RESPONSE TO THE EDITOR

Dear Authors,

According to the comments of the two reviewers, of which one suggested “reject” and one “major revisions” your manuscript needs substantial further revisions before it can be reconsidered for publication. Particularly the method and result descriptions of your study need to be improved. Reviewers identify similar shortcomings of your manuscript, which need special attention: (i) the methodology e.g. coupling of the models is unclear, (ii) the description and discussion of your findings need to be improved, (iii) to which extent are the results specific for the case study and to which extent and how could they be transferred to other sites.

I ask you to revise your manuscript in accordance with all the comments and recommendations of each of the reviewers. When you have completed your revision, please submit your revised manuscript with the changes marked, and a detailed item-by-item response to each of the reviewer's comments.

Best regards

Heidi Kreibich

Dear Editor,

Thank you for your time and efforts for helping us improve our manuscript. We have major revised our manuscript and a summary of the revision is provided as the following.

The description of the two models and the process of model coupling were modified in section **2.3** and **2.4**. In section **2.3**, we introduced the advantages and disadvantages of the two models and explained the reason for model coupling. In section **2.4**, we re-wrote the process of model coupling hoping to make it more clear and understandable. We further improved the description and discussion by amending the most paragraphs and spliting the original section **4.2** into new section **4.2** and **4.3** to disscuss the effectiveness at different hazard levels and the cost-effectiveness of LID practices. In section **5**, we concluded that the practice of model coupling could be applied to other sites, and that most findings could be transferred to other sites except that PP were more effective for urban inundation mitigation than GR.

Details of the changes are presented in the revised manuscript. The detailed item-by-item response to the reviewers’ comments are listed as the following. We deeply appreciate your consideration of our work. Please do not hesitate to contact us for any queries.

Best regards

On behalf of all the authors

Yang Rui

RESPONSE TO THE REFEREE #1

Dear Referee #1:

Thank you for the valuable comments. We have carefully read all the comments, and our responses to your questions are listed below. We greatly appreciate your time and efforts to help us to improve our manuscript for further revision and publication.

General comments

This study sought to evaluate the impacts of LID practices on urban inundation at a watershed scale in China. Extensive modeling was used to assessed various LID implementation scenarios with a hydrodynamic inundation model, which coupled SWMM and IFMS Urban models. The study is interesting and will contribute to the understanding of LID effectiveness related to flood reduction. However, the scientific quality and presentation quality were poor. First, English in this paper is poor. some contents are difficult to understand. I would strongly recommend the editing by an experienced or even better native English speaker. Next there some major and obvious weakness in methodology and results. I listed them below. Also, it requires lots of improvements in other sections.

Re: Thank you for your recognition for our research. The language of this paper has been proofread by "Editage", a worldwide professional editing company. Since it is still difficult to be understood, we will invite one or two native speakers in our research area to proofread it again. I am so sorry that the poor expression of this paper make you confused. Therefore, in the following part, we will try our best to explain your questions and we also have modified them in the revised manuscript. Thanks again for your patient reading and valuable advices.

Change in manuscript: The language of this paper was proofread by two native speakers again and the expression of this paper was improved. Some confusing problems were modified in the revised manuscript.

Introduction:

1. Review should be correct. In page 3 line 16, "we find that few researches use hydrodynamic models, like SWMM ...". In fact, there are many studies of SWMM in LID field, especially in 2017 in China. Also, the introduction is very universal, does not clearly lead to the specific content of the manuscript and is missing a central theme. For readers to quickly catch your contribution, it would be better to highlight major difficulties and challenges, and your original achievements to overcome them in a clearer way.

Re: Our statement about coupled models is imprecise. Thank you for your kind reminder, and we will modify the expression and here is the revised version of the last paragraph of Introduction.

It is noteworthy that peak flow reduction, runoff reduction, and hydrograph delay are widely used indexes when evaluating the performance of LID practices (Ahiablame and Shakya, 2016; Qin et al., 2013; Zhang et al., 2016). However, these indexes are not very intuitive and how LID practices perform on urban inundation is more beneficial to local residents, such as providing guides for their travel behaviours.Indeed, some 1D-2D models have been applied for flood management such like ESTRY-TUFLOW (Fewtrell et al., 2011), InfoWorks ICM (Russo et al., 2015) and MIKE FLOOD (Loewe et al., 2017). However, most of these models are not free that limits their applications, and the open-source model (like SWMM) with LID module that can be coupied to simulate the urban inundation is needed in recently researches (Burns et al., 2015, Wu et al., 2017, Hu et al., 2017).

Therefore, the goal of this study is to demonstrate through a case study the effectiveness of LID practices to mitigate urban inundation in an urban watershed. The specific objectives were to (1) establish a 1D-2D hydrodynamic model coupled SWMM and IFMS Urban; and (2) evaluate the effectiveness of LID practices under different scenarios and hazard levels; and (3) explore the effiency of designed scenarios that related to the effectiveness of LID practices and the proportion of implementation areas. This study hopes to enrich the inundation mitigation research of LID on an urban watershed scale and provide some references to urban stormwater management and inundation mitigation for local government.

Change in manuscript: We modified the paragraphs and listed the goals and specific objectives we want to achieve on Page 3, line 31 to Page 4, line 8.

"Peak flows reduction, runoff reduction, and hydrograph delays are widely used indexes for evaluating the performance of LID practices (Ahiablame and Shakya, 2016; Qin et al., 2013; Zhang et al., 2016). However, these indexes are not intuitive, and the performance of LID practices for urban inundation is more useful for local residents, such as providing a guide for their travel behaviour. Some 1D-2D models have been applied for flood management, such as ESTRY-TUFLOW (Fewtrell et al., 2011), InfoWorks ICM (Russo et al., 2015) and MIKE FLOOD (Loewe et al., 2017). However, most of these models have a cost, which limits their application, and an open-source model (like Storm Water Management Model, SWMM), with a LID module that can be coupled to simulate urban inundation, is needed (Burns et al., 2015, Hu et al., 2017, Wu et al., 2017).

The goal of this study was to evaluate the effectiveness of LID practices to mitigate urban inundation in an urban watershed using a case study. The specific objectives were to establish a 1D-2D hydrodynamic model that coupled SWMM and IFMS Urban, evaluate the effectiveness of LID practices under different scenarios and hazard levels, and explore the efficiency of the LID scenarios. We intended this study to enrich LID inundation mitigation research at the urban watershed scale and to provide a reference for urban stormwater management and inundation mitigation for local governments."

Materials and methodology:

1. Why you selected these two events? Were they have special characteristics?

Re: We chose two rainstorm events (11 May 2014 and 10 May 2016) for model simulation. On the one hand, the rainfall data and patterns for these two events are available that can be used for model calibration and validation. One the other hand, the increase in the frequency and intensity of urban flooding events associated with these types of rainstorm events (http://www.chinanews.com/gn/2014/06-10/6260988.shtml) highlights the need for these types of rainstorm events. So we think the two events have representations to carry out the research.

Change in manuscript: The two events are representative and have the complete records of rainfall and inundation data (Page 5, line 11 to 13).

"According to the integrity and availability of data, we chose two representative heavy rainstorm event datasets, 11 May 2014 and 10 May 2016 (Figure 3) for model simulation, which included the complete volume of rainfall every hour."

2. How you downscaled the dem resolution? The bias from downscaling was corrected?

Re: We resampled the DEM using Resample tool in ArcGIS 10.1. The aim is to compare the accuracy with the results of Kriging interpolation and we did not use the downscaled DEM for model simulation. This sentence seems useless and we will delete in the revised manuscript.

Change in manuscript: We deleted the useless paragraph on Page 5, line 9 –10.

3. land use area should be described as well as the implementation area of each LID scenario

Re: Revised as requested.

Change in manuscript: The total available area for PP and GR was on Page 7, line 17–18.

4. Is there discharge Data for SWMM calibration？

Re: According to our detailed investigation on local government agencies, there is no discharge data that can be used for our model calibration. Indeed, lacking hydrologic data is a common problem for this type of research and it is even worse in China. Notheless, using inundation data to calibrate the model is an alternative and wide accepted way to calibrate models, and it has been applied in Hu et al. (2017) and Wu et al. (2017).

Change in manuscript: Based on inundation data, this model was calibrated on Page 8, line 2–16.

5. Why you coupled SWMM and IFMS Urban models? What the advantages compared with others? This study discussed inundation depth, area and time. There three indices could be got from some 2D inundation model. As I know, the outputs of SWMM are outflow, peak flow, flood volume, etc. This study didn't mention any of them. So, why you need SWMM?

Re: The reasons for choosing and coupling these two models are not clearly stated in section 2.3 and 2.4 of our original paper, we have made some descriptions to revise it in our revised manuscript:

SWMM is a 1D rainfall-runoff model which can use the given hydrology data and hydrodynamics to simulate the quantity and quality of rainfall-runoff. Nontheless, when the node overflow occurs, SWMM cannot simulate the spatial and temporal distributions of surface inundation, but the IFMS Urban can using 2D shallow water equations. However, the simulations of IFMS Urban must base on the simulated results of SWMM. So we coupled these two models to realize the simulation on the spatial and temporal distributions of surface inundation. And the outputs of the coupled model are inundation depth, inundation areas and inundation time. Indeed, we are more concerned about the results of surface inundation, and the outputs of SWMM are not showed in this research.

SWMM is an open-source model and it has been widely used to simulate the hydrologic performance of LID practices. IFMS Urban has great compatibility with ArcGIS and SWMM, and it can simulate surface inundation using DEM. What's more, the process of data conversion and model coupling are accomplished in IFMS Urban, and it doesn't need any other software programming, which is convenient for researchers and non-expert users.

Change in manuscript: We reorganized the paragraphs to introduce the advantages of the two models. The introduction of SWMM and IFMS Urban has been shown at section ***2.3*** *(Page 5, line 25–Page 6, line 5).*

"SWMM is an open-source model that can simulate dynamic runoff quantity and quality from urban areas, and it has been widely used to simulate the hydrologic performance of LID practices (Rossman, 2010; Wu et al., 2013). However, SWMM cannot simulate the spatial and temporal distributions of surface inundation. Recently, some scholars have conducted simulationsusing secondary developments of this software (Seyoum et al., 2012; Son et al., 2016; Zhu et al., 2016). We expected that this application would be difficult to use in our study area due to differences in computer programming. Coupling a model with SWMM for 2D simulation is another way to simulate the spatial distribution of urban inundation (Huong and Pathirana, 2013; Wu et al., 2017).

The Integrated Urban Flood Modeling System (IFMS Urban) was developed by the China Institute of Water Resources and Hydropower Research (IWHR) in cooperation with other institutions. Based on the simulated results from SWMM, IFMS Urban can simulate the temporal and spatial distribution of urban inundation, and it is compatible with ArcGIS and SWMM. Data conversion and model coupling are accomplished in IFMS Urban, and it does not need additional software programming, which is convenient for researchers and non-expert users."

Results:

1. The results for hazard level seem very sensitive to the thresholds chosen. Please give information on the thresholds chosen.

Re: The main basis for the thresholds is according to the relationship between vehicle speed and inundation depth researched in Su et al. (2016). Comparing their results with the study status, we set the three hazard levels for this research. Indeed, different thresholds might inform the results for hazard level and researches on more accurate thresholds are needed in future studies. We will put it in the Limitations and future studies in the revised manuscript.

Change in manuscript: The main basis for the choice of thresholds is showm on Page 8, line 25–26, and the additional information is added on Page 12, line 20–22.

Page 8, line 25–26 :"based onaccording to the literature (Su et al., 2016) as well and observed data for as actual situation of the study area."

Page 12, line 20–22:"Another limitation was that the definition of the thresholds for hazard levels was not considered sufficiently in this study. The results for the three hazard levels would be different if the thresholds changed. Therefore, research on criteria and sensitivity analysis of thresholds is needed in the future."

2. Results are contradicted. The authors reported on Page 7 line 11-12 "the reduction effects become more evident as hazard level increases", "the roles of LID practices with respect to urban inundation mitigation are less obvious at High levels than thoseat Low levels". So which one is correct?

Re: From line 4-5 on page 7 of our manuscript, our research results show that for the High levels, the ***depth reduction*** after the construction of LID practices is from 0.11 m to 0.19 m (greater than that for the Low levels) and the ***depth reduction rates*** are from 22 % to 40 % (lower than those for the Low levels) under Scenarios 1 to 4. We didn't express clearly about the results in our original manuscript but we will improve it in the revised manuscript.

*Change in manuscript: We will mainly talk about the depth reduction rate in section **3.2** and the paragraphs have been improved on Page 8, line 26–Page 9, line 7.*

"Compared to the benchmark, the ranges of average depth reduction rates were 60–80, 27–54, and 22–40 % at low, medium and high hazard levels , respectively, for Scenarios 1 to 4 (Figure 5). Under different hazard levels, the average depth reduction rates increased from Scenarios 1 to 4. The average depth reduction rates at the low level were 38, 44, 43, and 40 % higher than the high level under Scenarios 1 to 4, respectively. These results suggest that most inundated areas could not be eliminated at the high level because of severe waterlogging."

3. please show the spatial distribution of reductions in inundation depths instead of average reduction

Re: Figure 5 shows the spatil distribution of reductions in maximum inundation depths of the study area. And from this figure we can see the spatial changes of inundation depth in different scenarios. So we didn't show the spatial distribution of reductions in inundation depths.

Change in manuscript: Besides, Figure 5 also shows the hazard levels of different scenarios. Therefore, we hope to keep this figure.

4. please give more information of PP and GR implementation area, otherwise, you cannot say PP performs better than GR

Re: Thanks to point out our careless on the information missing. Data information is as follows:

The available implementation area of PP and GR is 5.95 km^2 and 8.92 km^2, respectively. The depth reduction rates of 100% PP are 67%, 38% and 23% at Low, Medium and High levels, and the depth reduction rates of 100% GR are 61%, 31% and 21% in three hazard levels. The area reduction rates of 100% PP are 37%, 65% and 67% at Low, Medium and High levels, and the area reduction rates of 100% GR are 32%, 56% and 67% at three hazard levels. Although the implementation area of PP is smaller than GR, the effectiveness of PP on urban immunation mitigation is greater than GR. So we say that PP performs better than GR in this study.

Change in manuscript: The implementation area of PP and GR is added on Page 7, line 17–18, the reduction data is shown on Figure 5, and the comparison of them are present on Page 10, line 25–28.

Page 7, line 17–18 :"the available area for PP and GR was 5.95 km² and 8.92 km², respectively."

Page 10, line 25–28 :"Our analysis showed that, although the implementation area of PP was less than GR, PP provided better urban inundation mitigation than GR. This result may have been due to differences in the LID parameters, but it may also have been caused by the PP's more diffuse spatial pattern."

5. in section 3.3 you said the reduction in inundation area under High level was more obvious, but in section 3.1, reduction in inundation depth was less obvious. Please explain.

Re: Poor expression makes this part confusing to be understood but we have improved the expression in the revised manuscript. From the simulated results shown in section 3.2, the ***depth reduction*** after the construction of LID practices is greater but the ***depth reduction rate*** is lower under the High levels compared to Low levels (***question 2, Results***).

In section 3.3, the ***area reduction rate*** is greater under High level compared to other hazard levels (line 22 on page 7). This is because that after the construction of LID practices, in High level, the inundation depth has been decreased and most inundation areas are downgraded from High level to Medium or Low levels, but most inundation areas heavn't been eliminated which make the ***depth reduction rate*** lower than other levels. This is the reason why the ***depth reduction rate*** is lower and the ***area reduction rate*** is greater in High level compared with other levels.

*Change in manuscript: We modified the paragraphs in section **3.2** (Page 8, line 26–Page 9, line 7) and **3.3** (Page 9, line 22–26), and we added section **4.2** (Page 11, line 10–19) to explain the effectiveness at the high hazard level.*

Page 9, line 22–26 :"The average area reduction rates at the high level were up to 71–90 %, which were greater than those at the low level. This likely occurred because, after the implementation of LID practices, the depth of inundation decreased and most inundated areas were downgraded from a high level to a medium level or a low level."

Page 11, line 10–19: "At the high level, the average depth reduction rates decreased from 22 % to 40 %, and the average area reduction rates decreased from 71 % to 90 % under Scenarios 1 to 4. These results showed that the inundation hazard eased at a high level with the implementation of LID practices. However, at the high level, the average depth reduction rates were still 38–40 % lower and the average inundation time was 2.5–5.9 h longer when comperaed to the low level; this indicates that LID practices are more effective for urban inundation mitigation at a low hazard level. The hazard level analysis showed that although LID practices can downgrade the inundation hazard level to medium or low, most inundated areas cannot be eliminated at a high hazard level. This means that the inundation problem could not been resolved only with LID practices; other stormwater management methods should be applied to manage severe waterlogging in high hazard areas, such as restoring river systems, establishing urban wetlands, and improving urban drainage infrastructure."

6. please show the spatial distribution of reductions in inundation time instead of average

Re: Through the analysis of inundation depth and inundation area, we can draw the conclusions of this study approximately, and the analysis of inundation time comfirm effectiveness of LID practices from another aspect. Considering from the full text, inundation time is not the key point in this study, so we didn't show the map of inundation time. If necessary we will discuss it further in the revised manuscript.

Change in manuscript: If necessary we could add another figure (like Figure 5) in the next manuscript.

7. one of the key points in your study is to compare the differences of all scenarios at three hazard levels not to find the differences among three hazard levels

Re: Indeed we both consider the two groups of comparisons in results. From Figure 6 we can see that as the propotion rises from 25% to 100%, the ***depth reduction rate*** (a) and ***area reduction rate*** (b) both increase in the Low, Medium and High levels. It is clear that the reduction rate grows slowly associated with the increasing of proportion of LID implementation from 25% to 100%, which means the efficiency of LID implementation decreases from Scenario 1 to Scenario 4. To better describe the phenomenon, we will built a cost-effectiveness indicator (RPI) in the revised manuscript:

$$\mathrm{RPI} = \frac{R}{P}$$

R means reduction rate of inundation depth and inundation areas, and P means the proportion of LID implementation. From Table 6 we can see that the RPIs of 25% PP+25% GR are always higher than the other scenarios while higher RPI indicates higher efficiency. From the comparisons, we can conclude that the simple increase of the proportion of LID implementation cannot necessarily contribute to the higher efficiency. Finally, we find that the efficiency of 25 % PP + 25 % GR is higher than other scenarios in this study. This indicates that we should not only consider the effectiveness but also the cost of LID practices in the construction of "Sponge City".

Table 6 RPI under differrent scenarios.

		25%PP+25%GR	50%PP+50%GR	75%PP+75%GR	100%PP+100%GR
Maximum inundation depth		0.64	0.44	0.35	0.29
Average inundation depth	Low	2.40	1.48	1.05	0.80
	Medium	1.08	0.86	0.68	0.54
	High	0.88	0.60	0.48	0.40
Average inundation areas	Low	1.23	0.87	0.68	0.53
	Medium	2.22	1.37	0.97	0.75
	High	2.86	1.62	1.14	0.90

Change in manuscript: This has been added on Page 11, line 20–31.

"4.3 Cost-effectiveness of LID practices

Under Scenarios 1 to 4, the effectiveness of LID practices for urban inundation mitigation increased with more area implementing LID practices. However, Table 4 and Figure 5 show that the reduction rates grew slowly with the increase of LID practices from 25 % to 100 %, which suggests that the efficiency of LID practices decreased from Scenario 1 to Scenario 4. To better describe this phenomenon, we used a cost-effectiveness indicator (CEI) :

$$CEI = \frac{R}{P} \quad , \qquad (1)$$

where R is the reduction rate of inundation depth and inundation area, and P is the proportion of LID practices. Table 6 shows that the CEI decreased as the proportion of LID practices increased from Scenario 1 to Scenario 4, and the efficiency of the 25 % PP + 25 % GR scenario was higher than other scenarios (even higher than the 100 % PP + 100 % GR scenario). This indicates that simply increasing of the proportion of LID practices is not necessarily more efficient. Therefore, the effectiveness and the cost of LID practices should be considered in the construction of sponge cities."

Discussion:

1) The discussion is lacking depths. What are the same and different points comparing your study and others? What you studied from this research.

Re: Compared to the existing studies about LID, this study tries to explain the cost-effectiveness of LID for urban inundation risk mitigation. Moreover, this study focuses on the cost-effectiveness changes in different hazard levels under different scenarios.

1. The effectiveness of PP for urban inundation mitigation performs better than that of GR in this research. This conclusion might be different in other regions because of the differences of LID parameters, implementation area, spatial pattern, rainfall intensity, rainfall frequency and other factors. But it gives a reference for local residents and policy-maker that PP might be a good choice for local areas because of the great effectiveness and the large potential for reconstruction in the built-up region (PP could be gradually applied in roads and parking lots, while GR is hard to implement in density construction lands, especially in the urban villages);

2. Through the analysis in section 3.2 and 3.3, we can find that in High level, the inundation depth has been decreased and most inundation areas are downgraded from High level to Medium or Low levels, but most high inundation hazard areas heavn't been eliminated and the ***depth reduction rate*** is lower than other levels. This indicates that LID practices can only ease the inundation depth and downgrade the inundation hazard level in High level. And some other methods of stormwater management should be used together to deal with severe waterlogging in High level areas;

3. Through the analysis in ***question 7, Results***, we find that the RPI decreases as the proportion of LID implementation increases from Scenario 1 to Scenario 4 and the efficiency of 25 % PP + 25 % GR is higher than other scenarios in this study. This indicates that the simple increase of the proportion of LID implementation cannot necessarily contribute to the higher efficiency, and we should not only consider the effectiveness but also the cost of LID practices in the construction of "Sponge City". These findings may provide some suggestions for LID designs in other regions.

Change in manuscript: The Discussion has been modified and improved on Page 10, line 22.

2) The discussion on cost-effectiveness completely fell from the sky on page 9 line 3. You neither present how the costs were estimated nor discussed them in the Results.

Re: The main difference among scenarios from Scenario 1 to Scenario 4 is the proportion of LID implementation, and the cost will be higher as the proportion of LID implementation increases. Therefore, we develop a cost-effectiveness indicator (RPI) to discuss on the efficiency of LID practices (***question 7, Results***). We will add these descriptions in the revised manuscript.

Change in manuscript: This part has been added on Page 11, line 20–31.

3) In page 9 line 22, "we also find that spatial distribution of landscape patterns ...". This information completely fell from the sky. You neither present them in the Results.

Re: Thanks for pointing out the expression problem that these results are from Kim and Park (2016) and Giacomoni and Joseph (2017), and we will modify it in the revised manuscript.

Change in manuscript: The sentence has been modified on Page 12, line 30–32.

"However, the spatial distribution and landscape patterns of LID practices also contribute to urban flooding mitigation (Giacomoni and Joseph, 2017; Kim and Park, 2016), but few studies have considered these variables."

4) You reported 25% of PP and GR had the highest efficiency. Is it correct? Do you consider the effect of rainfall intensity and frequency? LID effectiveness is highly related to rainfall intensity and frequency.

Re: You made a very constructive suggestion. We did find that rainfall intensity and frequency will influence effectiveness of LID. However, this study focuses on the trade-offs between implementation cost and effectiveness of LID practices, and we did not change the rainfall intensity or other factors in this study. In our research, once-in-100-years heavy rain happened on 11 May 2014 (144.9 mm) is selected to simulate the urban inundation situation. Because we find heavy rain of this intensity attacks Shenzhen almost very year associated with climate change. In this research, place-based references are provided for the policy-makers, and we do not suppose all the findings of this research can be directly transferrable to other places, cities even countries but the analytical methods and the efficiency analysis.

Change in manuscript: Through the comparison between the 25 % PP + 25 % GR scenario and the 100 % PP + 100 % GR scenario, we find that wider implementation of LID practices may not lead to higher efficiency (Page 11, line 27–31). The effect of rainfall intensity and frequency has been added on Page 12, line 22–23.

Page 11, line 27–31:"Table 6 shows that the CEI decreased as the proportion of LID practices increased from Scenario 1 to Scenario 4, and the efficiency of the 25 % PP + 25 % GR scenario was higher than other scenarios (even higher than the 100 % PP + 100 % GR scenario). This indicates that simply increasing of the proportion of LID practices is not necessarily more efficient. Therefore, the effectiveness and the cost of LID practices should be considered in the construction of sponge cities."

Page 12, line 22–23:"The influences of rainfall intensity and frequency were not considered in this study, which is related to the effectiveness of LID."

Specific comments

1) Page (P) 1 line (L) 15-19, too long to understand.

Re: This study proposes a hydrodynamic inundation model, coupling SWMM (Storm Water Management Model, 1D) and IFMS Urban (Integrated Urban Flood Modeling System, 2D), to assess the effectiveness of LID practices under different scenarios and hazard levels. The results are shown as follows.

Change in manuscript: The sentence has been simplified on Page 1, line 14–18.

"This study used a hydrodynamic inundation model, coupling SWMM (Storm Water Management Model) and IFMS Urban (Integrated Urban Flood Modelling System), to assess the effectiveness of LID under different scenarios and hazard levels."

2) P1L25, considering cost-effectiveness, you don't give any information on it.

Re: The information about cost-effectiveness is mentioned above (***question 2, Discussion***).

Change in manuscript: This has been added on Page 11, line 20–31.

3) P2L4: what are secondary disasters? it is better to delete.

Re: Amended as requested.

Change in manuscript: This word has been deleted on Page 2, line 7–8.

4) P3L18-20, there some studies on this topic, please review them.

Re: Amended as requested.

Change in manuscript: The paragraph has been modified on Page 4, line 1–3.

"However, most of these models have a cost, which limits their application, and an open-source model (like Storm Water Management Model, SWMM), with a LID module that can be coupled to simulate urban inundation, is needed (Burns et al., 2015, Hu et al., 2017, Wu et al., 2017)."

5) P3L29, give rainfall information from April to September.

Re: April to September marks the rainy season in Shenzhen. There are 38 rainstorm days (95% of the whole year) in 2017 and the average rainfall is 170-350 mm every month during this period.

Change in manuscript: The information has been added on Page 4, line 14–15.

"There were 38 rainstorm days (95 % of the year) in 2017 and the average rainfall was 170–350 mm every month during this period."

6) P4L5-10. simplify the description.

Re: The study site is located in Guangming New District of Shenzhen, China (Fig. 1). The total area of this study site is 37.68 km^2 with 69.8 % of it is the construction land. Because of the intensive inundation disasters, Guangming New District was selected as the first pilot area for LID practices in Shenzhen in October 2011. Therefore, there is a need to research the effectiveness of LID practices on urban inundation mitigation in this area.

Change in manuscript: The paragraphs have been reorganized on Page 4, line 17–20.

"The study site was located in Guangming New District of Shenzhen, China, and it is in the Maozhou River Basin (Figure 1). The total area of our study site was 37.68 km2, of which 69.8 % was impervious surfaces. Guangming New District was selected as the first pilot area for LID practices in Shenzhen in October 2011 because of the intensity of its inundation disasters. There is a need to research the effectiveness of LID on urban inundation mitigation in this area. "

7) P4L12, delete"needed for modeling".

Re: Amended as requested.

Change in manuscript: The phrase has been deleted on Page 5, line 2.

8) P4L18-19, how to do.

Re: We resampled the DEM using Resample tool in ArcGIS 10.1.

Change in manuscript: The sentence has been deleted on Page 5, line 9–10.

9) P4L20-22, improve.

Re: The reason why we choose the two events is mentioned above (***question 1, Materials and methodology***) and we will improve it in the revised manuscript.

Change in manuscript: The sentence has been improved on Page 5, line 11–13.

10) P5L1-3, improve.

Re: We have reorganized section 2.3 and 2.4 in the revised manuscript.

Change in manuscript: The sentence has been improved on Page 6, line 14–17.

"Model coupling occurred in IFMS Urban. First, an unstructured 2D grid model was meshed with an average cell size of 15 m; second, ground elevations were assigned to each grid; finally, each node was linked with a corresponding grid for water exchange, and the distribution of surface inundation was calculated with 2D shallow water equations."

11) give clear information on the model.

Re: The detailed information about the model is introduced above (***question 5, Materials and methodology***) and we will improve it in the revised manuscript.

*Change in manuscript: The introduction has been added on section **2.3** (Page 5, line 25–Page 6, line 5).*

12) P5L31-32, "we found ..."???

Re: We have not explained the details for this part. In fact, there are some special attributes for buildings on the dense construction land in our research area. Through the detailed urban planning and field investigations of our research area, we found the 80% of the residential lands are urban villages, desnsely constructed on construction lands. The structures and shapes of roofs for urban villages are diversity which makes it difficult to build green roofs on them. More important, the complex owenership and financing pathways which also make it difficult to construct the green roofs for the dense construction lands in our research area. Therefore, we temporarily didn't set green roof in the dense construction land in this study.

Change in manuscript: The sentence has been improved on Page 7, line 12–14.

"Through remote sensing images and field investigations, we found that urban villages have diverse roof structures and shapes, which makes it difficult to implement green roofs."

13) P6L3, strength? is it density?

Re: We will instead "Construction strength" of "construction density" here.

Change in manuscript: The phrase has been modified on Page 7, line 19.

14) P6L19, relative error 30% is acceptable?

Re: Lacking observation data is a universal problem in model simulation, and some models did not have a calibration (Hu et al., 2017). In this study, the relative error of calibration seems a little high, while the relative errors of validation are 5-20%, which is met the requirements of the Standard for Hydrologic Information and Hydrologic Forecasting in China (GBT_22482-2008). If there are more detailed inundation records, the model can be further improved in the future study. We will discuss the limitation in section 4.4 Limitations and future studies.

Change in manuscript: The phrase has been modified on Page 8, line 14–16 and Page 12, line 19–20.

Page 8, line 14–16:"In this study, the relative error of calibration were a little higher, while the relative errors of validation were 5–20 %, which met the requirements of the Standard for Hydrologic Information and Hydrologic Forecasting in China (GBT_22482-2008)."

Page 12, line 19–20 :"Moreover, the accuracy of the coupled model could be further increased with more observed data and information."

15) P6L24-25, give more literature to support

Re: Amended as requested.

Change in manuscript: The standard has been added on Page 8, line 14–16.

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RESPONSE TO THE REFEREE #2

Dear Referee #2:

Thank you for the positive comments and constructive suggestions on this paper, which we fully taken into account in the revised version of the paper. In the supplement we address and reply to the questions below.

1. Page 3, lines 16-18, 'However, we find that few researchs use...': I do not think that this is right. Dynamic models have maybe not been used much to test the measures for mitigation by permeable pavement and green roofs, but such coupled models (1d pipe drainage network model and 2d surface flow model) exist and are used for urban flood management (just a few arbitrarily chosen examples: R. Loewe, C. Ulrich, N.Sto. Domingo, O. Mark, A. Deletic and K. Arnbjerg-Nielsen (2017): Assessment of urban pluvial flood risk and efficiency of adaptation options through simulations - A new generation of urban planning tools. Journal of Hydrology 550, 355-367. B. Russo, D. Sunyer, M. Velasco and S. Djordjevic (2015): Analysis of extreme flooding events through a calibrated 1d/2d coupled model: the case of Barcelona (Spain). Journal of Hydroinformatics 17(3), 473- 490. M. J. Burns, J. E. Schubert, T. D. Fletcher and B. F. Sanders (2015): Testing the impact of at-source stormwater management on urban flooding through a coupling of network and overland flow models. WIREs Water 2. 291-300)

Re: Our statement about coupled models is imprecise. Thank you for your kind reminder, and we will modify the expression and here is the revised version of the last paragraph of Introduction.

It is noteworthy that peak flow reduction, runoff reduction, and hydrograph delay are widely used indexes when evaluating the performance of LID practices (Ahiablame and Shakya, 2016; Qin et al., 2013; Zhang et al., 2016). However, these indexes are not very intuitive and how LID practices perform on urban inundation is more beneficial to local residents, such as providing guides for their travel behaviours.Indeed, some 1D-2D models have been applied for flood management such like ESTRY-TUFLOW (Fewtrell et al., 2011), InfoWorks ICM (Russo et al., 2015) and MIKE FLOOD (Loewe et al., 2017). However, most of these models are not free that limits their applications, therefore the open-source model (like SWMM) with LID module that can be coupied to simulate the urban inundation is needed in recently researches (Burns et al., 2015, Wu et al., 2017, Hu et al., 2017). Therefore, the goal of this study is to demonstrate through a case study the effectiveness of LID practices to mitigate urban inundation in an urban watershed. The specific objectives were to (1) establish a 1D-2D hydrodynamic model coupled SWMM and IFMS Urban; and (2) evaluate the effectiveness of LID practices under different scenarios and hazard levels; and (3) explore the effiency of designed scenarios that related to the effectiveness of LID practices and the proportion of implementation areas. This study hopes to enrich the inundation mitigation research of LID on an urban watershed scale and provide some references to urban stormwater management and inundation mitigation for local government.

Change in manuscript: The paragraphs has been modified on Page 3, line 31–Page 4, line 8.

"Peak flows reduction, runoff reduction, and hydrograph delays are widely used indexes for evaluating the performance of LID practices (Ahiablame and Shakya, 2016; Qin et al., 2013; Zhang et al., 2016). However, these indexes are not intuitive, and the performance of LID practices for urban inundation is more useful for local residents, such as providing a guide for their travel behaviour. Some 1D-2D models have been applied for flood management, such as ESTRY-TUFLOW (Fewtrell et al., 2011), InfoWorks ICM (Russo et al., 2015) and MIKE FLOOD (Loewe et al., 2017). However, most of these models have a cost, which limits their application, and an open-source model (like Storm Water Management Model, SWMM), with a LID module that can be coupled to simulate urban inundation, is needed (Burns et al., 2015, Hu et al., 2017, Wu et al., 2017).

The goal of this study was to evaluate the effectiveness of LID practices to mitigate urban inundation in an urban watershed using a case study. The specific objectives were to establish a 1D-2D hydrodynamic model that coupled SWMM and IFMS Urban, *evaluate the effectiveness of LID practices under different scenarios and hazard levels, and explore the efficiency of the LID scenarios. We intended this study to enrich LID inundation mitigation research at the urban watershed scale and to provide a reference for urban stormwater management and inundation mitigation for local governments."*

2. 2.2 Data, part 4: What were the criteria for removing nodes and pipelines? A reduction from 4502 to 597 pipelines and from 1175 to 653 nodes seems a bit more that deleting some redundant and incorrect data. How was it tested that the data were redundant?

Re: Indeed, the actural drainage networks are compulsory and substantial. Nontheless, SWMM cannot accurately simulate when the data is huge. Besides, after the data conversion process for applying into the SWMM, some overlaps and break points for the pipelines are generated, which makes lots of nodes and pipelines useless. Therefore, we have to simply the drainage data for model building and the criteria shown below:

a. Add nodes when the pipeline is too long;

b. Keep or add the corner nodeschanging diameter nodes, or large variation range of slope nodes;

c. Keep the parallel pipelines and nodes on both sides of the roads;

d. Delete the useless nodes and pipelines in this model.

Change in manuscript: The criteria have been added on Page 5 line 16–21 .

"We simplified the drainage data for building the model because the urban pipe network is intricate and substantial: add nodes when the pipeline is too long; keep or add the nodes that change the diameter and slope of pipeline; keep the parallel pipelines and nodes on both sides of the roads; and delete the useless nodes and pipelines in this model. Finally, the 4502 pipelines and 1175 nodes in this study were generalized to 597 pipelines and 653 nodes, including 56 outlets and 597 inspection nodes (Figure 2)."

3. 2.4 Coupling the SWMM/IFMS Urban models: As written above, I think that one does not learn much about the coupling. Also, Figure 4 does not help in this respect. One just learns that the models were coupled. But how were they coupled? Is inflow and outflow from and to manholes possible? What were the criteria for inflow and outflow? What was the spatial resolution of the geometry of a street? What timesteps were chosen for coupling? Either more discussion about the coupling is needed, which means that one also need to know more about the numerical schemes used for the two different models, or it does not make sense to have a section for this part.

Re: SWMM is a 1D rainfall-runoff model which use the given hydrology data and hydrodynamics to simulate the quantity and quality of rainfall-runoff. Notheless, when the node overflow occurs, SWMM can't simulate the spatial and temporal distributions of surface inundation, but the IFMS Urban can using 2D shallow water equations. However, the simulations of IFMS Urban must base on the simulated results of SWMM. So we coupled these two models to realize the simulate on the spatial and temporal distributions of surface inundation. What's more, the process of data conversion and model coupling are all accomplished in IFMS Urban, and it doesn't need other software programming or specialized knowledge, which is convenient for researchers and non-expert users. So we don't want to make it complicated or list algorithm and formula in this part. The spatial resolution of the geometry of a street is 15 m. The timestep of calculation is 10 s and the timestep of output is 200 s.

Change in manuscript: Here we listed the main processes of model coupling for readers to understand the important parts in the coupled model (Page 6, line 14–17). The principles of calculation engine and details can be found on the useral manual, while we did not want to make it complex in this part of study. If necessary, we could add the introduction of algorithms and formulas in the next vision.

"Model coupling occurred in IFMS Urban. First, an unstructured 2D grid model was meshed with an average cell size of 15 m; second, ground elevations were assigned to each grid; finally, each node was linked with a corresponding grid for water exchange, and the distribution of surface inundation was calculated with 2D shallow water equations."

4. Page 5, lines 18-20: This sentence is unclear. Also: What is innovative about the coupling?

Re: SWMM is a 1D hydrodynamics model which can simulate the quantity and quality of rainfall-runoff but it can't simulate the urban inundation, while the IFMS Urban is a 2D model which can simunate the urban inundation but it must base on the results of SWMM. Through coupling, we build a 1D-2D hydrodynamic model that can simulate the spatial and temporal distributions of surface inundation. Based on this coupled model, we can evaluate the effectiveness of LID from inundation depth, inundation area and inundation time. And this coupled model both takes in the advantages of SWMM and IFMS Urban (open-source, free, great compatibility with ArcGIS and 2D inundation simulation), which is convenient for researchers and non-expert users.

Change in manuscript: The sentence has been removed and the reasons why we choose and couply the two models have been shown on Page 5, line 25–Page 6, line 5.

"SWMM is an open-source model that can simulate dynamic runoff quantity and quality from urban areas, and it has been widely used to simulate the hydrologic performance of LID practices (Rossman, 2010; Wu et al., 2013). However, SWMM cannot simulate the spatial and temporal distributions of surface inundation. Recently, some scholars have conducted simulationsusing secondary developments of this software (Seyoum et al., 2012; Son et al., 2016; Zhu et al., 2016). We expected that this application would be difficult to use in our study area due to differences in computer programming. Coupling a model with SWMM for 2D simulation is another way to simulate the spatial distribution of urban inundation (Huong and Pathirana, 2013; Wu et al., 2017). The Integrated Urban Flood Modeling System (IFMS Urban) was developed by the China Institute of Water Resources and Hydropower Research (IWHR) in cooperation with other institutions. Based on the simulated results from SWMM, IFMS Urban can simulate the temporal and spatial distribution of urban inundation, and it is compatible with ArcGIS and SWMM. Data conversion and model coupling are accomplished in IFMS Urban, and it does not need additional software programming, which is convenient for researchers and non-expert users."

5. Page 5, line 26: Why was a geostatistical method (Kriging) used for interpolation? I do not see the connection to geostatistics for a digital elevation model in a city.

Re: We need DEM when building the 2D model. However, the accuracy of DEM production from Geospatial Data Cloud can not meet our demand (for example, 6 m, 13 m). However, the high accuracy DEM is confidential and difficult to obtain in China. Alternatively, we find the ground elevation of nodes in pipe network data has a higher accuracy (for example, 6.588 m, 13.483 m), and the nodes on the roads are relatively dense. So we use a geostatistical method (Kriging) to get a high accuracy DEM of the roads with the elevation data of nodes on the roads.

Change in manuscript: The additional information is added on Page 12, line 16–19.

"Lacking accurate data is a common limitation for most studies. In this study, highly accurate elevation data for the study area is confidential and difficult to obtain; therefore, the ground elevation of streets were interpolated from the dense nodes of the pipe network. This method may have affected the simulation results."

6. Page6, top: Please explain why green roofs should not be possible in a dense construction land.

Re: We have not explained the details for this part and thank you for your kind reminder. In fact, there are some special attributes for buildings on the dense construction land in our research area. Through the detailed urban planning and field investigations of our research area, we found the 80% of the residential lands are urban villages, desnsely constructed on construction lands. The structures and shapes of roofs for urban villages are diversity which makes it difficult to build green roofs on them. Thereforce, we temporarily didn't set green roof in the dense construction land in this study.

Change in manuscript: The explanation is added on Page 7, line 12–14.

"Through remote sensing images and field investigations, we found that urban villages have diverse roof structures and shapes, which makes it difficult to implement green roofs."

7. Modeling part (Section 2): Please explain how green roofs and permeable pavements are realized in the model. I assume that a storage for a roof area is assigned (or an existing one is increased) and that there is a soil compartment which gets a connection to the paved area if the pavement is permeable. As this is the key process that is here investigated, I think it is necessary to outline these things (and it is not enough to refer to the manuals of the models).

Re: The simulation designs and parameter setting for PP and GR are listed in Table 1 of our paper, which are strictly desinged according to the manual of SWMM and some highly cited studies of LIDs (Ahiablame and Shakya, 2016; Chui et al., 2016; Kong et al., 2017; Qin et al., 2013).

Change in manuscript: We modified the paragraphs on Page 7, line 11–12.

"The parameters for PP and GR are listed in Table 1, which were designed based on SWMM requirements and LID research (Ahiablame and Shakya, 2016; Chui et al., 2016; Kong et al., 2017; Qin et al., 2013)."

8. Page 7, top: Please explain why the classification in hazard levels is made. What can be learned from the classification? It is written that the changes of inundation level are different for the different classes. But what does one make out of this fact? More discussion about consequences would be useful.

Re: Through the classification in hazard levels, we can explore the effectiveness of LID practices in different hazard levels, especial in the High level. Through the analysis in section 3.2 and 3.3, we can find that in the High levels, the inundation depth has been decreased (***depth reduction rates*** are from 22% to 40 %) and most inundation areas are downgraded from High levels to Medium or Low levels (***area reduction rates*** are from 71% to 90 %), but most inundation areas heavn't been eliminated and the ***depth reduction rate*** is lower than other levels (lower 38-40% than Low level). This indicates that LID practices can only ease the inundation depth and downgrade the inundation hazard level and can't thoroughly resolve the inundation problem in High level. And some other methods of stormwater management should be used together to deal with severe waterlogging at High level areas.

Change in manuscript: The discussion about effectiveness under hazard levels has been added on Page 11, line 10–19.

"4.2 Effectiveness at different hazard levels

At the high level, the average depth reduction rates decreased from 22 % to 40 %, and the average area reduction rates decreased from 71 % to 90 % under Scenarios 1 to 4. These results showed that the inundation hazard eased at a high level with the implementation of LID practices. However, at the high level, the average depth reduction rates were still 38–40 % lower and the average inundation time was 2.5–5.9 h longer when comperaed to the low level; this indicates that LID practices are more effective for urban inundation mitigation at a low hazard level. The hazard level analysis showed that although LID practices can downgrade the inundation hazard level to medium or low, most inundated areas cannot be eliminated at a high hazard level. This means that the inundation problem could not been resolved only with LID practices; other stormwater management methods should be applied to manage severe waterlogging in high hazard areas, such as restoring river systems, establishing urban wetlands, and improving urban drainage infrastructure."

9. Page 7, line 4: Please name scenarios 1 to 4

Re: Amended as requested.

Change in manuscript: We modified the scentence on Page 8, line 29.

10. Figure 6: What is meant by percentage GR and PP? Both with the same percentage?

Re: The proportion means the percentage of the total available implementation areas of LID. Here the ***percentage GR and PP*** means the proportion of Scenario 1 to Scenario 4 (from 25% to 100%) in Figure 6.

Change in manuscript: We have modified this figure to show the data of scenario 1 to scenario 6 (Figure 5).

11. Page 7, lines 14-18: I do not see where this conclusion comes from. Is this concluded from the numbers in Table 4? What is here meant by performance? Reduction of maximum inundation? This paragraph needs clarification.

Re: We did not put the data in the part that the ***depth reduction rates*** of 100% PP are 67%, 38% and 23% at Low, Medium and High levels, and the ***depth reduction rates*** of 100% GR are 61%, 31% and 21% at three hazard levels. Here the performance means the average depth reduction rate. We will reorganize this paragraph.

Change in manuscript: The data has been added in Figure 5, and the paragraph has been reorganized on Page 9, line 8–15.

"Figure 5 shows that the average depth reduction rates of 100 % PP and 100 % GR scenarios were between the 25 % GR + 25 % PP and 50 % GR + 50 % PP scenarios under different hazard levels. These results suggest that LID combinations may be more effective in reducing urban inundation than a single type of LID practice. Based on the comparison of the two LID practices, we found that the average depth reduction rates of the 100 % PP scenario were 67, 38 and 23 % at the low, medium and high levels, respectively. These were 6, 7, and 2 % higher than the average depth reduction rates of the 100 % GR scenario.These results suggest that PP may perform better than GR for reducing the depth of inundation."

12. Page 7, lines 28-31: Again it is not clear where these numbers come from. I do not find it in the Figures. In Figure 6, the single 100 percent cases are not shown.

Re: We did not put the data in the part that the ***area reduction rates*** of 100% PP are 37%, 65% and 67% at Low, Medium and High levels, and the ***area reduction rates*** of 100% GR are 32%, 56% and 67% at three hazard levels. We will add the data in Figure 6.

Change in manuscript: The data has been added in Figure 5.

13. Page 8, line 11: This needs explanation. Why is it difficult to mitigate? Is the reason the topography? I think that such a statement needs to be more specific.

Re: The topographical attributes, such as concaves and potholes, are easy to lead to some places got inundation on the road surfaces. If these places are not or not enough drainage pipes to drainage the rainwater, it is difficult for them to mitigate the influences of urban inundation even there are LIDs. Because of these long-time inundation time areas, the average inundation time increases 0.1 h after the implementation of LID practices (***question 15***).

Change in manuscript: We modified the sentences and mainly explained why the average inundation time increases after the implementation of LID practices. on Page 10, line 10–21.

"This result did not indicate that LID practices cannot decrease inundation time or that the model had errors. The inundation time decreased for all hazard levels, butfor the low and medium levels, some areas inundated for a short-time were no longer flooded, which resulted in a different urban inundation area after the implementation of LID practices. Therefore, the average inundation

time was longer than before LID practices were implemented at the low and medium levels. As LID practices were implemented, the average inundation time decreased continuously from 4.1 to 2.3 h under scenarios 1 to 4."

14. Page 8, lines 12-13: How can one see in these figures that the infrastructure is not perfect? And what infrastructure is here meant and how does it influence the inundation? Also: How can one see from these figures that the LID practices are not perfect? In which sense are they not perfect?

Re: Here we want to explain why some places are difficult to mitigate (***question 13***). These sentences are not rigorous and we will modify them in the revised manuscript.

Change in manuscript: This scentence has been removed.

15. Page 8, lines 13-15: I could not follow the reasoning. Why does the mitigation of short-time inundation areas lead to an increase in the average inundation time with LID measures? Is here something meant along the lines: If a storage due to green roofs helps to keep water back, leading to less inundation depth, the storage will at the same time lead to a longer inundation time (it holds the water back, but releases it eventually)? I am just guessing and I think this needs a better explanation.

Re: Indeed, this is because the statistical number of urban inundation areas are not the same before and after the implementation of LID practices. Here we want to explain why the average inundation time increases 0.1 h after the implementation of LID practices. Because of the implementation of LID practices, the inundation time has been decreased in all hazard levels. However, for the Low level some short-time inundation areas previously affected by surface runoff are freed from urban flooding after the construction of the LID projects, which makes the total number of inundation areas decreases after the implementation of LID. More important, the most freed areas are short-time inundation areas. Although LID practices make existing urban inundation areas' inundation time shorten, the statistical data suggest that the average of the lasting inundation areas' inundation duration is a little longer than that before LID practices. It is also suggests the great effectiveness of LID practices at Low level. We will modify the sentences in line 11-15 and make them clearer to understand.

Change in manuscript: Same to Question 13.

16. Section 4.1, Comparison of permeable pavement and green roofs: What is the reasoning of the different effects? This should be explained based on the mitigation mechanisms. The last sentence sounds a bit strong. I do not think that one test case can use as a proof, if no general reasoning is given for the different performances.

Re: The available implementation area of PP and GR is 5.95 km^2 and 8.92 km^2, respectively. Although the implementation area of PP is smaller than GR, the effectiveness of PP on urban immunation mitigation is greater than GR in this study (***question 11, 12***). Except the differences of LID parameters, the reason of the different effects might be that PP is built both on low ad high construction lands, while GR is only built on low density construction lands. Indeed, the effectiveness of PP for urban inundation mitigation were different from studies (Qin et al., 2013, Ahiablame and Shakya, 2016, Zhang et al., 2016, Hu et al., 2017), and PP can not always perform better because that the effectiveness is depended on the parameters, implementation area, spatial pattern, rainfall intensity, rainfall frequency and other factors in different regions. Here we want to give a reference for local government that PP might be a good choice for local areas because of the great effectiveness and the large potential for reconstruction in the built-up region (PP could be gradually applied in roads and parking lots, while GR is hard to implement in density construction lands, especially in the urban villages).

Change in manuscript: The paragraph has been added on Page 10, line 25–Page 11, line 3.

"Our analysis showed that, although the implementation area of PP was less than GR, PP provided better urban inundation mitigation than GR. This result may have been due to differences in the LID parameters, but it may also have been caused by the PP's more diffuse spatial pattern. PP have shown varying effectiveness for urban inundation mitigation in different studies (Ahiablame and Shakya, 2016; Hu et al., 2017; Qin et al., 2013; Zhang et al., 2016), and PP cannot always perform better because the effectiveness depends on the characteristics, implementation area, spatial pattern, rainfall intensity and rainfall frequency in different regions. Our study shows that PP may be a good choice for local governments because of its effectiveness for stormwater management and its potential use for reconstruction in built-up areas. PP could be gradually applied to roads and parking lots, while GR is harder to implement in densely urbanized areas, especially in the urban villages. "

17. Page 8, line 29: I would be a bit more careful with the word 'comprehensively'. The paper shows one case study. I do not think that this is a comprehensive exploration of inundation mitigation in an urban watershed.

Re: We will delete the word.

Change in manuscript: The word has been deleted on Page 11, line 23.

18. Page 9, lines 10-14: As before, I do not see the point about infrastructure. How is poor infrastructure reflected in the model? If not at all: How can one draw any conclusions about this point from a modeling study that does not capture this effect? If yes: What exactly is meant by poor infrastructure and how is this realized in the model?

Re: The scentences in lines 10-14 are not rigorous. Indeed, we find that the efficiency decreases as the proportion of LID implementation increases from Scenario 1 to Scenario 4 and the efficiency of 25 % PP + 25 % GR is higher than other scenarios in this study. This indicates that the greater proportion of LID implementation might not lead to the higher efficiency, and we should not only consider the effectiveness but also the cost of LID practices in the construction of "Sponge City".

*Change in manuscript: The sentence has been deleted on Page 12, line 10–13 and the paragraph has been reorganized in section **4.3**.*

19. Page 22-23: Maybe this sentence is only not formulated well. But I do not see how from this study one could see anything about landscape patterns ('we find that the...' sounds as if it is a conclusion from this study). The landscape patterns are not discussed, so one cannot conclude about this point. For this reason, I can also not see how 'this provides a new perspective'. Or is here simply meant that this point should be studied in the future? In this case the sentences need to be reformulated.

Re: Thanks for pointing out the expression problem that these results are from Kim and Park (2016) and Giacomoni and Joseph (2017), and we will modify it in the revised manuscript.

Change in manuscript: The sentence has been modified on Page 12, line 30–32.

"However, the spatial distribution and landscape patterns of LID practices also contribute to urban flooding mitigation (Giacomoni and Joseph, 2017; Kim and Park, 2016), but few studies have considered these variables"

20. Conclusions: I think it should be mentioned that the findings in this study apply to the one test case considered. It is not clear if the results are more general and could be transferred to other sites. In particular: Numbers can certainly not be transferred.

Re: This study is a simulation-based research on a local basis. Although the results cannot be transferable to other places directly, the analytical methods, including the coupling model, cost-effectiveness analysis during the sponge city construction can be transferable. We will list the main conclusions below:

1. The coupling model with SWMM and IFMS Urban can be applied to evaluate the effectiveness of LID for urban inundation risk mitigation and can be transferred to other sites.

2. The effectiveness of PP for urban inundation mitigation performs better than that of GR in this research. This conclusion might be different in other regions but it gives a reference for policy-maker on a local basis.

3. LID practices can only ease the inundation depth and downgrade the inundation hazard level but can't thoroughly resolve the inundation problem in High level. Therefore, some other methods of stormwater management should be used together to deal with severe waterlogging at High level areas.

4. The greater proportion of LID implementation might not lead to the higher efficiency, and we should not only consider the effectiveness but also the cost of LID practices in the construction of "Sponge City".

Change in manuscript: The conslusion has been improved on Page 13, line 4–12.

"This study constructed a 2D inundation model that coupled SWMM and IFMS Urban at the urban watershed scale; the model was used to evaluate the effectiveness of LID practices for mitigating urban inundation under different scenarios and hazard levels. We found that the coupled model could be applied to evaluate the effectiveness of LID for urban inundation risk mitigation, and it can be used for different cities of different counties. The model showed that PP were more effective for urban inundation mitigation than GR. This conclusion may be different in other regions, but it can be used by policy makers on a local basis. LID practices can only affect the inundation depth and downgrade the inundation hazard level, but cannot resolve inundation problems at a high hazard level. Therefore, other methods of stormwater management should also be applied to manage severe waterlogging. Wider implementation of LID practices may not lead to higher efficiency, and the cost and effectiveness of LID practices should be considered in the construction of sponge cities."

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A list of modifications related to comments

Please notice that page and line numbers are those of the revised version. And because of the deletion of Figure 4, the Figure 5 is the old Figure 6 and the Figure 4 is the old Figure 5.

Location	Comments in Referee #1	Comments in Referee #2
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Effectiveness of low impact development for urban inundation risk mitigation under different scenarios: a case study in Shenzhen, China

Jiansheng Wu[1,2], Rui Yang[1], Jing Song[3]

[1]Key Laboratory for Urban Habitat Environmental Science and Technology, Shenzhen Graduate School, Peking University, Shenzhen 518055, PR China
[2]Key Laboratory for Earth Surface Processes, Ministry of Education, College of Urban and Environmental Sciences, Peking University, Beijing 100871, PR China
[3]Department of Urban Planning and Design, The University of Hong Kong, Hong Kong

Correspondence to: Jing Song (songjing@hku.hk)

Abstract. The increase in impervious surfaces associated with rapid urbanization is one of the main causes of urban inundation. ~~In order to eliminate the adverse effects caused by impervious surfaces, many scholars have begun to research the use of low~~ Low impact development (LID) practices have been~~to~~ studied for mitigation of urban inundation~~mitigate urban inundation risk~~. This study ~~proposes~~ used a hydrodynamic inundation model, coupling SWMM (Storm Water Management Model~~, 1D~~) and IFMS Urban (Integrated Urban Flood Modelling System~~, 2D~~), ~~to simulate inundation depth, area, and time of stormwater inundation on an urban watershed scale, as well as~~ to assess the effectiveness of ~~two~~ LID ~~practices, permeable pavement (PP) and green roof (GR),~~ under different scenarios and hazard levels~~25 % GR + 25 % PP, 50 % GR + 50 % PP, 75 % GR + 75 % PP, 100 % GR + 100 % PP, 100 % PP, 100 % GR scenarios, and Low, Medium, High hazard levels~~. The results showed that~~the following. 1)~~ LID practices can effectively ~~eliminate~~ reduce ~~inundation risk for most areas under Low hazard level for~~ urban inundation. ~~They can ease the inundation risk for places under higher hazard levels for urban inundation under different scenarios. More specifically,~~ T~~t~~he maximum inundation depth was reduced by 14–~~-~~29 %, average inundation areas were reduced by 34–~~-~~55 %, and average inundation time was reduced by 0–~~-~~43 % under~~in~~ the six scenarios. ~~2)~~ The effectiveness of LID practices differed for the three hazard levels, with better mitigation of urban inundation at a low hazard level than at a high hazard level. ~~In this study, the performance of~~Permeable pavement (PP) mitigated~~ PP~~urban inundation ~~is~~ better than green roofs (GR)~~that of GR~~ under the different scenarios and hazard levels. ~~3)~~ We found that more implementation area with LID was not necessarily more efficient~~The scenario of 100 % PP + 100 % GR has the best effectiveness for inundation reduction, but that of~~and the scenario of 25 % PP + 25 % GR was~~is~~ more efficient~~ when considering cost-effectiveness~~for the study area than other scenarios. The results of this study can ~~serve as~~be used by~~ a reference to~~ local governments to~~, and~~ provide suggestions ~~regarding~~ for urban inundation control, disaster reduction~~,~~ and urban renewal~~, and so on~~.

1 Introduction

In recent years, urban stormwater inundation hazards have occurred frequently in ~~a number of~~ major cities all over the world, leading to significant property damage ~~huge losses~~ in local areas (Bhattarai et al., 2016). In China, according to a report by the Ministry of Housing and Urban-Rrural Development (MOHURD) in 2010, 62 % of 351 cities have suffered from inundation hazards, and 137 of these have had~~them faced the~~ negative effects from~~of~~ urban floods on more than three occasions from 2008 to 2010. In 2012, 2013, 2014, and 2015, the number of cities that suffered urban inundation was 184, 234, 125, and 154, respectively, including Beijing, Shanghai, Guangzhou and~~,~~ Shenzhen~~, and other large cities~~. Urban inundation ~~and secondary disasters associated with it are~~ increasingly threatens~~ing to~~ the sustainable development of urban areas.

Rapid urbanization has become an important cause of frequent urban stormwater inundation,~~Some researches point out that,~~ in addition to extreme precipitation and low standards for urban drainage infrastructure~~, rapid urbanization has become an important cause of frequent urban stormwater inundation~~ (Arnold, 1996; Beckers et al., 2013； Claessens et al., 2006; Zahmatkesh et al., 2015b). ~~The~~ R~~r~~apid expansion of ~~the~~ citiies~~y~~ generally leads to an increase in impervious surfaces, which makes the hydrological characteristics of the urban surface change significantly~~a lot~~ (Arnold, 1996; Jacobson, 2011; Rose and Peters, 2001). ~~On the one hand,~~ I~~i~~mpervious surfaces replace~~d~~ rivers, lakes, green spaces, and urban forests;~~, as they~~ weaken the flood control capability of the urban system; and change~~for~~ infiltration, evaporation, filtration, and storage (Hao et al., 2015; Jacobson, 2011; Meyer, 2001).~~;~~ ~~on the other hand,~~ T~~t~~he expansion of impervious areas accelerates rainwater convergence on urban surfaces, resulting in increased runoff and peak flows (Hatt et al., 2004; Leopold et al., 1995; Liu et al., 2015). The increase in runoff and peak flows taxes~~put pressure on~~ urban drainage facilities and exacerbate the risk of urban inundation.

To solve the problem of urban inundation, scholars in China have suggested~~put forward~~ the "Sponge City" initiative, which allows cities to act as~~ a~~ sponges to filtrate, purify, evaporate, and store rainwater (Mao et al., 2017; Sang and Yang, 2016). ~~As one of the important development concepts, l~~L ow impact development (LID), an important development concept for sponge cities, has been applied in sponge city construction (Luan et al., 2017); it~~and~~ is widely applied~~cable~~ to reduce~~ing~~ the impacts of urban inundation associated with rapid urbanization (Dietz and Clausen, 2008; Dietz, 2007; Xia et al., 2017; Zahmatkesh et al., 2015a). LID is a stormwater management strategy that uses microscale and localized practices to control the runoff and pollution caused by a storm (Damodaram et al., 2010; EPA, 2000; HUD, 2003). Since the 1990s, LID practices have been widely used in countries in Europe, the United States of America, and ~~some~~ other developed countries.~~, and the types of~~ LID practices ~~have been enriched to~~ include ~~permeable pavements~~PP, ~~green roofs~~GR, bioretention, swales, infiltration wells/trenches, infiltrating wetlands, and rain barrels (Hunt et al., 2010).

The hydrological effectiveness of LID practices has been~~ further~~ researched through field and laboratory studies (Abbot and Comino-Mateos, 2003; Berndtsson, 2010; Davis, 2008; Davis et al., 2012; Fassman and Blackbourn, 2010). For example, Hood et al. (2007) monitored low impact residential development and traditional residential development in ~~the town of~~ Waterford, Connecticut, USA, and found that LID practices helped lower runoff, peak flows, and discharge volumes. Dreelin et al. (2006) designed a test to compare the performance of asphalt and ~~permeable pavement~~PP parking lots in Athens, Georgia, USA, and their results showed that the porous parking lot contributed 93 % less runoff than the asphalt lot during natural storm events. Bliss et al. (2009) constructed and monitored a ~~green roof~~GR in Pittsburgh, Pennsylvania, USA~~,~~ and reported that the GR reduced runoff ~~was reduced~~ by up to 70 %~~,~~and reduced peak flows ~~reduced~~ by 5–~~-~~70 %;~~, and~~ the hydrograph was delayed by several hours ~~when comparing a green roof to~~ more than a normal roof for the same building.

~~Considering the value of exploring the effectiveness of LID practices in actual situations,~~ M~~m~~any scholars have focused on simulations at a large~~r~~ scale, such as watersheds (Ahiablame et al., 2012; Dietz and Clausen, 2008; Roy et al., 2008; Salvadore et al., 2015), to explore the effectiveness of LID practices. For example, Palla and Gnecco (2015) reported that the LID combination~~s~~ of ~~green roof (~~GR~~)~~ and ~~permeable pavement (~~PP~~)~~ ~~could~~ decreased runoff and peak flows by 23 % and 45 %, respectively, and delayed the hydrograph by up to 19 % at the urban catchment scale. Trinh and Chui (2013) conducted a simulation and found that GR could reduce the peak flows by 50 % and delay the hydrograph by 2 hours, bio-retention (BR) systems could reduce the peak flows by 50 %, and the ~~effectiveness of~~ combined~~ations of~~ GR and BR systems ~~even~~ could reduce the peak flows to a~~the~~ pre-urbanized level. Morsy et al. (2016) reported that rain gardens can~~ould~~ mitigate runoff by~~to~~ approximately 15, 27~~-~~, and 38 % for 2-, 5-, and 10-year storm events, respectively, which reduced the watersheds flood risk ~~in watersheds~~. Ahiablame et al. (2013) assessed the effectiveness of rain barrels/cisterns and ~~porous pavement~~PP in two urbanized watersheds near Indianapolis, Indiana, USA;~~,~~ by using~~and through~~ simulations, they found~~ind~~ that LID practices reduced runoff and pollutant loads; they listed some ~~scenarios of~~ LID combinations that are good retrofitting options for local areas.

~~It is noteworthy that peak flow reduction, runoff reduction, and hydrograph delay are widely used indexes when evaluating the performance of LID practices for mitigating urban inundation risk (Ahiablame and Shakya, 2016; Qin et al., 2013; Zhang et al., 2016). However, these indexes are not very intuitive; in fact, the spatial distribution of urban inundation and its changes with rain time are more beneficial to local residents, such as providing guides for their travel behaviours. Some recent studies have constructed 2D models to simulate the spatial distribution of surface inundation and evaluate the risks of inundation (Hu et al., 2017; Wu et al., 2017). However, we find that few researchs use hydrodynamic models, like SWMM, which not only can realize the simulation of the spatial distribution of urban inundation but also can explore the dynamic effectiveness of LID practices on inundation mitigation. Further, existing literature seldom explores the efficiency of LID practices under different scenarios (LID combinations), which can provide support for LID practice construction for areas vulnerable to urban inundation. Therefore, we aim to fill these gaps by conducting this study. In order to explore the performance of LID practices for mitigating impacts of urban inundation, we establish a 2D hydrodynamic model to evaluate the inundation depth, area, and time of PP and GR, two widely used LID practices, under different scenarios and hazard levels, and evaluate the efficiency of every scenario. This study enriches the inundation mitigation research of LID on an urban watershed scale and provides some references to urban stormwater management and inundation mitigation.~~

Peak flows reduction, runoff reduction, and hydrograph delays are widely used indexes for evaluating the performance of LID practices (Ahiablame and Shakya, 2016; Qin et al., 2013; Zhang et al., 2016). However, these indexes are not intuitive, and the performance of LID practices for urban inundation is more useful for local residents, such as providing a guide for their travel behaviour. Some 1D-2D models have been applied for flood management, such as ESTRY-TUFLOW (Fewtrell et al., 2011), InfoWorks ICM (Russo et al., 2015) and MIKE FLOOD (Loewe et al., 2017). However, most of these models have a cost, which limits their application, and an open-source model (like Storm Water Management Model, SWMM), with a LID module that can be coupled to simulate urban inundation, is needed (Burns et al., 2015, Hu et al., 2017, Wu et al., 2017).

The goal of this study was to evaluate the effectiveness of LID practices to mitigate urban inundation in an urban watershed using a case study. The specific objectives were to establish a 1D-2D hydrodynamic model that coupled SWMM and IFMS Urban, evaluate the effectiveness of LID practices under different scenarios and hazard levels, and explore the efficiency of the LID scenarios. We intended this study to enrich LID inundation mitigation research at the urban watershed scale and to provide a reference for urban stormwater management and inundation mitigation for local governments.

2 Materials and methodology

2.1 Study site

Shenzhen is ~~located~~ in the coastal area of Guangdong Province in southern China (Figure~~.~~ 1). It has a~~Belonging to the~~ subtropical maritime monsoon climate;~~,~~ Shenzhen is hot and rainy in summer and mild in winter, and the average annual rainfall is 1837 mm. April to September is~~marks~~ the rainy season in Shenzhen, and during this period, precipitation is concentrated and stormwater overflows are~~is~~ frequent. There were 38 rainstorm days (95 % of the year) in 2017 and the average rainfall was 170–350 mm every month during this period. Accordingly, urban inundation was~~is~~ particularly serious in this period; ~~which~~it caused loss of life~~ leads to inconvenient~~ and economic losses for~~to~~ local residents~~, and even the loss of lives~~.

The study site was located in Guangming New District of Shenzhen, China, and it is in the Maozhou River Basin (Figure 1). The total area of our study site was 37.68 km^2, of which 69.8 % was impervious surfaces. Guangming New District was selected as the first pilot area for LID practices in Shenzhen in October 2011 because of the intensity of its inundation disasters. There is a need to research the effectiveness of LID on urban inundation mitigation in this area.

~~The study site is located in Guangming New District of Shenzhen, China (Fig. 1). Because of the heavy inundation disasters, Guangming New District was identified as the first pilot area for LID practices in Shenzhen in October 2011 by MOHURD. To date, 17 LID practices have been completed in Guangming New District. Thus, this provides us the opportunity to check the effectiveness of LID practices on urban inundation mitigation.~~

~~The study site is a rapid urbanization zone of Guangming New District, about 37.68 km², and located in the Maozhou River Basin. At this study site, construction land area is 26.31 km², which accounts for 69.8 % of the total area. Using the investigation and land use map shown in Fig. 1, we find that the developed areas are dominated by industrial land and residential land, and this intensive development easily led to urban inundation during the heavy rainy season, such as during the heavy rain on 11 May 2014, with 144.9 mm of rainfall within 24 h and a maximum hourly rainfall of 23.6 mm, which caused serious urban inundation and great loss to the residents and production.~~

2.2 Data

The model input data~~ needed for modelling mainly~~ included inundation, land use, a digital elevation model (DEM), weather, and pipe network data.

~~1.~~ The land use data (2013~~ year~~) and pipe network data were~~are~~ provided by the Shenzhen government.~~ According to remote sensing images and the needs of model building, w~~We ~~make a ~~generalized~~ation for~~ the original data and divided the study area into water, low density construction land, high density construction land, bare land, woodland, grassland, and agricultural land~~,~~ using remote sensing images~~namely, seven land use types in total~~ (Figure~~.~~ 1).

~~2.~~ The DEM of the study area (Figure~~.~~ 2) ~~is~~was downloaded from the Geospatial Data Cloud~~, and the~~ (~~resolution is~~ 30 m resolution). ~~In order to correspond to the size of the grid in IFMS Urban model, we resampled the DEM to 15 m×15 m in ArcGIS.~~

~~3.~~ The weather data were~~are~~ sourced from the Shenzhen Meteorological Data System (https://data.szmb.gov.cn/). According to the integrity and availability of data, w~~W~~e chose two representative heavy rainstorm event datasets, ~~from~~ 11 May 2014 and 10 May 2016 (Figure~~.~~ 3) for model simulation, which included the complete volume of rainfall every hour. The corresponding inundation data were obtained from the Shenzhen SanFang (flood, drought, and wind defence) headquarters and the Guangming New District Urban Construction Bureau.

~~4.~~ We simplified the drainage data for building the model b~~B~~ecause the urban pipe network is intricate and substantial: add nodes when the pipeline is too long; keep or add the nodes that change the diameter and slope of pipeline; keep the parallel pipelines and nodes on both sides of the roads; and delete the useless nodes and pipelines in this model.

~~we deleted some redundant and incorrect data and retained the major nodes and pipelines.~~ Finally, the 4502 pipelines and 1175 nodes in this study~~ site~~ were generalized to 597 pipelines and 653 nodes, ~~respectively,~~ including 56 outlets and 597 inspection nodes (Figure~~.~~ 2).

2.3 SWMM and IFMS Urban models

~~This study uses SWMM (Storm Water Management Model, 1D) to construct a 1D sewer model. SWMM, based on hydrology and hydrodynamics, is an urban storm water management model d~~Developed by the United States Environmental Protection Agency ~~US EPA~~ (US EPA ~~Environmental Protection Agency~~), ~~.~~ SWMM is an open-source model that can simulate ~~the~~ dynamic runoff quantity and quality from~~ primarily~~ urban areas, and it has been widely used to simulate the hydrologic performance of~~ specific types of~~ LID practices (Rossman, 2010; Wu et al., 2013). However, SWMM cannot simulate the spatial and temporal distributions of surface inundation. Recently, some scholars have conducted simulationsusing secondary developments of this software (Seyoum et al., 2012; Son et al., 2016; Zhu et al., 2016). We expected that this application would be difficult to use in our study area due to differences in computer programming. Coupling a model with SWMM for 2D simulation is another way to simulate the spatial distribution of urban inundation (Huong and Pathirana, 2013; Wu et al., 2017).

The Integrated Urban Flood Modeling System (IFMS Urban) was developed by the China Institute of Water Resources and Hydropower Research (IWHR) in cooperation with other institutions. Based on the simulated results from SWMM, IFMS Urban can simulate the temporal and spatial distribution of urban inundation, and it is compatible with ArcGIS and SWMM. Data conversion and model coupling are accomplished in IFMS Urban, and it does not need additional software programming, which is convenient for researchers and non-expert users.

~~The building processes of the SWMM model are shown in Fig. 4. Some measurement parameters, such as area, slope, impermeability, etc., of sub-catchments can be calculated with formulas. Other parameters, such as the Manning coefficient, depression store, etc., must be calibrated several times to be determined. First, referring to the SWMM Model Manual and other literature (Rossman, 2010; Wu et al., 2017), we determine the reference range of these parameters. Then, according to the reported urban inundation data, we calibrate the model to obtain relatively accurate parameters.~~

2.4 ~~Coupling the SWMM/IFMS Urban~~ Coupled model~~s~~

SWMM was applied to construct a 1D sewer model. The study area was simplified to 577 sub-catchments, 597 pipelines, and 653 nodes. Details of model building and of SWMM's parameters can be found in many published studies (e.g., Rossman, 2010; Qin et al., 2013; Wu et al., 2017). Model coupling occurred in IFMS Urban. First, an unstructured 2D grid model was meshed with an average cell size of 15 m; second, ground elevations were assigned to each grid; finally, each node was linked with a corresponding grid for water exchange, and the distribution of surface inundation was calculated with 2D shallow water equations. The coupled model had the advantages of SWMM and IFMS Urban, and could be applied to simulate urban inundation and evaluate the performance of LID practices.

~~SWMM can simulate the dynamic rainfall runoff process, but it cannot simulate the spatial distribution (2D) of surface inundation. Recently, some scholars have conducted some experiments using secondary development on this software (Seyoum et al., 2012; Son et al., 2016; Zhu et al., 2016), but due to differences in computer programming, it might be difficult to copy these applications to other urban areas. Therefore, coupling a model with SWMM and the other models that can realize the 2D simulation is another way to simulate the spatial distribution of urban inundation (Huong and Pathirana, 2013; Wu et al., 2017).~~

~~This study innovatively selects SWMM and IFMS Urban (Integrated Urban Flood Modeling System, 2D) to carry out a 2D simulation model. IFMS Urban was developed by China Institute of Water Resources and Hydropower Research (IWHR) in cooperation with other institutions. Through meshing the study area into grids, IFMS Urban can analyse urban inundation, and it has great compatibility with ArcGIS and SWMM. IFMS Urban considers the 2D shallow water equations during its calculation process for urban inundation simulation, and it also considers the coupling effect between the urban pipe network and the grids when simulating urban inundation. Therefore, this system can be applied for urban inundation simulation. This study innovatively to couple SWMM and IFMS Urban to simulate the spatial distribution of inundation and to explore the effectiveness of LID practices.~~

~~First, we divide the study area into quadrilateral grids. As the smallest calculation unit, the grid's edge is approximate 15 m. Then we assign elevation to the grids. Regrettably, we do not have a high precision DEM for the entire research area; therefore, we cannot assign elevations for the areas that are easily inundated. After the field investigation, however, we found that most inundation areas are on the streets, and we have accurate elevation data for the manholes (nodes) on the ground. Using the elevation date of these nodes, we obtain the ground elevation of the streets in our research area through Kriging interpolation with the help of ArcGIS. And then we assign the elevation of the streets to the grids. Finally, we build a 2D inundation analysis model coupled SWMM and IFMS Urban (Fig. 4).~~

2.5 Scenarios of LID combinations for simulation

Considering the feasibility and representativeness of LID practices for urban inundation mitigation, we~~this study~~ chose two types of LID practices, GR and PP, to simulate and explore their effectiveness for mitigation of~~on~~ urban inundation~~ mitigation~~. The parameters for PP and GR are listed in Table 1, which were designed based on SWMM requirements and LID research (Ahiablame and Shakya, 2016; Chui et al., 2016; Kong et al., 2017; Qin et al., 2013). Through remote sensing images and field investigations, we found that urban villages have diverse roof structures and shapes, ~~of roofs for urban villages are diversity~~ which makes it difficult to implement green roofs~~ on them. it is impracticable to add LID practices to the surfaces of high density construction lands given their development strength~~. Therefore, we established~~this research sets~~ principles for the implementation~~construction~~ of LID practices: GR can only be built on low density construction land~~s~~, and PP can be built~~ both~~ on low and high construction land~~s~~ and~~as well as~~ on some streets. According to these principles, the available area for PP and GR was 5.95 km^2 and 8.92 km^2, respectively. ~~we~~ We set a series of proportions from 25 % to 100 % for~~representing~~ the ~~construction~~ density ~~strength~~ of different types of LID combinations, ~~to simulate and explore the effectiveness of LID practices for mitigating urban inundation under different scenarios. Finally,~~ and a benchmark and six scenarios ~~were~~ are designed below~~, and the parameters for LID practices (Chui et al., 2016; Cipolla et al., 2016; Qin et al., 2013; Zhang, 2015) are shown in Table 1~~:

Benchmark: No LID practices

Scenario 1: 25 % GR + 25 % PP

Scenario 2: 50 % GR + 50 % PP

Scenario 3: 75 % GR + 75 % PP

Scenario 4: 100 % GR + 100 % PP

Scenario 5: 100 % PP

Scenario 6: 100 % GR

3 Results

3.1 Model calibration and validation

The coupled model was~~is~~ calibrated using~~ the~~ rainfall and ~~-~~inundation data from 11 May 2014. Based on the relevant literature and the SWMM manual, we determined the final SWMM parameters (Table 2) through several calibration iterations. From the final calibration results (Table 3~~ 3~~), we found~~can find~~ that, except for ~~I~~inundation site Gm 20, the absolute value of the maximum inundation depth between the observed and simulated value was approximately~~is in the range of~~ 0–~~-~~0.14 m~~,~~ and the relative error was ranged from~~is~~ 0–~~-~~30 %.

The rainfall and ~~-~~inundation data on 10 May 2016 was chosen to further validate the coupled model. Three valid datasets were simulated with the coupled model using observed urban inundation data on 10 May 2016 from the Guangming New District Urban Construction Bureau.~~Based on the actual urban inundation data on that day from the Guangming New District Urban Construction Bureau, there are three valid datasets to be simulated with the coupled model.~~ ~~From Table 3, t~~The results showed that the absolute values of the differences between the observed and simulated ~~in~~ maximum inundation depths ~~between the observed and simulated~~ were~~is~~ 0.04 m (Gm 11), 0.05 m (Gm 12) and 0.02 m (Gm 20), and the relative errors were~~are~~ 20, 7, and 5 %, respectively.~~ ~~In this study, the relative error of calibration were a little higher, while the relative errors of validation were 5–20 %, which met the requirements of the Standard for Hydrologic Information and Hydrologic Forecasting in China (GBT_22482-2008).~~According to similar research (Wu et al., 2017), the calibration and validation results of the model are acceptable for simulating rainfall-inundation~~

3.2 Inundation depth under different scenarios

Figure 4~~5~~ and Table 4 show the simulation results of inundation depths under different scenarios. Compared to the benchmark, the reduction rates of maximum inundation depth were~~are~~ 16, 22, 26, and 29 % under scenarios 1 to 4, respectively~~, when the proportion of LID combinations increases from 25 to 100 %~~. ~~And t~~The results for the~~between~~ 100 % PP scenario and 100 % GR scenario showed that PP and GR had approximately ~~almost have~~ the same performance at the maximum inundation depth~~,~~ and both scenarios reduced maximum inundation by ~~of the reduction rates are~~ 14 %.

To further explore the impacts of LID practices on inundation mitigation, we set three hazard levels for ~~in terms of~~ the depth~~s~~ of urban inundation: l~~L~~ow (< 0.2 m), m~~M~~edium (0.2– ~~m~~ 0.4 m), and h~~H~~igh (≥~~>=~~ 0.4 m), based on~~according to~~ the literature (Su et al., 2016)~~ as well~~ and observed data for ~~as actual situation of~~ the study area. Compared to the benchmark, ~~the range of average inundation reduction depths at Low, Medium and High levels were 0.04-0.06 m, 0.07-0.14 m, and 0.11-0.19 m, respectively under Scenarios 1 to 4. Correspondingly,~~ the ranges of average ~~inundation~~ depth reduction rates were 60~~~~~–80~~ %~~, 27~~~~~–54~~ %~~, and 22–~~~~~40 % at l~~L~~ow, m~~M~~edium and h~~H~~igh hazard levels , respectively, for~~under~~ s~~S~~cenarios 1 to 4 (Figure 5~~6~~). ~~Based on the simulation results of these four scenarios, we clearly note that u~~Under different hazard levels, the average ~~inundation reductions and~~ depth reduction rates increased from scenarios 1 to 4.~~as the proportion of LID combinations~~

~~increases. Additionally, we clearly see that reductions for the Low level are 0.07, 0.10, 0.12, and 0.13 m lower than those of the High level under Scenarios 1 to 4, respectively, while t~~The average depth reduction rates at the ~~L~~low level were~~are~~ 38, 44, 43, and 40 % higher than ~~those at~~ the ~~H~~high level under s~~S~~cenarios 1 to 4, respectively. These~~is~~ results suggest~~means~~ that most inundated areas could not be eliminated at the high level because of severe waterlogging. ~~the reduction effects become more evident as hazard level increases, while reduction rates decrease. This is due to the fact that few reductions in Low risk areas will result in improvements, which means the roles of LID practices with respect to urban inundation mitigation are less obvious at High levels than those at Low levels.~~

~~Further~~ Figure 5~~, we determine~~shows that the average depth reduction rates~~performances~~ of 100 % PP and 100 % GR scenarios were~~are~~ between the~~scenarios of~~ 25 % GR + 25 % PP and 50 % GR + 50 % PP scenarios under different hazard levels. These results suggest that ~~the effectiveness of~~ LID combinations may~~ight~~ be more effective in reducing urban inundation ~~better~~ than ~~that of~~ a single type of LID practice. Based on the comparison of the two LID practices, we foun~~in~~d that the average depth reduction rates of the 100 % PP scenario were~~are~~ 67, 38 and 23 % at the low, medium and high levels, respectively. These were 6, 7, and 2 % higher than ~~those of~~ the average depth reduction rates of the 100 % GR scenario.~~ at Low, Medium, and High levels, respectively.~~ These~~is~~ results suggest~~means~~ that PP may~~ight~~ perform better than GR for reducing the depth of~~in~~ inundation~~ depth reduction~~.

3.3 Inundation areas under different scenarios

Figure 5~~6~~ shows changes in the inundation area~~ changes~~ under different scenarios and hazard levels. ~~According to the simulation results of Scenarios 1 to 4, the range of inundation areas are 116-79.1, 8.7-4.9, and 0.6-0.2 ha under Low, Medium, and High levels, respectively.~~ Compared to the benchmark~~ (167.6, 19.5, and 2.1 ha)~~, the ranges of average area reduction rates were~~are~~ 31–~~-~~53, 55–~~-~~75, and 71–~~-~~90 % ~~for~~at l~~L~~ow, m~~M~~edium, and h~~H~~igh levels, respectively, ~~under~~ for s~~S~~cenarios 1 to 4~~, respectively~~. ~~It is clear that t~~The ~~impacts of~~ inundation areas reduced ~~under~~ at different hazard levels after~~since~~ ~~adding~~ the implementation of LID practices~~ onto the original land use~~. The average area reduction rates ~~under the~~at the ~~H~~high level~~ which~~ were~~are~~ up to 71–~~-~~90 %, which were greater than those at the low level. ~~seem to be more obvious.~~ This likely occurred because, after the implementation of LID practices, the depth of inundation decreased and most inundated areas were downgraded from a high level to a medium level or a low level. ~~This means that although inundation areas under the High level have the lowest reduction rates for inundation depth, most of them can be effectively reduced to lower hazard levels (Medium or Low).~~

For the 100 % PP and 100 % GR scenarios, the reduction in the~~s of~~ inundation areas was~~are~~ similar to the 25 % PP + 25 % GR scenario, which also suggested~~further proves~~ that LID combinations are more effective than single LID practice~~s~~. ~~At Low and Medium levels, the inundation areas of 100 % PP are 9 ha and 1.6 ha less than those of 100% GR, while both of them perform the same at the High level, which means that despite inundation depth or inundation area, both of PP and GR perform the same in High level areas.~~The average area reduction rates for the 100 % PP scenario were 37, 65 and 67 % at the low, medium and high levels, respectively, which were 5, 9, and 0 % higher than those for the 100 % GR scenario.

3.4 Inundation time under different scenarios

Inundation time is another way to represent~~s~~ inundation risk~~ from another perspective~~. ~~From Scenarios 1 to 4, ~~Table 5 shows~~we clearly see~~ that the inundation time for~~under~~ m~~M~~edium and h~~H~~igh levels was~~is~~ longer than the inundation time for~~that under~~ the l~~L~~ow level under~~given~~ the same scenario~~ (Table 5)~~, which reflects increased risk of inundation~~danger~~ at~~under~~ m~~M~~edium and h~~H~~igh levels~~ than under a Low level~~. As the implementation area~~proportion~~ of LID ~~combinations~~ increased~~s~~, the average inundation time decreased~~s~~ under the three hazard levels. The 100 % PP and 100 % GR scenarios had lower inundation time ~~perform a little better~~ than the 25 % PP + 25 % GR scenario~~Scenario 1~~, and the inundation time for~~of~~ the 100 % PP scenario was~~is~~ 1.3 h less than the inundation time for the 100 % GR scenario.

~~It is worth noting that, c~~Compared to the benchmark, the average inundation time ~~of~~ at the l~~L~~ow and m~~M~~edium levels in the 25 % PP + 25 % GR scenario ~~Scenario 1~~ increased~~s~~ slightly, while it~~ only~~ decreased~~s~~ slightly~~a little~~ at the h~~H~~igh level. This ~~phenomenon~~ result did~~does~~ not indicate~~mean~~ that ~~the performance of~~ LID practices~~ is~~ cannot ~~useful for~~ decreas e~~ing~~ inundation time or that the model had~~s~~ errors. The inundation time decreased for all hazard levels, butfor the low and medium levels, some areas inundated for a short-time were no longer flooded, which resulted in a different urban inundation area after the implementation of LID practices. Therefore~~Because of this~~, the average inundation time was~~is a little~~ longer than~~ that~~ before LID practices were implemented at the low and medium levels. ~~From the above-mentioned analyses of inundation depth, area, and time, we can know that areas under low risk to urban inundation are easily improved. It is undeniable, however, that there are still some inundation areas having a long inundation time that are difficult to mitigate. From Fig. 5 we can see that most of them are located in areas where the drainage infrastructures are not perfect and LID practices are not arranged. Thus, because of the mitigations of many short-time inundation areas, the average inundation time rises from 4 to 4.1 h in this scenario.~~ As ~~the proportion of~~ LID ~~combinations~~ practices were implemented~~increases~~, ~~the inundation areas are mitigated, and~~ the average inundation time decreased~~s~~ continuously from 4.1 to 2.3 h under scenarios 1 to 4~~ for 100 % PP + 100 % GR, in total~~.

4 Discussion

4.1 Performance of PP and GR

~~To ensure~~Researching the effectiveness of LID practices for urban inundation mitigation is~~ very~~ important for stormwater management. Our analysis showed that, ~~From the above-mentioned analysis, ~~although the implementation area of PP was less than GR, ~~we find that the effectiveness of~~ PP provided better~~for~~ urban inundation mitigation ~~performs better~~ than ~~that of~~ GR ~~in terms of the three indexes~~. This result may have been due to differences in the LID parameters, but it may also have been caused by the PP's more diffuse spatial pattern. PP have shown varying effectiveness for urban inundation mitigation in different studies (Ahiablame and Shakya, 2016; Hu et al., 2017; Qin et al., 2013; Zhang et al., 2016), and PP cannot always perform better because the effectiveness depends on the characteristics, implementation area, spatial pattern, rainfall intensity and rainfall frequency in different regions. Our study shows that PP may be a good choice for local governments because of its effectiveness for stormwater management and its potential use for reconstruction in built-up areas. PP could be gradually applied to roads and parking lots, while GR is harder to implement in densely urbanized areas, especially in the urban villages.~~Many studies have also proven that PP has better performance than GR in runoff reduction (Zhang et al., 2016) and urban flooding mitigation (Qin et al., 2013). Objectively speaking, except for the effectiveness of LID parameters, the size, spatial pattern, and other factors may also have an impact on the performance of LID practices. Therefore, the performances of PP and GR are different for different study areas. The findings of this study suggest some advantages of PP that might suit local developed areas very well, which can provide some suggestions to local stormwater management officials. The findings also prove that compared to a single LID practice, combinations of LID practices should be applied at the local community level for urban inundation mitigation.~~

4.2 Effectiveness at different hazard levels

At the high level, the average depth reduction rates decreased from 22 % to 40 %, and the average area reduction rates decreased from 71 % to 90 % under scenarios 1 to 4. These results showed that the inundation hazard eased at a high level with the implementation of LID practices. However, at the high level, the average depth reduction rates were still 38–40 % lower and the average inundation time was 2.5–5.9 h longer when comperaed to the low level; this indicates that LID practices are more effective for urban inundation mitigation at a low hazard level. The hazard level analysis showed that although LID practices can downgrade the inundation hazard level to medium or low, most inundated areas cannot be eliminated at a high hazard level. This means that the inundation problem could not been resolved only with LID practices; other stormwater management methods should be applied to manage severe waterlogging in high hazard areas, such as restoring river systems, establishing urban wetlands, and improving urban drainage infrastructure.

4.3~~2~~ Cost-effectiveness~~Efficiency~~ of LID practices

~~Through~~ Under ~~scenario~~ scenarios 1 to 4~~, simulations~~, the ~~performance~~ effectiveness of LID practices for urban inundation mitigation ~~on the urban watershed scale has been explored~~ increased with more area implementing LID practices~~comprehensively~~. However, Table 4 and Figure 5 show that the reduction rates grew slowly with the increase of LID practices from 25 % to 100 %, which suggests that the efficiency of LID practices decreased from scenario 1 to scenario 4. To better describe this phenomenon, we used a cost-effectiveness indicator (CEI) :

$$\mathrm{CEI} = \frac{R}{P}, \tag{1}$$

where R is the reduction rate of inundation depth and inundation area, and P is the proportion of LID practices. Table 6 shows that the CEI decreased as the proportion of LID practices increased from scenario 1 to scenario 4, and the efficiency of the 25 % PP + 25 % GR scenario was higher than other scenarios (even higher than the 100 % PP + 100 % GR scenario). This indicates that simply increasing of the proportion of LID practices is not necessarily more efficient. Therefore, the effectiveness and the cost of LID practices should be considered in the construction of sponge cities.~~We found that 25 % PP + 25 % GR was~~

~~the best choice for inundation mitigation in these scenarios for the selected research area, though its performance was not the best. Compered to benchmark, 25 % PP + 25 % GR reduced the maximum inundation depth by 14 % and the total inundation areas by 34 %, while 100 % PP + 100 % GR reduces the maximum inundation depth by 29 % and the total inundation areas by 55 %. It's clear that the efficiency of 25 % PP + 25 % GR is higher than that of other scenarios. Therefore, when considering cost-effectiveness on inundation mitigation, the best LID combination is about 25 % in this study area.~~

~~This study also found a limitation for the application of LID practices. For example, in the Low risk areas, when the percentage of PP and GR increases from 25 % to 50, 75, and 100 %, the average inundation reduction rate rises from 60 % to 74, 79, and 80 %, respectively. It is clear that the reduction rate grows slowly while the percentage increases proportionally, which means the marginal benefits of LID decrease. The same phenomenon also occurs in Medium and High risk inundation areas.~~

~~The phenomena described above indicate that the risk in some inundation areas is difficult to mitigate in the study area, especially in places with low terrain or poor infrastructure. For these areas, the continuous increase of the construction strength of LID practices evidently cannot mitigate the risk of urban inundation; instead, it will decrease the efficiency of LID practices in the whole urban watershed.~~

4.4~~3~~ Limitations and future studies

~~Our study site is large but lacks accurate data for depth of urban inundation,~~Lacking accurate data is a common limitation for most studies. In this study, highly accurate elevation data for the study area is confidential and difficult to obtain; therefore, the ground elevation of streets were interpolated from the dense nodes of the pipe network. This method may have affected the simulation results. Moreover, the accuracy of the coupled model could be further increased with more observed data and information. Another limitation was that the definition of the thresholds for hazard levels was not considered sufficiently in this study. The results for the three hazard levels would be different if the thresholds changed. Therefore, research on criteria and sensitivity analysis of thresholds is needed in the future. The influences of rainfall intensity and frequency were not considered in this study, which is related to the effectiveness of LID.

~~which limits the accuracy of parameter calibration and validation, and further limits the accuracy of the simulation results. Furthermore, the simulation is simplified without considering the roles played by pumping stations and the river networks for urban inundation mitigation. Although most existing research has similar problems (Hu et al., 2017; Wu et al., 2017), we still think the accuracy of the simulation needs to be improved for future studies.~~

In China, urban inundation appears~~seems~~ to be increasing~~more and more serious~~, and LID practices could~~should~~ be ~~focused on as~~ efficient strategies for urban inundation mitigation. At present, most research has focussed~~es~~ on the area with~~a number of~~ LID practices and the effects ~~that play a dominant role~~ on urban inundation mitigation. However, ~~we also find that~~ the spatial distribution ~~of~~ and landscape patterns of LID practices also contribute~~s~~ to urban flooding mitigation (Giacomoni and Joseph, 2017; Kim and Park, 2016~~; Giacomoni and Joseph, 2017~~), but few studies have considered these variables~~. This provides a new perspective for further research on the effectiveness of LID practices on urban inundation mitigation~~. In addition, more studies should consider ~~determining how to~~ effective~~ly~~ integration~~e~~ of LID practices into urban development (Chui et al., 2016), especially for places ~~extremely~~ vulnerable to urban flooding~~, is still worth discussing in the future~~.

5 Conclusion

This study~~We~~ constructed a 2D inundation model that coupled SWMM and IFMS Urban at~~on~~ the urban watershed scale;~~d~~ the model was used to ~~and~~ evaluate~~s~~ the effectiveness of LID practices for mitigating urban inundation under different scenarios and hazard levels. ~~The conclusions are described below:~~ We found that the coupled model could be applied to evaluate the effectiveness of LID for urban inundation risk mitigation, and it can be used for different cities of different counties. The model showed that PP were more effective for urban inundation mitigation than GR. This conclusion may be different in other regions, but it can be used by policy makers on a local basis. LID practices can only affect the inundation depth and downgrade the inundation hazard level, but cannot resolve inundation problems at a high hazard level. Therefore, other methods of stormwater management should also be applied to manage severe waterlogging. Wider implementation of LID practices may not lead to higher efficiency, and the cost and effectiveness of LID practices should be considered in the construction of sponge cities. ~~First, LID practices can effectively eliminate most inundation risk at the Low level and ease the inundation risk at higher levels under different scenarios. Compared to the benchmark, the simulation results suggest that the maximum inundation depth can be reduced by 14-29 %, the total inundation area can be reduced by 34-56 %, and the average inundation time can be reduced by 0-43 %. Second, the mitigation effectiveness of 100 % PP is better than that of 100 % GR in terms of inundation depth, inundation area, and inundation time under different scenarios and hazard levels. Further, PP is suitable for application to reduce the impacts of urban inundation for local areas. Third, combinations of LID practices are more effective for mitigating urban inundation than single LID practices. The effectiveness of inundation reduction under the scenario of 100 % PP + 100% GR is the best among the six scenarios; however, its efficiency is the lowest. In the contrast, 25 % PP + 25 % GR has good performance when considering the effectiveness for mitigating inundation and the construction of LID practices, which means the best LID combination is about 25 % in this study area. Facing urban inundation comprehensively using a variety of stormwater management measures may be the most effective method.~~

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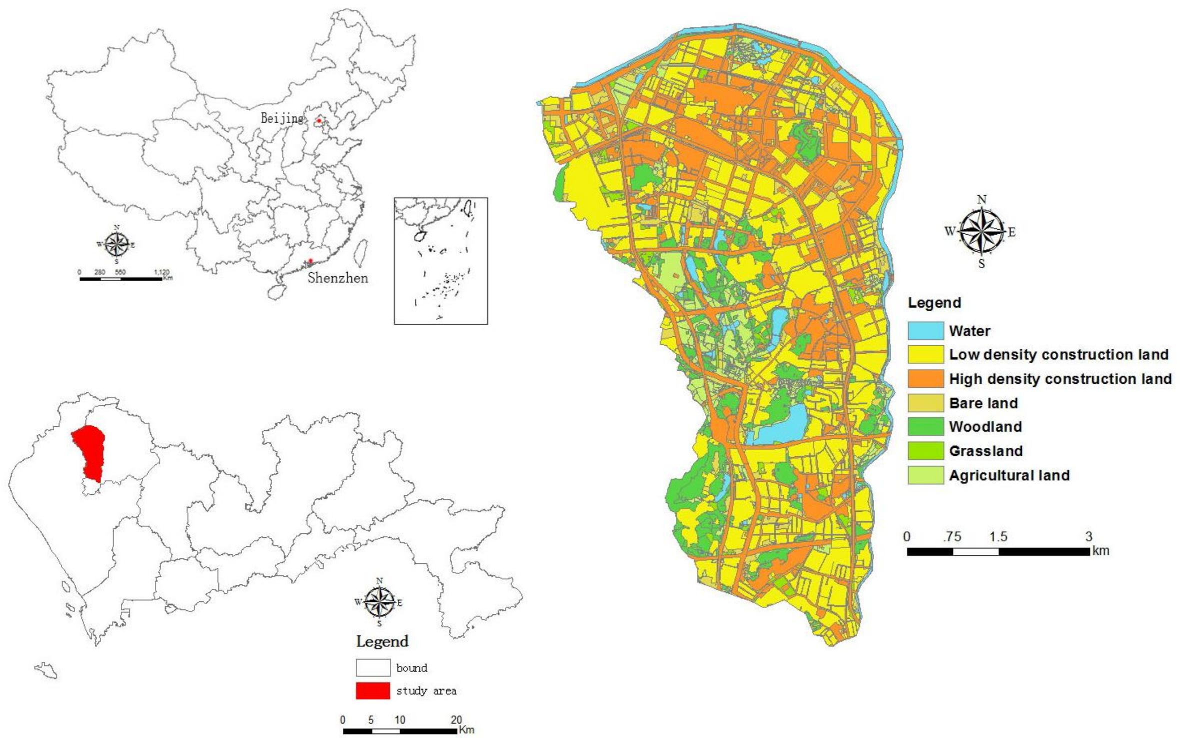


Figure 1: Location and land use map of the study area in the Guangming New District of Shenzhen, China.

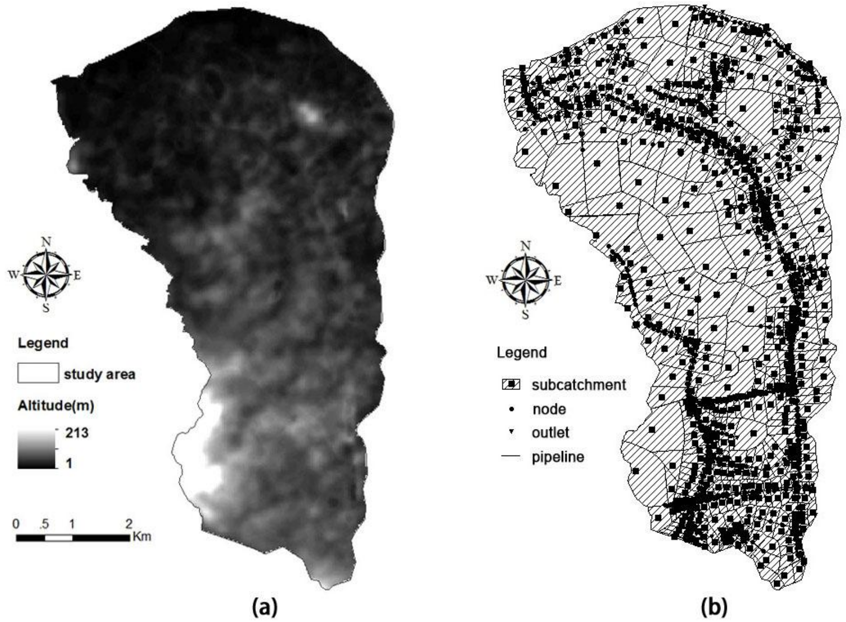
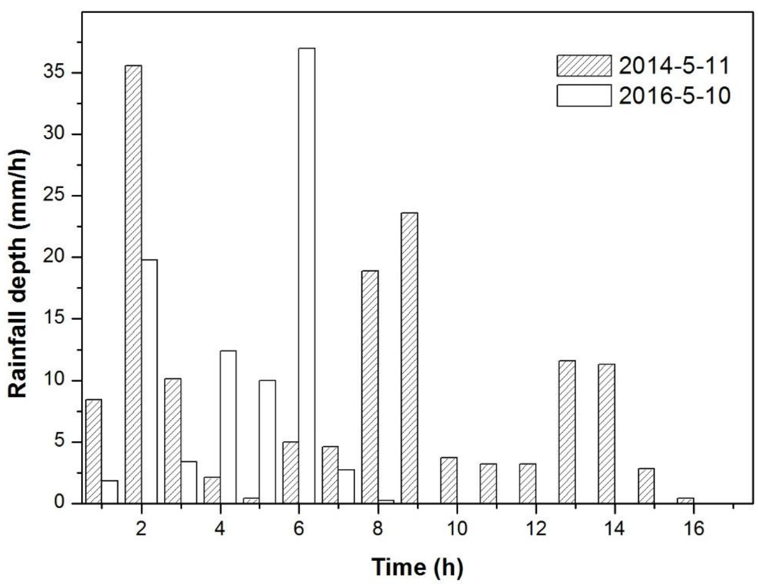
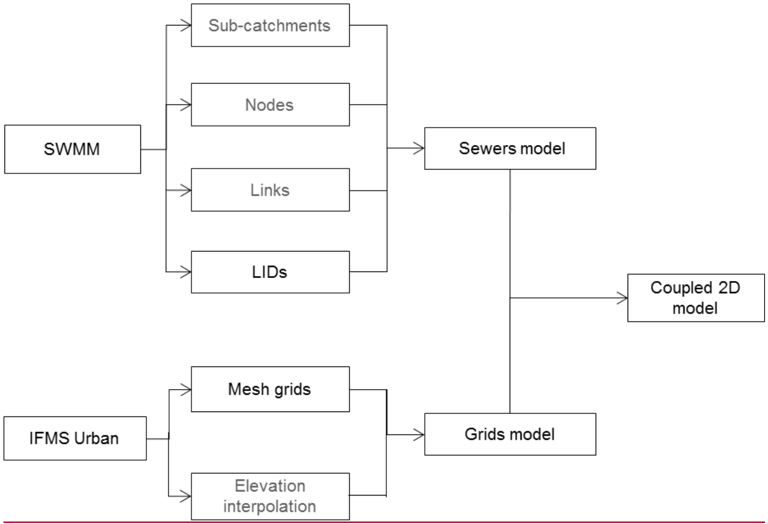


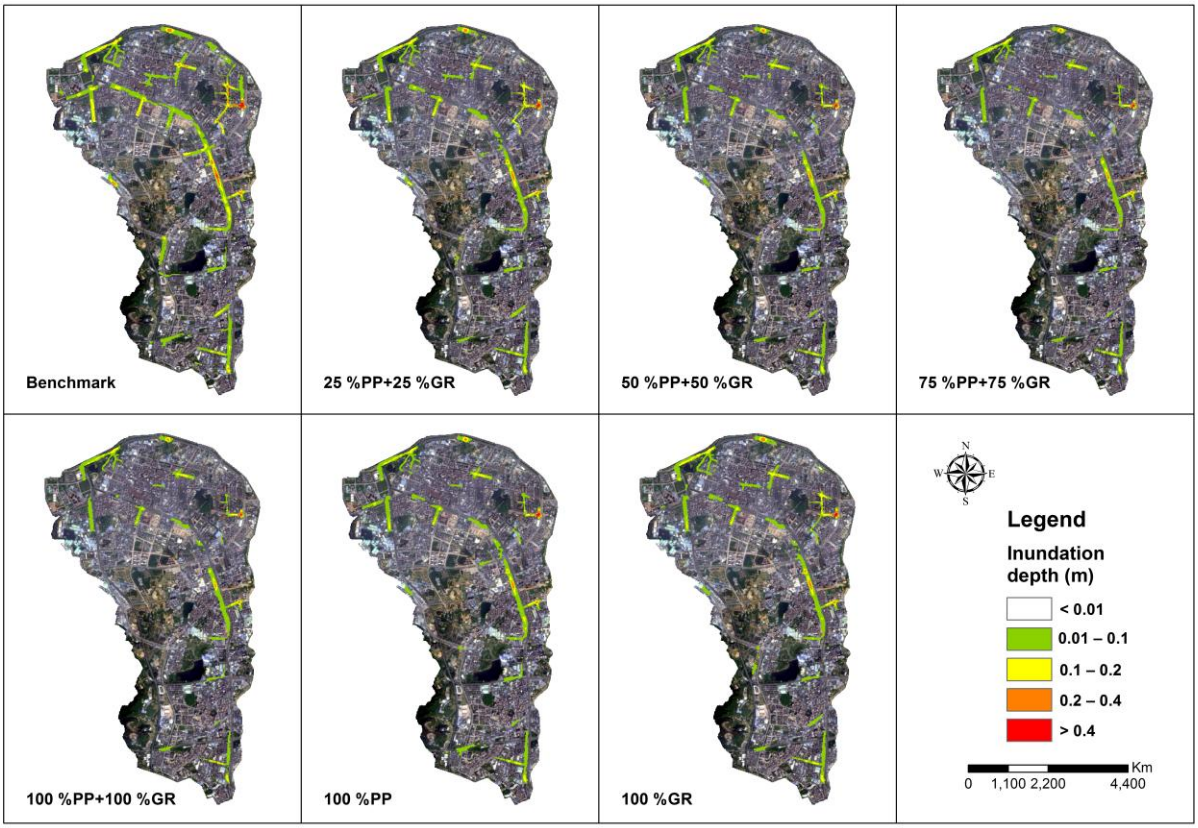
Figure 2: Altitude (a) and SWMM model (b) of the study area.

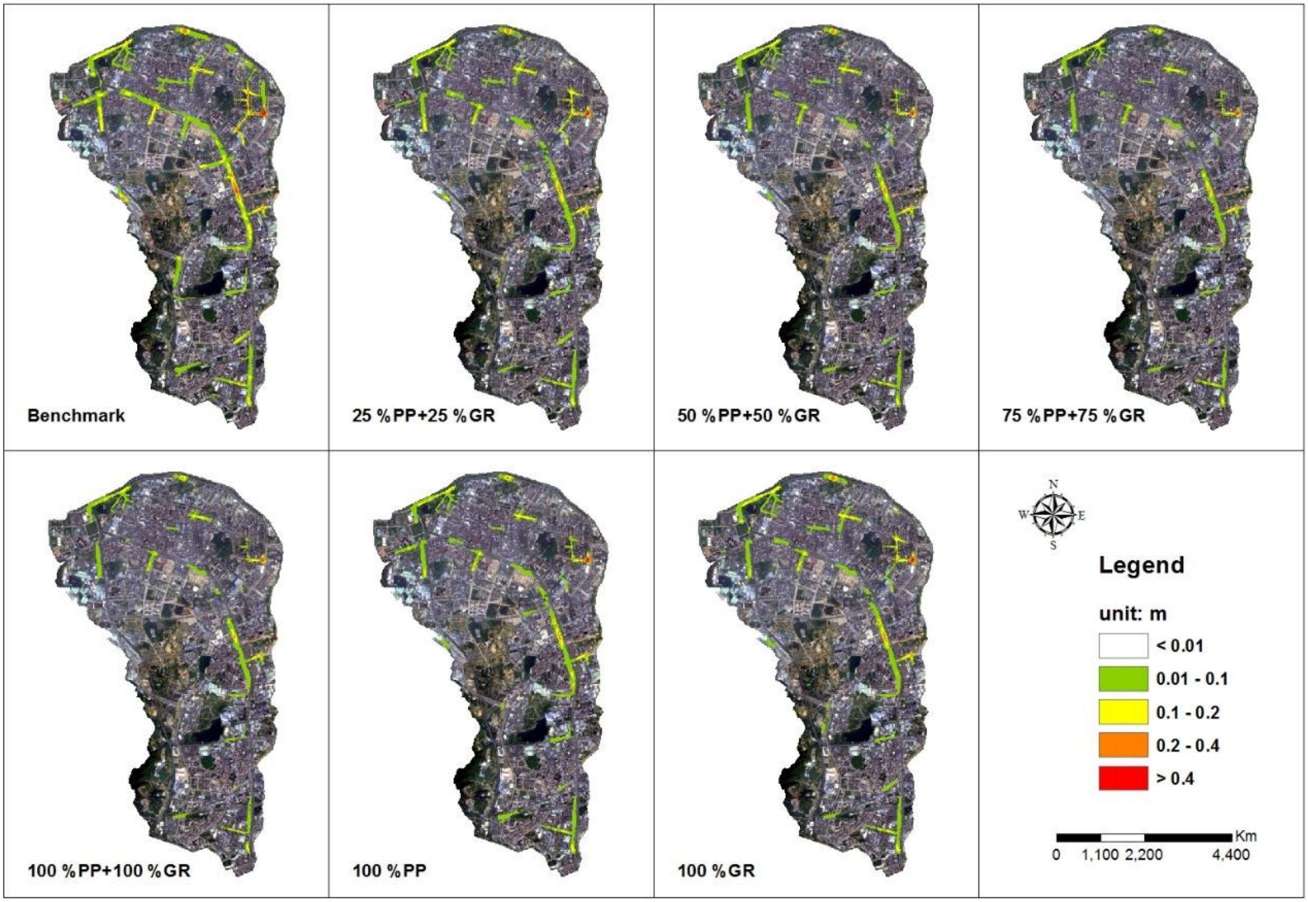


Figure~~.~~ 3: Rainfall intensity for ~~the~~ events on 11 May 2014 and 10 May 2016 in the study area.

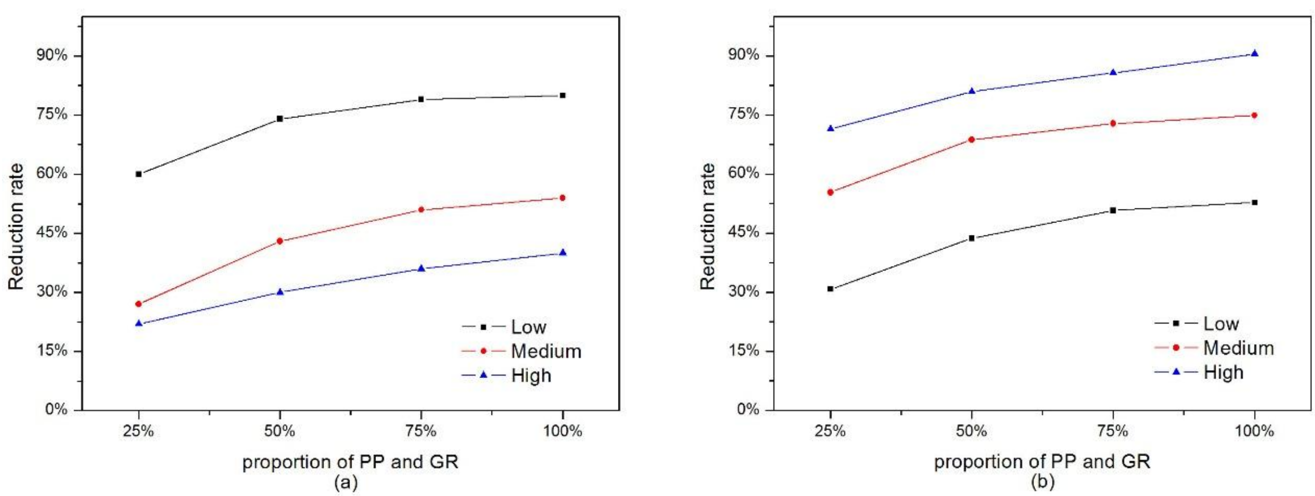


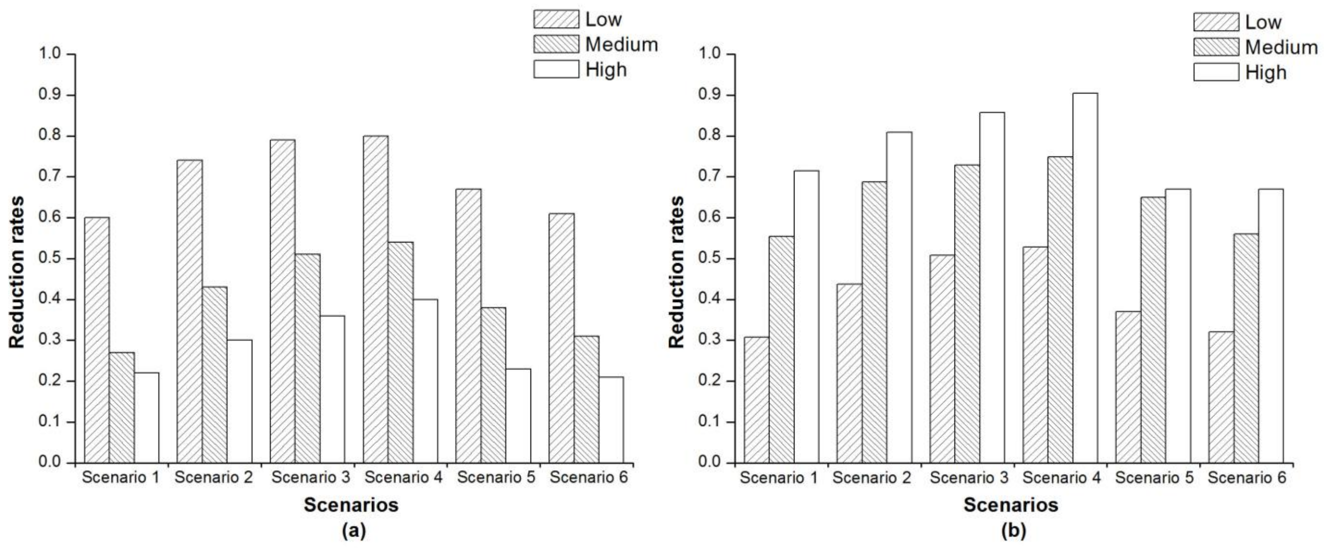
~~Figure. 4: Processes of coupled inundation model building.~~


Benchmark
25 %PP+25 %GR
50 %PP+50 %GR
75 %PP+75 %GR
100 %PP+100 %GR
100 %PP
100 %GR
N
W
E
S
Legend
Inundation depth (m)
< 0.01
0.01 – 0.1
0.1 – 0.2
0.2 – 0.4
> 0.4
Km
0
1,100
2,200
4,400



Figure~~.~~ 4~~5~~: Inundation depth maps of the study area under different scenarios.





Figure~~.~~ 5~~6~~: Reduction rates of average inundation depth (a) and inundation areas (b) under different scenarios and hazard levels.

Table 1: LID parameters in SWMM.

LID types	structure	parameter	value
PP	Surface	Berm height (mm)	2
		Vegetation volume fraction	0
		Surface roughness (Manning's n)	0.014
		Surface slope (%)	1
	Pavement	Thickness (mm)	100
		Void ratio (v~~V~~oids/s~~S~~olids)	0.25
		Impervious surface fraction	0
		Permeability (mm/h)	250
		Clogging factor	0
	Storage	Thickness (mm)	150
		Void ratio (v~~V~~oids/s~~S~~olids)	0.4
		Seepage fate (mm/h)	1.2
		Clogging factor	0
GR	Surface	Berm height (mm)	3
		Vegetation volume fraction	0.1
		Surface roughness (Manning's n)	0.017
		Surface slope (%)	1
	Soil	Thickness (mm)	100
		Porosity (volume fraction)	0.5

	Field capacity (volume fraction)	0.2
	Wilting point (volume fraction)	0.024
	Conductivity (mm/h)	30
	Conductivity slope	5
	Suction head (mm)	60
Drainage mat	Thickness (mm)	3
	Void fraction	0.5
	Roughness (Manning's n)	0.1

Table 2: Primary calibrated parameters in SWMM.

SWMM parameters	calibrated value
N-Imperv	0.015
N-Perv	0.15
Dstore-Imperv/mm	2
Dstore-Perv/mm	5
Zero-Imperv/%	25
Roughness	0.013
Max.Infil.Rate~~/~~(mm/h)	76
Min.Infil.Rate~~/~~(mm/h)	12
Decay Constant	2
Drying Time	5

Table 3: ~~Comparison of i~~Inundation depth in~~between~~ the observed and simulated results.

Inundation site	Storm on 11 May 2014			Storm on 10 May 2016		
	Observed~~Reported~~	Simulated	RE (%)	Observed~~Reported~~	Simulated	RE (%)
Gm 11	0.25	0.32	28	0.2	0.24	20
Gm 12	0.55	0.69	25	0.7	0.75	7
Gm 20	0.5	0.24	-52	0.4	0.42	5
Gm 21	0.45	0.46	2	—	—	—
Gm 24	0.2	0.26	30	—	—	—
Gm 22	0.2	0.2	0	—	—	—
Gm 16	0.2	0.23	15	—	—	—

"—" means data miss, "RE" means "relative error", unit: m.

Table 4: Maximum inundation depth under different scenarios.

	Bench mark	100 % PP	100 % GR	25 % PP+25 % GR	50 % PP+50 % GR	75 % PP+75 % GR	100 % PP+100 % GR
maximum inundation depth (m)	0.69	0.59	0.59	0.58	0.54	0.51	0.49
Reduction rate (%)	—~~-~~	14	14	16	22	26	29

Table 5: Inundation time under different scenarios and hazard levels.

	B~~b~~enchmark	100 % PP	100 % GR	25 % PP+25 % GR	50 % PP+50 % GR	75 % PP+75 % GR	100 % PP+100 % GR
Low (h)	3.4	3.3	3.3	3.7	3.3	2.5	2.2
Medium (h)	7.7	7.5	7.7	8.2	7.1	6	4.7
High (h)	10.6	9.3	8.4	9.6	7.6	6	4.7
Total (h)	4	3.6	3.6	4.1	3.6	2.8	2.3

Table 6: CEI under different scenarios.

		25 % PP+25 % GR	50 % PP+50 % GR	75 % PP+75 % GR	100 % PP+100 % GR
Maximum inundation depth		0.64	0.44	0.35	0.29
Average inundation depth	Low	2.40	1.48	1.05	0.80
	Medium	1.08	0.86	0.68	0.54
	High	0.88	0.60	0.48	0.40
Average inundation areas	Low	1.23	0.87	0.68	0.53
	Medium	2.22	1.37	0.97	0.75
	High	2.86	1.62	1.14	0.90