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Coupled 1D-2D hydrodynamic inundation model for sewer overflow: Influence of modeling parameters

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Abstract

This paper presents outcome of our investigation on the influence of modeling parameters on 1D-2D hydrodynamic inundation model for sewer overflow, developed through coupling of an existing 1D sewer network model (SWMM) and 2D inundation model (BREZO). The 1D-2D hydrodynamic model was developed for the purpose of examining flood incidence due to surcharged water on overland surface. The investigation was carried out by performing sensitivity analysis on the developed model. For the sensitivity analysis, modeling parameters, such as mesh resolution Digital Elevation Model (DEM) resolution and roughness were considered. The outcome of the study shows the model is sensitive to changes in these parameters. The performance of the model is significantly influenced, by the Manning's friction value, the DEM resolution and the area of the triangular mesh. Also, changes in the aforementioned modeling parameters influence the Flood characteristics, such as the inundation extent, the flow depth and the velocity across the model domain.

Keywords: Inundation; DEM; Sensitivity analysis; Model coupling; Flooding

1. Introduction

Small-scale urban flooding in most cities around the world, where underground sewers are employed to transport both storm and wastewater, is usually caused by sewer overflow due to inadequate carrying capacity of sewers. Most of the existing inundation models that could be explored to predict small-scale urban flooding are designed for prediction of flooding in large flood events, such as river floods. Therefore, some changes to these models are essential before they could be efficiently adopted as candidates for 1D-2D coupling for small-scale urban flood modeling. The quest for

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effective models to predict small-scale urban flooding, resulted in the development of a new 1D-2D model, obtained from coupling together an existing 1D Storm Water Management Model.

(SWMM, http://www.epa.gov/ednnrmrl/models/swmm/index.htm#Description,2008), 2D inundation model, BREZO (Begnudelli et al., 2008; Begnudelli and Sander, 2006; Brett, 2008). The process involved in the development of new 1D-2D model, its subsequent application for optimization have been reported elsewhere (Adeogun et al., 2012; Delelegn et al., 2011). However, during simulation with 1D-2D models, large number of parameters (calibration values), input data are required. In such a situation, it is expected that the simulation model would be sensitive to the quality of the data employed in simulation, model development. In view of the aforementioned statement, conduct of a sensitivity analysis on a simulation model might be instrumental to identifying specific area of concentration during model development, calibration. Also sensitivity analysis might provide useful information on the influence of quality of data employed during model simulation on the accuracy, validity of the model, thus paving the way for model improvement.

Sensitivity Analysis (SA) is basically an extension of an uncertainty analysis, aiming to determine the contribution of uncertainty in individual input parameters on the output (Crosetto et al., 2000; Moel et al., 2012). SA is usually performed as a series of tests in which an input parameter into a model is changed during model simulation and response to the changes in model performance due to the change in the input is then observed. Thus, SA has been regarded as a useful tool in model building as well as in model evaluation (Crosetto et al., 2000). The conduct of sensitivity analysis on a model during simulation enables to identify parameters that have significant influence on model performance. Identifying the dominant factors influencing model performance could pave the way for reduction of the influence of these factors on the model performance, in terms of uncertainties introduced by the factors (Moel et al., 2012). For instance, Hunter et al. (2008) has reported the influence of calibration procedures on model performance of some selected 2-D hydrodynamic models by employing different pairs of roughness coefficients chosen from a wide but plausible range (Hunter et al., 2008). In the same vein, Bates and De Roo (2000) studied the effect of friction parameter and grid size on model performance of a 2-D hydrodynamic model and the authors concluded that bed friction, a parameter during model simulation, significantly influenced performance of the model (Bates and De Roo, 2000).

Against this background, sensitivity analysis has been performed on our recently developed 1D-2D inundation hydrodynamic model to provide insight into influence of input parameters on the model performance. Input parameters, such as mesh resolution, DEM resolution and roughness were considered in the study.

2. Sensitivity analysis and case study area

Local and global approaches are the two approaches to SA usually employed in practice (Pappenberger et al., 2008). In the local approach, input parameters are varied one at a time while keeping the other input parameters constant (Saltelli, 1999). This is achieved by varying input parameters manually one at a time to evaluate the model performance to the change in the input and random sampling and regression analysis are common techniques used in this approach (Turanyi, 1990). However, only the sample space around the baseline situation is explored and interaction between input parameters is not considered (Moel et al., 2012). On the other hand, the global approach of SA considers the entire sample space, and the total variation around the output is apportioned to the different input parameters while accounting for the interaction between these parameters (Ratto et al., 2001).

Furthermore, uncertainty analysis normally employed to study variation of model parameters in simulation models can be categorized into pre-calibration and post-calibration sensitivity analysis (Tsegaye, 2008). The pre-calibration SA is done prior to calibration of the model to identify the sensitive and insensitive model parameters, without prior knowledge of their values. This makes it possible to put more effort into calibration of sensitive parameters during the calibration phase of model development. Monte Carlo Simulation (MCS) is commonly used in pre-calibration uncertainty/sensitivity analysis. MCS is a global method which considers many possible values within the entire input parameter distribution to estimate the sensitivity of the model performance to a change in input parameters. In contrary, post-calibration uncertainty/sensitivity analysis, is used to investigate the effect of changes in optimized model input parameters on model performance. This analysis provides an indication of risk associated with decision-making using predictions of flood models due to inaccuracies of model input parameters.

The local SA is the simplest method to quantify the effect of individual parameters on model performance. In this approach, the input parameters are perturbed by a given percentage away from the correct (or optimized) value, while

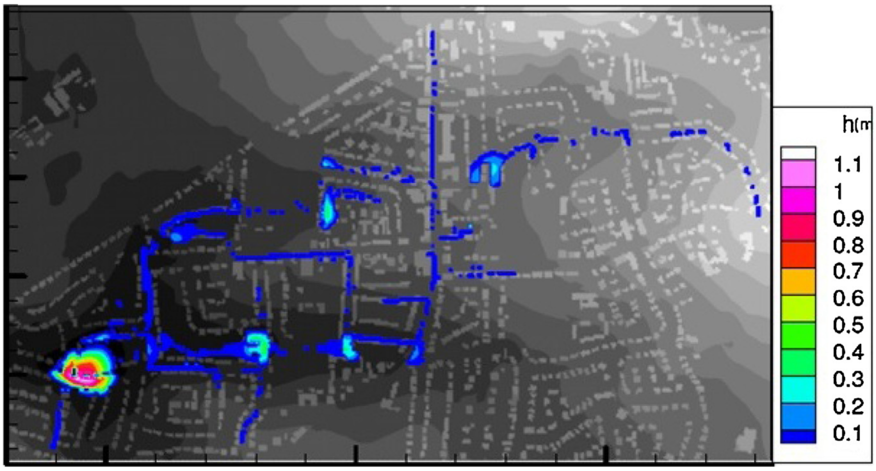

Fig. 1. Flood map of Central model (West Garforth case study area) showing water depth (h).

the other input parameters are kept constant, and the response of the model output to the change is monitored. In this study, model parameter sensitivity at pre-calibration stage was considered.

The sensitivity analysis was conducted on the developed coupled model which was applied to a case study area situated in West Garforth, a town within the City of Leeds in West Yorkshire, England with a population of about 15,000 inhabitants. According to the final report of West Garforth Integrated Urban Drainage Pilot Study DEFRA (DEFRA report, 2008), town mainly consists of low density residential development area served by two separate drainage systems; namely one in the northern area and the other in the southern area. Flooding at this site was reported to have been caused mainly by surcharged overflow due to inadequate hydraulic capacity of the existing drainage system (Hellmers, 2009). The resulting flood map of the case study area after simulation is as shown in Fig. 1.

2.1. Parameters for sensitivity analysis

2.1.1. Effect of mesh resolution on the developed 1D-2D model

The effect of changes in mesh resolutions and roughness parameter were studied on the developed inundation model using a carved domain generated from the case study area in the city of West Garforth, UK. The carved domain was created by using ArcGIS tool to plot the resulting flood map after simulation as flood points overlaying the computational domain of the selected case study area. A shape file encapsulating the flood point area is drawn and has an estimated computational area of about 44 Hectare which represents 59 percent of the total computational domain of the case study area. *Triangle software* developed by Shewchuk (1996) was used to generate exact Delaunay triangulation, constrained Delaunay triangulation and high quality meshes of the sub-domain created. Generation of some of the required files needed to run the coupled model was also carried out using the triangle software. The effect of mesh resolution on the modeling result was achieved by varying the grid sizes of the computational domain with the use of constant modeling parameters (simulation period and time step) for each of the simulations. The pictorial view of the steps involved in the sub-domain creation is as displayed in Figs. 2 and 3. The variation in the grid sizes is as listed in Table 1.

Table 1
Effect of the change in mesh resolution on the performance of 1D-2D inundated model.

Mesh resolution (m^2)	Triangular mesh	Computational time (minute)	Inundated area (m^2)
7	98,495	23.50	13,093
8	86,315	21.00	11,635
20	34,347	7.00	9884
32	21,541	4.50	9476
112	6162	2.20	6537
200	3405	1.20	5458

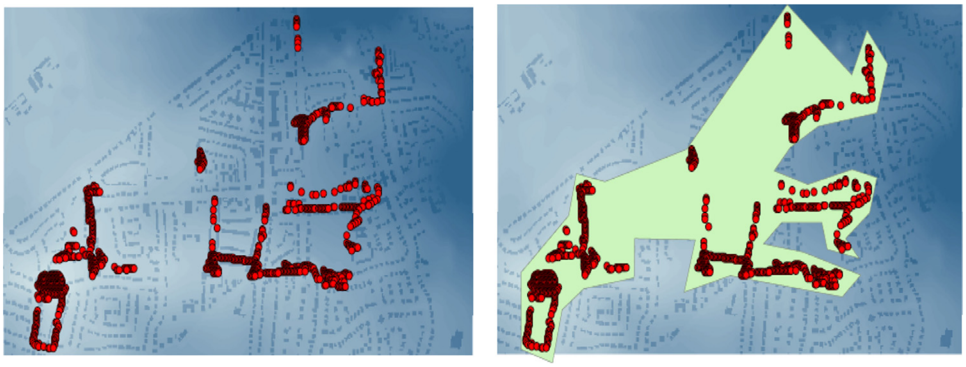

Fig. 2. Flood map plotted as points on the computational domain of the case study area. Note the carved domain on the LHS.

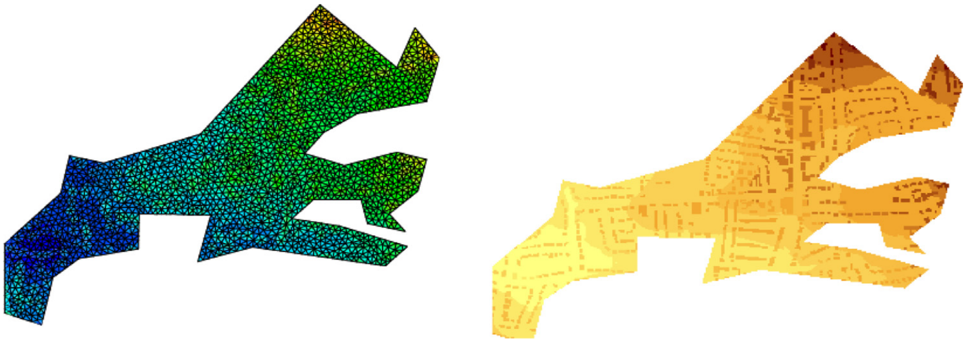

Fig. 3. Triangulation and attribution of the created sub-domain with roads and buildings.

2.1.2. Effect of DEM resolution and roughness parameter on flood simulation results

In the real world, topography is one of the critical factors affecting the propagation of flood wave in a channel and its surrounding floodplain. In order to understand how the variation of the DEM resolutions and roughness parameter affects the modeling performance, a hypothetical case study area of 200×100 m was set up and triangulated into 3857 computational cells. Other necessary files to run the model were produced using Triangle software. The triangular mesh and the DEM of the hypothetical domain are shown in Fig. 4.

3. Results and discussion

3.1. Effect of mesh resolution

The effect of change in mesh resolution on the performance of the developed coupled hydrodynamic model is as presented in Table 1. Also, flood maps (normal and maximum flood maps scenarios) for mesh resolutions (7 m^2 and 8 m^2) and (112 m^2 and 200 m^2) are as shown in Figs. 5 and 6, respectively.

The results indicated that a lower computational time was achieved at high resolutions (112 m^2 and 200 m^2). However, the output flood map deviated greatly from the result obtained with lower resolutions (7 m^2 and 8 m^2). It was also noticed that as the mesh resolution increases from 7 m^2 to 200 m^2, the inundated area also diminishes in value. However, lower grid resolutions give a good representation of the flood event but with high computational time.

3.2. Effect of friction parameter

The sensitivity of the developed model to changes in the value of friction parameter was investigated by considering frictional values from physically plausible range: 0.02–0.05, representing the real world system (Chow, 1959). The Manning's parameter was varied in conjunction with different mesh resolutions. The influence on flood extent maps is as shown in Figs. 7 and 8. Also, summary of the results (flood extent map area and computational cost) of each simulation

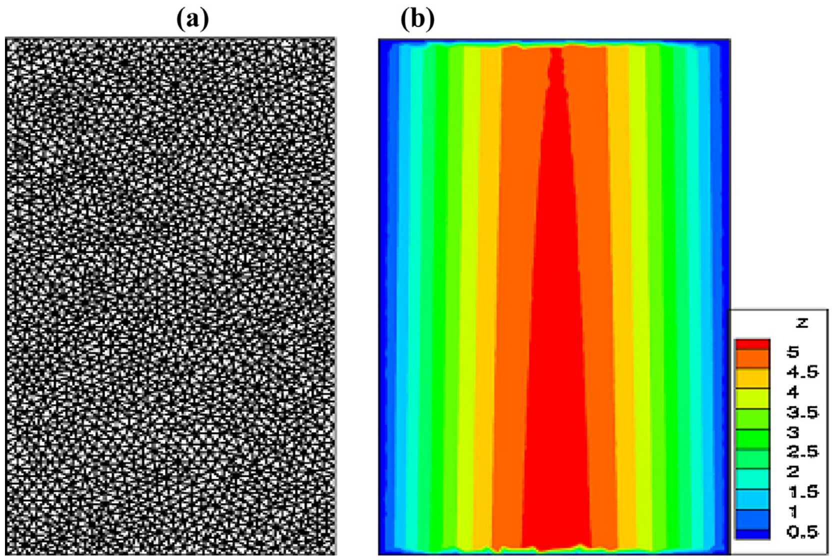

Fig. 4. Hypothetical case study area of 200 m × 100 m triangulated into 3857 computational cells. Triangular mesh (a); DEM (b).

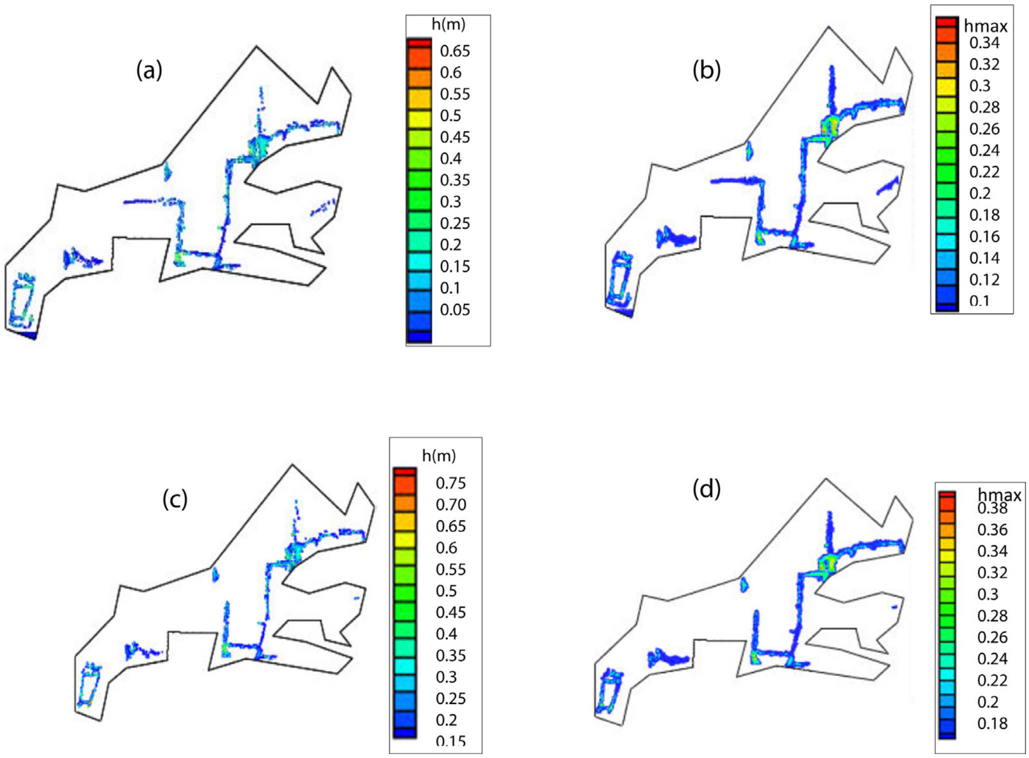

Fig. 5. Normal and Maximum Flood Map scenarios for 7 m^2 (a and b) and 8 m^2 (c and d) area resolutions.

are presented in Table 2. Inferring from the results presented in Table 2, it is obvious that flood wave propagation in urban floodplain is influenced by the friction parameter and this effect is a function of the time necessary for its propagation. The flow velocity of flood as it propagates on the floodplain is given by Eq. (1)

$$V = \frac{1.49}{n} \times R^{0.66} \times S^{0.5} \quad (1)$$

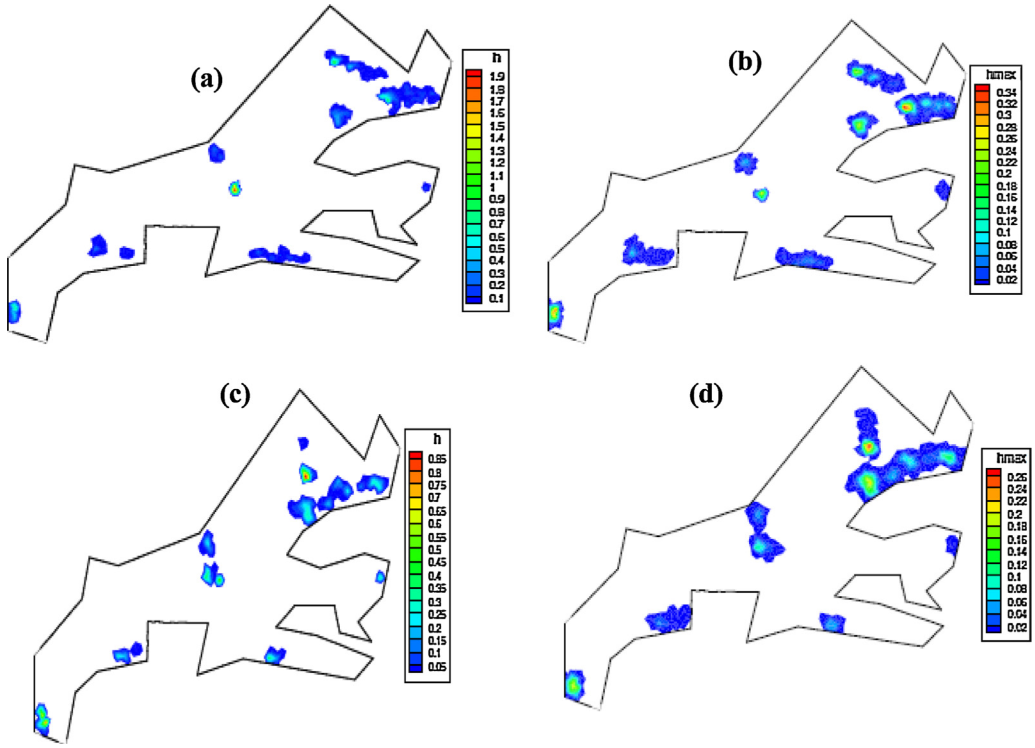

Fig. 6. Normal and maximum Flood Map scenario for 112 m^2 (a and b) 200 m^2 (c and d) area resolutions.

Table 2
Effect of variation in Manning's value and the associated computational time for each of the simulation.

Mesh area (m^2)	Manning's value	Flood extent map (m^2)	Computational time (minute)
5	0.020	391.4	1.39
	0.035	382.8	1.40
	0.040	380.2	1.41
	0.050	377.4	1.41
10	0.020	172.0	1.02
	0.035	166.4	1.05
	0.040	164.8	1.05
	0.050	163.1	1.06
50	0.020	185.8	na
	0.035	181.9	na
	0.040	181.4	na
	0.050	180.2	na
100	0.020	206.6	na
	0.035	206.1	na
	0.040	206.1	na
	0.050	205.8	na

na: not available.

where V, is the flow velocity (m/s); R, the hydraulic radius (m); S, the slope; and n, the Manning's friction parameter. From Eq. (1), the friction parameter, n, is inversely proportional to the flow velocity of flood. In other words, increasing the floodplain resistance decreases the flow velocity and this eventually reduces the area covered by the flood. The effect is much pronounced with finer mesh resolution (5 m^2) where the inundation area has a total reduction of 14 m^2 when the Manning's value changed from $n = 0.02$ to $n = 0.05$. However, as the mesh area increased, the influence of

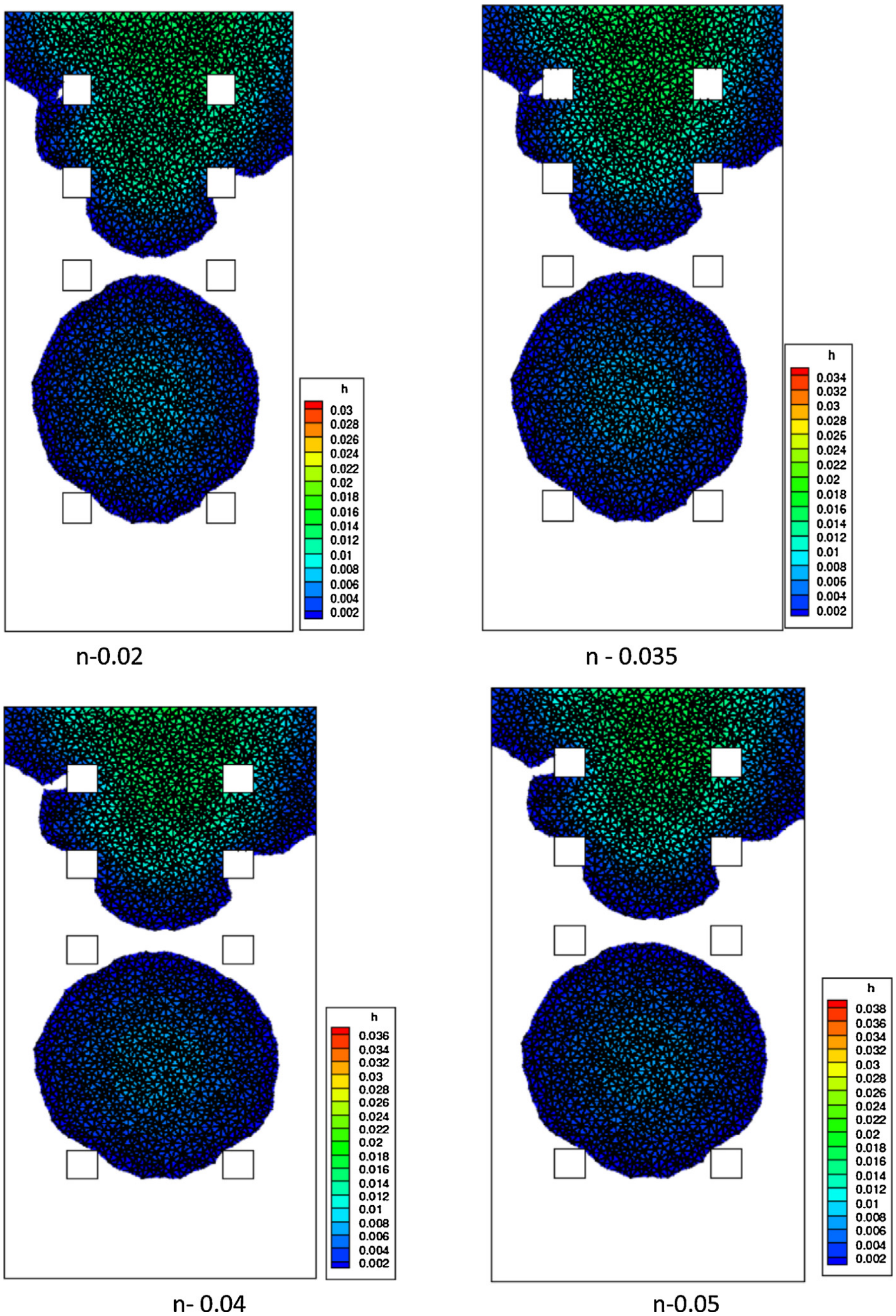

Fig. 7. Flood extent maps when $n = (0.02, 0.035, 0.04, 0.05)$ and the mesh resolution is 5 m.

Manning parameter tends to be more insignificant on the flood extent map. Hunter et al. (2008) explained that the best way to reduce model uncertainty is to find a better way of estimating the model parameter, especially friction parameter or to constrain these through a robust calibration process. It was also reported that despite the frequent urban flood, it has been quite difficult to get a field observation of urban flooding and no mechanism for their routine monitoring or post event re-constructing are available. Therefore, it becomes imperative to examine the impact of physically plausible range of friction parameters on any urban flood modeling study rather than relying on single deterministic simulation.

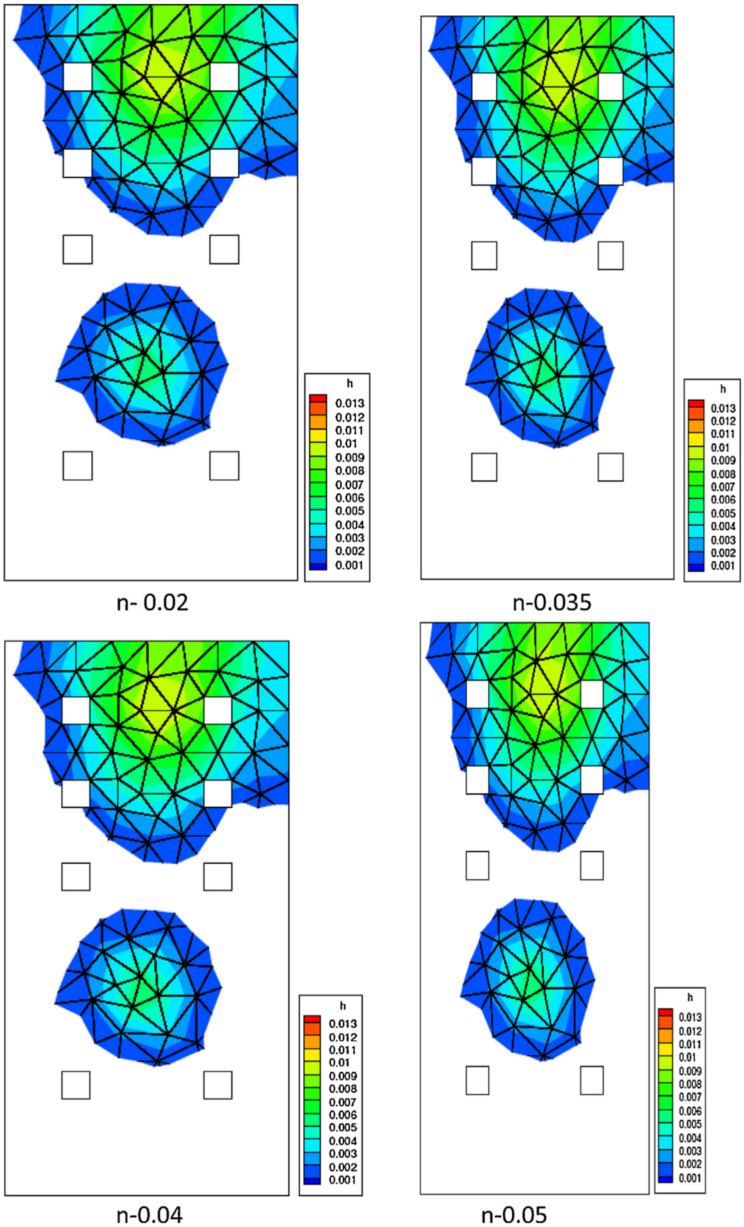

Fig. 8. Flood extent maps for $n = (0.02, 0.035, 0.04, 0.05)$ and mesh resolution of $100\,m^2$.

3.3. *Effect of Digital Elevation Model (DEM)*

In hydraulic flood modeling, it is of great interest to know the influence of low resolution DEM on the performance of 1D-2D inundated model. In flood modeling, selection of appropriate resolution is always a dilemma. A low resolution DEM results in a larger loss of information while a high resolution DEM results in excessive computational time. The response of the developed model to changes in DEM resolutions is as shown in Fig. 9. Also summary of the results is presented in Table 3. The results showed a relatively small difference in the inundated areas as the DEM was varied from 1 m to 5 m. However, a sizeable increase in inundated area was noticed as DEM resolution was increased to 6 m. At the same time, the use of DEM resolution of 10 m produced an unacceptable representation of modeling result.

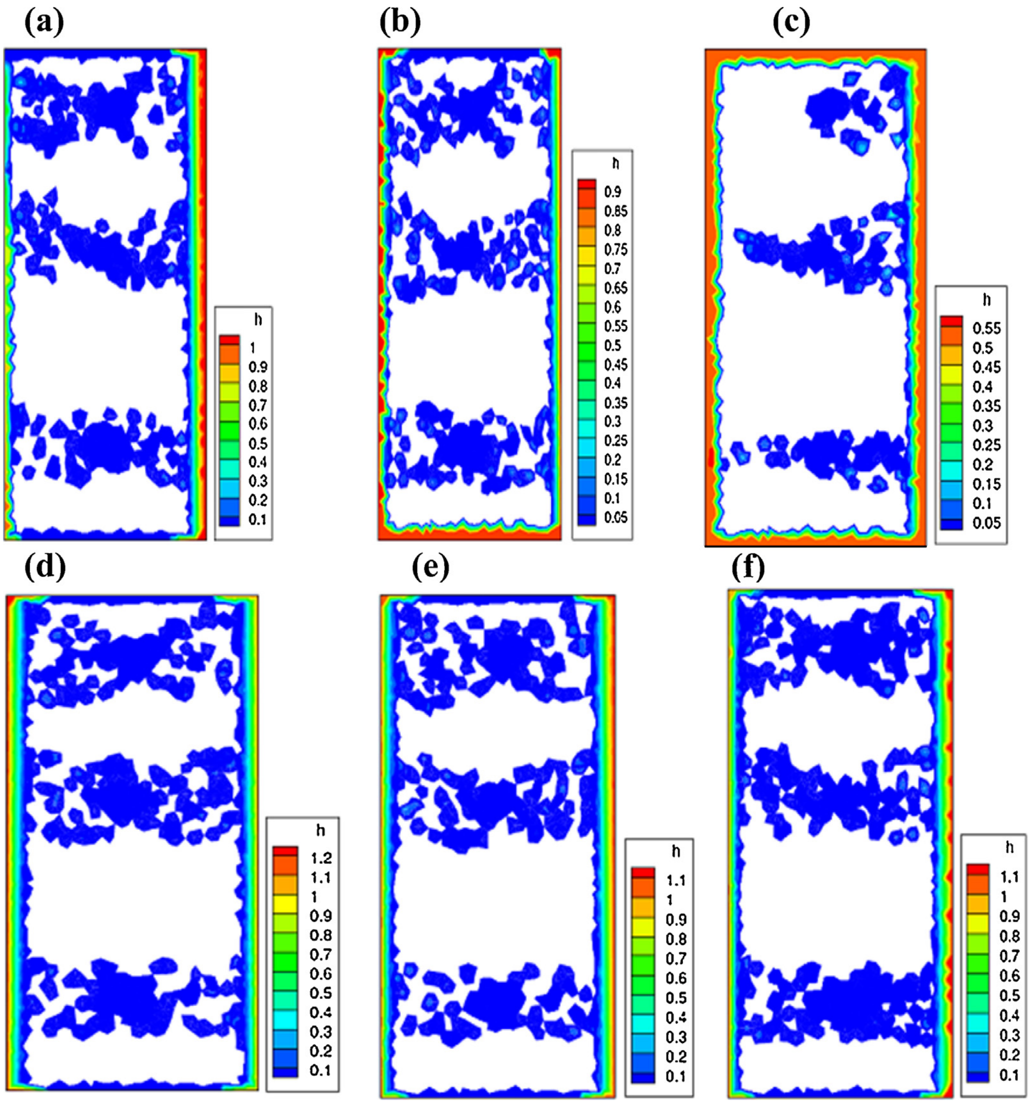

Fig. 9. Flood Map extent produced for different DEM resolution. (a)1 m resolution; (b) 2 m resolution; (c) 4 m resolution; (d) 5 m resolution; (e) 6 m resolution; (f) 10 m resolution.

Table 3
Effect of DEM on the performance of 1D-2D inundated model.

DEM resolution	Inundated area (m^2)	Maximum water depth (m)
1	234.8	1.2
2	235.3	1.1
3	244.1	1.1
4	244.6	1.1
5	244.6	1.0
6	320.4	0.9
10	166.4	0.6

4. Conclusions

In this study, SA has been carried out on the developed urban 1D-2D inundated coupled model (obtained by coupling an existing 1D – SWMM model with 2D – hydrodynamic model, BREZO). The influence of the model parameters was carried out to determine where effort should be concentrated during the process of model improvement in terms of quality and model output.

The sensitivity analysis conducted on the model showed that the developed model is sensitive to changes in model parameters, most especially the grid sizes and the roughness parameters. A better representation of flood map was achieved at lower grid sizes but with high computation cost, while the use of larger computational grid sizes reduces the computational cost but good representation of the inundated area is compromised. Consequently, it is obvious that a trade-off exists between the grid size and the model performance (i.e. time and accuracy). Therefore, it can be concluded that a careful selection of computational grid size is essential prior to flood modeling in order to strike a balance between the time and the model accuracy.

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