Improving the performance of city-scale hydrodynamic flood modelling through a GIS-based DEM correction method

Yun Xing^{1,3} · Huili Chen² · Qiuhua Liang² · Xieyao Ma³

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Abstract

Flood modelling can provide useful information to support flood risk assessment and management. The accuracy of flood simulation results is highly dependent on the quality of input data. In particular, digital elevation models (DEMs) may directly influence the performance of flood predictions and improper representation of complex urban features including buildings and bridges may lead to incorrect prediction of flooding paths and extents, and consequently miscalculate flood risk. In this work, a geographic information system (GIS)-based correction method is proposed to make modifications in high-resolution DEMs by adding building complexes and removing unphysical representations of bridges for a more realistic description of flood paths in considering the flow connectivity in intensely urbanized areas and with the objective of obtaining more accurate flood simulation results. The proposed DEM correction method is applied to support large-scale urban flood modelling in Fuzhou City, China, using an established hydrodynamic flood model known as High-Performance Integrated hydrodynamic Modelling System (HiPIMS). Comparisons are made to the simulation results with and without the DEM improvements using the proposed correction method. The results demonstrate that correct representation of the artificial structures in the urban DEM can significantly improve the flood simulation results.

Keywords Urban flood inundation · Hydrodynamic model · Digital elevation model · High-resolution simulation · DEM correction

✉ Huili Chen
H.Chen2@lboro.ac.uk

¹ Key Laboratory of Meteorological Disaster, Ministry of Education/Joint International Research Laboratory of Climate and Environment Change/Collaborative Innovation Centre On Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing 210044, China

² School of Architecture, Building and Civil Engineering, Loughborough University, Leicestershire LE11 3TU, UK

³ School of Hydrology and Water Resources, Nanjing University of Information Science and Technology, Nanjing 210044, China

1 Introduction

The risk of urban flooding is expected to rise in the twenty-first century and beyond due to rapid urbanization and increasing frequency of extreme precipitation events as a result of climate change (Milly et al. 2002; Nirupama and Simonovic 2007; Semadeni-Davies et al. 2008; Hanson et al. 2011; Fadhel et al. 2018; Zhou et al. 2019; Ziegler 2012). Many severe urban flood events have been reported across the world in the last two decades, for example, Hull, UK in July 2007, New York City, US in October 2012, Beijing, China in July 2012, Uttarakhand, India in July, 2013, Western Japan in July 2018, Northern Queensland, Australia in February 2019 and Zhengzhou, China in July, 2021. These urban floods have caused severe economic losses and even fatalities (Blake et al. 2013; Coulthard and Frostick 2010; Zhang et al. 2015).

It is necessary to effectively manage urban flood risk to mitigate the losses (De Sherbinin et al. 2007; Li et al. 2013; Wu et al. 2016; Pour et al. 2020). Numerical modelling has been widely used to provide essential information to support flood risk assessment and management (Dawson et al. 2011; Liang et al. 2017; Coles et al. 2017; Li and Willems 2020). Following rapid advancement of computing technology and availability of high-resolution data, hydrodynamic models are now capable of performing high-resolution flood predictions to provide temporal and spatial characteristics of flood inundation even in the highly complex urban environments (Ernst et al. 2010; Yin et al. 2016b).

Nowadays, high-resolution DEMs have become more accessible and have been incorporated into urban flood modelling and risk assessment (Tsubaki and Fujita 2010; Sampson et al. 2012; Meesuk et al. 2015; Tyrna et al. 2018; Arrighi and Campo 2019; Kim et al. 2020). But still, the quality of the topographic data or DEM has been widely recognized as one of the most important factors that affects the reliability of hydrodynamic modelling results (Leitão et al. 2009; Fewtrell et al. 2011; Saksena and Merwade 2015; Savage et al. 2016; Bhuyian and Kalyanapu 2018). Yin et al. (2016a) compared the city-scale simulation results produced on DEMs of different resolutions for the inundation induced by Hurricane Sandy in New York City in October 2012. Coarse-resolution DEMs have been found to cause non-negligible simulation errors and increase model uncertainties. A DEM at sufficiently fine resolutions (~5 m or finer) is essential to correctly capture flow directions and ensure flow connectivity for urban flood simulation.

However, according to existing studies, inadequate representation of certain urban features (e.g. bridges, roads and walls) still exists in the spatially high-resolution DEMs, which may give rise to incorrect prediction of flow directions and flood paths and hence affect overall accuracy of the simulation results (Hunter et al. 2008; Ozdemir et al. 2013; Leandro et al. 2016). For example, De Almeida et al. (2016) used a 10 cm DEM to support hydrodynamic simulations in a small region of Alcester, Warwickshire, UK, and found that small changes of the roads in the DEM can have significant impacts on flow connectivity and lead to non-negligible changes in the simulated flood peak. Therefore, proper representation of these micro-scale topographic features in high-resolution DEMs is of great importance to ensure the accuracy of flood simulation results. Manual approaches have been adopted by researchers to modify and improve DEMs to better represent relevant urban features including streets, river channels and under-bridge areas (Noh et al. 2018; Wang et al. 2018; Tyrna et al. 2018). In urbanized areas, digital maps for the positions and shapes of bridges are usually produced and owned by

relevant governmental authorities such as transport or water resources department but are often distributed in different authorities and hardly accessible, especially in developing countries. Freely available satellite imagery faces the limitation of inadequate spatial resolution and partly or un-presentation of bridges due to trees obstruction when capturing bridge features.

An automatic approach is desired to better represent the key topographic features in high-resolution DEMs to support accurate urban flood simulation. Evans (2008) developed empirical rules to distinguish artificial bridges from their surrounding natural features for a DEM generated from point clouds of LiDAR data. Similarly, Abdullah et al. (2012) proposed an algorithm to detect objects including elevated roads, bridges and buildings, and applied filter operations to modify the original DEM in accordance with reality. As these approaches require high density point cloud data and are often computationally expensive, their applications are limited to relatively small-scale urban areas. Also, the performance of these approaches and the resulting modified DEMs has not yet been tested and confirmed in applications for urban flood modelling.

In this work, a new automatic GIS-based DEM correction method for identifying and correcting artificial structures (i.e., buildings, road and river bridges) is proposed to improve the representation of these structures in DEM to support more reliable large-scale urban flood modelling. The performance of the DEM correction method is tested and confirmed by using the corrected DEM to support the simulation of a real-world flood event using the hydrodynamic flood model HiPIMS (Xia et al. 2019). The rest of the paper is organized as follows: Sect. 2 describes study area and dataset; the proposed automatic GIS-based correction method and the adopted hydrodynamic model are introduced in Sect. 3; then in Sect. 4, a major urban flood event induced by intense rainfall is simulated on different DEMs to evaluate the performance of the proposed DEM correction approach and investigate the effects of typical terrain features on the simulation results and flood hazard; and finally brief conclusions are drawn in Sect. 5.

2 Study area and data

The highly urbanized area of the Fuzhou city, situated in eastern part of Fujian Province in the Southeast China, is chosen as the case study in this work (Fig. 1). The study site opens to the estuary of Min River on its south side and is surrounded by mountains on the other three sides. High-resolution DEM (2 m) of the study site was provided by the Fuzhou Planning Design and Research Institute and tested against field measurements. The values of DEM elevation vary from 0.8 to 873.6 m, with an average of 132.5 m. The slope varies from 0° to 89.6°, with an average of 11.8°. The land use data also provided by Fuzhou Planning Design and Research Institute includes buildings, roads, open built-up spaces (e.g. plazas and car parks), green fields, mountain areas and water bodies.

The study area is dominated by the middle-south subtropical transitional maritime monsoon climate with two distinct rainfall seasons. The frontal rainy season comes between April and June, with prolonged but relatively light rainfall. The typhoon rainy season from July to October is commonly dominated by heavy rainfall of short duration. Although it is vulnerable to flooding from multiple sources, i.e. fluvial flooding, pluvial flooding and coastal flooding, Fuzhou mainly suffers from major flooding as a result of typhoon-induced intense rainfall. For example, two successive typhoons (Typhoon Meranti and Typhoon Megi) and the following flooding in September 2016 caused over RMB 1.87 billion of

Fig. 1 Maps of the study area of Fuzhou city in the Southeast China

direct economic loss and affected over 0.67 million people across the city. The powerful Typhoon Megi (28th September 2016) brought heavy rainfall of over 263.9 mm in a few hours and hourly precipitation up to 25.4 mm was recorded at the national weather station of Fuzhou (see Fig. 2). The tidal levels measured at the station near Jiefang Bridge are also presented in Fig. 2. The first rainfall peak is shown to coincide with the high tide occurring between 9 pm of 27th September and 5 am of 28th September, but no storm surge was reported to create coastal flooding. Flooding occurred in different locations of the city with an average depth of over 0.5 m and the maximum depth of greater than 1.0 m. Field survey data of the event was made available by Fuzhou Planning Design and Research Institute, which included water depth observations collected at 368 survey points during this flood event. The locations of the in-situ survey points were chosen on the basis of the experience accumulated from several previous flood disaster events and these survey points were

Fig. 2 Hourly rainfall records from the Fuzhou gauge station and the tidal level measured at the station near Jiefang Bridge during Typhoon Megi

mostly located at low-lying areas generally suffering from severe inundation conditions (shown in Fig. 1b).

3 Methodology

3.1 GIS-based method to correct high-resolution DEM for urban flood modelling

Considering buildings and bridges as important terrain features determining flooding paths in urban areas, the proposed DEM correction method will focus on these two key urban terrain features, especially for bridges. Currently, OpenStreetMap provides detailed building footprint polygons for the majority of cities throughout the world. Handling these building footprint polygons with GIS tool, buildings are represented by increasing the topographic elevation to a certain height (i.e. 10 m, approximately three-story height) in the raw DEM, which effectively creates ‘islands’ that obstruct flood water as in reality (Brown et al. 2007; Hunter et al. 2008; Cea et al. 2010). Although ‘island-like’ topographic features for buildings may present sudden terrain changes, the runoff produced over the building roofs is automatically included in the flood simulations without necessity of special treatment under the adapted hydrodynamic numerical scheme (Xia et al. 2017). Bridges are commonly manifested as humps on DEMs that block the flood flows, unrealistically forming ponds or reservoirs upstream and diverting the flows parallel to the edge of the bridges. The blockage effect may lead to inaccurate flood simulation results and underestimation of flood risk in the downstream areas, at least locally. Unlike buildings, for large-scale urbanized areas, bridges and culvert structures especially those over roads cannot be directly derived from increasingly available digital maps and thus it is in consequence necessary to develop an automatic method to identify the locations of the bridges and then correct the DEM to ensure intrinsic flow connectivity, and subsequently reliable flood simulations results. The approach for representing the bridge structures in a DEM to ensure correct flow connectivity can be divided into three steps:

3.1.1 STEP 1: Preliminary identification for locations of bridges in DEM

As a bridge is either part of a road network or a structure across a river, further bridge identification process can be focalized onto the sub-DEMs collocated with the footprints of roads and rivers derived from land use data using GIS tools. When focusing on the sub-DEMs of roads and rivers, the amount of data for analysis can be reduced with an improved efficiency. Examples of the extracted sub-DEMs for the road networks and the river channels are illustrated in Fig. 3a–d.

Bridges are built mostly perpendicular to the central line of rivers and roads with certain specific interchanges overlapping some roads. Some bridges may intersect with rivers or roads at certain angles, displaying as humps with a certain width over rivers and roads in the raw DEM. As shown in Fig. 3f, h, the preliminary identification of the possible locations of bridges can be firstly achieved by an exhaustive search of all possible humps through the rows or columns of the road and river areas and marking their edges. To explain what needs to be captured to identify a hump, a segment on the vertical profile of a sub-DEM is marked by a black rectangular in Fig. 3f, h. Zooming in this segment for analysis in Fig. 3e, g, it can be seen that the edges of the hump area (marked with subscripts j and n) clearly have elevations that are significantly higher than their neighbouring grid

Fig. 3 Preliminary identification for locations of bridges in DEM: **a–d** extracted sub-DEMs of road networks and river channels; **f, h** the elevation profiles along the central lines at the *x*-direction and the flow direction, respectively; **e, g** zoom-in view of example segments

points representing the water surface (or the underlying roads). Hence, the height criteria may be firstly applied to assign the hump as a possible candidate of a bridge by evaluating the minimum height difference between the hump surface level and the underlying road/water surface level (denoted by h_d). h_d can be approximated as a value smaller than the design clearance height under the bridge as specified by General Specifications for Design of Highway Bridges and Culverts (JTG D60-2015, general specifications of China). When the height differences between the neighbouring grid points satisfy

$$z_j - z_i > h_d \quad (1)$$

$$z_n - z_m > h_d \quad (2)$$

the identified hump may possibly be a bridge. $h_d = 1.5$ m is adopted in this work according to the General Specifications for Design of Highway Bridges and Culverts (JTG D60-2015), which is confirmed to be an appropriate value following numerical experiments.

As a bridge normally has a certain width to ensure multi-lanes operation, the bridge width may be another criterion to exclude the possible small protrusions erroneously identified due to the defects in the raw DEM. To further affirm the captured hump as a possible bridge, the distance between the two edges of a hump calculated as $(n - j) * r$ should satisfy

$$W_{\min} < (n - j) * r < W_{\max} \quad (3)$$

where $W_{\min}$ and $W_{\max}$ represent the minimum and maximum width of the bridge deck specified by General Specifications for Design of Highway Bridges and Culverts (JTG D60-2015) and r is the raster size (2 m for the DEM under consideration). In this work, $W_{\min}$ is taken as 5 m for a bridge deck consisted of one or two lanes which may present the narrowest one in cities. The value of $W_{\max}$ is taken as 50 m in for the bridges with their deck wider than six lanes. The selected values give satisfactory results in this work and no unreasonably large humps have been detected.

After this preliminary searching and identification procedure, there may still exist some small humps that are incorrectly captured, which must be further corrected to ensure proper representation of urban topography for accurate flood simulation. This will be achieved by implementing a Seeded Region Growing (SRG) method in the following step.

3.1.2 STEP 2: SRG to refine the exact bridge locations

Once possible bridge locations are preliminarily detected in the sub-DEMs and stored as raster data in Step 1, the SRG method (Adams and Bischof 1994; Shih and Cheng 2005) is applied to the preprocessed results to expand the so-called seeds to derive the exact boundaries of the bridges. On a raster DEM as considered in this work, the elevation data stored in each cell is analogous to a certain property of a pixel in an image and the SRG method can be implemented on such a DEM according to the following 3 principles:

- The set of cells defined as seeds give a correct representation of the bridge since the seeds are distributed over the pre-detected hump that indicates the possible bridge location;
- The homogeneity principle/criterion is established with the bridge height and the elevation difference between the bridge and its surrounding land or water surface areas;
- The growing process repeats for each seed until the criterion is violated.

As illustrated in Fig. 4, the elevation of a seed cell A_n is compared with that of its four immediate neighbours $N(i)$. If the elevation difference satisfies the following inequality (4), the neighbouring cell is marked as a seed (i.e. the cell will be given a value of '1' to

Fig. 4 The growing process of the SRG method

represent a seed); otherwise, the neighbouring cell is a ‘normal’ cell and will be given a value of ‘2’.

$$\min_{i \in T} \left\{ z(i) - \text{mean}_{j \in A_{n(i)}}(z(j)) \right\} < d \quad (4)$$

where T represents the set of unallocated pixels which border at least one of the seeds (as shown by the grey cells in Fig. 4), $z(i)$ denotes the elevation of cell i , and d is the growth threshold that needs to be calibrated for better results. For the city of Fuzhou as considered in our work, $d=1.0$ is adopted for the sub-DEMs containing rivers and $d=0.3$ is used for road networks, which are decided by trial and error.

3.1.3 STEP 3: Bridge-removal for flow connectivity using an interpolation method

Once the exact locations and areas of the bridges are identified, the bridges must be removed to ensure flow connectivity by modifying the elevation of the cells covering the bridge areas in the raw DEM. This may be achieved through interpolation from the surrounding elevation data on the raw DEM. Herein the commonly used inverse distance weighted (IDW) method (Shepard 1968) is employed, which estimates the unknown value by calculating the weighting average from the surrounding cells according to the inverse of their distance to the cell under consideration. By applying the processing approach proposed by Chen et al. (2018), the elevation values in the vicinity of the removed bridges along the river/road centre line are calculated before the interpolation to ensure the continuity of topographic elevation and terrain slope. For example, when interpolating the elevation values after removing a river-crossing bridge, the calculation is based on the nearest upstream and downstream cells or pixels outside the bridge area, taking into account the slope. In this work, a moving 5×5 window is adopted to traverse the cells for a sequential searching of any interpolated cells to achieve satisfactory results and the interpolated value $Z(x)$ on a given cell is calculated using the IDW method as

$$Z(x) = \frac{\sum_{i=1}^n \frac{w_i(x)z_i}{\sum_{i=1}^n w_i(x)}} \quad (5)$$

$$w_i(x) = \frac{1}{d(x, x_i)^p} \quad (6)$$

where the subscript i denotes the cell in the moving 5×5 window, x is the centre of the respective cell, w_i is the weight calculated for cell i with d being the distance between the interpolated point/cell and cell i , the power p is an arbitrary positive real number (usually $p=2$) and n is the total number of cells used in the interpolation process. The calculation is carried out by taking into account the slope of the river or terrain being considered to ensure the smoothness of the interpolated elevation, which is important for the accurate hydrodynamic simulation of surface flood flows.

3.2 Hydrodynamics model description

In this work, the High-Performance Integrated hydrodynamic Modelling System (HiPIMS) (Xia et al. 2019) is adopted to perform flood simulations to investigate and confirm the

effectiveness the DEM correction approach. HiPIMS solves the full 2D shallow water equations (SWEs), which are written in a matrix form as

$$\frac{\partial \mathbf{q}}{\partial t} + \frac{\partial \mathbf{f}}{\partial x} + \frac{\partial \mathbf{g}}{\partial y} = \mathbf{R} + \mathbf{S}_b + \mathbf{S}_f \quad (7)$$

where t is time, x and y are the Cartesian coordinates, $\mathbf{q}$ is the vector containing the conserved flow variables, $\mathbf{f}$ and $\mathbf{g}$ are the flux vector terms in the two Cartesian directions, $\mathbf{R}$, $\mathbf{S}_b$ and $\mathbf{S}_f$ contain the source terms representing the effects of rainfall, bed slope and bed friction. The vector terms are, respectively, given by

$$\begin{aligned} \mathbf{q} &= [h, uh, vh]^T, \quad \mathbf{f} = \left[uh, u^2h + \frac{1}{2}gh^2, uvh \right]^T, \quad \mathbf{g} = \left[vh, uvh, v^2h + \frac{1}{2}gh^2 \right]^T \\ \mathbf{R} &= [R - I - D, 0, 0]^T, \quad \mathbf{S}_b = \left[0, -gh \frac{\partial b}{\partial x}, -gh \frac{\partial b}{\partial y} \right]^T, \quad \mathbf{S}_f = \left[0, -\frac{\tau_{bx}}{\rho}, -\frac{\tau_{by}}{\rho} \right]^T \end{aligned} \quad (8)$$

where u and v are the two depth-averaged velocity components, h is the total water depth, b represents the bed elevation above datum, g is the acceleration due to gravity, R is the rainfall rate, D is the drainage loss, I is the infiltration rate, ρ is the water density, and τ_{bx} and τ_{by} are the friction stresses calculated using

$$\tau_{bx} = \rho C_f u \sqrt{u^2 + v^2} \quad \tau_{by} = \rho C_f v \sqrt{u^2 + v^2} \quad (9)$$

where $C_f = gn^2/h^{1/3}$ is the roughness coefficient with n being the Manning coefficient.

The adopted numerical schemes strictly preserve the lake at rest condition (i.e. C -property) and ensure non-negative water depth for applications involving wetting and drying over irregular bed topography, especially for the urban DEM with a large amount of artificial structures (Xia et al. 2017; Xia and Liang 2018).

3.3 Performance indicators

Evaluation indicators including the true positive rate (TPR) and the Precision are selected and applied to evaluate the performance of the bridge identification and DEM correction approach. Other indicators including root-mean-squared error (RMSE) and Fit statistics (F) are also utilized to compare and assess the hydrodynamic simulation results.

TPR represents the ratio of the number of correctly detected bridges (N_{positive}) to the number of reference bridges (N_{ref}):

$$\text{TPR} = \frac{N_{\text{positive}}}{N_{\text{ref}}} \quad (10)$$

The precision is the ratio of N_{positive} to the total number of bridges being identified ($N_{\text{positive}} + N_{\text{false}}$):

$$\text{Precision} = \frac{N_{\text{positive}}}{N_{\text{positive}} + N_{\text{false}}} \quad (11)$$

where N_{false} is the number of bridges that are incorrectly identified. Whilst TPR describes the capability of the identification method for correctly capturing the bridges against the references, Precision indicates whether the method correctly identifies humps as bridges.

RMSE is used to compare the simulated water depths with field measurements at a point-by-point basis. F -statistics is adopted to quantify how well the simulated flood extent matches the measured extent or reference solution and can be calculated as follows:

$$F(\%) = \frac{A - B}{A + B + C} \times 100 \quad (12)$$

with A counts the number of correctly predicted wet/flooded cells, B denotes the number of cells erroneously predicted as wet/flooded, and C indicates the number of cells erroneously predicted as dry (Horritt et al. 2010).

4 Results and discussion

4.1 Analysis of the GIS-based correction results of the DEM

A comparison between the raw DEM and the DEM with corrected representation of buildings and bridges for flood modelling is shown in Fig. 5. As the urban area is characterized by densely distributed buildings, the raw DEM including the zoom-in view in Fig. 5a cannot reflect well the reality. After applying the proposed building treatment method, buildings are represented as ‘islands’ (zoom-in view in Fig. 5b), which allows the floodwater to flow around and better reflects the reality. As also shown in the zoom-in view of Fig. 5b, both of the river-crossing and road-crossing bridges are well detected and removed from the original DEM to restore flow connectivity. The interpolated topographic elevation in the bridge areas is smooth and consistent with the surrounding topography.

Bridges in the primary roads and main rivers channels are identified and corrected to improve urban flood modelling. The identified river-crossing and road-crossing bridges are marked in Fig. 6 and compared with references. The references are manually identified and obtained from remote sensing images available in Google Earth along specific roads and

Fig. 5 The DEMs of the study area: **a** raw DEM; **b** corrected DEM

Fig. 6 Bridge identification: **a** the reference bridges; **b** the identified bridges; **c** comparing the identified river-crossing bridges with the references; **d** comparing the identified road-crossing bridges with the references

Table 1 The performance indicators calculated for identified bridges against references (associated with the results in Fig. 6c, d)

	N_{ref}	$N_{positive}$	N_{false}	TPR (%)	Precision (%)
River-crossing bridges	103	79	8	76.7	90.8
Road-crossing bridges	37	22	7	59.5	75.9

channels. The calculated values of the performance indicators (i.e. TPR and Precision) are listed in Table 1.

According to Table 1, more than 75% of the reference river-crossing bridges are successfully detected ($\text{TPR}=76.7\%$), returning a high Precision of 91%. As river-crossing bridges normally have relatively simple spatial patterns and perpendicularly cross the river channels, the automatic pre-detection process captures well the related humps on the DEM through a simple search along the central lines of rivers. On the other hand, most of the road-crossing bridges stay parallel to the course of the roads and have relatively complex patterns, the TPR and precision are calculated to 59.5% and 75.9%, respectively, which are both lower than the river-crossing bridges.

In addition to bridge identification, the SRG results regarding ‘exact’ locations of the bridges and their covering areas are compared against the reference remote sensing images. Figure 7 shows the results of 8 typical sites marked in Fig. 6b, presenting the visual comparison between the SRG detections and the corresponding observations from the remote sensing images.

Sites 1–4 in Fig. 7 are the river-crossing bridges. In each of these sites, the left subplot (i.e. the zoom-in map) shows the seed cells marked as black points, which are identified by the automatic identification process (Step 1 as introduced in Sect. 3.1). The middle subplot shows the covering area of each bridge determined by the SRG method (Step 2 in Sect. 3.1), which is compared with the remote sensing image on the right subplot. It can be seen that the river-crossing bridges are well captured, and their seed cells are well distributed along the respective river central lines. The geometrical shape of these identified bridges matches well those in the remote sensing images even for the ones on a narrow river channel as shown for Site 3 and a braided river in Site 4.

For the road-crossing bridges (Sites 5–8), the bridge locations are well identified with the seeds automatically distributed at the correct places. The results for Sites 5 and 6 confirm that the covering areas of the road-crossing bridges can be captured by the automatic seeding and SRG procedures when they are on the relatively flat terrain. Some small

Fig. 7 Comparing the detected locations of the bridges and their covering area with the references from remote sensing images

discontinuities existing due to terrain irregularities may need manual corrections. Interestingly, the automatic seeding and SRG procedures also detect several tunnels across the mountain area, as illustrated in (7) and (8). But it is not surprising that only the starting and ending parts of the tunnels are captured. Whilst this may demonstrate an extra potential of the proposed method, tunnels identification is not considered in this study and may be explored further in the future.

As mentioned in Sect. 3.1, the voids created by removal of bridges in the DEM must be filled using an IDW interpolation method. The IDW interpolated results are presented in Fig. 8 for the 8 sites as shown in Fig. 7. The IDW method implemented using a moving 5×5 scanning window successfully fill the voids and no unphysical discontinuous topography can be found, referencing with the surrounding elevations. The IDW method starts the interpolation process from the nearest upstream and downstream cells outside the void and hence the surrounding elevation in the immediate vicinity is taken into consideration and affects the interpolation results.

4.2 Influence of the corrected DEM on urban flood modelling results

4.2.1 Urban floods induced by a design rainfall event

Four DEMs created with different levels of GIS-based corrections are used to set up and run HiPIMS to investigate the influence of DEM corrections on flood simulations results. The four DEMs being created are: (1) DEM-a includes corrections for buildings and road-crossing bridges but not river-crossing bridges; (2) DEM-b applies corrections for buildings and river-crossing bridges but not road-crossing bridges; (3) DEM-c corrects both types of bridges but not buildings; and (4) DEM* is created after both bridges and buildings are corrected using the aforementioned methods. The flood simulation result on DEM* is used as a reference to evaluate the performance of other three DEMs. On these DEMs, a 100-year design rainfall event of 2 h duration is then applied to drive the hydrodynamic flood simulations, together with a coastal boundary condition of 5 m tidal level above the Luo Zero Height Datum which is widely used in the Southeast China including Fujian Province.

Against the reference result obtained on DEM*, the performance indices introduced in Sect. 3.3 are calculated for the HiPIMS simulation results produced on other DEMs.

Fig. 8 The elevation profiles and the interpolation results obtained using the IDW method

Table 2 The RMSE and fit statistics (F) calculated for the maximum inundation depths and the maximum inundation extents predicted on different DEMs

	DEM-a	DEM-b	DEM-c
RMSE (m)	0.10	0.04	0.32
F (%)	95.0	99.3	51.2

Fig. 9 The absolute difference between the maximum inundation depths predicted on DEM* and other DEMs: **a** depth difference between predictions on DEM-a and DEM*; **b** locations of the river-crossing bridges; **c** locations of the road-crossing bridges; **d** depth difference between predictions on DEM-b and DEM*; **e** depth difference between DEM-c and DEM*; **f** area covered by the buildings

Table 2 presents the values of $RMSE$ and Fit statistics (F) calculated, respectively, for the maximum inundation depths and the maximum inundation extents predicted on different DEMs. As the buildings cover a total area of 25.8 km² and the total area covered by bridges is merely 0.48 km² (with the areas covered by river-crossing bridges and road-crossing bridges count at 0.31 km² and 0.17 km², respectively), the influence of building correction is found to be generally greater, as indicated by the returned values for $RMSE$ and F .

Figure 9 shows the difference between the maximum inundation depths predicted on the three DEMs and that produced on DEM*. As illustrated in Fig. 9a, on DEM-a where no correction is made for river-crossing bridges, the locations predicted with large depth difference are dispersedly distributed in the whole domain. Figure 9a1 and a2 provide the zoom-in views for two locations where the local maximum depth difference has exceeded 1 m since the unremoved bridges block the river flows. Clearly, the flood depth and extent upstream of the bridge is substantially overestimated. On the other hand, the flood depth and extent downstream of the bridge are underestimated as expected. The influence may

extend up to 2 km away from the location of the bridge, which may lead to incorrect interpretation of the flood risk.

Figure 9d shows depth difference between the maximum inundation depths predicted on DEM-b and DEM*. On DEM-b, no correction is applied for road-crossing bridges and it is evident that large depth difference is predicted in those areas close to the road-crossing bridges. When the landscape close to the bridge is relatively flat, the obvious depth difference only appears locally in the areas close to the bridge and the affected area is largely confined within the roads, as demonstrated in the zoom-in map in Fig. 9d1. When the surrounding topography presents small slopes, the depth difference starts to extend to a larger area, as shown with Fig. 9d2.

Whilst the appearance of uncorrected bridges normally imposes non-negligible but localized impact on the flood simulation results, the effect of buildings may be over most areas of the urban domain. This is evidenced by the result produced on DEM-c where no correction is applied for buildings (Fig. 9e), in comparison with the results obtained on DEM* (Fig. 9f).

Fig. 10 The inundation maps at the three stages predicted on the raw DEM (left column), corrected DEM (middle column), and the difference between the inundation depth (right column)

4.2.2 Real-world flood inundation induced by Typhoon Megi

To further test and confirm the performance of corrected DEMs on real-world flood simulations, the 2016 flood event induced by Typhoon Megi is considered and the hydrodynamic simulation results at three different stages of the event are chosen for further analysis. The three stages are chosen to be: (1) at the beginning of the rainfall; (2) when both the rainfall and the tidal level reach the peaks; and (3) when rainfall intensity starts to decrease.

Fig. 10 presents the inundation maps predicted at the three aforementioned stages on the original raw DEM and the corrected DEM, together with their difference. At the beginning of the event, although most of the urban domain has not yet been severely inundated, clear difference in flood depth between the two simulations can be still detected in some locations, e.g. the small zone marked with ‘A’ in Fig. 10c. Clear overestimation of water depth can be detected on the raw DEM. Zone ‘A’ is situated close to the northern mountain area but with relatively low elevation. Several bridges are identified in its downstream river channels, which are numerically interpreted as humps or dams and create clear blockage effect on the surface water flow (Fig. 10a) although the inundation depth and flow are still relatively small at this stage.

When the precipitation reaches its peak (~04:00 on 28th), obvious inundation over most of the urban area is predicted on both the raw DEM and the corrected DEM. The inundation depth is predicted to be deeper in many locations on the raw DEM (Fig. 10d) than on the corrected DEM (Fig. 10e), which is clearly reflected on the depth difference map in Fig. 10f. In Fig. 10f, Zone B is situated in a relatively low-lying land downstream of Zone A. The inundation depth in Zone B is underestimated on the raw DEM since a non-negligible amount of floodwater coming from the upstream hillslopes is blocked by fake humps (i.e. bridges without treatment) on the main roads and river channels between Zone A and B. In Zone C which is located near to a river channel with a relatively higher ground elevation, the inundation depth and extent are also incorrectly predicted due to the unrealistic interruption to flow connectivity caused by bridges on the raw DEM. In addition to blocking water flow in rivers, the uncorrected bridge structures also interrupt overland flows and slow down the water flows converging into the downstream river channels, leading to overestimation of inundation depth over a wider urban area on the raw DEM.

Fig. 11 Maximum inundation maps predicted on **a** raw DEM; **b** corrected DEM; **c–e** zoom-in views on raw DEM; **f–h** zoom-in views on corrected DEM

Fig. 12 Comparing the predicted flood depths on the two DEMs with the field observations

Table 3 The RMSEs calculated for maximum depths against observations in the sample zones

	Zone A	Zone B	Zone C	Zone D	Zone E
Observation points	21	49	15	30	18
Corrected DEM	0.274 m	0.308 m	0.170 m	0.540 m	0.315 m
Raw DEM	0.837 m	0.381 m	0.245 m	0.496 m	0.309 m

When the flooding process continues to evolve, the difference between the simulation results becomes more obvious, as shown on the depth difference map in Fig. 10i predicted for 09:00 on 28th. The simulation on the raw DEM tends to overestimate the inundation depth in a large area across the city, which may be largely avoided by implementing the GIS-based correction method proposed in this work to ensure the correct flow connectivity. It is also noted in the depth difference map in Fig. 10i that lower water levels in the larger river channels to the south of the domain are predicted on the raw DEM than on the corrected DEM. This, as expected, presents further evidence to confirm the effectiveness of the proposed GIS-based DEM correction method.

Figure 11 presents and compares the maximum inundation maps predicted, respectively, on the raw DEM and the corrected DEM. Generally, more severe inundation with deeper water depth and larger inundation extent can be observed on the raw DEM than on the corrected DEM. The zoom-in views at three sample zones A, B and C are shown in Fig. 11 c–h, with the topographic features presented with 3D rendering effects to give a better visualization. Zone A is predicted to be mostly flooded with a relatively homogeneous maximum depth over 1 m (even 2 m at certain locations) on the raw DEM. On the corrected DEM, due to the blockage effects created by buildings, less floodwater is predicted to enter the building complex farther away from the primary roads and most of the water is concentrated in the spaces between the buildings, which better reflects the reality. The maximum water depth is predicted to be between 0.5 and 1.0 m in the building complex in this zone

on the corrected DEM, which is consistent with the field observations. For Zones B and C, similar conclusions may be drawn, i.e. the influence of the artificial structures on flood predictions may be more evident on the maximum water depth in the areas distributed with dense buildings.

The simulated results on the raw and corrected DEMs are further compared with the field measurements in terms of the maximum water depth at the aforementioned 368 observation points. The RMSE calculated for the simulation result on the corrected DEM is 0.32 m, which is smaller than that returned for the raw DEM (0.45 m). Figure 12 further compares the maximum depths predicted on the two DEMs with the observations, specifically for the sample zones A ~ E as marked in Fig. 10. The corresponding RMSEs are listed in Table 3, together with the numbers of observation points inside each zone. For the 21 observation points in Zone A, the RMSE is calculated to be 0.837 m for the prediction on the raw DEM. Whilst on the corrected DEM, the RMSE is returned to be 0.274 m, demonstrating a more accurate simulation. This is also confirmed by Fig. 12a in which the maximum depths predicted on the corrected DEM are marked as red circles which are distributed mostly along the reference line of 45 degrees. The comparisons at the 49 observation points in Zone B and at the 15 observation points in Zone C show similar results. However, for Zone D presented with a dense distribution of buildings and no bridge, the results on the raw DEM and the corrected DEM are both not well consistent with the field measurements and this may reflect the uncertainty of hydrodynamic simulations for areas with dense buildings. In Zone E, although multiple bridges have been detected and removed, the improvement in the simulation results on the corrected DEM is surprisingly not obvious. Since the ground elevation of this area becomes much lower after removing the bridges, floodwater may erroneously accumulate in the locations close to some observation points, leading to large deviations.

In general, although with certain uncertainties, the simulation results generally confirm that it is important to properly handle artificial structures in the background DEM data for more reliable hydrodynamic urban flood simulations and the proposed GIS-based correction method can effectively improve urban DEMs to produce better flood simulation results through better representation of urban building structures and improving flow connectivity.

4.3 Impact of corrected DEM on flood hazard estimation

In addition to the analysis about the water depth and flow velocity described in the previous sections, the influence of the corrected DEM on the flood hazard estimation is analysed in this section by taking advantage of the flood hazard function proposed by Cox et al. (2010). As listed in Table 4, the function is consisted of four flood hazard levels with regard to the safety of adults being exposed to flood water flows. The tolerable flow value (D.V) is determined following the impact of the water flows on the human ability to keep

Table 4 Flood hazard levels for the safety of adults (from Cox and Blacka 2010) used in flood hazard estimations

D.V* ($\text{m}^2 \text{s}^{-1}$)	0	0–0.6	0.6–0.8	0.8–1.2	> 1.2
Flood hazard levels for the safety of adults	Safe	Low hazard	Moderate hazard	Significant hazard	Extreme hazard

*D.V is the tolerable flow value

Fig. 13 Times series of the simulated area in three flood hazard classes (moderate, significant and extreme hazard) during Typhoon Megi for the corrected DEM and the raw DEM. **a1–a3** are the results obtained for urbanized land surface excluding river channels; **b1–b3** are the results obtained for the entire study domain

the standing or wading state. As the low hazard level may not be of significant sense in practical account, the results presented here focus on the three higher flood hazard levels (moderate, significant and extreme hazard) and comparisons are made for the area of different flood hazard level when carrying out the simulations with or without the proposed approach for the DEM corrections.

In Fig. 13, times series of the simulated area corresponding to the three flood hazard levels (moderate, significant and extreme hazard) during Typhoon Megi are displayed and compared for the corrected DEM and the raw DEM. Since the flood hazard estimation based on the flood flow conditions may be entirely different on the urbanized land surface and in the river channels, the estimation results are presented separately with Fig. 13a illustrating the results obtained when only land surface is included in the calculation whereas Fig. 13b considering the entire study domain (including the river channels in the study domain). In Fig. 13a, it can be seen that the differences between the estimation results with and without the DEM corrections (including both buildings and bridges) are mostly concentrated around peak hours for the Typhoon event on the urbanized land surface. As the velocity of the flood flow is generally low on the urbanized land surface, the tolerable flow value (D.V) is primarily determined by the accumulated water depth and the simulations with the raw DEM tend to overestimate the flood hazard level with larger reproduced inundation extents. When the river channels are included in the estimations, the differences between results with the corrected DEM and the raw DEM extend onto nearly the whole span of the flood event. With the improved presentation of flow connectivity with the DEM corrections, the flood hazard estimation is influenced by both the rainfall and the tidal level. As the topographical characteristics of the urbanized area are better captured and represented with the proposed DEM correction approach in this work, the estimated flood hazard may be closer to what may happen in reality.

5 Conclusions

A GIS-based DEM correction method for applications in large-scale urbanized areas is proposed in this work to improve city DEMs by better representing complex urban terrain features (e.g. buildings and bridges) for more accurate hydrodynamic simulation of urban flooding. The proposed DEM correction method is applied to the city of Fuzhou, China. The performance of the corrected DEM is tested and confirmed by simulating the hypothetical flooding process caused by design rainfall and a real-world flood event induced by Typhoon Megi. From the results, the following conclusions may be drawn:

1. The proposed GIS-based correction method can improve urban DEMs to ensure flow connectivity for rainfall-induced overland flows and flood flows in river channels whilst keeping the topographic characteristics of the raw DEM. Due to more proper representation of buildings and bridges, the corrected DEM improves the accuracy of hydrodynamic flood simulation by removing the unphysical blockage effects caused by buildings and different types of bridges.
2. Comparison between the hydrodynamic simulation results for Typhoon Megi induced flooding predicted on the raw and corrected DEMs shows that buildings have strong influence on the simulation results especially in those areas distributed with dense building complexes and it is important to correctly represent the buildings using the DEM correction method to ensure more reliable results.
3. For a typical flood event in Fuzhou (e.g. the event induced by Typhoon Megi), the DEM improved by proposed correction method is found to evidently enhance the performance of hydrodynamic modelling and a reduction of ~30% is achieved in RMSE calculated for maximum inundation depth against measurements at 368 observation points.

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Declarations

Conflict of interest The authors declare no conflicts of interest.

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