Integrated 1D and 2D model for better assessing runoff quantity control of low impact development facilities on community scale

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Abstract:

This study proposes a modelling framework of integrated one-dimensional (1D) and two-dimensional (2D) hydrodynamic modelling to evaluate the effectiveness of sponge city construction at community scale. Through a case study in Zhuhai, we integrate Stormwater Management Model (SWMM) and Cellular Automata Dual-DraInagE Simulation (CADDIES) 2D model to analyze the rainfall-runoff process involving green infrastructures. SWMM is applied to analyze the change of surface runoff control effects before and after the implementation of sponge city low impact development (LID) facilities, and CADDIES is adopted to simulate the propagation of excess runoff on the surface. The results show that the LID facilities can effectively reduce the runoff volume of small and medium-sized rainfall events since the maximum runoff reduction rate is 94.4%. For long-term operation, the LID can capture 52.9% of annual rainfall volume and reduce annual runoff by 28.0%. However, the CADDIES 2D model simulations indicate that LID facilities have little effect on flood alleviation in specific regions under extreme rainfall conditions. In addition, we compared the modelling performance using four different terrain Digital Elevation Model (DEM) resolutions and found that 1m terrain DEM resolution can produce comparable results to 0.25m DEM with a fraction of computational time. We also find that the MIKE FLOOD model and the integrated model of SWMM and CADDIES 2D can obtain similar simulation results, the p-value = 0.09 which is greater than 0.05, but SWMM-CADDIES integrated model is more suitable for small-scale simulation.
Key words:

Integrated modelling; Cellular Automata Dual-DraInagE Simulation (CADDIES); Sponge city construction assessment; Low impact development (LID); Runoff quantity control

1. Introduction

High intensity urbanization has triggered serious problems in urban water management such as flooding, environment deterioration, water resources shortage (Jia et al. 2017, Jiang et al. 2018, Yang and Cui 2012, Zhang et al. 2016) and sustainability (Ding et al. 2019). In response to these prominent challenges, China has been exploring and advocating solutions for better stormwater management (Cheng and Wang 2018, Xu et al. 2018, Zhang et al. 2019a). Since 2015, many Chinese cities have begun the sponge cities pilots that adopt various types of low impact development (LID) facilities to deal with water quality and quantity challenges (Su et al. 2019, Wang et al. 2019a, Xu et al. 2019). The main purpose is improving the hydrological cycle to better control surface runoff and reduce pollution, as well as tackling other aspects, including water ecology, water resources, water safety, and water environment (Han and Wu 2019, Shao et al. 2016).

At present, many urban hydrodynamic models are widely used to assess the effectiveness of sponge city constructions, including the U.S. Environmental Protection Agency’s (EPA) Stormwater Management Model (SWMM) (USEPA 2019), InfoWorks Integrated Catchment Modelling (ICM) (Wallingford 2019) and MIKE URBAN (DHI 2016). Jia et al. (2012) used coupled SWMM–BMPDSS model to generate the time series data of surface runoff from different types of land uses and analyze the placement and optimization of best management practices (BMPs). Rujner et al. (2018) simulated the hydrological response of a grass swale to runoff inflows by using the hydrological model MIKE SHE. Wang et al. (2019a) simulated actual and design flood events in a pilot sponge city and integrated the outcomes with a 3D VR environment. Table 1 shows a summary of different models. Most of the studies analyzed either the one-dimensional (1D) pipe flow, or the two-dimensional (2D) surface flow, or the difference before and after the LID-BMPs construction in the drainage system of study area. However, very few studies involve integrated simulations of all these aspects.
Table 1. Researches on simulation of different area by using various hydro-hydraulic model.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Model</th>
<th>Developer</th>
<th>Model types</th>
<th>Simulation area</th>
<th>Simulation content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Randall et al. (2019)</td>
<td>SWMM</td>
<td>U.S. EPA</td>
<td>Open Access</td>
<td>Beijing</td>
<td>1D pipe flow ●</td>
</tr>
<tr>
<td>Kwak et al. (2016)</td>
<td>XPSWMM</td>
<td>XP SOLUTION</td>
<td>Commercial</td>
<td>Korea</td>
<td>2D surface flow ●</td>
</tr>
<tr>
<td>Elshorbagy et al. (2018)</td>
<td>PCSWMM</td>
<td>CHI</td>
<td>Commercial</td>
<td>Saskatoon</td>
<td>LID-BMPs ●</td>
</tr>
<tr>
<td>Zhou et al. (2019)</td>
<td>ICM</td>
<td>HSPF U.S. EPA</td>
<td>Open Access</td>
<td>Jiaxing</td>
<td>●</td>
</tr>
<tr>
<td>Nayeb Yazdi et al. (2019)</td>
<td>SUSTAIN</td>
<td>Tetra Tech</td>
<td>Commercial</td>
<td>Virginia</td>
<td>●</td>
</tr>
<tr>
<td>Chen et al. (2014)</td>
<td>MIKE FLOOD</td>
<td>DHI</td>
<td>Commercial</td>
<td>Northern India</td>
<td>●</td>
</tr>
<tr>
<td>Patra et al. (2016)</td>
<td>TUFLOW</td>
<td>WB and University of Queensland</td>
<td>Commercial</td>
<td>South-Eastern Australia</td>
<td>●</td>
</tr>
<tr>
<td>Wang et al. (2018)</td>
<td>CADDIES</td>
<td>EXETER Academic</td>
<td>London</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This research investigated how LID facilities reduce stormwater runoff (including drainage and surface flow) by using integrated SWMM and CADDIES model in a community of Zhuhai city to quantify the benefits of sponge city construction in flooding reduction. The evaluation indicators, including the flood response index ($F_r$), the single event runoff volume control rate ($C_r$), the runoff reduction rate ($R_r$) and the volume capture ratio of annual rainfall ($V_a$), were used to compare the scenarios before and after the sponge city construction. These indicators can comprehensively evaluate the effectiveness to control stormwater runoff volume in a specific area.

The impact of different input DEM resolutions on the simulation results was also analyzed to find the appropriate spatial resolution for the balance between accuracy and efficiency of modelling. Finally, we compared this integrated model to a model already well established in industry (MIKE FLOOD) to evaluate the accuracy of the simulation results.

Although various studies have been conducted to understand the performance of sponge city measures in the improvement of urban water, the analyses covering the full urban water cycle that requires integrated 1D and 2D modelling simulations are limited. This research therefore can serve to be a guide for the planning and designing of sponge cities in practical projects.
2. Material and methods

2.1 Study area

The presented case study is a community with a 1.7-hectare area located in the Doumen District, Zhuhai city, Guangdong province, China (Figure 1). The community has no drainage system, and relies solely on LID facilities with percolating pipes and the surrounding municipal pipe network to eliminate stormwater runoff. The average annual precipitation in Zhuhai is 2055 mm, in which 83.4% concentrates between April and September. The average annual rainy day (daily rainfall ≥ 0.1 mm) is 153.4 days, which includes 26 heavy rain days (daily rainfall ≥ 25 mm).

![Figure 1. Geographical location, elevation and SWMM modeling](image)

Note: The red star in Figure 1 is the study area; the blue dotted range in the lower left corner is the Doumen District of Zhuhai where the research area is located; the upper left corner is the ground elevation of research area while the upper right corner is the coupled elevation between the ground, LID facility and building of the research area; the lower right corner is the simulation diagram of the study area in SWMM model.

2.2 Data collection

The rainfall data was recorded by an automated rain gauge on site at one-minute-intervals. Discharges were measured using two online flow monitors (Water Level range: 0-10 m; Velocity: -6 - 6 m/s) installed at the outlets (THWater 2019). The devices recorded outflow per minute from the outfall during rainfall to an accuracy of 0.2 mm. A total of 40 rainfall events were recorded in 2019 and only 5 independent events (separated by a 6-hour interval without rainfall) produced runoff. The rainfall event that occurred on June 25th, 2019 was used to calibrate and validate the
SWMM and the other four events are further adopted for in-depth analyses. The rainfall event for model calibration and validation has a rainfall depth of 35.4 mm and a relatively short duration of 40 min. The average 1-min rainfall intensities for all rainfall events are between 0.004 - 0.1 mm/min while the rainfall durations are between 5 and 3,420 min.

2.3 Model description

SWMM is an open source software that has been widely used for planning, designing, and evaluation of flow dynamics and water quality within urban drainage systems (Johannessen et al. 2019, Tuomela et al. 2019). Since version 5.1.013, SWMM further included a LID module for reflecting the functionalities of green stormwater infrastructures such as rain gardens and permeable pavements (USEPA 2019). Therefore, SWMM is able to simulate the influences of various sponge city measures via the LID module to evaluate their performance using indicators such as $V_{ct}$ and the pollutant reduction rate (Randall et al. 2019, Xu et al. 2017). SWMM, however, is limited to 1D simulations and cannot simulate the surface flow in a specific area. Therefore, the Cellular Automata Dual-DraInagE Simulation (CADDIES) model which performs a 2D pluvial flood inundation simulation using simple transition rules for modelling complex physical systems can be integrated with SWMM for efficient calculation of urban surface flow under a wide range of rainfall storms to fully evaluate flooding and water environment issues in the area (Gibson et al. 2016). The urban flooding simulation through CADDIES can lead to reduced computational times and the simulation results show consistency with the results of the InfoWorks ICM model. (Wang et al. 2019b).

2.4 Model settings

2.4.1 Model setup and integration

In this study, the SWMM is used to simulate the rainfall-runoff response and the flow within drainage system. Manholes are considered as the interface linking overland surface and underground drainage network. According to ground elevation and land-use, the area is divided into 60 sub-catchments (Figure 1 bottom right corner). This study analyzes the runoff quantity scenarios before (Scenario 1) and after (Scenario 2) the construction of sponge city LID facilities.
For Scenario 1, no sinking depth is set for the green space, the road surface is impervious, and the runoff only relies on gravity in sewer pipes. For Scenario 2, the runoff infiltrates through LID facilities first, and then drains the excess runoff into the municipal drainage system through the permeate pipes. Two types of LID facilities (rain garden and permeable pavement) are implemented for each sub-catchment in the area. The input data of LID facilities are set according to their construction drawings. The sub-catchment data include drainage area, width, percentage of impervious areas, and average sub-catchment terrain slope. The area of 60 sub-catchment ranges from 0.001 to 0.218 ha, the widths from 2.34 to 46.66 m. Since the area is not large, the slopes of all sub-catchments are uniformly set to 0.2%. SWMM also requires the soil infiltration capacity of pervious areas and the underground storm-water pipelines information, therefore, these parameters are set according to actual conditions.

CADDIES, a grid cell based 2D model is used for surface flow simulation. The input data and model settings for CADDIES, includes terrain elevation, rainfall or inflow hydrographs, time interval, resolution, and boundary conditions. The terrain elevation model is interpolated from the measured elevation points (Figure 1 upper left corner), where the building heights are also included in the model (Figure 1 upper right corner).

SWMM is applied first to calculate the surface runoff for each sub-catchment. The simulated runoff is then used to evaluate the performance of sponge city LID facilities and drainage network. The excess runoff (that is beyond the capacity of sponge LID facilities) will turn into overland flow that becomes an input for the CADDIES model used to simulate the propagation of surface flow. The total volume of overland flow, surface water depth and outflow discharge are used to assess the capacity of LID facilities in runoff control.

2.4.2 Model calibration and validation

Since the overland flow processes were not monitored, we only calibrate and validate SWMM model. The rainfall event on the 25th June, 2019 is used for both model calibration and validation. The northwest outfall is used for model calibration while southwest outfall for model validation. The Nash–Sutcliffe efficiency (NSE) index is chosen to evaluate the simulation results for model calibration and validation (Gong et al. 2017). According to the current assessment standard for
sponge city effects, the NSE of the model calibration and validation should not be less than 0.5 (MHURD 2019).

2.5 Assessment and analysis methods

One of the main objectives in this study is evaluating the performance of LID facilities in reduction of overland flow. Four rainfall conditions (i.e. 2-hr design rainfall with 20-, 30-, 50- and 100-year return periods) are considered to quantify the effectiveness before and after the implementation of LID facilities (Figure 2). The local rainfall intensities are calculated as:

\[
i = \frac{847.172 \times (1 + 0.659 \times \ln P)}{(t + 5.373)^{0.391}}
\]

where \(i\) (mm/h) is the average rainfall intensity; \(P\) (a) is return period; and \(t\) (min) is the duration of rainfall.

![Figure 2](image)

**Figure 2.** Distribution of 20, 30, 50, 100-year designed 2h rainfall events in Zhuhai city.

The variations of flooding extents within the community under different rainfall conditions are used to evaluate the performance in overland flow reduction. A long-term analysis is also conducted via simulating all rainfall events within 2009 to determine the annual runoff total control rate before and after LID facilities construction.

The \(F_d\) for a given rainfall event is defined as:

\[
F_d = \frac{\text{the flood area}}{\text{the community area}} \times 100\%
\]

The \(C_r\) for a given single rainfall event is defined as:

\[
C_r = \frac{V_{dLID}}{V_{rainfall}} \times 100\%
\]
Where $V_{\text{after}}$ is total runoff volume after sponge city construction (m$^3$), $V_{\text{rainfall}}$ is the total volume of rainfall (m$^3$).

The $R_e$ for a given rainfall event is defined as:

$$R_e = \frac{V_{\text{after}}}{V_{\text{before}}} \times 100\%$$

Where $V_{\text{before}}$ is total runoff volume before sponge city construction (m$^3$).

The $R_{cr}$ for a given rainfall event is defined as:

$$R_{cr} = \frac{D_{cr}}{D_{ar}} \times 100\%$$

Where $D_{cr}$ is the annual average captured rainfall (mm) while $D_{ar}$ is the regional annual average rainfall (mm).

3. Results and discussions

3.1 Calibration, validation and simulation results

Figure 3 shows the simulated hydrographs and the measurements at the two outfalls for the model calibration. The NSE for model calibration and validation are 0.72 and 0.91, respectively. Although both NSE and $R^2$ are greater than 0.7, a slight difference between the monitored and simulated values can be seen in Figure 3. This difference is mainly due to the short warm up time of the model and the instability of monitoring data. Overall, the results of model calibration and validation are satisfactory, and the established model can be integrated with CADDIES and used for the following analysis.

![Figure 3](image-url)

**Figure 3.** Simulated and observed hydrographs on June 25, 2019 for (a) northwest outfall, (b) southwest outfall.
3.2 Stormwater control assessment of LID facilities

3.2.1 Flooding alleviation effects under extreme stormwater events

This study uses 2-hour designed rainfall events in 20-100 years to conduct an overall flooding assessment of the two scenarios before and after the sponge city LID facilities construction. By using CADDIES 2D model, the difference of maximum flooding depths before and after the sponge city construction is little which changing from 0.19 to 0.18 m. It can be seen from Figure 4 that the sponge city construction has little effect on the flooding problems of the community since the $F_n$ before and after the sponge construction are less than 0.1%, which means there is nearly no differences between these two scenarios under the designed rainfalls of 20-100 years. Figure 5 depicts the flooding areas during each designed rainfall event. Similarly, the number of flooding areas after sponge city construction is only slightly less than before.

It should be noted that the process of flooding after the end of rainfall is not analyzed. Because the calculation of the infiltration process has been carried out in the SWMM, no infiltration parameters (infiltration rate = 0) are set in the CADDIES, so in this 2D model, the flooding will not disappear after the end of the rainfall events.

![Figure 4. The peak number of flooding grids of each design rainfall and the corresponding $F_n$.](image-url)
Figure 5. Changes in the number of flooding grids under each design rainfall event.

Many studies have shown that the sole application of LID facilities at runoff sources has limited contribution in easing flooding problems in urban- or basin-scale, which is consistent with the results of this study (De Vleeschauwer et al. 2014, Lee et al. 2012, Rezaei et al. 2019). Li et al. (2019) pointed out the definition of sponge city construction, which includes not only the LID practices at sources, but also the midway drainage pipes and the terminal excessive stormwater drainage system. Sin et al. (2014) used SWMM 5.0 to calculate the total runoff before and after LID facilities construction, the results showed that the Rr was only 9% (from 54.2 to 49.3×10^3 m^3) for a whole basin with the area of 156.84 ha.

3.2.2 Contributions of LID facilities

The statement that the source LID facilities have little impact on the urban flooding problems is only valid for heavy stormwater events with a large return period. In fact, heavy stormwater events or similar extreme rainfall events only account for a very small part of the annual rainfall events in a certain area (about 1%), which means that if most small and medium-sized rainfall events are controlled, it can also have significant positive benefits for rainfall-runoff problems in specific region (Guo et al. 2010). Therefore, this study further analyzes the capacity of the source LID facilities to control runoff volume through the simulation of several monitored small and medium rainfall events and the daily rainfall series in the typical years (2009) of Zhuhai city.
During the period from May to August 2019, there was basically no significant runoff in the study area under small rainfall events (under 15 mm). But for rainfall events with more than 20 mm, the uncertainty of the results became very large. We choose four rainfall events (Table 2) for the simulation analysis, in which two outfalls in the study area have a complete runoff process. The total runoff volume of each outfall under each rainfall before and after the sponge city LID facilities construction is obtained. Then the R, before and after the construction and the C, after the construction are calculated. After the construction of the sponge city, the study area can effectively reduce the runoff volume and improve the C, of the whole area. However, under different rainfall events, the runoff R, and the C, greatly changed. This is due to different rainfall event have different characteristics, i.e. rainfall depth, rainfall duration, antecedent dry period and rainfall intensity, while each characteristic could influence the runoff quantity control capacity of LID practices (Batalini de Macedo et al. 2019, Gong et al. 2018, Hernández-Crespo et al. 2019, Sun et al. 2019, Yang et al. 2019). However, most studies have shown that the runoff quantity control capacity of the LID facilities is negatively correlated with rainfall depth, that is, with the increase in rainfall depth, the runoff control capacity of LID facilities is reduced (Hakimdavar et al. 2014, Stovin et al. 2015).

<table>
<thead>
<tr>
<th>Date</th>
<th>Rainfall Depth (mm)</th>
<th>Scenario</th>
<th>Runoff Volume (m³)</th>
<th>R (%)</th>
<th>C (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Northwest</td>
<td>Southwest</td>
<td>Total</td>
</tr>
<tr>
<td>31 May, 2019</td>
<td>24.2</td>
<td>2</td>
<td>104.4</td>
<td>95.4</td>
<td>199.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>119.4</td>
<td>167.4</td>
<td>286.8</td>
</tr>
<tr>
<td>18 June, 2019</td>
<td>42.6</td>
<td>2</td>
<td>241.8</td>
<td>262.8</td>
<td>504.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>271.2</td>
<td>346.8</td>
<td>618</td>
</tr>
<tr>
<td>2 July, 2019</td>
<td>110.6</td>
<td>2</td>
<td>506.4</td>
<td>484.2</td>
<td>990.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>604.2</td>
<td>635.4</td>
<td>1239.6</td>
</tr>
<tr>
<td>31 July, 2019</td>
<td>47.2</td>
<td>2</td>
<td>8.4</td>
<td>4.8</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>133.2</td>
<td>104.4</td>
<td>237.6</td>
</tr>
</tbody>
</table>

As can be seen from Table 2, when the rainfall is large, the R, and C, of Scenario 2 are not completely negatively correlated with the rainfall depth compared with the Scenario 1. The rainfall depth of events on May 31, 2019 and July 2, 2019 differed by 86.4 mm, but the total C, after the construction is only 4.1%. The reason is that the rainfall event on May 31, 2019 was a short duration heavy rainfall. Although the rainfall depth on July 2, 2019 was larger than the previous event, it lasted for a long time, so the average rainfall intensity was only one-tenth
compared with the former event. Therefore, the total \( C_r \) on July 2, 2019 is far larger than that of May 31, 2019. Meanwhile, the rainfall depth on June 18, 2019 was similar to the rainfall on July 31, 2019 (42.6 mm and 47.2 mm), but the \( R_r \) and \( C_r \) of the two events are very different. The main reasons are their differences of rainfall duration and average rainfall intensity. In addition, antecedent dry period is also one of the key factors affecting the final \( R_r \) and \( C_r \) (the antecedent dry period difference between these two events is 5 days). In general, for small and medium-sized rainfall events, the source LID facilities can significantly reduce the total runoff volume and increase the total \( C_r \) within the study area.

\( V_{cr} \) is a very important indicator in the current China sponge city construction assessment standard, which can effectively measure the environmental benefits brought by the sponge city construction (Zhang et al. 2019b). In this study, the daily rainfall series in the typical year (2009) of Zhuhai city is selected as the boundary condition of the model and the runoff volume of two outfalls of the whole year is summed up. The runoff hydrographs before and after sponge city construction is shown in Figure 6. The total rainfall depth in Zhuhai in 2009 was 2000.6 mm. The SWMM simulation results show that compared with Scenario 1, the total \( R_r \) is 28.0%, and the \( V_{cr} \) increase from 34.5% to 52.9%, which means the overall trend is similar to the simulation of single event rainfall.

![Figure 6](image)

**Figure 6.** The corresponding runoff hydrographs of northwest and southwest outfall before and after LID construction under the annual rainfall during 2009.

Guo et al. (2019) has carried out multi-objective evaluation of \( V_{cr} \) by setting multiple LID construction scenarios. It was found that when the layout, quantity or area of LID facilities are
different, $V_{cr}$ would also produce corresponding changes which can reach about 89%. Randall et al. (2019) also used a hydrologic model to assess the $V_{cr}$ of a 133 km$^2$ area and resulted for 80% of total runoff was controlled when source LID facilities was constructed. However, in this study, $V_{cr}$ is only 52.9%, far less than 80% of other studies. The reason is mainly due to the different rainfall characteristics in different regions. The average annual rainfall in Zhuhai exceeds 2000 mm while the above two studies were carried out in Qingdao and Beijing, China, with annual rainfall of only 709 mm and 525.4 mm. Zhuhai is located in southern China where has more dense rainfall events with longer rainfall duration (shorter antecedent dry period), while Beijing and Qingdao are northern cities of China, where most of the rainfalls are in the rainy season with short duration. As mentioned earlier, the source LID facilities are more suitable for controlling scattered small and medium-sized rainfall events. Therefore, the $V_{cr}$ in this study is low.

3.3 Resolution effect on CADDIES 2D model

CADDIES 2D model is based on cellular automata (CA) theory. The key factor of calculation speed depends on the number of cells in the raster data, and the raster data resolution also affects the accuracy of the model simulation (Wang et al. 2018). Defining the appropriate grid size in 2D flood simulations is critical for optimizing the modelling performance to obtain accurate results with minimum computational time. In order to find the most suitable terrain resolution in the specific area, we explore the simulation accuracy and speed of CADDIES 2D model by comparing different terrain resolutions in the study area. Due to the small size of the study area (1.7 ha), grid widths of 0.25 m, 1 m, 5 m and 10 m are set to analyze the accuracy of the simulation results of CADDIES model and then compare the results by Analysis of Variance (ANOVA). ANOVA can reasonably judge whether there are significant differences in the simulation results using different DEM resolutions. When the $p$-value is less than 0.05, there is a significant difference in the simulation results while there is no significant difference in the simulation results when the $p$-value is greater than or equal to 0.05. The simulation results of the inundation in this study are reflected by the $F_{cr}$.

Table 3 shows the $F_{cr}$ simulation results using different DEM resolutions under different return periods. As the grid size grows or decreases, the total number of grids also varies widely. Through
the ANOVA of the simulation results using four different resolution DEM data, it is found that the simulation results of the four data sets are significantly different since the p-value < 0.001, but when only considered first three resolutions with the grid size of 0.25 m, 1 m and 5 m, there is no significant difference in \( F_n \) (p-value = 0.43, much greater than 0.05). Therefore, there is a significant difference in the simulation results if and only if the grid resolution is 10 m. In this study, the simulated inundation depth results are also analyzed by ANOVA. The results show that the runoff depth calculated by CADDIES 2D model using four different resolution DEM data under the same return period also have significant difference since the p-value = 1.8\times 10^{-10} which is much smaller than 0.01. Only when the DEM resolution is 0.25 m and 1 m, the simulation results have a high degree of similarity and consistency. Therefore, when the DEM data is selected based on the accuracy of the simulation results for the study area, the DEM data with the grid size of 0.25 m and 1 m can obtain accurate simulation results compared with rougher resolution DEM data like 5 m or 10 m.

**Table 3.** \( F_n \) of different grid sizes under different return periods.

<table>
<thead>
<tr>
<th>Return period (yrs)</th>
<th>Grid size (m)</th>
<th>Grid area ( (m^2) )</th>
<th>Total grids</th>
<th>Flooding Area ( (m^2) )</th>
<th>( F_n ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.25</td>
<td>0.0625</td>
<td>561824</td>
<td>1128</td>
<td>3.21</td>
</tr>
<tr>
<td>30</td>
<td>0.25</td>
<td>0.0625</td>
<td>561824</td>
<td>1183</td>
<td>3.37</td>
</tr>
<tr>
<td>50</td>
<td>1</td>
<td>1</td>
<td>35114</td>
<td>1232</td>
<td>3.51</td>
</tr>
<tr>
<td>100</td>
<td>5</td>
<td>25</td>
<td>1362</td>
<td>1302</td>
<td>3.71</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>100</td>
<td>342</td>
<td>1050</td>
<td>3.08</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
<td>100</td>
<td>342</td>
<td>1400</td>
<td>4.09</td>
</tr>
<tr>
<td>50</td>
<td>10</td>
<td>100</td>
<td>342</td>
<td>1400</td>
<td>4.09</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
<td>100</td>
<td>342</td>
<td>1400</td>
<td>4.09</td>
</tr>
</tbody>
</table>

However, when considering the model running time (simulation speed), the DEM data with a resolution of 0.25 m is about 15 times greater than that of 1 m when doing the same simulation. Faster simulation times increase model productivity when the similar simulation results are available, which also reduces the pressure on the computer when the model is running thus...
allowing for greater number of scenarios to be trialed within a time-frame. In this study, the 1m resolution terrain DEM data for a simulation of a small community of 1.7 ha can obtain accurate simulation results with a shorter simulation time. However, when the simulated area is large, in order to maintain the higher model calculation efficiency, we can consider using the DEM data with rougher resolution, or reducing the resolution of non-flooding area (like building roof), and increasing the resolution of the area where easy to waterlog such as road surface. This can improve the speed of the model whilst maintaining the accuracy of the simulation results at the same time (Chen et al. 2012).

3.4 Comparison simulation results with MIKE FLOOD

The different models sometimes use different runoff-producing and converging functions, thus have difference applied domains. the integrated SWMM-CADDIES model is compared with MIKE URBAN (1D) and MIKE 21 (2D) in MIKE FLOOD to analyze the differences of simulation results under different runoff-producing and converging models, and to determine which type of model can achieve higher precision for small-scale simulations.

In SWMM, Each LID facility is defined as a separate sub-catchment, roof and road runoff, etc. first flow into the LID facilities for runoff quantity and quality treatment and then discharge into the drainage system. However, unlike SWMM, in MIKE URBAN, only the simulation of the drainage network using the MOUSE engine (which does not have LID model) can be coupled with the MIKE 21 model (which is also a 2D hydrodynamic model) to obtain simulation results of the drainage system and surface flow. Therefore, when MIKE URBAN is used, the LID facilities are not defined as separate sub-catchments, but integrate into each catchment. The runoff volume effect of LID facilities is simulated by adjusting the initial rainfall losses. The proportion of LID facilities occupying the entire catchment area and the storage capacity of each facility is modeled strictly according to its actual situation. In this section, the results of the MIKE URBAN and MIKE 21 coupled model with the SWMM and CADDIES 2D models are compared to explore the accuracy of the simulation results of the integrated SWMM and CADDIES model. Only Scenario 2 is used for comparison analysis in this section. The boundary conditions are annual rainfall events of typical year and 2-hour design rainfall events in the Zhuhai city with return period of 20,
30, 50 and 100 years.

3.4.1 Runoff and drainage system model

Figure 7 shows the simulated runoff hydrographs of the SWMM and the MIKE URBAN model under typical annual rainfall (2009). The results show that the two models have a high degree of consistency through the simulation of the drainage system process. The simulated total annual runoff is 16,057.0 m³ using SWMM while 16,149.8 m³ obtained by the MIKE URBAN model (only 92.8 m³ differences of a whole year). By calculation, the $V_c$ obtained by SWMM and MIKE URBAN model are 52.9% and 52.7%, respectively. When comparing the simulation results of 2-hour design rainfall events by ANOVA, it is found that the simulation results of the two models are also not significantly different since the p-value is 0.09 (greater than 0.05).

![Figure 7. The simulated runoff hydrographs of SWMM and MIKE URBAN under the annual rainfall during 2009.](image)

Although two models have produced similar results, the model parameters set in the modeling process are quite different because their differences between runoff-producing and converging models. In this study, the runoff-producing model used by SWMM is Horton infiltration model and the converging model are nonlinear reservoir methods. In addition to the manual information of nodes, conduits and catchment, the infiltration parameters, hydraulic parameters and various
structural layer information of the LID facilities are required to be more precise. Therefore, using SWMM to simulate a community scale area like this study (clear drainage system information and small amount of data) can achieve higher accuracy. However, for the simulation of watershed scale, manual input of drainage system information is cumbersome while the characteristics of the catchment are more complicated. Therefore, the fixed runoff coefficient method is used to calculate the runoff in MIKE URBAN model, and the time-area curve method is used for the calculation of flow. The required parameters are less, but at the same time, the accurate and efficient simulation can be performed for the local runoff-producing and converging process. Therefore, compared with MIKE URBAN, SWMM is more suitable for small-scale simulation.

3.4.2 2D hydrology model

After analyzing the simulation results of the SWMM and MIKE URBAN models, it is found that the two models have a high degree of consistency. We further compare the CADDIES 2D model with the MIKE 21 model to perform a comparison of 2D hydraulic simulation results.

The CADDIES 2D model uses discrete grid and CA transfer rules for flood simulation calculations. The CA transfer rule refers to the water transfer calculation using the relevant state variables of last time step on the grid and its surrounding grids, that is, the new state of a grid does not depend on the new state of any other grids on the same time step. However, the principle of MIKE 21 is to solve the continuous equation and momentum conservation equation of dynamic flow by finite difference method.

In order to simulate the waterlogging in the study area more clearly under heavy rainfall events, this study uses 2-hour design rainfall events in the Zhuhai area with return period of 100 years as boundary conditions to simulate the surface flow by using these two models. The simulation results of the two models are basically the same since no significant runoff accumulation occurring in both CADDIES and MIKE 21. The waterlogging only occurs in the LID facilities (the area with the concave depth) in the study area. However, compared with Mike 21, the CADDIES 2D model can reach twice the speed of MIKE 21. Therefore, CADDIES 2D model is more efficient when the same conclusion can be obtained, and the parameters in the CADDIES 2D model are less.
4. Conclusions

A systematic study is conducted to investigate the contributions of LID facilities on stormwater runoff management by using integrated SWMM and CADDIES 2D models. The resolution effect on the CADDIES simulation results is then carried out. Finally, the simulation results of SWMM and CADDIES 2D are compared with that of MIKE FLOOD. Key conclusions of the study are given below.

In this study, the SWMM and CADDIES 2D integrated model is used to construct a 1D and 2D simulation model for a community in Zhuhai city. The SWMM model is calibrated and validated using an historical event. The NSE of two outfalls are all above 0.7. Through analysis, sponge city construction in this community can effectively reduce the total runoff volume under medium and small rainfall events. In 2009, for example, the $V_{cr}$ after sponge city construction can be increased by nearly 20%. However, the source LID facilities cannot cope with the less-frequent rainstorm events. In this study, the difference of $F_{cr}$ before and after the sponge construction is less than 0.1%.

The resolution of the DEM data strongly influences the simulation results of the CADDIES 2D model. It is found that for the small-scale region such as the community in this study, using the resolution (raster data grid size) of 0.25 m - 1 m can obtain more accurate simulation results. When the grid size of the local DEM data is 5 m or 10 m, the simulation results are significantly different. However, when the calculation speed of the CADDIES 2D model is considered simultaneously while ensuring the accuracy of simulation results, the computational time required for the 0.25m resolution is much higher than that of 1m resolution. So, 1 m resolution is more suitable for the input of the CADDIES 2D model. When the study area is large, the resolution of the DEM data can be scaled down.

The results also show that the SWMM and MIKE URBAN models have a high degree of consistency when performing drainage network simulation even though the mechanism of their runoff-producing and converging models is different. When 2D hydrodynamic simulation was considered, both CADDIES 2D and MIKE 21 model can accurately simulate the surface flow.

When the same rainfall event is used, the simulation results are similar. But compared with MIKE FLOOD, the integrated SWMM-CADDIES model is more suitable for small-scale simulations.
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References


Tuomela, C., Sillanpää, N. and Koivusalo, H. 2019. Assessment of stormwater pollutant loads and


