Influence of Uncertainties in DEM Resolution and Surface Friction to the Building Treatment Methods in Urban Inundation Modelling

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Abstract. This study evaluates the influence of uncertainties in DEM resolution and surface friction to building treatment method by conducting several simulations with various input parameters. A common two-dimensional hydrodynamic model is applied in a study area to produce the inundation results for every simulation. Comparison analysis between the simulation results and observed data suggest that the performance of building treatment method and urban inundation modeling is affected by the uncertainties in DEM resolution and surface friction. Moreover, different building treatment methods show disparity in sensitivity to the changes in model input. In practical terms, we can choose one of these methods based on the practical conditions, including available data, basin conditions and time constraints. The findings in this study are important for improving urban inundation models and for using their predictions in decision-making for various urban environments, which may provide some valuable insights into the flood management and risk assessment for the urban sites.

1. Introduction
The urban flood inundation, due to its frequent occurrence and high destructive effect, has become a hot topic of the urban disaster researches. Urban inundation models, which can provide numerical simulation for the inundation extent, depth and flow rate, serve as an important tool in urban flood risk management, loss assessment and drainage system design. In recent years, urban inundation model based on the mathematical conservation laws for both mass and momentum have been proposed and tested in various urban environments [1]. Compared to rural basins, urban inundation modelling is more complex due to the spatiotemporal inhomogeneity of underlying surface in urban region. Demand for accurate describe the flood wave propagation and inundation in highly urbanized area places a high requirement for the quality of model input. Digital Elevation Models (DEMs) are one of the most important spatial input data sets in urban inundation modelling because of the dominant role played by topography in urban flooding. In recent years, DEM with fine resolution (1-5m), which can capture the small-scale features (e.g. buildings, roads, kerbs), have been made available through LiDAR (Light Detection and Ranging). The use of high quality topography significantly facilitates the implement of urban inundation model in complex urban environments but also brings increased computational cost. In view of this, researchers have devoted their efforts to explore the sensitivity of model performance to DEM resolutions for selecting the best scale of DEM grid for efficient-accurate inundation modelling. Many studies have demonstrated that the outputs of hydrological models are influenced by DEM resolution [2]. B Dixon and J Earls utilized the SWAT model integrated with ArcView to examine how sensitive the SWAT model was to the resolution of DEMs while predicting the stream flow. They found that SWAT is indeed sensitive to the resolution of the DEMs, and...
suggested the effects of resolution cannot be ignored in modelling stream flows using a distributed watershed model [3]. H Ozdemir evaluated the scale effects in urban flood modelling by using LISFLOOD-FP model, and concluded that increasing the terrain resolution significantly affects modelled water depth, extent, arrival time and velocity [4]. J Savage quantifying the importance of spatial resolution and other factors through global sensitivity analysis of LISFLOOD-FP model, and found that for localized water depths the spatial resolution and DEM are much more important than other input factors [5]. Moreover, model sensitivities to DEM resolution may be exaggerated in urban area with flat terrain, as a small change in spatial resolution can lead to a large relative change in the model terrain. Surface friction is another source of uncertainty in urban inundation modelling. In rural applications, the influence of surface friction values of Manning’s is well understood [6]. The interaction between friction values and performance of inundation has also been investigated by the Yu and Lane using a 2D diffusive wave model [7]. However, on the best our knowledge, all the studies mentioned above are focus on the effect of variation in DEM and surface friction value to the output of hydraulic model. The influence of uncertainties in model input of DEM resolution and Manning’s n to the performance of building treatment method and urban inundation model is less consider and needed to be explored.

The objectives of this study are: (1) explore and quantify the difference of modelling results for simulations using varied building treatment method with different DEM resolutions and surface friction values; (2) obtain a better understanding of the sensitivity of building treatment method to uncertainties in DEM resolutions and surface friction values; (3) To determine accepted guidelines for the choice of DEM resolutions and surface frictions for flood inundation modelling. Therefore, the performance in inundation depths for each simulations are compared side-by-side in Section 3 and Figure 3 and 4 to reveal how the uncertainties in DEM resolutions and surface friction values affect the building treatment methods and urban inundation simulation.

2. Methodology

2.1. Study Area

The study area for this paper is the campus of a university that is located in the city of Wuhan, China, as shown in Figure 1. The campus covers a total area of 2.33 square kilometres with elevation range from 24m to 147m. It can be seen from Figure 1 that there are approximately 498 buildings in the study area, which are densely distributed along the roads of the campus. As there is no significant water system that lies in or flows across the campus, surface runoff in the study area appears to be mainly drained by the storm sewer system consists of 54 pipelines and 617 manholes. This campus is selected as a case study because it is characterised by typical urban landscaping and has repeatedly experienced extreme floods and inundations due to the rainfall intensity in Wuhan and a poorly engineered flood control infrastructure.

![Figure 1. Study Area: the campus of a university in Wuhan City, China](image-url)
2.2. Inundation Model
LIFLOOD-FP, a two-dimensional hydrodynamic model developed by the school of geographical sciences of University of Bristol, is selected as the inundation model for this study. It is one of the most popular urban inundation models which have been used as a research tool in many literatures [8]. Elevation from a DEM is an important spatial input for the 2D hydrological model such as LISFLOOD-FP. Many studies have demonstrated that in LISFLOOD-FP, the quality of input DEM and surface friction value has a large influence on the simulated surface flow, especially in a topographically complex urban area.

2.3. Building Treatment Method
Unlike the rural floodplain, urban watersheds are characterized by obstacles of varying shapes and length scales; these obstacles, including buildings, significantly affect the flood propagation on the urban floodplain, such as changes in storage volume and flow direction. Furthermore, buildings may act as storage for flood water when the inundation depth exceeds the height of building entrances. To account for these building effects on the surface flow in urban region, building treatment methods which reflect the building features by various terrain processing approaches are introduced in the urban inundation modelling. However, the traditional building treatment methods (e.g. BH and BB method) only account for the blockage effect of buildings. The representations for the storage and resistance effects of buildings, which also have considerable impacts on surface water flooding in urban environments, have been less considered in these methods. In other applications, larger groups of buildings are ignored or parameterized as surface friction (BR method). This cannot properly account for the blocking effects of buildings on flow, which in turns affects the prediction quality. In our pervious study, an improved building treatment approach (IBTA) was proposed to account for all building effects in surface wave movement [9]. In this approach, the ground elevations of DEM cells occupied by buildings were raised by the threshold (h) of the building entrance height. A higher roughness coefficient was assigned to the areas where buildings were located. To the best of our knowledge, to date few papers have focused on the problem of how to estimate the entrance height from the analysis of building features (geometry, size, roof height, etc.). Therefore, in IBTA for study area, the value of h was set to 0.4m. This selection of the threshold of building entrance height is based mainly on the statistical sampling method. In future work, we intend to collect more measurements of building entrance height and investigate model sensitivity to the selection of the threshold to propose a method for threshold selection.

![Figure 2. Rainfall Record of the Flood Event Occurred on 1 July 2016](image-url)
2.4. Precipitation Data
In this study, the flood event that occurred on 2016.7.1 is used to validate the performance of building treatment method and inundation model. The rainfall record of this flood event is given in Figure 2. According to the Hubei Climatic Data Center report released on 2016.7.2, the 2016.7.1 rainstorm greatly affected the traffic, commerce, production, government agencies and educational institutions, and resulted in 9 deaths and direct economic losses up to 34.7 million dollars in Wuhan City. However, measurements of surface and channel flow for this flood event are unavailable in the study area. Therefore, the performance of building treatment method and inundation model is validated based on the observed inundation depth obtained from 15 monitoring points. These monitoring points are well distributed over the study area and most of them are located at intersection of roads.

2.5. Model Inputs
Among the model inputs, DEM resolution and Manning’s n for overland flow are the key sensitive parameters. In this study, DEM data with 30m regular resolution are obtained from the freely-available global DEM products of ASTER GDEM2. Despite the irregular grid can effectively reduce the computing load and potentially enable more efficient description of building features, the use of it are not detailed in this study due to high pre-processing required for input preparation. The original DEM data are subsequently resampled to various resolutions by using bilinear interpolation method in ArcGIS to establish the simulations for sensitivity analysis. Moreover, Errors in the floodplain topography from the DEM source are a low concern since they are beyond the scope of this study.

According to the user’s manual of LISFLOOD-FP, the Manning’s n value of overland flow ranges from 0.011 to 0.8, depending on the land use types. In a number of studies, various Manning’s n values were assigned to every type of land use based on the empirically determined values from the existing literatures [10]. For instance, Manning’s n values of 0.013, 0.015, 0.025 and 0.035 were assigned to asphalt road, brick, gravel and short grass surfaces, respectively. However, the demands posed by field applications of inundation models in terms of data preparation, model parameterization and execution are remarkable. Many flood inundation models have commonly used a uniform Manning’s n value for the entire floodplain to reduce the computational cost [2–5]. Given that the study area in our study consists of residential land use with some institutional and educational portions and some open areas with shrub cover, a uniform Manning’s n value was chosen for the entire study area in every simulation scenarios to simplify the representation. In several field validation studies for the BR method, a large resistance parameter value (e.g., n = 0.5) is assigned to cells that fall within building footprints, whereas a Manning’s n value of 0.02 is assigned to the other cells to account for the typical urban land use type. Thus, for the IBTA and BR method in this study, a constant Manning’s n value of 0.5 was assigned to the cells located within buildings to compensate for the resistance effects caused by the internal structural impedance.

The entire model input that considered in this study is projected to GCS_WGS_1984 datum by ARCGIS and then imported into the LISFLOOD-FP model.

2.6. Experimental Design and Model Validation
In this study, the influence of uncertainty in DEM resolution and surface friction to four building treatment methods (BH, BB, BR and IBTA method) in urban inundation modelling is evaluated by conducting 128 simulations with model input differing in DEM resolutions and Manning’s n values for overland flow. In order to separate two uncertainty sources, the 128 simulation scenarios are categorized into two groups: (1) 13 simulations for each building treatment method with DEM resolutions range from 1m, 5m to 60m (with interval of 5m) at a constant value of Manning’s n=0.02 for overland flow; (2) 19 simulations for each building treatment method with the spatially uniform Manning’s n value varying from 0.01 to 0.1 (with interval of 0.05) at a constant 30m DEM. In order to separate the uncertainties in DEM resolution and surface friction from other sources of uncertainty, other model conditions are kept constant for every simulation.

Then, the sensitivity of building treatment method and model output to the various DEM resolution and surface friction values are assessed by the comparison analysis between the performances of every simulation scenarios, which are detailed in the next section. For each simulation, the performance of
building treatment method and model output is evaluated by the root mean square error of maximum inundation depths (RMSE\(_D\), in meters), which can be calculated as follows:

\[
RMSE_D = \left( \sum_{i=1}^{15} (d_i^s - d_i^o)^2 \cdot 15^{-1} \right)^{1/2}
\]  

(1)

Where \(d_i^s\) and \(d_i^o\) indicate the simulated and observed value of maximum inundation depths, respectively; and \(i\) indicates the index of the monitoring points range from 1 to 15.

3. Results and Discussions

3.1. Model Response to DEM Resolutions

Figure 3 shows the model response of RMSE\(_D\) for the simulation group of varying DEM resolutions. It is noted that the variations in the model performances of RMSE\(_D\) show a similar trend in Figure 3 for the building treatment methods of BB, BH and IBTA. The use of substantially coarser resolution of DEM data yields worse values of global measures of model performance. RMSE\(_D\) produced by these building treatment methods all reaches their minimum in the simulations using the finest DEM data with 1m resolution. This is because in building treatment method that based on topographic processing approaches (e.g. BH, BB and IBTA method), a smaller DEM grid size can achieve a better representation for the building features, thus in turn results in higher accuracy in simulation results. On the contrary, the performance of inundation depth modeling for BR method seems to be less sensitive to the DEM resolutions. Note that an increase in DEM grids size from 1m to 60m resulted in only 94% increase in RMSE\(_D\) for BR method, whereas IBTA method experiences a 578% increase in RSMED as grids size increased from 1m to 60 m. This is because the building effect is described by applying a higher Manning’s \(n\) value within the areas occupied by building for the BR method, in which case the impact of DEM resolutions on the outputs of urban inundation modeling is remarkably reduced. Moreover, IBTA method generally perform the best performance in inundation depth modeling when the resolution of DEM is below 20m , which is in accordance with the outcome in our previous study[9], revealing the IBTA has an advantage in building representation for urban areas.

![Figure 3. Model Response of RMSE\(_D\) for Varying DEM Resolutions](image)

3.2. Model Response to Surface Frictions

Figure 4 shows the model response of RMSE\(_D\) for the simulation group of varying Manning’s \(n\) for overland flow. It is noted that for the IBTA method, the error in simulated inundation depths decrease
firstly with the increase in value of Manning’s n until the RMSE_D reaches the minimum of 0.17m when n=0.020. Then the model performance of RMSE_D continues to deteriorate as the Manning’s n becomes higher. Similar situation are occurred in the simulation results produced by BR method, suggesting an optimal value of n=0.025 (where the RMSE_D is 0.21m) in the urban inundation modelling for the study area. However, less sensitivity of RMSE_D to surface friction values are presented by the simulations using BB and BH method. This is attributed to the building representation methodology for these two methods which depict buildings with an elevated ground elevation. The building features may be lost in the terrain processing conducted by BB and BH method when the DEM data become coarser, thus results in poor performance in inundation simulation. Moreover, although the campus mainly consists of urban land cover (roads, school buildings and student apartment blocks), it is noted that considerable amounts of open areas with woods cover and shrub cover can be found in the satellite image of the campus. This could explain why the optimal Manning’s n for overland flow obtained in Figure 4 is higher than the empirically derived values for the typical urban land use type (smooth concrete, ordinary concrete lining and brick with cement mortar) that listed in the LISFLOOD-FP user guide.

Figure 4. Model Response of RMSE_D for Varying Manning’s n for Overland Flow

Considering the results in Figure 3 and 4, it is indicated that the sensitivities of simulated inundation depth to the DEM resolution and surface friction value varied substantially depending on the choice of building treatment method for urban inundation modeling. For BB and BH method, modeling results are more sensitive to the DEM resolution than Manning’s value, and the contrary situation can be found in the simulation based on the BR method. Moreover, for IBTA method which represents the building effect through both modified elevation and surface friction value, the modeling results are simultaneously affected by the DEM resolution and Manning’s value.

4. Conclusions
A sensitive analysis is used in this study to explore the influence of uncertainties in DEM resolution in conjunction with changes in surface friction value on various building treatment methods for urban inundation modeling. The results indicate that every building treatment method considered in this study is sensitive to at least one source of input uncertainty. In practical terms, we can choose one of these methods based on the practical conditions, including available data, basin conditions and time constraints. Understanding of sensitivity of building treatment method to the uncertainties of model
input can facilitate not only the implementation of urban inundation model in data sparse area but also the development of a theoretical framework for spatial-temporal scales in hydrogeological models. Finally, the lack of detailed observational data for flood events in study area, especially the measurements of inundation extent and surface flow, will undoubtedly challenge the promotion of key findings in this study. However, the major aim of this paper is to determine influence of uncertainty in DEM resolution and surface friction to the building treatment methods, rather than to develop a detailed flood inundation report for the 2016.7.1 rainstorm event in the study area. It is noted that differences in RSME_D between simulation scenarios that discussed in Section 3 may not be optimal, but should be sufficient to highlight the sensitivity of building treatment methods to the uncertainties in model input. Therefore, the absence of observed data for the inundation area and surface flow does not limit the significance of the present study.

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