can take place simultaneously as well as man-made modifications of the river. These kinds of changes were not included in the modeling parameters. Therefore, integrating hydrological modeling with geomorphologic modeling that shows prediction of changes will be of benefit to the hydrological engineers of which a higher accuracy prediction could be obtained.

ACKNOWLEDGEMENTS

The author/authors would like to thank the Ministry of Higher Education, Malaysia, Department of Irrigation and Drainage, Malaysia, University Tun Hussein Onn Malaysia and University Teknologi MARA for the support of this research.

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