

2D FLOOD INUNDATION SIMULATION BASED ON A LARGE SCALE PHYSICAL MODEL USING COARSE NUMERICAL GRID METHOD

Muhammad Azraie Abdul Kadir¹, *Ismail Abustan², Mohd Firdaus Abdul Razak³

^{1,2,3}School of Civil Engineering, Universiti Sains Malaysia (USM)

*Corresponding Author, Received: 07 Jan. 2019, Revised: 13 Jan. 2019, Accepted: 31 Jan. 2019

ABSTRACT: The implementation of various 2D numerical modeling techniques in the flood inundation analysis is vastly explored. However, understanding of the flood inundation uncertainty of this technique still limited. This paper evaluates 2D hydraulic models (HEC-RAS) in term of ability to simulate the surface flow of the large scale physical model. A physical model was developed based on high-resolution DEM (0.5m resolution) data of Sungai Bertam with scale 1/25. A total area of 23 m x 7 m and 20.8 m channel length was constructed. The experimental physical model was run with various inflow value and used to calibrate and analyze the numerical simulation. Although the simulated result showed a good agreement with the physical model experiment, some uncertainty still needs to consider. This uncertainty happens due to the change in channel geometry which leads to the turbulence phenomenon.

Keywords: Flood inundation modeling, HEC-RAS, Physical model, 2-dimensional model

1. INTRODUCTION

The numerous economic damages and many people have suffered due to flood in the last decades. Therefore, it is necessary to properly and urgently tackle these issues [8]. A various solution has been proposed and implemented for flood risk management in infrastructure development planning and flood protection method including current trend real-time flood forecasting also known as flood nowcasting. Most of this solution required preliminary planning or major planning based on analysis and prediction of flood using flood inundation modeling [1,7]

A lot of flood inundation model has been developed and enhanced with different capabilities and function. Recently, there is growing interest among researchers on the implementation of the 2D coarser numerical grid method. This method can use large grid size and at the same time implementing subgrid to improve the accuracy of the topography information. The capability of this method is the coarser numerical grid method can be used in high-resolution topography through mass conservation. These methods can effectively be used to compute the spatial variability in free surface elevation as most of the application shows free water surface is smoother than actual bathymetry. The effectiveness of this technique needs to quantify at the free surface elevation and also mix surface as known most of the area consists of the mix surface elevation.

A large-scale physical model of flood inundation experiments quite rare in the literature such as [3] who carried out a simplified urban district model in the laboratory to investigate the influence of buildings on flood inundation. [6] build a distorted physical model of Ürkmez dam to investigate the flood propagation due to dam break resulting from the trapezoidal shaped breach. [9] carried out an urban district model experiment of Alpine Toce River in order to investigate the flooding of a populated area.

This paper examines the 2D flood inundation model with control large physical model experiment in order to quantify the effectiveness of coarse numerical grid method.

2. STUDY AREA

Sungai Bertam is located in 101° 23' 55'' E and 4° 25' 0'' N which is at the north-western corner of the State of Pahang Darul Makmur in Peninsular Malaysia within Cameron Highlands catchments. Upper Sungai Bertam has been selected due to the availability and possible risk face due to the downstream human activity and dam release at the upstream. This river also consists of constant man-made channel and floodplain which give good control of the physical model condition. Fig. 1 shows the selected area of Sungai Bertam. The white line shows cross section frame of channel and floodplain used to develop the physical model. This cross-section also is known as station after this.



Fig.1 View of the selected area of Sungai Bertam

3. METHODOLOGY

3.1 Data Availability

Topography data for Sungai Bertam which is DEM with 0.5 m resolution was generated using UAV. This data combined with river cross-section profile taken from Jabatan Pengairan dan Saliran Malaysia (JPS). The upstream flow condition was based on recommendation dam release by Tenaga Nasional Berhad (TNB).

3.2 Physical Model

3.2.1 Scaling of the Model

From the hydraulic point of view, the flow condition has to be similar on the scale model and on the real situation. The dimensional analysis emphasizes five non-dimensional numbers characterizing the flow, called Froude Fr , Reynolds Re , Euler Eu , Weber We and Cauchy Ca numbers. The surface flow is a free surface process dominated by gravity phenomena. Therefore, the Froude similarity must be respected. This requires that the ratio between the gravity and the inertia forces (which is the Froude number Fr) are both equal in the model and in the prototype. Eq. (1) shows the Froude number equation.

$$Fr = \frac{V}{\sqrt{gL}} \quad (1)$$

Where v is the average velocity of the flow; g is the acceleration due to gravity and L is the hydraulic depth

3.2.2 Physical Model Setup

The scale used for the physical model was 1/25

gives the total area of the physical model was 23m x 11.5m. Table 1 shows the physical model characteristic of the prototype and model. Due to the large-scale model involve, proper setup or construction of physical model are needed. 7 step or process involves which is setting up the base of the physical model with thick plywood, build the wall for the boundary of the physical model and place the channel (made by the transparent prospect) and a cross-section of floodplain (made by soft plywood with 0.8 m cross-section interval). After that, in between of the floodplain cross section was filled with non-cohesive material (sand) until reach approximately 2.5 cm below floodplain cross-section. This 2.5 cm above sand was filled with concrete mix. After that, the surface was smoothening using span. After 1 day, the surface of the physical model was wiped with waterproofing. Fig. 2 shows the whole system of the physical model.

Table 1 The physical model characteristic of the prototype and model

Characteristic	Prototype	Model
Channel Length (m)	520	20.8
Channel Width (m)	6	0.24
Maximum Floodplain (m)	97	3.88



Fig. 2 View of the whole system of physical model

3.2.3 Physical Model Experiment

For this study, the inflow was gradually introduced to the physical model until reach the needed inflow. Five different inflow were physical experimentally simulated in Case 0, Case 1, Case 2, Case 3 and Case 4 with inflow 32 l/s, 8 l/s, 24 l/s, 40 l/s and 64 m³/s respectively (in the actual condition: 100 m³/s, 25 m³/s, 75 m³/s, 125 m³/s and 200 m³/s). Then, the water surface elevation, velocity profile and flood extent for each station will be recorded. Additional data for 40 l/s inflow

experiment of flood area was measured using images captured by Unmanned Aerial Vehicle (UAV) and analyzed using ArcGIS software.

3.3 Numerical Model

3.3.1 HEC-RAS 2D

The HEC-RAS modeling system, developed by the Hydrological Engineering Center (HEC) of the US Army Corp of Engineers [10]. The HEC-RAS being used widely in hydraulic and flood inundation modeling is a 1D model code that can handle both steady and unsteady flow conditions. For unsteady condition, it solves the full St. Venant equation using an implicit finite difference scheme, by means of a solver adapted from the UNET model by [2]. Recently, HEC-RAS has been enhanced its capability with 2D model code that handles unsteady flow condition. This model code solves either 2D St. Venant equation or 2D diffusion wave using an implicit finite volume scheme. In term of grid or meshing, HEC-RAS implementing subgrid based on subgrid bathymetry approach [4]. This approach used the pre-computed stage at earlier modeling process to collect optimum information of hydraulic radius, volume and cross-section area. Although actual high-resolution details are lost, this information enough to model flood inundation simulation.

3.3.2 Model Simulation

For numerical modeling, the same inflow was simulated based on the actual condition of Sungai Bertram. Fig 3 shows the geometry configuration of the model. The average grid size (black line) used was 40m x 40m (80 times larger than DEM resolution), minimum grid size used was 23m x 23m (46 times larger than DEM resolution) and two breaking (red line) was developed along left and right floodplain of the channel to critically explored the breaching of the flow to the floodplain.

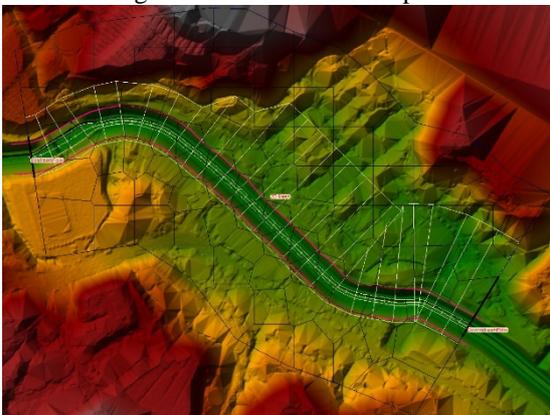


Fig 3 Geometry configuration for the model

The white line is the physical model frame. The outflow boundary considered as free flow.

Case 0 used as calibration purpose and the inflow value of this case was selected because of the wet area reach the channel and also floodplain as this study considered only two friction classes, one for the channel and one for the floodplain.

Manning's n value for the channel range from 0.008 to 0.010, equivalent to values quoted for lucite channel [5]. Values for the floodplain range from 0.013 to 0.016 equivalent to a surface concrete float finish [5]. This enables the full range of possible frictional values to be explored. The goodness of fit index of mean absolute error (MAE) was used to optimize the calibration processes. Mean absolute error (MAE) and another goodness of fit index were used in the analysis which is mean relative absolute error (MRAE) defined as follows:

$$MAE = \frac{\sum_{i=1}^n |X_{obs,i} - X_{mod,i}|}{n} \quad (2)$$

$$MRAE = \frac{\sum_{i=1}^n |X_{obs,i} - X_{mod,i}| / X_{obs,i}}{n} \quad (3)$$

Where n is the total number of the station; X_{obs} is the observed values at station i ; X_{mod} is the modeled value at station i .

For this study, each model was assessed by comparing the simulated flood extent at all station (29 stations) with those observed during the calibration case experiment. Fig 4 shows the result of the calibration as a contour plot of MAE value over both type of Manning's n value, showing the optimum as a close to 0 value.

Base on the result, manning's channel and floodplain used are 0.0098 and 0.0153 respectively.

The other parameter used in this study were: the HEC-RAS model can simulate for 1D, 2D and coupled 1D-2D. However, for this study only for the 2D, which did not consider the other two simulation method.

All modeling result was taken after 1hr simulation which is considered at the stable condition. The comparison between physical model experiment and numerical model simulation will be done in the actual scale of Sungai Bertam which mean the physical model experiment result was being upscale. Besides, station 1 and station 29 will be neglected due to inflow and outflow effect.

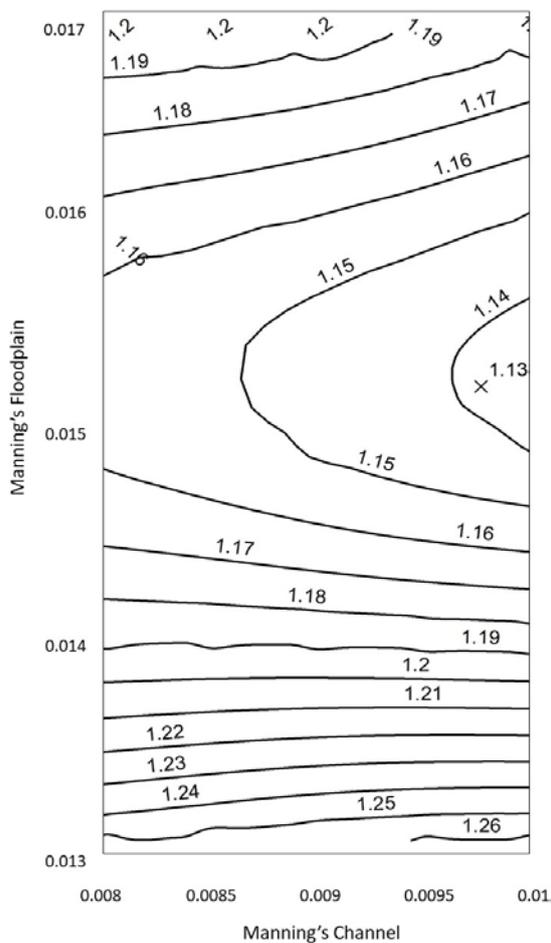


Fig 4 Calibration of the model: mean absolute error (MAE) versus the two model parameters for the calibration experiment.

4. RESULTS AND DISCUSSION

In this section we first describe the performance of the model in term of water surface elevation, then we discuss the accuracy of the model to simulate the physical model experiment in term of flood extent.

4.1 Comparing Water Surface Elevation

Fig. 5, Fig. 6, Fig. 7, and Fig. 8 shows the comparison of water surface elevation profile along the channel between the physical model and numerical model.

The result points out that, there is a significant difference in station 1 and station 2 which are inflow and outflow of the physical model. The significant differences arise due to the experimental setup and not due to the experimental simulation. So that, this station will be not considered.

For case 25 m³/s at the upstream flow, there is no data for numerical model specifically for station 1 and station 2. It probably due to the limitation of topography information gathered by HEC-RAS

when using large grid size where details high-resolution topography are lost and need to be covered by adding break line at the location with a sudden change in elevation.

Comparing between the physical model and numerical for all cases shows the physical model consists of several fluctuation conditions and this fluctuation increase by increasing the inflow value. The fluctuation happens due to change of slope and width of the channel at station 2 until 4, where at the station 4 there is a hydraulic jump. Drastically reduction of flow at station 12 happens due to the straight channel which causes the flow velocity to start to increase. At station 25 and 26, the bend location also influences the fluctuation of the WSE. Different from a numerical model, the result shows constantly gradual reduction of WSE along the channel. This significant difference between physical model and numerical model caused by the 2-dimensional model of HEC-RAS was less considered the change of channel geometry and also the effect of turbulence.

The overall accuracy of the numerical model shows good agreement between the physical model and numerical model as shown in MAE and MRAE analysis in Table 2. The increase of the inflow value shows the accuracy tends to slightly reduce the MAE. This is significantly influenced by the fluctuation happen along the channel for the physical model.

In summary, the 2-dimensional model can simulate the average or mean WSE profile only and less suitable to understand the actual situation or condition of WSE profile.

4.2 Comparing Flood Extent

Fig. 9, Fig. 10, Fig. 11 and Fig. 12 shows the comparison of the flood extent between the physical model and numerical model.

Case 2, Case 3 and Case 4 show a comparison of flood extent between the physical model and numerical model give similar trend with comparison in term of WSE which mean if the WSE comparison shows physical model higher than a numerical model at a specific station, it also gives a similar result in flood extent. The only difference is in Case 2 at chainage 80 shows the contrary outcome.

For case 1, the result gives significant different with physical model results. At the chainage 20 m no flood extent data and then follow with constant large flood extent than the physical model result. This result contrary with WSE result where the WSE of physical model higher than WSE numerical model. This outcome verifies the influence of the

grid setup (sizing and break line) to the model simulation. Although large grid size can be used in the

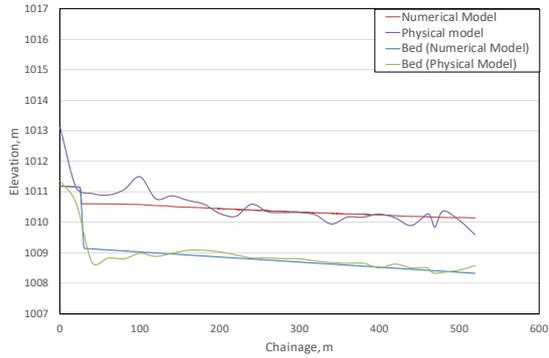


Fig. 5 Comparison WSE at 25 m³/s inflows

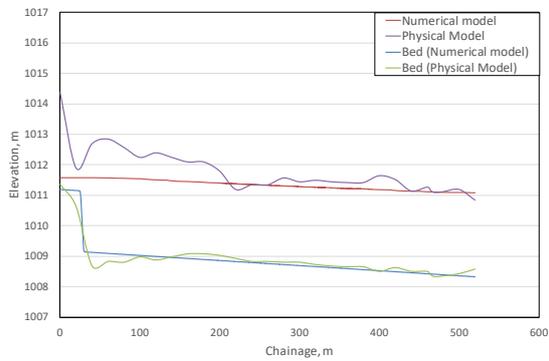


Fig. 6 Comparison WSE at 75 m³/s inflows

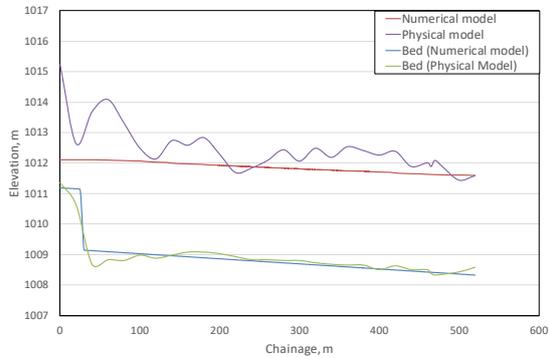


Fig. 7 Comparison WSE at 125 m³/s inflows

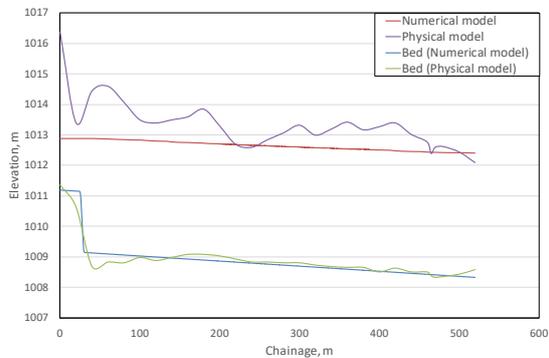


Fig 8. Comparison WSE at 200 m³/s inflows

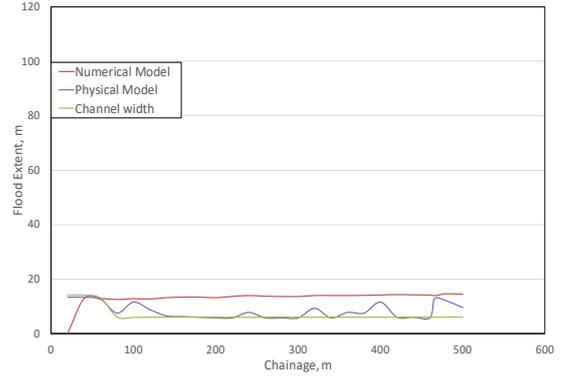


Fig. 9 Comparison flood extent at 25 m³/s inflows

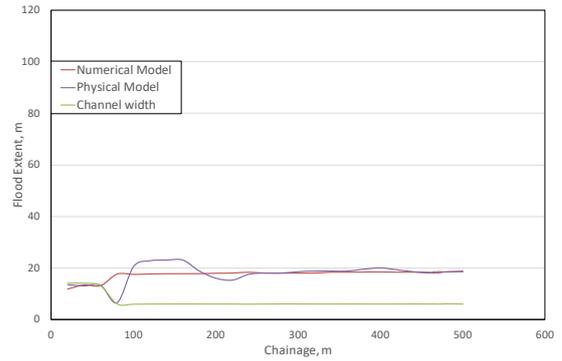


Fig. 10 Comparison flood extent at 75 m³/s inflows

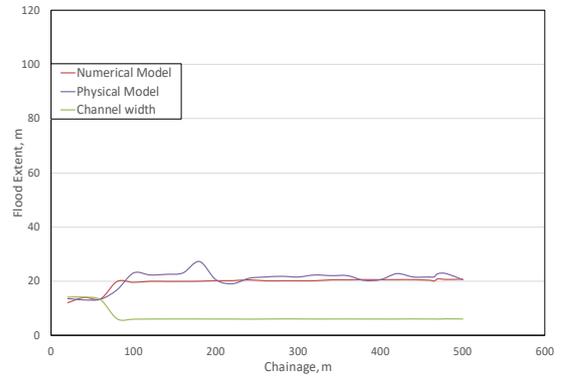


Fig. 11 Comparison flood extent at 125 m³/s inflows

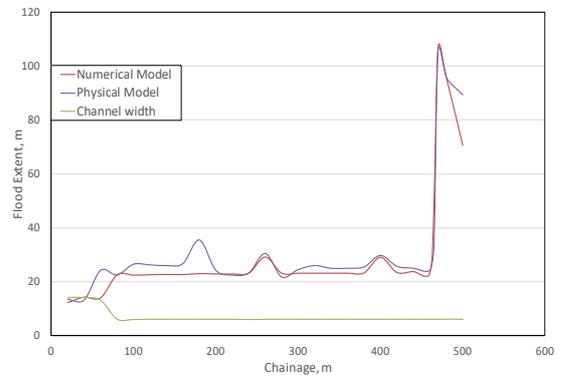


Fig 12 Comparison flood extent at 200 m³/s inflows

simulation, but the used of break line are essential to consider.

In term of location and flood area, there are 4 locations where flow breaching happens in both physical model and numerical model. The clear result can be seen in Fig. 13 and Fig. 14 which shows the flood extent at the 200 m³/s. Dotted box shows the location of flow breaching. The location 1, 2 and 3 show insignificant because the breaching flow does not breach too far from the floodplain boundary line. This breaching due to the topography elevation of that particular location. The significant result shows at location 4 where the flood extent reaches far from the boundary of a physical experiment. The width of the flow breaching also large compared with the other location. The outcome of this result shows proper flood mitigation management needs to be done in this area in order to reduce the flood risk in the area.

In term of the accuracy of the numerical model, Case 1 which is the lowest inflow shows the highest error in MRAE which is 0.832. This problem caused by similar reason in WSE. The other case shows an increase in the inflow value gives a significant increase in the MAE value. Table 2 show details of the MAE analysis.

More than 1m MAE for Case 2, 3, and 4 mostly influence by the cross-section interval used in the physical model setup which is 0.8 m (equal to 20 m at the actual condition) while the topography resolution of the numerical model 0.5 m. This outcome support by the flood extent results in Fig. 13 and Fig. 14. Dry area for numerical model happens in the middle of wet area mostly in between station 28 and 29 which mean physical model less considered the elevation of the dry area. The result of station 28 also the major element contribute to the high MAE for Case 4.

The overall accuracy of the numerical model shows good agreement between the physical model and numerical model as shown in MRAE analysis.

Table 2 Model result of MAE with MRAE in brackets, for depth and flood extent

Model code	Depth	Flood Extent
Case 1	0.200m (0.190)	5.758m (0.832)
Case 2	0.382m (0.139)	1.727m (0.131)
Case 3	0.565m (0.159)	1.769m (0.082)
Case 4	0.605m (0.137)	3.509m (0.110)

5. CONCLUSIONS

This study investigates the accuracy of the 2D model to numerically simulate a large physical model experiment with scale 1/25 using coarse grid numerical method by testing the few inflow boundary condition.

The performance of overall shows good agreement between the physical model and numerical model except the flood extent at the lowest inflow boundary condition case. This indicated the grid configuration of the 2D model is important. This finding confirms the capabilities 2D model to simulated flood inundation using large grid size. Future study on the influence of grid and subgrid of HEC-RAS model needs in order to determine the highest performance of computation processes and acceptable grid and subgrid combination.

6. ACKNOWLEDGMENTS

We gratefully acknowledge the School of Civil Engineering of Universiti Sains Malaysia for providing the required research facilities for this work. We are also thankful to the reviewers of this paper for reviewing the paper and providing their valuable suggestions. We would also like to acknowledge TNB Sdn. Bhd. for providing the financial support to carry out this works.

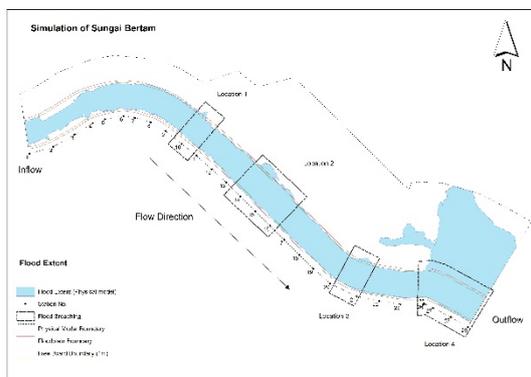


Fig 13 Physical Model Flood Extent for 200 m³/s inflows

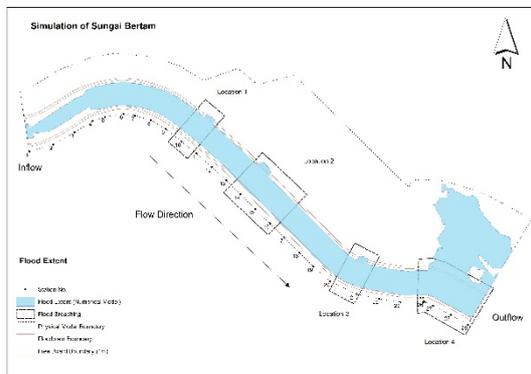


Fig 14 Numerical Model Flood Extent for 200 m³/s inflows

7. REFERENCES

- [1] Achleitner, S., Fach, S., Einfalt, T., and Rauch, W., Nowcasting of rainfall and of combined sewage flow in the urban drainage system. 11th International Conference on Urban Drainage, Edinburg. 2008.
- [2] Barkau, R.L., UNET one-dimensional unsteady flow through a full network of open channels. Davis: User's Manual, US Army Corps of Engineers, Hydrologic Engineering Center, 1997.
- [3] Beretta, R., Ravazzani, G., Maiorano, C., and Mancini, M., Simulating The Influence of Building on Flood Inundation in Urban Areas. *Geoscience*, Vol. 8, Issue 77, 2018.
- [4] Casulli, A. High-Resolution Wetting and Drying Algorithm for Free-Surface Hydrodynamics. *Int. J. Nemer. Meth. Fluids*. 2008.
- [5] Chow, V.T., *Open-channel hydraulics*. New York: McGraw-Hill, 1959.
- [6] Güney, M.S., Tayfur, G., Bombar, G., and Bayram, D.O., Experimental investigation of flood propagation due to trapezoidal breach in the distorted physical model of Ürkmez Dam. 6th International Perspective On Water Resources & The Environment Conference, 2013.
- [7] Hénonin, J., Russo, B., Roqueta, D.S., Sanchez-Diezma, R., Domingo, N.D.S., Thomsen, F., and Mark, O., Urban Flood Real-Time Forecasting and Modelling: A State-Of-The-Art Review. DHI Conference, 2010.
- [8] Pit, M., The Pitt review: learning lessons from the 2007 floods, Technical Report, UK Cabinet Office, London, UK, 2008.
- [9] Testa, G., Zuccalà, D., Alcrudo, F., Mulet, J., and Soares-Frazão, S., Flash Flood Flow Experiment in a Simplified Urban District. *Journal of Hydraulic Research*, Vol.45, 2007, pp.37-44.
- [10] USACE, HEC-RAS river analysis system user's manual. Version 4.1. Davis, California: Hydrologic Engineering Center, 2010.

Copyright © Int. J. of GEOMATE. All rights reserved, including the making of copies unless permission is obtained from the copyright proprietors.
