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Discussions

Impacts of future climate change on urban flood risks: benefits of climate mitigation and adaptations

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Abstract

As China is urbanized, flooding has become a regular feature in major cities. Assessing potential urban flood risks under climate change has become crucial for better managing such risks given the severity of the devastating disasters (e.g., the current 2016 flooding across China). Although the impacts of future climate change on urban flood risks have been investigated in many existing studies, the effects of both climate mitigation and adaptations have rarely been accounted for in a consistent framework. In this study, we assess the benefits of (1) avoided greenhouse gas (GHG) emissions and (2) adapting drainage systems on urban flood risks within the context of global warming through a case study in the Northern China. The urban drainage model, Storm Water Management Model (SWMM), was employed to simulate urban floods under current conditions and two feasible adaptation scenarios (i.e., pipe enlargement and low impact development), driven by bias-corrected meteorological forcing from five general circulation models (GCMs) in the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive Based on the results, the volume of urban floods is projected to increase by 52% in the period of 2020-2040 when compared to that in 1971–2000 under the business-as-usual scenario (i.e., Representative Concentration Pathways (RCP) 8.5). The magnitudes of urban floods are found to increase nonlinearly with changes in precipitation intensity, and highest risks associated with floods with smaller return periods below 10 years are identified. Despite the high level of uncertainty, it is obvious that avoided greenhouse emissions will be beneficial in terms of reducing risks associated with urban floods. On average, the magnitude of projected urban floods under RCP 2.6 is 13% less than that under RCP8.5, demonstrating the importance of global-scale efforts on GHG emission reduction in regulating local to regional hydrometeorological responses. Moreover, the two feasible adaptation scenarios are shown to be able to further reduce risk associated with floods effectively.

This study highlights the importance of accounting for local climate adaptation efforts in assessing urban flood risks under a changing climate.

Keywords: Climate change, urban flood risks, mitigation, adaptation of drainage systems

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1. Introduction

Floods are one of the most hazardous and common disasters in urban areas and can cause enormous impacts on the economy, environment, city infrastructure and human society (Chang et al., 2013; Ashley et al., 2007; Zhou et al., 2012). Urban drainage systems have been constructed to provide carrying and conveyance capacities to prevent urban flooding at a desired frequency. The design of the drainage capacity is, however, generally based on historical precipitation statistics that are assumed to be stationary and thus do not incorporate potential changes in precipitation extremes (Yazdanfar and Sharma, 2015; Peng et al., 2015; Zahmatkesh et al., 2015). For example, in Danish design guidelines for urban drainage, a delta change of 0.3 and 0.4 are recommended for the 10- and 100-year return period respectively with an anticipated technical life time of 100 years (Arnbjerg-Nielsen, 2012). The systems are likely to be overwhelmed by the additional runoff effects induced by climate change which may lead to flood damages, disruptions of transportation systems, and increased human health risks (Chang et al., 2013; Abdellatif et al., 2015). This necessitates examining the system performance in response to non-stationary changes of future hydroclimate in terms of both frequency and magnitude and the consequent flood damages (Mishra, 2015; Karamouz et al., 2013; Yazdanfar and Sharma, 2015; Notaro et al., 2015).

Impacts of climate change on extreme precipitations and urban floods were documented in a number of case studies. Ashley et al. (2005) showed that floods risks may increase by almost 30 times in comparison to current situation and effective responses are necessary to cope with the increasing risks in the UK. Larsen et al. (2009) estimated the potential future increase in extreme one-hour precipitation events over Europe due to climate change and a typical increase between

20% are 60% was found. Willems (2013) found that an increase up to about 50% of current design storm intensity in Belgium are projected for the 10-year return period by the end of this century.

As China is urbanized, flooding has become a regular feature of its cities with 62% of Chinese cities surveyed experiencing floods and direct economic losses up to $100 billion between 2011 and 2014 (China Statistical Yearbook 2015). The current 2016 flooding has affected more than 60 million people, with more than 200 killed and $22 billion in losses across China. Hence, assessing changes in urban flooding is very important for managing urban flood risks through designing new and re-designing existing urban infrastructures that are resilient to future climate change. While it is speculated that urban flood damages will increase in the future (Yang 2000 and Ding et al., 2006), their magnitudes are hard to assess due to uncertainties associated with future climate scenarios, as well as the lack of understanding on plausible adaptations and mitigations strategies and their consequences.

Without mitigating the global GHG emissions, climate change is projected to result in more pronounced damages for urban drainage infrastructures. At the same time, in areas where precipitation intensity increases significantly, effective adaptation measures and related investments should be given high priorities to prevent runoff volumes from exceeding system capacities. Although it is widely accepted that the revision and adaptation of drainage systems may experience more challenges due to potential changes in precipitation extremes, less work has been done to investigate the relationship between changes in precipitation intensity and flood risks to provide additional insights for design strategies. More importantly, investigations on the benefits

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of global-scale GHG mitigation and local-scale adaptations in reducing adverse climate impacts on urban flood risks are typically conducted separately, rather than in a consistent manner.

In this study, the effects of climate change on the hydrological and hydraulic performances of an urban drainage system were investigated. Specifically, we quantify the impacts of future precipitation intensity changes at different return periods on flood risks under various climate scenarios. We then evaluate the ability of current drainage system in coping with the projected climate impacts. By designing two adaptation strategies in the study region, we investigate how much risks can be reduced. Importantly, by comparing the benefits of reducing GHG emissions globally and local adaptation strategies, we aim to advance our understanding on effective approaches in reducing the potential urban flood risks in a changing environment.

2. Materials and Methods

a. Study region

The study region (Hohhot City) is located in the south central portion of Inner Mongolia, China, and lies between the Great Blue Mountain to the north and the Hetao plateau to the south, which has a north-to-south topographic gradient. The drainage area in year 2010 was about 210.72 km^2 and served a residential population of 1.793 million (Figure 1a). The land use types in the region can be classified into five categories, agricultural land (8%), residential areas (38%), industrial land (13%), green spaces (7%), and other facilities (34%, including municipal squares, commercial districts, institutions). The planned drainage area in 2020 is about 307.83 km^2 and the detailed description of the land use category and distribution is shown in Figure 1b.

The region is within a cold semi-arid climate zone, characterized by cold and dry winters and hot and humid summers. The regional annual mean precipitation is approximately 396 mm with large intra-seasonal variations. The current drainage system can be divided into three large sub-basins (Figure 1c) and 326 sub-catchments with a total pipeline length of 249.36 kilometers. The drainage network has a higher pipeline cover rate in the central part, but with a rather low design standard for events with return period less than one year. Historical records on storm water drainage and flood damages show that the region has been experiencing an increase in flood risks mainly due to climate change and urbanization. A new drainage system is required by the regional water authorities to cope with the increasing flood risks in the future.

b. Climate change scenarios

Climate projections by five GCMs from phase 5 of the Coupled Model Intercomparison Project (CMIP5) archive are obtained from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) (Warszawski et al., 2014). The climate projections were bias-corrected against reference dataset of the WATCH forcing data (WFD) for the overlapping period using parametric quantile mapping (Piani et al., 2010; Hempel et al., 2013). This dataset represents a complete climate change picture in that it includes both the mean properties and variation of future climates. Several studies have demonstrated the value of this bias-correction climate projections in quantifying the impacts of climate change on global and regional hydrology (e.g., Piontek et al., 2014; Elliott et al., 2014; Haddeland et al., 2014; Leng et al., 2015a,b). Unlike most previous studies that only used data from one or two GCM in climate change impact studies on urban floods, we used the bias-corrected climate data from all five GCMs (HadGEM2-ES, GFDL-ESM2M, IPSLCM5A-LR,

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MIROC-ESM-CHEM, and NorESM1-M) under two Representative Concentration Pathways (RCPs) (i.e., RCP2.6 and RCP8.5) for our analysis. The impacts under the scenario RCP8.5 are compared with that in the scenario RCP2.6 to explore the benefits of climate mitigation on regional urban flood risks.

c. Urban drainage modelling

The Storm Water Management Model (SWMM 5.1) developed by the United State Environmental Protection Administration (EPA) is one of the well-known urban storm water models for simulating rainfall-runoff routing and pipe dynamics under either single or continuous events (Rossman and Huber, 2016). With climatic and rainfall inputs, SWMM is applied to evaluate variations in hydrological and hydraulic processes and the performance of the drainage system under selected mitigation and adaptation scenarios in the context of global warming. The hydrological component requires inputs of precipitation, sub-catchment properties, such as the drainage area, width reflecting the time of concentration, imperviousness. The pipe network requires inputs of manholes, pipelines, outfalls, and connections to sub-catchments (Zahmatkesh et al., 2015; Chang et al., 2013). Basic flow routing models include steady flow, kinematic and dynamic wave methods. Infiltration can be described by the Horton, Green-Ampt or Curve Number (SCS-CN) methods. Dynamics of pipe flow are calculated based on the continuity equation and Saint-Venant equations (Rossman and Huber, 2016). Overflow occurs once the surface runoff exceeds the pipe capacity and is expressed by the parameter of Total Flood Volume (TFV) at each overloaded manhole. Other types of results include the catchment peak flows, maximum flow rate of pipelines and flooded hours of manholes. It should be noted that SWMM is not capable of simulating surface inundation dynamics and cannot provide accurate estimation of the inundated zones and depths. The TFV value is thus used to approximately reflect the flood

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condition and system overloading of the drainage system. Nevertheless, surface inundation models (e.g., Apel et al., 2009; Horritt and Bates, 2002; Vojinovic and Tutulic, 2009) are applicable if more accurate information of the overland flow characteristics is needed.

Rainfall inputs are calculated from the regional storm intensify formula (SIF) using historical climatic statistics (Zhang and Guan, 2012), as shown in Equation 1.

$$q = \frac{A(1 + Dlg(P))}{(t+b)^c} \qquad \text{Eq. (1)}$$

where q is the rainfall intensity; A, b, c and D are constants to describe the regional parameters of design flow. P and t are the design return period and duration of storm, respectively. For this region, A, b, c and D equal to 635, 0, 0.61 and 0.841, respectively.

The Chicago Design Storms (CDS) approach is then employed to estimate synthetic rainfall hyetographs for a number of prescribed return periods, based on the parameters of the derived SIF (Zhang et al., 2008). In this study, there are in total 10 return periods of interest, i.e. the 1, 2, 3, 10, 20, 50, 100, 200, 500 and 1000-year events. The projected changes in precipitation intensity at various return periods are calculated based on the climate projection for each GCM-RCP combination (Table 1). The derived change ratios are then multiplied to the synthetic rainfall hyetographs to drive the future precipitation intensity scenarios. The kinematic wave routing and the Horton infiltration model are used for model simulations. The model results, especially the overloaded manholes, are validated against historical records of flood events.

d. Flood risk assessment

The TFV values corresponding to each rainfall event at various return periods are simulated by the SWMM. The TFV - return period relationship, as a proxy for flood damage illustration (Zhou et

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al., 2012; Olsen et al., 2015), is established to reflect the changes in flood consequence as a function of return period. Generally, more intense rainfall inputs will induce higher TFVs. Similarly, for flood risk description, the TFV is further linked to the occurrence probability of the event (Figure 2), which is used to demonstrate the relative contributions of individual return periods to total flood risks. Therefore, it is not surprising that the larger events, associated with higher flood damage may contribute less to the total flood risk/annual damage given their low probabilities of occurrence. It is expected that climate change will increase the magnitude of system overflow and lead to an upward trend in the damage curve. Consequently, the peak of the risk curve is likely to move towards the areas with lower return periods. Mitigation and adaptation, on the contrary, are aimed to reduce or prevent those impacts of global warming on flood damage and risks.

e. Design of adaptation scenarios

Changes in precipitation intensity associated with climate change have the potential to overburden the drainage systems. In this study, two adaptation scenarios are designed to explore the effects of adaptation on reducing flood risks induced by climate change. The first scenario adapts the drainage system as planned by the water authorities to cope with the designed standard of a 3-year design event. It involves two main improvements of the current drainage, by enhancing the pipeline diameters and expanding the pipe network. The design is implemented in the SWMM model as shown in Figure 1c.

A variety of site-specific factors can also influence the drainage performance in managing the surface runoff, such as the imperviousness of land area in the drainage basin. The second scenario is to increase the permeable surfaces (e.g. green spaces) and reduce the regional imperviousness. This scenario is referred as to the Low Impact Development (LID) scenario that aims to explore the potential of decentralized and green measures, such as permeable pavements, infiltration trenches, and green roofs. Using the geographical information system (GIS), we select sub-catchments that are amendable for LID adaptation based on the difference between the current and planned land use types. Specifically, the weighted mean imperviousness (WMI) is calculated for each sub-catchment polygons in the two maps, using the commonly applied impervious factors (Pazwash, 2011; Butler and Davies, 2004) for each type of land use. As shown in Figure 1d, a positive change in the WMI indicates that the area is expected to experience decreased regional mean imperviousness in designed adaptation scenarios, and vice versa.

3. Results

a. Impacts of future climate change on urban floods

Figure 3 shows the predicted impacts of future climate change on urban floods using the current drainage system by the near future period 2020-2040 as compared to the historical period. It is found that without mitigation or adaptation (i.e., RCP8.5 and the current drainage system), climate change is projected to lead to significant increase in the total flood volume (TFV) for various return periods. We note that a small proportion of the projected TFVs (i.e. lower bound at return periods 1, 3 and 1000 years) fall below the current TFV curve. Under such circumstance, climate change will lead to decreased precipitation intensities and so that the TFVs drop accordingly. Despite the large uncertainty associated with climate models, in particular with the 1, 10 and 1000 years, the poor service performance of the current system is evident. Overall, urban flooding is projected to increase by 52% on average with a standard deviation of ~73% as projected by the multi-model ensemble median in the period of 2020-2040, with the largest increase (258%) associated with the 1-yr events and the smallest increase (12%) associated with the 100-yr events.

b. Benefits of climate mitigation on reducing urban floods

Figure 4 shows the avoided flood risks due to GHG mitigations (i.e. the difference between RCP2.6 and RCP8.5) and the related uncertainties. Although large uncertainties exist as indicated by the bounds of the damage and risk curves, a consistent trend of damage and risk reduction can be observed between the scenarios with and without climate mitigation. The mitigation effects quantified through the relative changes of the median TFVs show that future urban flood management would benefit most from the global GHG mitigation for floods with smaller return periods. For example, an increase of 936.44 m^3 in total flood volume is projected for the 1-year event due to climate change (i.e., under RCP8.5), while 52% of which would be reduced under the climate mitigation scenario (i.e., under RCP2.6). As for the occurrence probability (Figure 4b), notably, the peak of risks is projected to shift from 1-yr events under the RCP8.5 scenario towards 2-yr events under the RCP2.6 scenario, in which global-scale GHG mitigation is in place. Such a shift in risks towards less frequent return periods, combined with a flatter risk curve, demonstrates the benefits of climate mitigation in reducing the flood risks. Integrated over all return periods, the increase in flood risks under RCP2.6 is projected to be 13% less than that under RCP8.5 in the multi-model ensemble median.

c. Benefits of adaptation on reducing urban floods

The effects of the two proposed adaptation scenarios in drainage systems were then examined for the 10 rainfall events. Figure 5 shows the spatial location of overloaded pipelines (red colour) with

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and without adaptations under present climate conditions, with the 3-yr event (recommended service level) and 50-yr event (one typical extreme event) selected for illustration. It is found that current pipe capacities are insufficient to cope with the flooding especially when experiencing the 50-yr event without adaptations. The poor performance of the drainage system leads to scattered flooding across the region. Overall, the percentage of overloaded manholes (POM) and the ratio of flood volume (RFV) ratio is up to 37% and 35% in current drainage system, respectively. With proposed adaptation scenarios, such risks can be reduced to zero. The benefits of local adaptations are also evident when experiencing more intense precipitation (i.e. 50-yr events), by reducing the POM and RFV from 67% and 50% to 19% and 17%, respectively.

In the context of climate change, we first assessed the correlation between the projected changes in precipitation intensity with the changes in TFVs (i.e., $CTFV=TFV_c/TFV_{nc}$, where c and nc represent results with and without climate change impacts) with and without adaptations. It is found in Figure 6 that performance of the current drainage system (no adaptation) is less sensitive to climate change (i.e., with a flatter slope). For example, for return periods of 3, 50 and 500 years, the CTFV is projected to be 1.6166, 1.3221 and 1.3544 with increase of precipitation intensity by 1.3369, 1.2119 and 1.2449, respectively. With smaller return periods, in particular the 1-yr event, a larger increase in the CTFV is observed. The results indicate that the service level of current drainage system is too low to even cope with present-day precipitation extremes, not to mention those in the future. Therefore, the CTFV is almost independent of the drainage capacity, and exhibits significant linear relationship with the changes in precipitation intensity.

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For both adaptation scenarios, a considerable increase in the ratio between the CTFV and changes in precipitation intensity is observed for return periods below 10 years. This implies that the designed adaptation can effectively attenuate events with small return periods and thus lead to low TFV_{nc} values. As a result, relative changes in TFVs of these events (i.e., percentage of change) are higher with increased precipitation intensity under climate change. For intense precipitation events with return period ≥50 years, however, more consistent results are found for both adaptation scenarios. This result implies that although the performances of drainage systems with designed adaptation measures are significantly improved compared to that of the current system, risks associated with events heavier than 50-year return period remain large as flooding under such events will push the adapted drainage systems to their upper limits.

d. Climate mitigation versus drainage adaptation

Figure 7 shows the comparison of benefits (i.e., avoided TFVs) as results of the designed adaptation measures and GHG mitigation as functions of the return period. It is evident that the designed local-scale adaptation and global-scale GHG mitigation are effective in reducing future urban flood risks, but the benefits are clearly correlated with the return period. In general, the benefits of both climate mitigation and adaptation of the drainage system are projected to weaken gradually with the increase of rainfall intensity (i.e. larger return periods). Importantly, the two proposed adaptation strategies are found to be more effective in reducing urban floods than the global mitigation of GHG emissions for the study region. In most cases, the benefits of adaptation more than double the level that can be achieved by mitigation. In extreme cases, the reduction in urban flood risks through adapting the drainage system is found to be five times more than that through climate mitigation (i.e., for the return periods of 2-10 years). Such effectiveness of reducing urban floods through the designed adaptation measures has great implications for the local authority in managing urban flood risks. Notably, the second scenario (LID+pipe) achieves a higher level of risk reduction than the pipe scenario across all return periods. This implies that implementation of LID measures to augment drainage system is more effective from the hydrological perspective by reducing upstream loadings when compared to adapting the pipe system alone.

4. Uncertainty and Limitations

There are a number of uncertainties that can affect the results of this study due to uncertainties associated with every step in the impact assessment modeling, namely, the structure/parameters of the drainage model, emission scenarios, GCMs, climate downscaling/bias-correction approaches. Specifically, climate projections by GCMs are subject to significant uncertainties in particular regarding precipitation (Covey et al., 2003). Precipitation from GCMs differs significantly from observations, which make it difficult to use GCM outputs directly as inputs to urban drainage models. In this study, similar to that in many other impact studies, the delta change method was applied to combine climate change information produced by GCMs with observational precipitation intensity. Using this method, climate inputs for a future time period are computed by multiplying the ratios between future and current time periods from GCMs to the observed time series. Then, changes in urban flood risks are investigated using observed and adjusted climate data. Disadvantages of this method lie in that transient climate changes cannot be represented and that changes in intra-seasonal or daily climate variability are not taken into account (Leng and Tang, 2014).

The drainage model itself is also subject to uncertainties associated with the representation of drainage system itself. The calculation of flood volume is inevitably affected by uncertainties associated with current and future land cover maps, catchment properties and geographical conditions. Although progresses have been made to estimate drainage network and subcatchment division by field surveys and geographic information systems, the uncertainty related to the process can still be high due to accumulation of uncertainty sources. This study employs a 1D drainage modeling approach, which is less computationally demanding but fails to represent the complexity of surface inundation. The estimation of the damage and risk of flooding are based on the description of flood volume from overloading nodes, which neglects the surface flood propagation from upstream to downstream nodes and could therefore underestimate the downstream flooding conditions. Two dimensional flood models can be incorporated to provide assessment of surface inundation extent and relevant hazard indicators. Further, due to limited data on planned adaptation scenarios, especially for the LID measures, a simplified modeling approach was used to take advantage of existing data. In a situation where more detailed case study data and planning documents are accessible, the LID modeling should be significantly improved by implementing more advanced approaches (Elliott and Trowsdale, 2007; Zoppou, 2001). Evaluation of additional adaptation strategies, such as flood retention by rain gardens and green roofs, needs to be explored to gain a more comprehensive understanding of LID systems. In particular, the cost-effectiveness of the adaptation measures needs to be examined to better understand the feasibility of different adaptation scenarios. Nevertheless, given these limitations, this study stands out from previous climate impact assessment studies on urban floods by proposing two feasible adaptations strategies and compare their benefits to that from the GHG mitigation within a consistent framework.

5. Summary and Conclusions

In recent year, more and more studies on the improvement/adaptation of existing drainage systems in response to climate change have emerged (Chang et al., 2013; Zhou et al., 2012; Abdellatif et al., 2015). Despite these efforts on examining the climate change impacts on urban drainage systems, limited attention has been paid to the joint analyses on urban flooding risks associated GHG mitigation and adaptation measures in a changing climate. This study assesses potential urban flood risks in response to future climate change in a typical urban area (Hohhot City), North of China. In particular, we focus on potential changes in future urban flood risks under various mitigation and adaptation scenarios in a consistent evaluation framework.

Although large uncertainties in the damage and risk estimations exist, some robust conclusions can be drawn based on our results. Without climate mitigation or adaptation, significant increases in flood risks are projected due to intensified precipitation for all investigated return periods, especially for return periods lower than 10 years. Overall, floods risks are projected to increase by 52% under the multi-model ensemble median in the period of 2020-2040, and the magnitudes of increase depend on precipitation intensity. Such increases in flood risks can be reduced considerably by climate mitigations through reducing GHG emissions. For example, the risks for 1-yr events can be reduced by 50% by switching the climate scenario from RCP8.5 to RCP2.6, demonstrating the benefits of GHG mitigations.

Besides the global-scale efforts of GHG mitigations, regional/local adaptations can be implemented to reduce the adverse impacts of climate change on local floods. Here, we demonstrated the value of adaptation measures by designing two alternative scenarios and compare

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their effectiveness to that of GHG mitigation. We found that the designed adaptation scenarios are much more effective in reducing future flood risks, through which the achieved risk reduction is more than double the level that can be achieved through the mitigation scenario. In addition, it is found that implementing LID measures in the local context to augment adaptations in the pipe can be more effective in reducing flood risks from the hydrological point of view.

We acknowledge that findings from this case study are subjected to limitations associated with climate scenarios, drainage model, and the region of interest. However, this study can provide insights on urban flood managements for similar urban areas in China, many of which are still equipped with highly insufficient drainage capacities. The existing drainage service level is generally below or merely at return period of one to two years in many cities, therefore needs to be extensively upgraded to handle the potential impacts in response to non-stationary precipitation extremes. Appropriate adaptation measures at the regional level can significantly enhance the performance of drainage systems and reduce the potential flood damage. Through a comprehensive investigation of future urban floods, this study confirmed a large increase of potential urban floods in response to future climate change and highlight the effectiveness of adaptation in drainage systems in coping with such risks. Our results have great implications for decision-making for better managing urban floods and emphasize the importance of accounting for both global-scale GHG mitigation and local-scale adaptation in assessing future climate impacts on urban flood risks in a consistent framework.

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Table 1 Projected changes in precipitation intensity under return periods ranging from 1yr to 1000yr by five Global Climate Models under two Representative Concentration Pathways (RCPs)

		1	2	3	10	20	50	100	200	500	1000
GFDL-ESM2M	RCP8.5	2.12	1.23	1.34	1.25	1.27	1.21	1.08	1.12	1.24	1.23
	RCP2.6	1.74	1.08	1.03	1.11	1.07	1.15	1.14	1.15	1.19	1.16
HadGEM2-ES	RCP8.5	0.62	1.08	1.09	1.06	1.01	1.03	1.17	1.26	1.23	1.14
	RCP2.6	0.36	1.20	1.19	1.04	1.02	1.11	1.31	1.26	1.37	1.24
IPSL-CM5A-LR	RCP8.5	1.44	1.17	1.28	1.17	1.08	1.09	1.02	1.10	1.12	1.13
	RCP2.6	0.74	1.04	1.18	1.01	1.06	1.03	1.01	0.99	0.95	1.00
MIROC-ESM-CHEM	RCP8.5	2.13	1.38	1.30	1.51	1.32	1.23	1.17	1.27	1.16	1.31
	RCP2.6	0.71	1.12	1.14	1.18	1.10	1.07	1.01	1.09	1.01	1.09
NorESM1-M	RCP8.5	2.11	0.96	0.80	1.63	1.35	1.15	1.08	1.01	1.04	0.97
	RCP2.6	0.11	1.09	1.05	1.28	1.17	1.08	1.10	1.18	1.09	1.20

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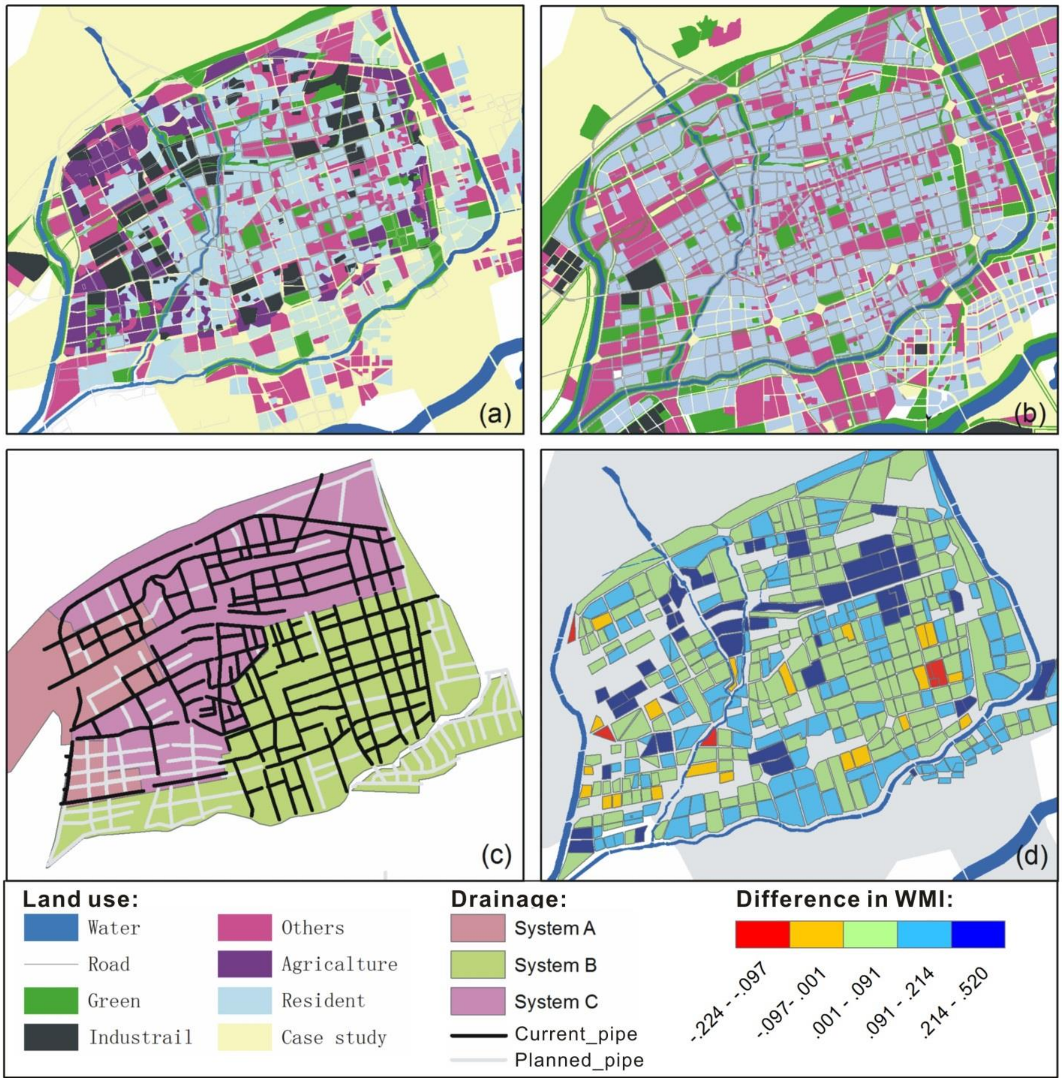

Figure 1 Land use of the study region for the year 2010 (a) and 2020 (b). Pipe network description of current and planned drainage systems (c). Difference in Weighted Mean Imperviousness (WMI) between year 2010 and 2020 (d).

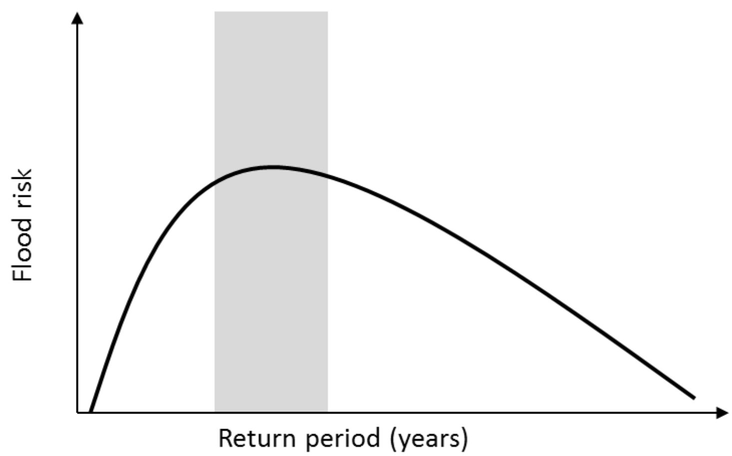

Figure 2 Illustration of urban flood risks under stationary drainage system. The grey area denotes the events that contribute higher percentage of the annual total damage.

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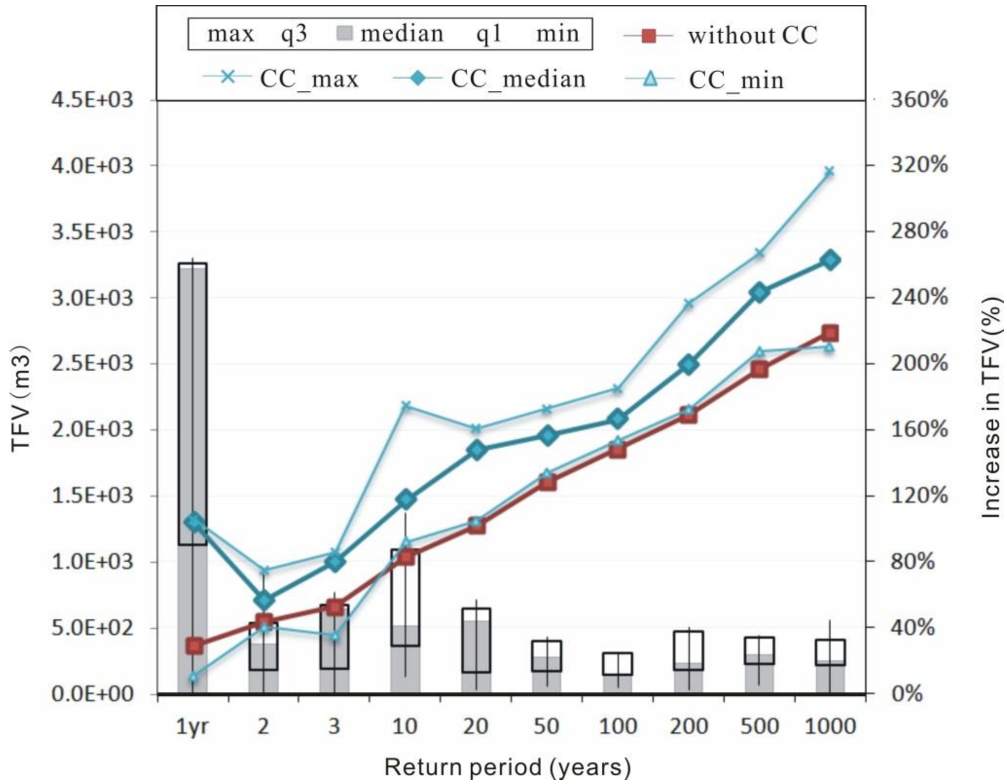

Figure 3 Projected total flood volume (TFV) with changes in precipitation intensity at various return periods under the RCP8.5 scenario.

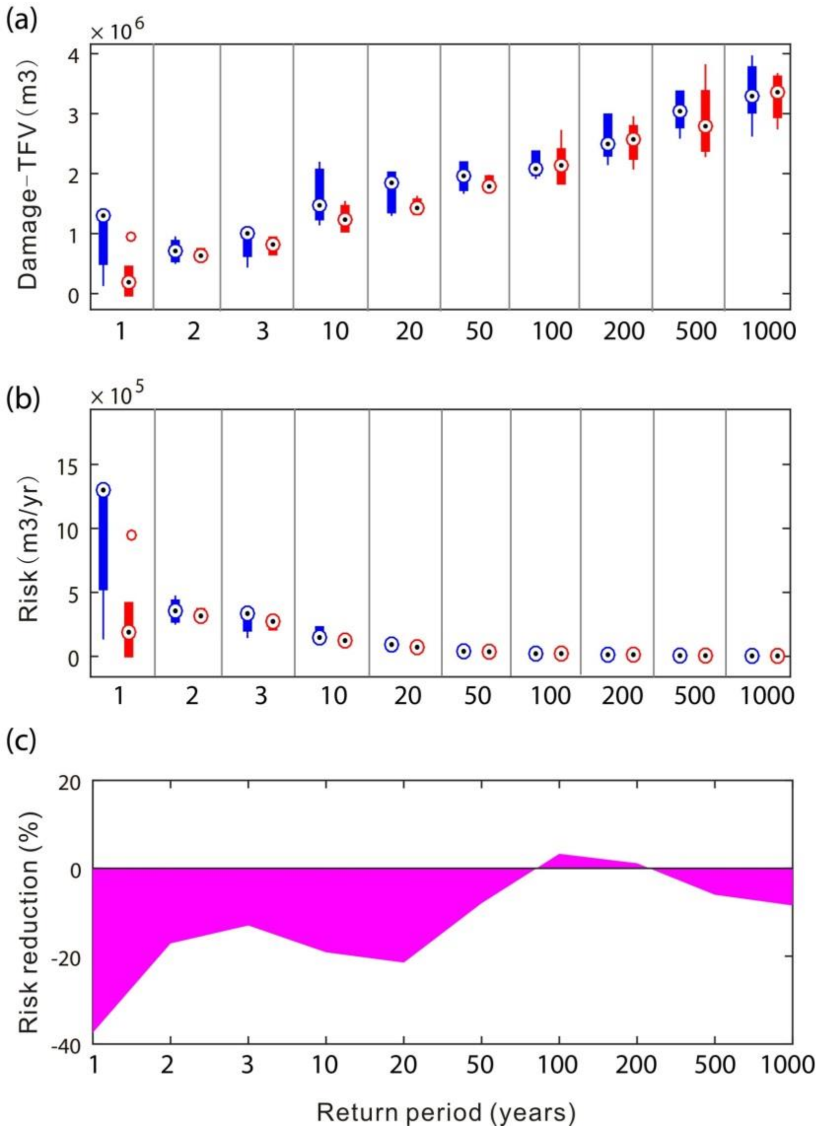

Figure 4 Comparison of flood damage (a) and risk (b) with changes in precipitation intensity of various return periods under RCP8.5 (blue) and RCP2.6 (red), and the avoided impacts (i.e. benefits of climate mitigation) in terms of risk reductions under RCP2.6 relative to RCP8.5 (c).

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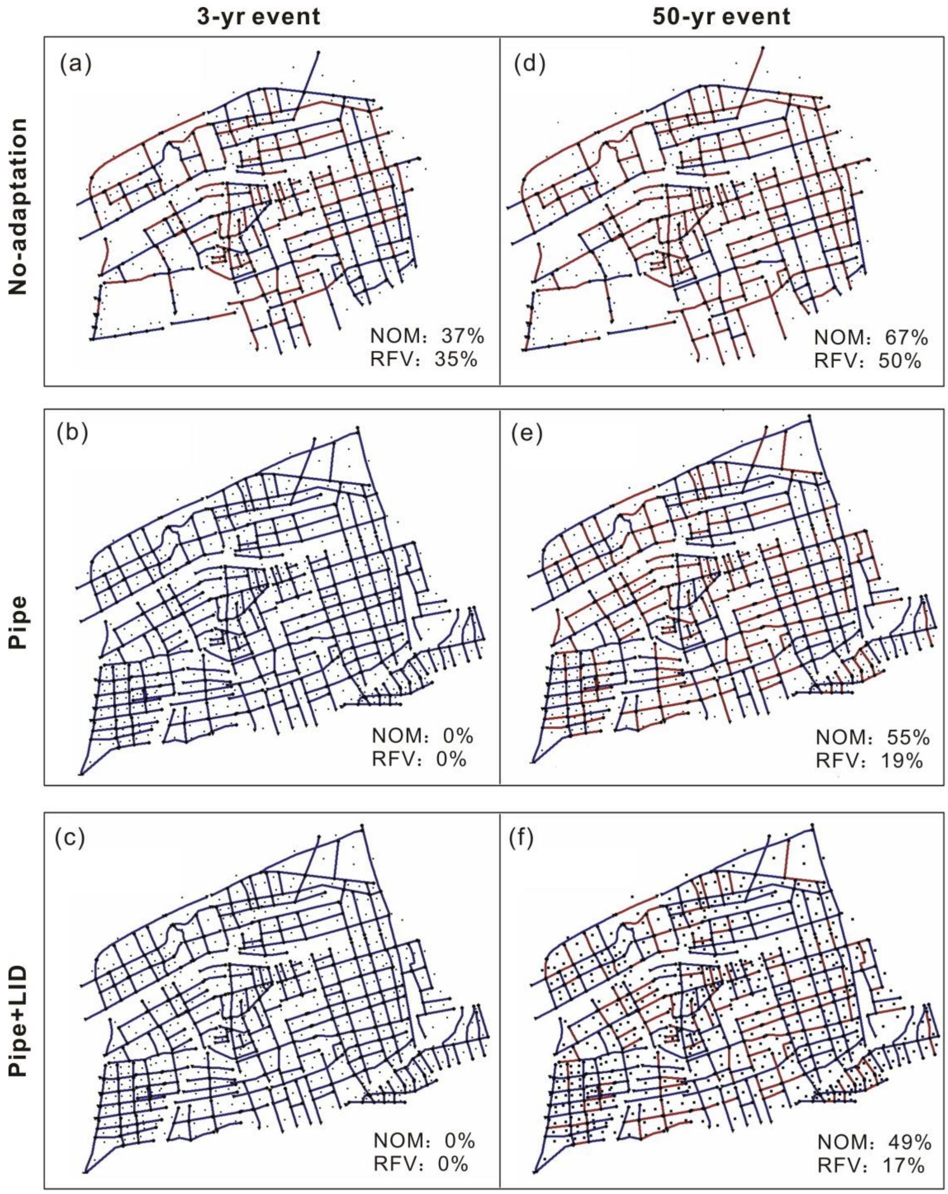

Figure 5 Spatial distribution of overloaded pipelines (red colour) induced by the current 3-yr (left column) and 50-yr extreme events (right column) without and with adaptations. The total percentage of overloaded manholes (POM) and ratio of flood volume (RFV) are summarized.

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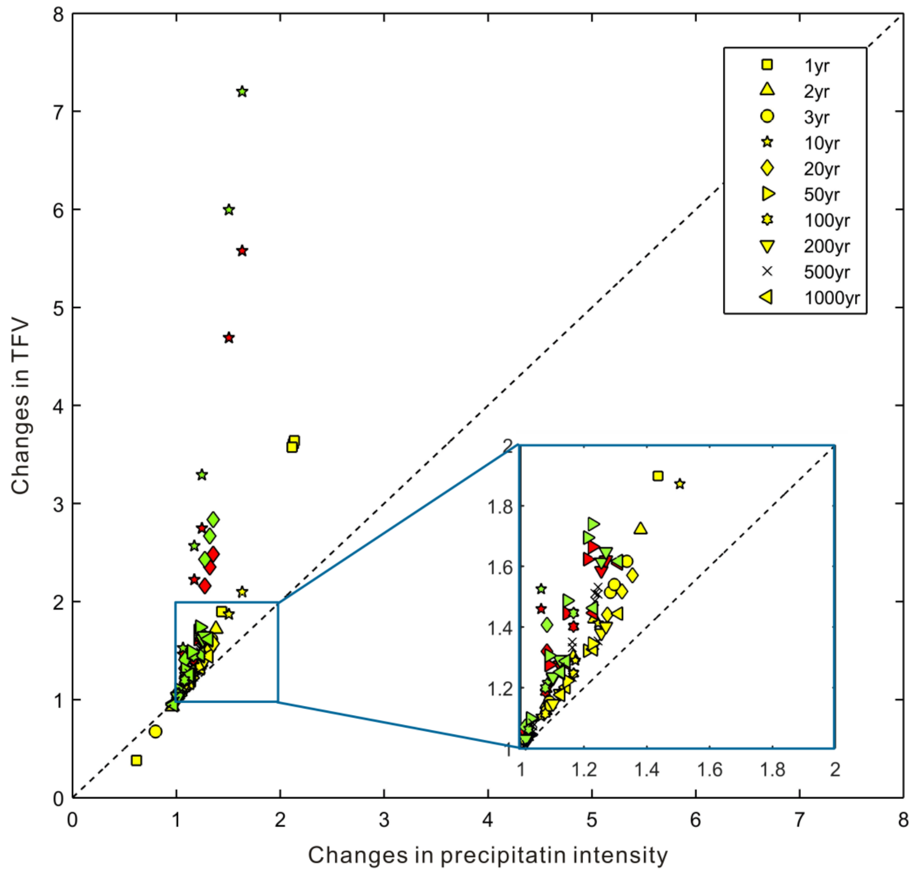

Figure 6 Response of CTFV to changes in precipitation intensity under the current drainage system (yellow) and two adaptation scenarios (i.e. Pipe in red and Pipe+LID in green) at various return periods.

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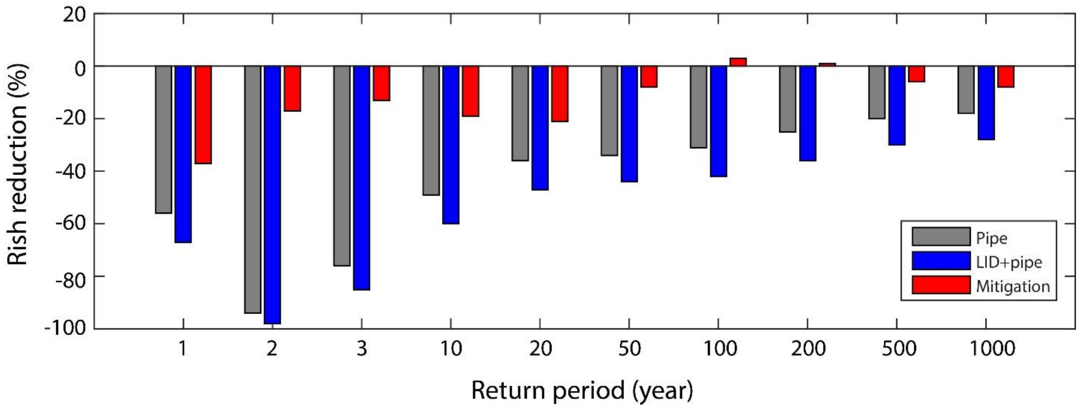

Figure 7 Comparison of benefits of climate mitigation and two adaptation strategies in reducing urban flood risks with changes in precipitation intensities at various return periods.