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Comparison of urbanization and climate change impacts on urban flood volumes: Importance of urban planning and drainage adaptation

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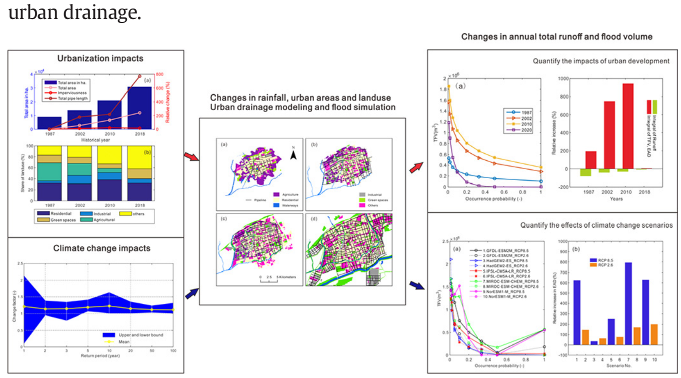
HIGHLIGHTS

- Investigate changes in landuse and drainage systems to assess urbanization impacts
- Projections of climate change based on 5 bias-corrected GCMs under RCP 2.6 and 8.5
- Evaluate hydrological runoff and total flood volume using SWMM drainage modeling
- Compare effects of climate change and urbanization on urban flood volume and risk
- Assess the role of urban drainage in mitigating urban flood volume

GRAPHICAL ABSTRACT

The study is set in a major city located in Northern China with a focus on comparing the impacts of recent urbanization and future climate change on urban runoff and flood volumes, in particular taking into account the role of urban drainage.



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ABSTRACT

Understanding the drivers behind urban floods is critical for reducing its devastating impacts to human and society. This study investigates the impacts of recent urban development on hydrological runoff and urban flood volumes in a major city located in northern China, and compares the urbanization impacts with the effects induced by climate change under two representative concentration pathways (RCPs 2.6 and 8.5). We then quantify the role of urban drainage system in mitigating flood volumes to inform future adaptation strategies. A geospatial database on landuse types, surface imperviousness and drainage systems is developed and used as inputs into the SWMM urban drainage model to estimate the flood volumes and related risks under various urbanization and climate change scenarios. It is found that urbanization has led to an increase in annual surface runoff by 208 to 413%, but the changes in urban flood volumes can vary greatly depending on performance of drainage system along the development. Specifically, changes caused by urbanization in expected annual flood volumes are within a range of 194 to 942%, which are much higher than the effects induced by climate change under the RCP 2.6 scenario (64 to 200%). Through comparing the impacts of urbanization and climate change on urban runoff and flood volumes, this study highlights the importance for re-assessment of current and future urban drainage in coping with the changing urban floods induced by local and large-scale changes.

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1. Introduction

Urban floods have great adverse socioeconomic impacts, and can cause disruptions to city services (e.g., transportation, sewerage, communication and electricity supply) and damages to urban infrastructure (Hlodversdottir et al., 2015; Karamouz et al., 2011; Wu et al., 2017; Yin et al., 2016). There is a growing concern that risk of flooding will increase in many regions of the world, especially in those metropolitan areas where there are a large number of population and assets (Huong and Pathirana, 2013; Jiang et al., 2018; Mahmood et al., 2017; Rosbjerg, 2017; Zhou et al., 2018). Among the various factors that contribute to increasing flood risks, changes in climate and urbanization are two of the most influential ones that challenge the current and future urban flood management strategies (Arnone et al., 2018; IPCC, 2014; Kaspersen et al., 2017; Mahmood et al., 2017; Wu et al., 2017). On the one hand, climate change exerts large impacts on water cycle and patterns of precipitation extremes, and thus can directly affect surface runoff and the frequency and magnitude of floods (Karamouz et al., 2011; Mahmoud and Gan, 2018; Yazdanfar and Sharma, 2015). On the other hand, urbanization associated with population and wealth growth is one of the most common causes of increasing impervious surfaces and socioeconomic vulnerability in urban areas to floods (Dawson et al., 2009; Huong and Pathirana, 2013; Li et al., 2013; Mahmoud and Gan, 2018).

Urban drainage is an essential part of city infrastructure that is designed to transport excess water away from urban areas to limit floods at an acceptable level of service (Egger and Maurer, 2015; Hlodversdottir et al., 2015; Kleidorfer et al., 2014). The implication of climate change and urbanization can not only lead to changes in surface floods, but also affect the planning and design of drainage system (Arnone et al., 2018; Semadeni-Davies et al., 2008; Willems, 2013). For instance, long-term changes in hydrological regimes, especially surface flooding routes and characteristics, can lead to transformation of city landuse and drainage system to avoid flood disruptions and damages. Meanwhile, improved management of urban floods along the development, typically through upgrading of drainage systems (Mahmood et al., 2017), can have direct effects on flood hazard and vulnerability by influencing the surface and underground routing and conveyance processes. Miller et al. (2014) pointed out that the degree of area serviced by a drainage system was a stronger determinant of hydrological runoff response than either impervious area or development type. It is thus essential to incorporate the role of drainage system in the assessment of changing conditions of urban floods in the context of climate change and urbanization.

Impacts of climate change on precipitation extremes have been widely studied under historical and future conditions (Arnbjerg-Nielsen, 2012; El-Jabi et al., 2016; Larsen et al., 2009; Mallakpour and Villarini, 2016; Thanvisitthpon et al., 2018). It is a common approach to use outputs of Global Climate Models (GCMs) with downscaling methods or finer-resolution Regional Climate Models (RCMs) to predict climate change effects (Karamouz et al., 2011; Prudhomme et al., 2010; Teutschbein and Seibert, 2012; van Roosmalen et al., 2010). In recent years, consequences of climate change on stormwater runoff, urban drainage and floods have received growing attention (Egger and Maurer, 2015; Grum et al., 2006; Hlodversdottir et al., 2015; Jung et al., 2015; Moghadas et al., 2018; Willems, 2013; Wu et al., 2017; Zahmatkesh et al., 2015). Previous assessments of urbanization impacts on hydrological regimes were mainly conducted based on modeling approaches (e.g., landuse development models, urbanization/socioeconomic scenarios) for a relatively large spatial scale, e.g., river catchment/basin (Aich et al., 2016; Arnone et al., 2018; Whitehead et al., 2018; Zhou et al., 2013). However, in those types of models landuse classifications and evolution characteristics of urban areas were often limited due to difficulties in collecting detailed historical data and/or establishing finer models for reconstructing/predicting landuse evolutions for historical and future conditions (Huong and Pathirana, 2013; Kaspersen et al., 2017; Mahmoud and Gan, 2018; Miller et al., 2014).

Understanding the drives behind changing flood risks is essential to inform future mitigation and adaptation strategies under nonstationary conditions. Previous studies provided valuable insights into hydrological impacts of climate change and urbanization on a relatively large spatial scale. For example, Todd et al. (2007) found out that landuse changes had a greater impact on hydrology in a watershed surrounding Indianapolis, Indiana, while Pumo et al. (2017) revealed a predominate role of climate change in determining hydrological responses in the Eldon river basin in Oklahoma, USA. In contrast, Aich et al. (2015) reported that landuse changes and climate variability contributed in roughly equal shares to increases in river flooding in the Sahel Zone. Nevertheless, effects on urban floods induced by climate change and urbanization at a city scale, in particular taking into account the role of drainage system in mitigating flood impacts, are still less understood (Huong and Pathirana, 2013; Kaspersen et al., 2017; Wu et al., 2017; Yazdanfar and Sharma, 2015).

This paper is to examine the impacts of urbanization and climate change on urban flood volumes and related risks in a city of Northern China, by taking into account the role of urban drainage system. We first assessed the changes in urban flood conditions due to landuse changes and drainage upgrading in the process of historical urbanization for the past 30 years. We then compared the urbanization impacts with the effects induced by projected climate change from five GCMs under two representative concentration pathways (RCPs 2.6 and 8.5). The results highlight the importance of reassessing the performance of current and future drainage systems in coping with the changing climate and urban development. This has great implications for many developing cities in China given their current low drainage capacities and poor service performances (Jiang et al., 2018; Lv and Zhao, 2013).

2. Materials and methods

2.1. Study region

The city of Hohhot is located in the southern central part of Inner Mongolia, China, lying between the Great Blue Mountains to the north and the Hetao Plateau to the south. The landscape is topographically high in the north and lower in the south. The local annual mean precipitation is approximately 396 mm, with relative large level of seasonal and interannual fluctuations (Guoqing et al., 2008; Shi et al., 2007). The region is characterized by cold and dry winters, but hot and humid summers. The rain season is between June and August, which accounts for more than 65% of the annual precipitation (Zhou et al., 2018). The land use is classified into five categories including residential areas, industrial districts, agricultural lands, green spaces, and others. Specifically, the category 'others' refers to a range of public facilities, such as municipal squares, transportation centers/hubs, institutions, and commercial districts.

Note that the investigated urban area covers the entire city, and thus is not within a larger basin (Supplementary Fig. S1). The drainage system is independent of other basins or hydrological systems. This means the drainage system only collects rainwater of the urban area, and there is no external springs contributing to the surface runoff. There are six main rivers and streams, where the drainage system conveys the stormwater runoff to during precipitation events. According to the local water authorities, flooding has occurred more frequently and severely in recent years. The increasing flooding is attributed to many factors, including the impacts of urbanization and climate change in the region, and the low level of service of the drainage system (Zhou et al., 2016; Zhou et al., 2018).

Three types of data were collected and processed, including (a) landuse changes for historical period 1987–2018, (b) drainage network data between 1987 and 2018, and (c) climate change scenarios by 2050s. Since most of the data were in a format such as images, texts and dataset, they need to be further treated for GIS and SWMM analyses. The temporal-spatial changes in landuse were analyzed and compiled based on historical remote-sensing images, aerial photographs and city maps provided by the local data authorities (i.e., the water authority and a large surveying and design company) (DSAAH, 2018; PRPSDC, 2018). First, all relevant maps and images were geo-coordinated in ArcGIS through georeferencing and spatial adjustment tools. The layouts and shapes of different landuse covers were then manually created based on the geo-coded maps for different historical periods. To ensure a reasonable level of accuracy, the statistics (e.g., catchment area, proportion of different land types) of the created landuse maps were further validated with internal reports and literature reference (Ding and Zhang, 2012; Erdeniqiqige et al., 2012). Primary data on drainage system were also collected from the local data authorities, which provided the records of drainage network and related modeling parameters (e.g., construction year, age, pipe diameter, length). Additional flood data include recent observations of flood conditions, typically local flood points and major flood events.

The input rainfall series are artificial rains in the format of Chicago Design Storms (CDS) generated based on a regional storm intensity formula (SIF) from local meteorological and water authorities (Zhou et al., 2018). The approach adopted mainly follows the standard procedure in urban drainage modeling in China, as documented in the National Guidance for Design of Outdoor Wastewater Engineering (MOHURD, 2016). Specifically, the SIF represents an Intensity-Duration-Frequency (IDF) relationship, which is a common approach in literature for estimating design rainfall hydrographs (Berggren et al., 2014; Cheng and AghaKouchak, 2014; Panthou et al., 2014; Willems, 2000). In China, the procedure for applying SIF to obtain CDS is outlined in the National Technical Guidelines for Establishment of Intensity- Duration-Frequency Curve and Design Rainstorm Profile (MOHURD, 2014; Qin et al., 2013), and has been widely adopted in a large number of Chinese urban drainage studies (Wu et al., 2016; Xie et al., 2017; Yin et al., 2016; Zhang et al., 2008; Zhou et al., 2018). The climate change projections were obtained from the Intersectoral Impact Model Intercomparison Project (ISIMIP) (Warszawski et al., 2014).

2.2. Historical urbanization

As shown in Fig. 1, the study region represents a typical developing city in China that has undergone significant urbanization in terms of centralization and extension of areas containing residential and public facilities between 1980 and 2018. The first urbanization boom occurred in early 1900s when the area gradually developed into peri-urban areas and small urban centers. This period, however, was not included in this study due to unavailability of the data. Starting in 1980s, the urban areas gradually increased, but at a relatively steady growth rate. In early 2000s, there was a trend towards the intensification of urban land in the region. In the following years, the city has re-experienced a significant level of landuse change and city expansion due to regional socio-economic development (Ding and Zhang, 2012; Erdeniqiqige et al., 2012). Further details on levels of urbanization and changes in landuse types for each time slice are illustrated in Fig. 1.

Historical evolution of the drainage system (e.g., extent, distribution and density of network) is described by the black linear features in Fig. 1 for different time periods. Initially in early 1980s (Fig. 1a), the drainage was built to serve the main urban area with a rather low design standard (i.e., handle rainfall events with return periods less than 0.5 year) (Zhou et al., 2016). Thereafter, the drainage network was gradually extended to cover the peri-urban area of the city (Fig. 1b). Nevertheless,

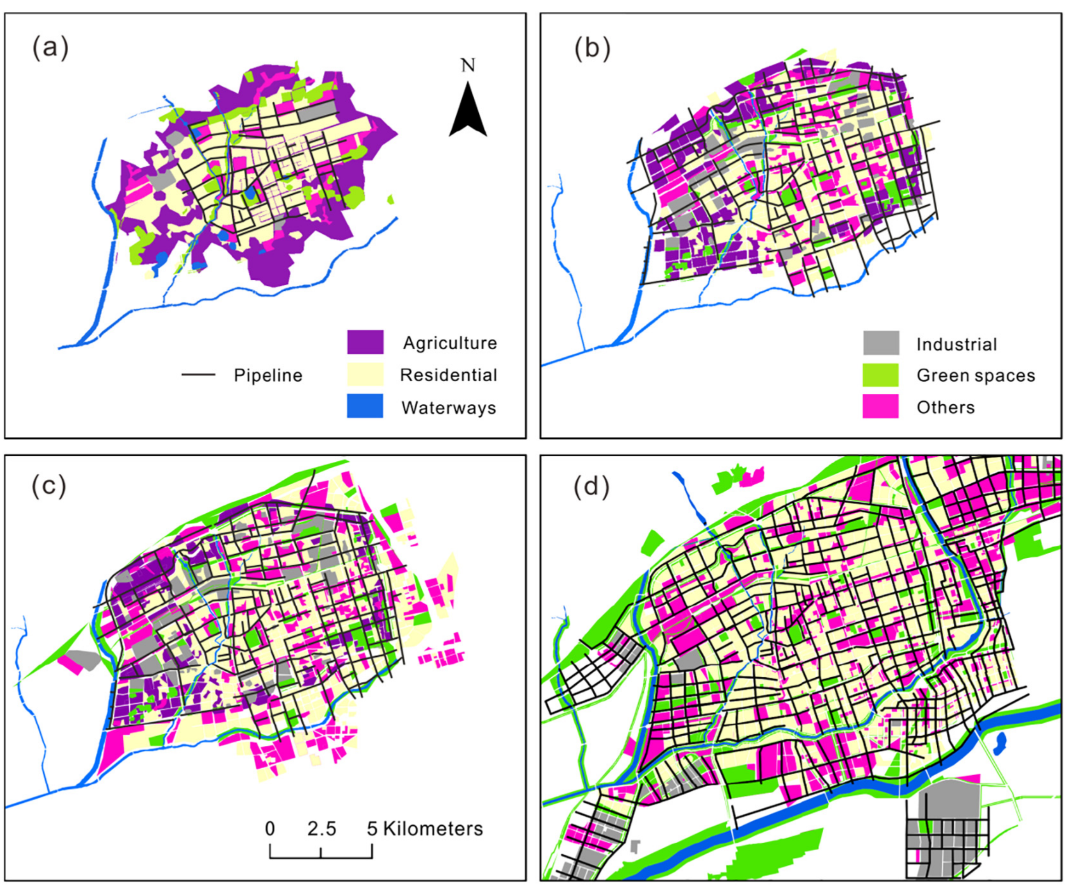

Fig. 1. Historical changes in landuse and drainage systems for year (a) 1987, (b) 2002, (c) 2010, and (d) 2018. The landuse category 'others' refers to a range of public facilities, including municipal squares, transportation centers/hubs, institutions, and commercial districts.

limited pipelines were renewed and thus the upgrading of the drainage capacity failed to keep pace with the level of urbanization. After 2002, new additions to the drainage mainly included the pipelines in the northern part of the area (Fig. 1c). The drainage system has evolved into a relatively complex one in 2010; however, there are still a large portion of pipelines equipped with capacities below service standards, especially in the central region. Due to the large increase in urban land cover and poor performance of the drainage system, the local water authorities initiated an adaptation project afterwards to upgrade the drainage conveyance capacity and coverage area (DSAAH, 2018; Zhou et al., 2016). It is shown in Fig. 1d that the network in 2018 contains an area much larger than previous ones, with a service level upgraded to a return period of 3 years.

Statistics are further summarized to describe the historical changes in total area, surface imperviousness and total pipe length over the past 30 years (Fig. 2). The areas of the urban basin for the four time periods (i.e., 1987, 2002, 2010 and 2018) are 9039, 13,898, 21,072 and 30,783 ha, respectively. The total area of urban land shows a steady increase over time and has more than tripled in 2018. In comparison, the changes in mean imperviousness are less dramatic, with a much lower rate of change in the study period. In terms of pipe length, note that there are two phases of rapid growth since 1987, especially with the marked increase between 2010 and 2018. Due to the aforementioned drainage adaptation project, the total pipe length in 2018 has increased six fold in comparison to that in 1987. However, little expansion of drainage network is observed between 2002 and 2010, implying that the upgrading of drainage did not keep pace with the demands of urban growth in that period.

As shown in Fig. 2b, the decrease in agricultural land and the increase in others category (e.g., public facilities and social service districts) are noteworthy throughout the period. Specifically, in 1987 it is shown that the dominant landuse types are agricultural (33%) and residential (32%), respectively, with limited industrial activities (4%) in the region. As a result of socioeconomic development and public infrastructure construction, in 2002 the proportions of industry (15%) and others category (21%) have both increased. Nevertheless, the main landuse types remain residential (31%) and agricultural (22%).

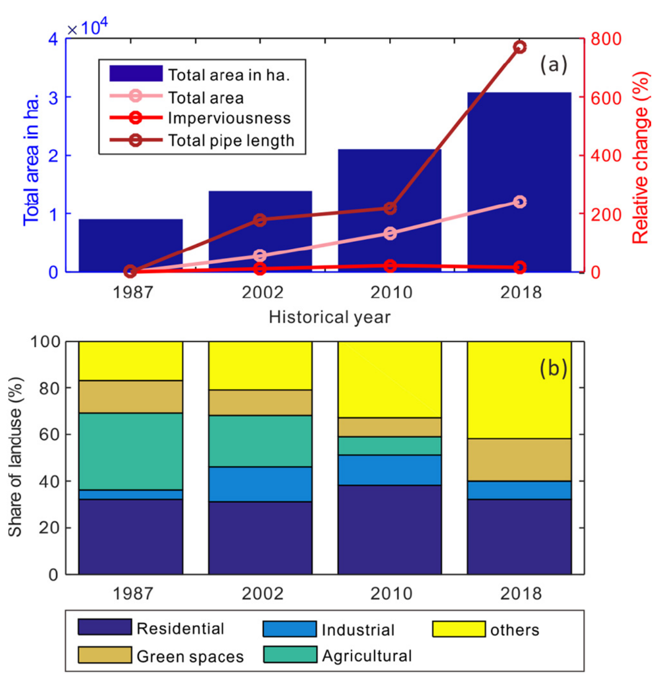

Fig. 2. Historical changes in (a) total area, imperviousness and pipe length, and (b) proportions of landuse types for 1987, 2002, 2010, and 2018, which can have direct impacts on the hydrological loads of drainage system and resulted urban flood volumes.

Along with the urbanization, the major land use types evolved into residential (38%) and others (34%) in 2010. Note that nowadays the original agricultural lands have been completely replaced, indicating a rapid conversion of landuse from agricultural to the rest types of urban use. Further, thanks to a better city planning as well as the drainage plan, there is a significant increase in public service facilities and green spaces in 2018.

2.3. Future climate change scenarios

The projections of climate change effects are obtained using bias-corrected climate from five GCMs from the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive. Specifically, we considered HadGEM2-ES, GFDL-ESM2M, IPSLCM5A-LR, MIROC- ESM-CHEM, and NorESM1-M under two representative concentration pathways (RCPs 2.6 and 8.5). RCP 8.5 represents the business-as-usual scenario, while RCP 2.6 is for the climate mitigation scenario. Comparing the projections under RCP2.6 with RCP8.5 allows for an examination of the benefit of climate mitigation for reducing flood risks. Therefore, there are in total ten different scenarios describing the future climate conditions.

We are aware of the large uncertainties associated with the climate model simulations. Therefore, instead of using raw climate simulations, the impacts of climate change on precipitation extremes are reflected using a change factor methodology, which is commonly used in urban drainage modeling (Kaspersen et al., 2017; Rosbjerg, 2017; Willems et al., 2012; Yazdanfar and Sharma, 2015; Zhou et al., 2012a, 2012b). This is because we have more confidence in the projected changes than the absolute values in climate model simulations. This pre-processing could also reduce the systematic errors in climate models to certain extent. The change factor is estimated as the relative difference between future and present (i.e., baseline) climate conditions (e.g., precipitation intensities simulated by GCMs) for a range of return periods. Specifically, for each year the annual maximum daily precipitation was assessed for both historical and future periods. The generalized extreme value (GEV) distribution is then fitted separately to the two sets of daily values (Coles, 2001; Katz et al., 2002). The goodness of fit was tested by calculating the Kolmogorov–Smirnov and Anderson–Darling statistics. We can then calculate the change factors by dividing the future climate simulations by historical climate simulations. Finally, to derive the future climate change scenarios, the change factors are multiplied to the rainfall time series under present climate for each return period.

Fig. 3 illustrates the mean, lower and upper bounds of change factors estimated from the 10 climate change scenarios. Note that there is a large uncertainty bound associated with the change factors of the 1-year return period, ranging from 0.11 (89% decrease) to 2.13 (113% increase) under different GCMs and RCPs. Generally, it is a tendency that the uncertainty of change factors decreases as a function of return period. For events with return periods larger than 20 years, it is projected that the intensity of extreme precipitations will increase by within a range between 1 and 35%.

2.4. Flood volume modeling and risk estimation

The U.S. EPA (Environmental Protection Agency) Stormwater Management Model (SWMM, Version 5.1) (Rossman and Huber, 2016) was used in this study to simulate the hydrological and hydraulic responses to impacts of urbanization and climate change. The SWMM is one of the best known rainfall-runoff simulation models that have been applied in extensive studies on urban drainage and floods (Jung et al., 2015; Kong et al., 2017; Wu et al., 2017; Zahmatkesh et al., 2015; Zare et al., 2012).

In SWMM the drainage system is described by a set of physical components including subcatchments, junctions, conduits and outlets. The hydrological behavior of urban areas is simulated by the subcatchment component. Key parameters include e.g., the shape, catchment area,

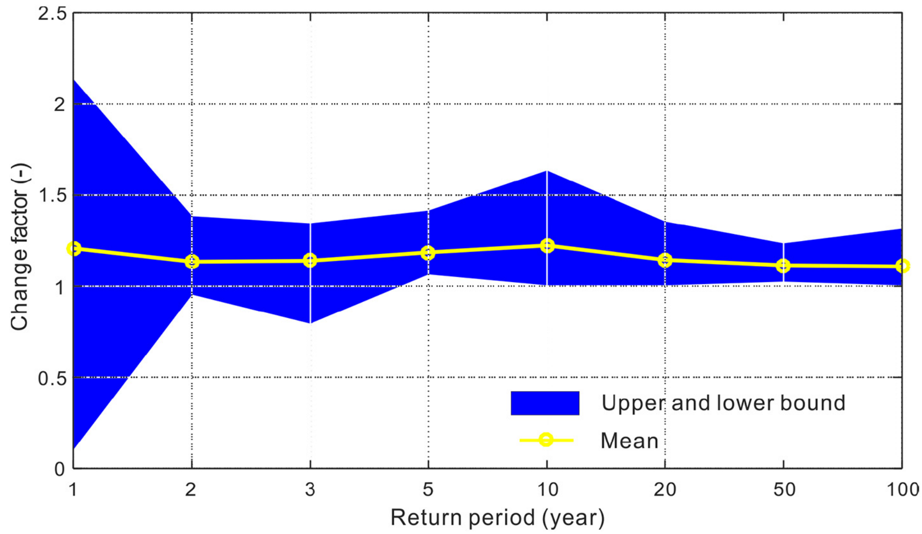

Fig. 3. Projected changes in precipitation intensities (i.e., climate change factors) for return periods ranging from 1 to 100 years by five GCMs under RCPs 2.6 and 8.5 pathways.

topography, imperviousness, landuse, flow length and width of subcatchments reflecting the time of concentration (Rossman and Huber, 2016). In this study as the drainage system has no inflows from other basins and thus the model is simulated with only direct rainfall inputs. Rain gage represents another key hydrological component and is used to describe the source and format of input precipitations that are applied to the subcatchments (Rossman and Huber, 2016). The input rainfall is described by a separate time series object in SWMM and can be synthetic design events or historical rainfall observations. The hydrological loads are then conveyed to the hydraulic components (i.e., pipes and manholes) to simulate the water dynamics (e.g., link discharge, water level) inside the pipelines. For hydraulic units, the parameters required for junctions and outlets comprise mainly the spatial location, invert elevation and maximum depth. Key parameters of conduit/pipe include the diameter, shape, length and spatial position. What's more, SWMM can perform hydraulic routing by three different models, including steady flow, kinematic wave and dynamic wave methods. Infiltration losses can be estimated using Horton, Modified Horton, Green-Ampt and Curve Number models (Rossman and Huber, 2016).

The impacts of urbanization are modeled by changes in subcatchment area and surface imperviousness, following previous studies (Kaspersen et al., 2017; Pumo et al., 2017; Weng, 2001; Yao et al., 2016). For each individual subcatchment, changes in size are estimated directly from the GIS-based geo-spatial dataset showing the evolution of case area for the different time slices. Imperviousness is assessed by the weighted mean method to account for impervious factors of all types of landuse within the subcatchment (Butler and Davies, 2010; Pazwash, 2011). Input rainfalls are assigned according to the local rainfall intensity formula $q = 635 * (1 + 0.841 * \lg(P))/t^{0.61}$, where q is the rainfall intensity (mm/min), t is the rainfall duration (min), and P is the return period (year). Specifically, a group of return periods are considered in this study, including the 1-, 2-, 3-, 5-, 10-, 20-, 50- and 100-year events. A 4-hour rainfall time series at 10-minute intervals is generated for each return period according to the SIF relationship. Climate change factors derived from the aforementioned 10 scenarios are then incorporated into the rainfall intensities to model the impacts of future climate conditions on urban floods. Parameters of hydraulic components (e.g., junctions and pipes) were also obtained from the GIS dataset. In addition, the Horton and kinematic wave methods were used for flow routing.

Note that as data collection is very constrained in the past decades in the region, only data on basic catchment parameters (i.e., catchment area and landuse) were collected and there is a lack of detailed measurements on hydrological behavior of the urban area, in particular the surface runoff flows in this study. Primary data to support validation work against historical records are the flood-prone areas recorded by the local water authorities. Results shown that the flooded points are in good agreement with the simulated overloading manholes of the drainage system (year 2010) (Zhou et al., 2016; Zhou et al., 2018).

As SWMM is not capable of simulating surface inundation conditions (e.g., flooded areas and overflow depths), the performance of drainage system and magnitude of urban floods are reflected by means of Total Flood Volume (TFV) summarizing the overflows from all overloaded manholes in SWMM. For a given condition/scenario, carrying out simulations for a range of return periods gives a flood damage-probability curve. The type of curve is typically characterized by a log-linear relationship describing changes in flood damage as a function of return period (see Eq. (1)), which further yields the expected annual damage (EAD) reflecting the annual risk of flooding (Eq. (2)) (Olsen et al., 2015; Rosbjerg, 2017; Zhou et al., 2012a, 2012b):

$$D(p) = a\ln(p) + b; p = \frac{1}{T} \tag{1}$$

$$EAD = \int_m^n D(p)d_p \tag{2}$$

where, D denotes the damage of a given recurrence probability (p). m and n are the lower and upper bounds of p, respectively. T is the return period, a and b are the coefficients of the log-linear relation, respectively. In this study, as the surface inundation conditions and related damage are not available, flood damage is reflected by the performance indicator TFV. As a result, through an integral of the TFV-probability curve, the EAD represents the total expected TFVs per year, as a simplified method describing the impacts of urbanization and climate change on urban flood volumes and flood risks (Zhou et al., 2018).

3. Results and discussion

3.1. Impacts of urbanization on surface runoff and flood volumes

First, large increases in total runoff volume (TRV) were noteworthy in 2002 and 2018 (Fig. 4a), due to the significant changes in landuse in terms of size and type of urban covers (Figs. 1 and 2). As for TFV (Fig. 4b), until 2010 the historical change patterns were similar to the ones for TRV. This implies that the drainage between 1987 and 2010 was not upgraded in time along the urbanization to improve the

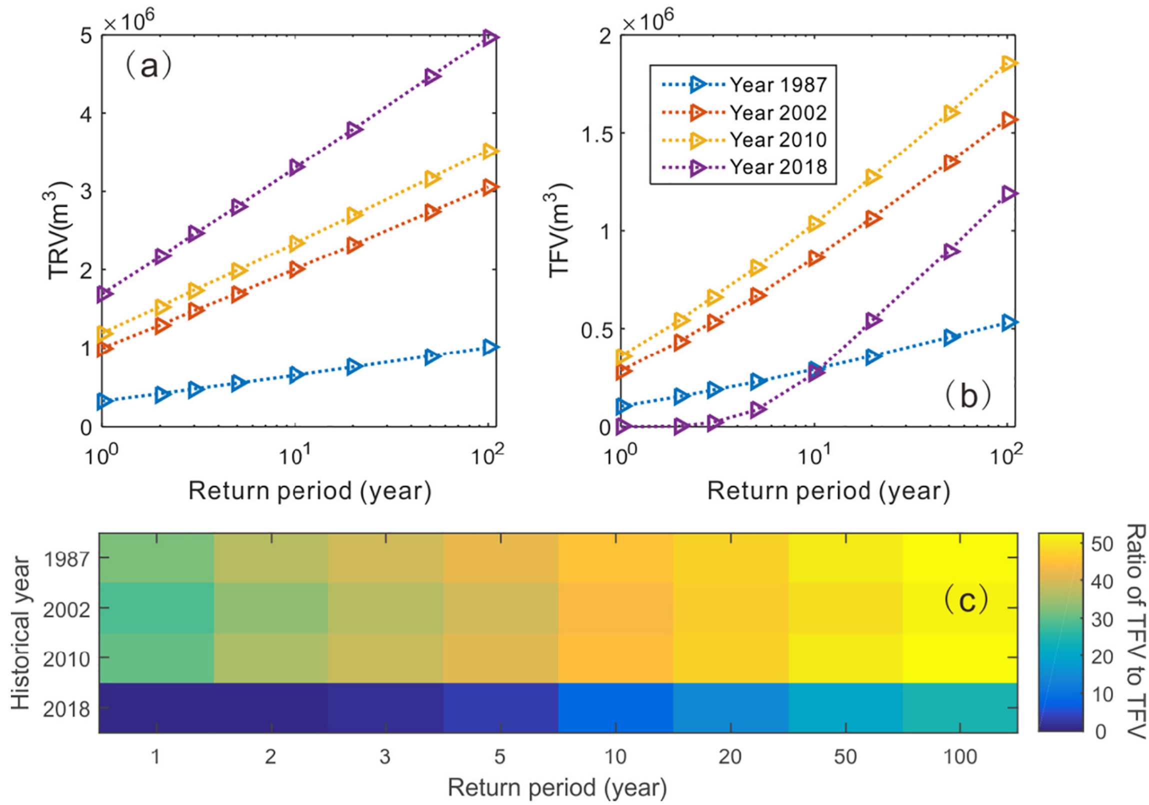

Fig. 4. Impacts of urban development on (a) total runoff volume (TRV), (b) total flood volume (TFV), and (c) system overloaded percentage (i.e., ratio of TFV to TRV) for historical years. It is shown that urbanization has led to general increases in annual surface runoff over time, within a range between 208 and 413%.

conveyance capacity and thus had little impact on TFV. In 2018, significant reductions in TFVs were noted for all return periods, thanks to the large-scale extension and enlargement of pipe network in the area. The results show the important role of drainage system in mitigating increasing runoff and urban floods brought by the urban development. Regarding the system overloaded percentage, it is shown that the overloading rate increases as a function of return periods for all years (Fig. 4c), indicating that the conveyance capability of drainage is more limited under large precipitation events. The overloading rate is highest under the most extreme event (i.e., the 100-year return period) in year 2010. Further, in line with the previous results, the overloading rates in 2018 exhibit noticeable reductions for all precipitation events, verifying the significant improvement in drainage performance as a result of the adaptation project.

Fig. 5a shows that the highest flood risk (i.e., annual TFVs in this study) occurred in 2010, due to the large extension of urban areas and

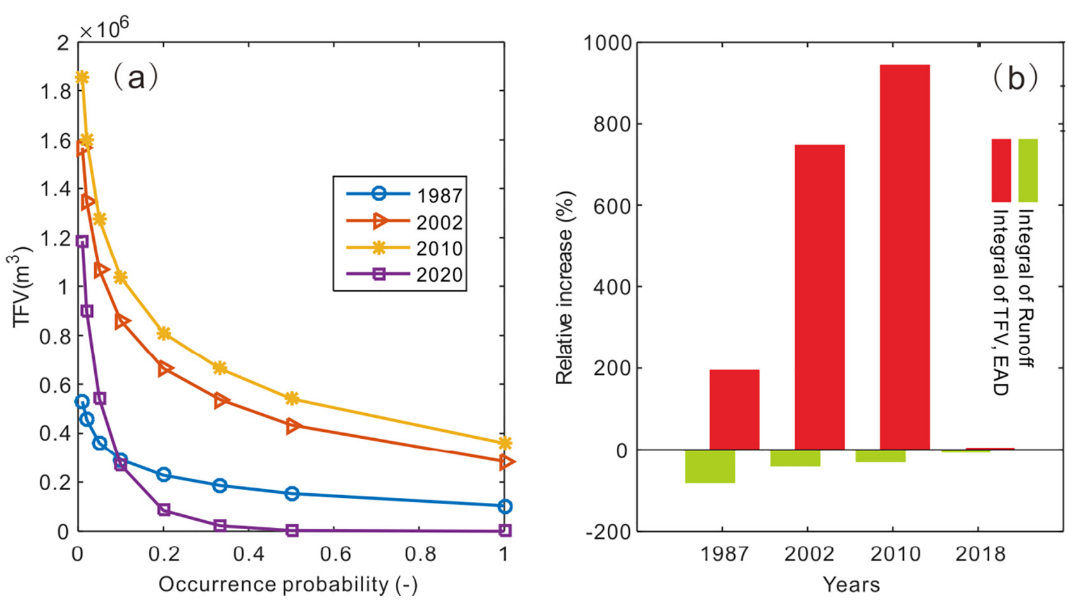

Fig. 5. (a) TFV-probability curves and (b) relative increase in integral of TRV and TFV (using 2018 as the baseline year) under the investigated historical years. The area under the TFV-probability curve reflects the total expected TFVs per year.

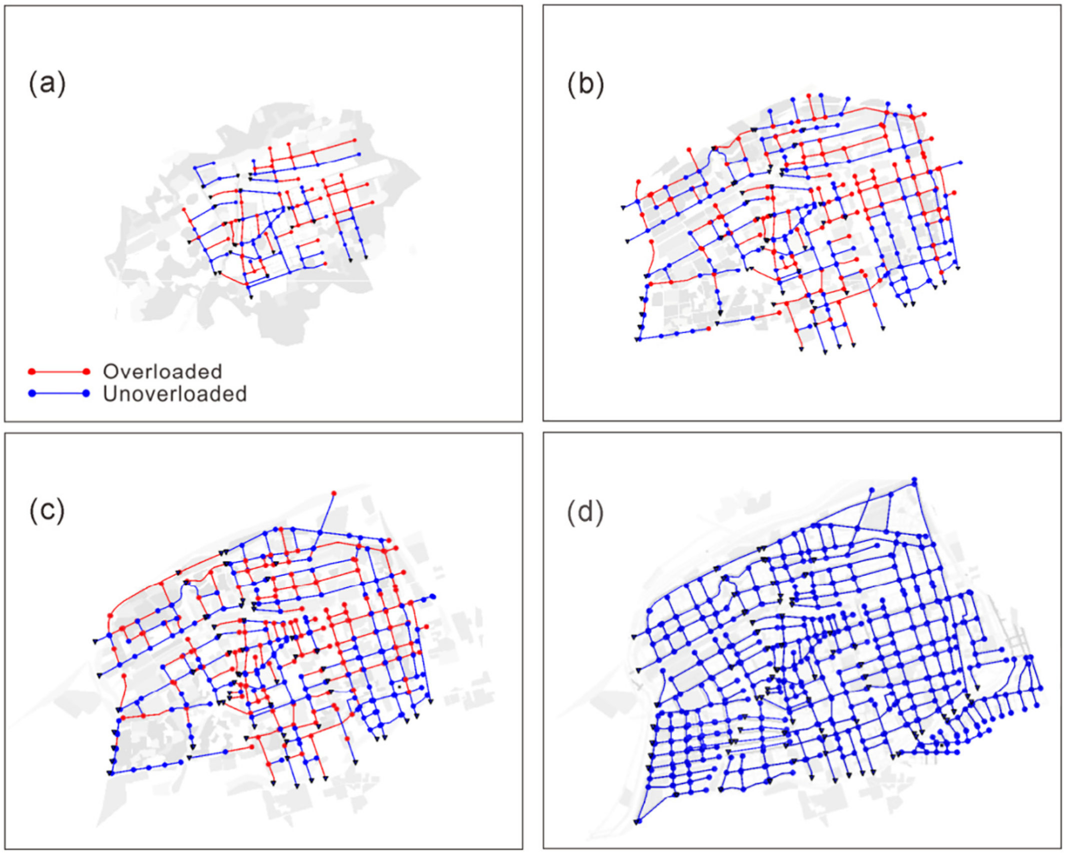

Fig. 6. Spatial distributions of overloaded manholes and pipes (highlighted in red) under the 3-year rainfall event for year (a) 1987, (b) 2002, (c) 2010, and (d) 2018.

highly insufficient drainage capacity. Much lower risks were observed for 1987 and 2018, but with different reasons. In 1987, there were limited urban areas and impervious pavements contributing to the surface runoff, and thus the resulted flood volume was rather small, despite the low level of drainage service. In contrast, in 2018 urbanization has brought a significant level of increase in total runoff, the low level of risk is attributed to the overall upgrading of the drainage system for flood control. Fig. 5b shows that there is over 940% increase in annual TFVs in 2010, despite its total runoff only accounts for 71% of that in 2018. Owing to the large-scale drainage upgrading, the expected total TFVs in 2018 is even lower than the one in 1987 by 194%. The results imply that there is a clear impact of landuse change on growing surface runoff, and more importantly, the role of drainage is essential in cities to mitigate negative flood impacts.

Spatially, there are a higher proportion of manholes and pipelines flooded in the central part of the area (Fig. 6). The edge regions are less affected as the pipelines were constructed in the later stages, and thus equipped with relatively larger conveyance capacities. Overall, the flooded locations are rather similar for historical years, as upgrades to the original drainage (in particular the central part) were inadequate over the years and the network extensions were mainly targeted to cope with the added hydrological loads in the edge areas. Results show that there are about 30 to 40% pipelines vulnerable to the 3-year rainfall before year 2018, indicating the unsatisfactory performance of the drainage system. Notably, the number of flooded manholes was reduced to zero as a result of the adaptation project, which significantly improved the drainage service level.

3.2. Impacts of future climate on flood volumes

Fig. 7 shows that although uncertainties exist arising from climate projections, negative impacts of climate change on urban flood conditions are clearly shown as the medians of TFVs are expected to increase for all return periods in comparison to the baseline year, with larger increases for heavier precipitation events. Specifically, there are relatively larger uncertainties associated with future flood volumes under the 1-, 10-, 20- and 100-year return periods. Changes in TFVs are projected to be smallest under the future 2-year return period. Similar patterns are observed in

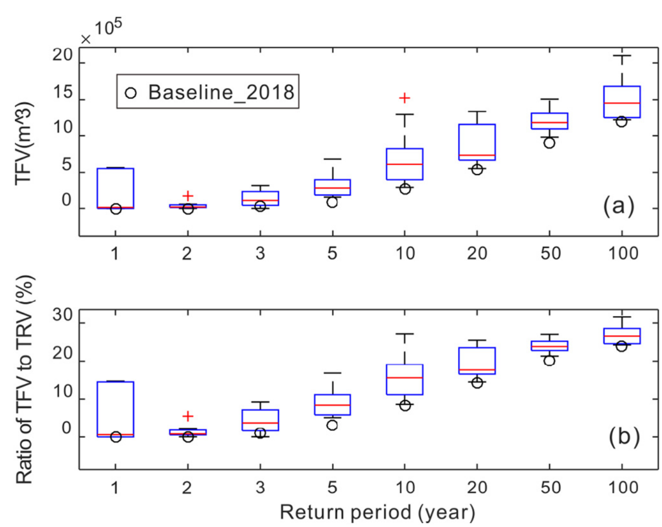

Fig. 7. Changes in (a) total flood volume (TFV) and (b) ratio of TFV to TRV in percentage at various return periods under projected climate change scenarios. The central red marks of boxplots illustrate the medians, the edges are the 25th and 75th percentiles, and the whiskers mark the 5th and 95th percentiles. The baseline values for year 2018 are illustrated by the central line of black circles.

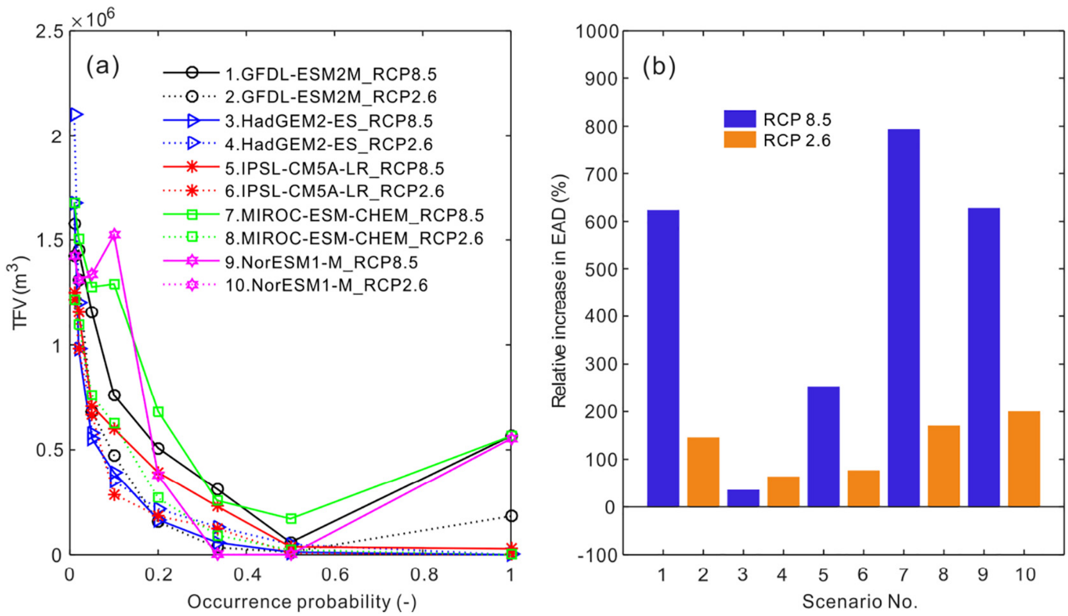

Fig. 8. Impacts of future climate on (a) TFV-probability curves and (b) relative increase in EADs (i.e., integral of TFVs) under the ten projected climate change scenarios in comparison to baseline year 2018.

the ratio of TFV to TRV under future climatic conditions in Fig. 7b. Note that despite there is a large uncertainty bound associated (0 to 15%), the median of the overloading ratio under the 1-year event is close to the baseline condition. Furthermore, the percentage of flood volume to total runoff increases with the increase of rainfall intensities. The median of the 100-year return period is up to 27%, which is 11% higher than that of the baseline condition.

It is shown in Fig. 8 that the benefits of climate change mitigation in reducing urban floods are evident as the simulated TFVs are generally larger under RCP 8.5 (i.e., a business as usual scenario, in solid lines) than the ones under the RCP 2.6 (i.e. a climate change mitigation scenario, in dotted lines). In comparison to the rest scenarios, there is a larger variability in model projections from NorESM1-M, MIROC-ESM-CHEM and GFDL-ESM2M under RCP 8.5. Overall, due to future climatic impacts, the integral of TFVs per year (Fig. 8b) is expected to increase by 299% on average based on the multi-model projections, with the largest increase (794%) in a worst-case scenario projected by MIROC-ESM-CHEM_RCP 8.5 and the smallest increase (36%) projected by the HadGEM2-ES_RCP 8.5 scenario.

When comparing the impacts of climate change on TFVs with ones from urbanization, it is found that urban development tend to induce more dramatic changes in surface runoffs and urban flood volumes in this study. More importantly, there can be significant alternations in resulted TFVs when taking into account the role of urban drainage along the development. Specifically, urbanization has led to changes in expected annual TFVs within a range of 194 to 942%, which is higher than that induced by climate change under the RCP 2.6 scenario (64 to 200%) and RCP 8.5 scenario (35 to 794%). The results have important implications for many developing regions in the world, which are still undergoing a rapid urbanization process and likely to be accompanied by large-scale landuse alternations and water infrastructure upgrading. Meanwhile, it is shown that most of the urbanization and climate change scenarios led to increase in annual surface runoff and total TFVs, which means an increasing flood risk is likely to occur even with the uncertainty. Better spatial planning and drainage design are thus addressed to gain socioeconomic and environmental benefits from improved urban flood management in coping with future local and regional changes.

Further, several limitations and uncertainties are acknowledged in this study. Even though the data on urban development and drainage system were obtained from multiple authorized sources (in particular the local water authority) to ensure a sufficient level of accuracy and reliability, the modeling of floods can still subject to uncertainties due to lack of detailed model parameters (e.g., soil conditions, surface hydrological measurements, operational conditions of pipelines), historical observations and records of flooding to validate the flood volumes. Unlike in large watersheds or river basins, where there are usually measuring stations to record annual rainfall and runoff flows, the data collection for urban drainage system is very constrained in the past years in China. Future research should pay more attention to data collection in relation to flood condition and damage (e.g., surface runoff, link discharge, manhole overloading) to improve the model quality. Nevertheless, this type of work will take time and require installation of new systems to record and monitor the process, which is beyond the scope of current study. The projections of future precipitations can also be surrounded by large uncertainties due to uncertainty associated with climate model assumptions, impact mechanism, influencing components, scenario periods, and the adoption of the change factor methodology. Despite 10 climate change scenarios were analyzed, they still represent limited ensemble of future climate impacts. Nevertheless, according to Ho et al. (2012) that the relative climate change signal simulated by GCMs is argued to be more reliable than the simulated absolute values. Our strategy is to address the uncertainty by estimating the statistics of the 10 climate scenarios to provide relatively comprehensive and detailed insights on future impacts.

Also, uncertainties are introduced due to a lack of capability of simulating the surface flood conditions (e.g., depths and locations) in our modeling approach. The impacts of urbanization and climate change are characterized by the total flood volume reflecting the flood volume from overloading manholes, which may not adequately address the actual conditions of flood damages and risks when neglecting the influences of surface topography and assets vulnerability. Two-dimensional surface inundation models (Apel et al., 2009; Leandro et al., 2009; Vojinovic and Tutulic, 2009) are applicable in future work to provide a more comprehensive and detailed assessment of flood damage and risks. Nevertheless, note that even when a 2D flood modeling approach is available, there can be higher uncertainty associated with the characterization of surface topographies and assets distributions for the historical years. In this study we investigated the relative change in annual TRV and TFV to reflect the influences on flood conditions due to urbanization and climate change.

4. Conclusions

The contribution of this study is to gain better understanding on the drivers behind increasing urban floods by comparing the impacts of urban development and climate change on hydrological runoff and flood volume in an urban context. In particular we have taken into account the essential role of urban drainage system by employing model simulations for different time periods. This has not been incorporated in previous literature and the results indeed highlight the importance of urban drainage system in coping with the changing flood risks in cities.

Detailed assessment of urban development, including changes in spatial layouts and scales, landuse types and surface imperviousness were performed in a GIS-based geo-spatial dataset and used as inputs to characterize subcatchment and drainage network for urban flood modeling. Impacts of climate change on precipitation extremes were assessed using a change factor methodology based on 10 bias-corrected scenarios projected from five GCMs under two representative concentration pathways. The 1D SWMM urban drainage model was used to simulate the hydrological runoff and total flood volume induced by various scenarios. The approach presented enables a quantitative evaluation of impacts of urbanization and climate change on urban floods and is applicable for other scales of flood assessment without methodological limitations.

It is found that due to urban development (i.e., extension of urban area and changes in landuse types), a large increase (208 to 413%) in surface runoff can be induced typically under accelerated urbanization stages. Increases in impervious covers can lead to direct impacts on surface flows and overburden of drainage system. When taking into account the development of drainage system, the urbanization impacts can be more complicated and less predictable. In our case, year 2010 was witnessed with the greatest flood risks due to a large extension of urban areas, alternations in landuse types, and lagged upgrades in drainage capacity in the period. Despite there is increasing surface runoff as a result of urbanization in the area, a noticeable reduction in annual TFVs is shown in 2018 thanks to the city-scale upgrading of the drainage system. This indicates that assessment of landuse changes alone cannot fully account for hydrological and hydraulic alternations in the urban context and it is important to consider current and further development of drainage system in formulating adaptation and mitigation strategies. Specifically, urbanization has led to changes in annual flood risks (i.e., annual integral of TFVs) within a range of 194 to 942% (with a mean value of 471%), which is much higher than that induced by climate change (36 to 794%, with a mean value of 299%), in particular under RCP 2.6 scenario (64 to 200%).

As discussed previously we acknowledge that the modeling results still come with large uncertainties due to e.g., adopted performance indicator, modeling approach, methodology assumptions and simplifications, and data limitation in this study. The methodology applied and the conclusions obtained could be extended, with necessary precautions. Nevertheless, this work provides a unique investigation on urbanization and climate change impacts on urban floods through integration of tools on detailed GIS mapping and evaluation, hydrodynamic modeling and risk-based flood assessment. Our results show the need and importance of assessing current and future urban drainage system in coping with the changing urban floods induced by local and regional changes. Climate change may have long-term, but more stable impacts on urban floods, while urbanization (in particular with introduction of new infrastructures, adaptation plans, and zoning and/or development policies) can have more direct and significant influences on flood conditions in an urban scale. This has important implications for many developing cities which are still accompanied by rapid urban development and infrastructure upgrades. To make sound decisions, policy makers need better understanding of role of climate change and urbanization in their specific cases to prioritize relevant mitigation and adaptation measures.

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References

Aich, V., Liersch, S., Vetter, T., Andersson, J., Müller, E., Hattermann, F., 2015. Climate or land use?—attribution of changes in river flooding in the Sahel zone. Water 7, 2796.

Aich, V., Liersch, S., Vetter, T., Fournet, S., Andersson, J.C.M., Calmanti, S., et al., 2016. Flood projections within the Niger River Basin under future land use and climate change. Sci. Total Environ. 562, 666–677.

Apel, H., Aronica, G.T., Kreibich, H., Thieken, A.H., 2009. Flood risk analyses-how detailed do we need to be? Nat. Hazards 49, 79–98.

Arnbjerg-Nielsen, K., 2012. Quantification of climate change effects on extreme precipitation used for high resolution hydrologic design. Urban Water J. 9, 57–65.

Arnone, E., Pumo, D., Francipane, A., La Loggia, G., Noto, L.V., 2018. The role of urban growth, climate change, and their interplay in altering runoff extremes. Hydrol. Process. 32, 1755–1770.

Berggren, K., Packman, J., Ashley, R., Viklander, M., 2014. Climate changed rainfalls for urban drainage capacity assessment. Urban Water J. 11, 543–556.

Butler, D., Davies, J., 2010. Urban Drainage. Third Ed. CRC Press, London 0415455251.

Cheng, L.Y., AghaKouchak, A., 2014. Nonstationary precipitation intensity- duration- frequency curves for infrastructure design in a changing climate. Sci. Rep. 4.

Coles, S., 2001. An introduction to statistical modeling of extreme values. Springer Series in Statistics. Springer, London.

Dawson, R.J., Dickson, M.E., Nicholls, R.J., Hall, J.W., Walkden, M.J.A., Stansby, P.K., et al., 2009. Integrated analysis of risks of coastal flooding and cliff erosion under scenarios of long term change. Clim. Chang. 95, 249–288.

Ding, T., Zhang, W., 2012. Analysis of urbanization process in Hohhot China. Economist 12, 203–207.

DSAAH, 2018. Drainage Service Administrative Authority of Hohhot. Accesed in October 2018 from. http://www.hspsglj.com/ws.

Egger, C., Maurer, M., 2015. Importance of anthropogenic climate impact, sampling error and urban development in sewer system design. Water Res. 73, 78–97.

El-Jabi, N., Caissie, D., Turkkan, N., 2016. Flood analysis and flood projections under climate change in New Brunswick. Can. Water Resour. J. 41, 319–330.

Erdeniqiqige, Alatengtuya, Wudun, 2012. Evolvement characteristics of urban form of hohhot in nearly hundred years: a GIS study. J. Inn. Mong. Norm. Univ. (Nat. Sci. Ed.) 41 (6), 675–680.

Grum, M., Jorgensen, A.T., Johansen, R.M., Linde, J.J., 2006. The effect of climate change on urban drainage: an evaluation based on regional climates model simulations. Water Sci. Technol. 54, 9–15.

Guoqing, P., Wu, C., Junqi, L., Haiyan, L., 2008. Urban runoff pollution control quantity and its design rainfall in China. China Water Wastewater 24, 25–29.

Hlodversdottir, A.O., Bjornsson, B., Andradottir, H.O., Eliasson, J., Crochet, P., 2015. Assessment of flood hazard in a combined sewer system in Reykjavik city centre. Water Sci. Technol. 71, 1471–1477.

Ho, C.K., Stephenson, D.B., Collins, M., Ferro, C.A.T., Brown, S.J., 2012. Calibration strategies a source of additional uncertainty in climate change projections. Bull. Am. Meteorol. Soc. 93, 21–26.

Huong, H.T.L., Pathirana, A., 2013. Urbanization and climate change impacts on future urban flooding in Can Tho city, Vietnam. Hydrol. Earth Syst. Sci. 17, 379–394.

IPCC, 2014. Impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge http://www.ipcc.ch/report/ar5/wg2/.

Jiang, Y., Zevenbergen, C., Ma, Y.C., 2018. Urban pluvial flooding and stormwater management: a contemporary review of China's challenges and "sponge cities" strategy. Environ. Sci. Pol. 80, 132–143.

Jung, M., Kim, H., Mallari, K.J.B., Pak, G., Yoon, J., 2015. Analysis of effects of climate change on runoff in an urban drainage system: a case study from Seoul, Korea. Water Sci. Technol. 71, 653–660.

Karamouz, M., Hosseinpour, A., Nazif, S., 2011. Improvement of urban drainage system performance under climate change impact: case study. J. Hydrol. Eng. 16, 395–412.

Kaspersen, P.S., Ravn, N.H., Arnbjerg-Nielsen, K., Madsen, H., Drews, M., 2017. Comparison of the impacts of urban development and climate change on exposing European cities to pluvial flooding. Hydrol. Earth Syst. Sci. 21, 4131–4147.

Katz, R.W., Parlange, M.B., Naveau, P., 2002. Statistics of extremes in hydrology. Adv. Water Resour. 25, 1287–1304.

Kleidorfer, M., Mikovits, C., Jasper-Tonnies, A., Huttenlau, M., Einfalt, T., Rauch, W., 2014. Impact of a changing environment on drainage system performance. In: Brunone, B., Giustolisi, O., Ferrante, M., Laucelli, D., Meniconi, S., Berardi, L., et al. (Eds.), 12th International Conference on Computing and Control for the Water Industry. Elsevier Science Bv, Amsterdam, pp. 943–950 Ccwi2013. 70.

Kong, F., Ban, Y., Yin, H., James, P., Dronova, I., 2017. Modeling stormwater management at the city district level in response to changes in land use and low impact development. Environ. Model. Softw. 95, 132–142.
Larsen, A.N., Gregersen, I.B., Christensen, O.B., Linde, J.J., Mikkelsen, P.S., 2009. Potential future increase in extreme one-hour precipitation events over Europe due to climate change. Water Sci. Technol. 60, 2205–2216.
Leandro, J., Chen, A.S., Djordjevic, S., Savic, D.A., 2009. Comparison of 1D/1D and 1D/2D coupled (sewer/surface) hydraulic models for urban flood simulation. J. Hydraul. Eng. ASCE 135, 495–504.
Li, G.F., Xiang, X.Y., Tong, Y.Y., Wang, H.M., 2013. Impact assessment of urbanization on flood risk in the Yangtze River Delta. Stoch. Env. Res. Risk A. 27, 1683–1693.
Lv, Z., Zhao, P., 2013. First report about urban flood in China: 170 cities unprotected and 340 cities down-to-standard. Zhongzhou Constr. 15, 56–57.
Mahmood, M.I., Elagib, N.A., Horn, F., Saad, S.A.G., 2017. Lessons learned from Khartoum flash flood impacts: an integrated assessment. Sci. Total Environ. 601-602, 1031–1045.
Mahmoud, S.H., Gan, T.Y., 2018. Urbanization and climate change implications in flood risk management: developing an efficient decision support system for flood susceptibility mapping. Sci. Total Environ. 636, 152–167.
Mallakpour, I., Villarini, G., 2016. Analysis of changes in the magnitude, frequency, and seasonality of heavy precipitation over the contiguous USA. Theor. Appl. Climatol. 1–19.
Miller, J.D., Kim, H., Kjeldsen, T.R., Packman, J., Grebby, S., Dearden, R., 2014. Assessing the impact of urbanization on storm runoff in a pen-urban catchment using historical change in impervious cover. J. Hydrol. 515, 59–70.
Moghadas, S., Leonhardt, G., Marsalek, J., Viklander, M., 2018. Modeling urban runoff from rain-on-snow events with the US EPA SWMM model for current and future climate scenarios. J. Cold Reg. Eng. 32, 14.
MOHURD, 2014. Technical Guidelines for Establishment of Intensity-Duration-Frequency Curve and Design Rainstorm Profile (In Chinese). Ministry of Housing and Urban-Rural Development of the People's Republic of China and China Meteorological Administration Accessed on October 2018 from. http://www.mohurd.gov.cn/wjfb/201405/W020140519104225.pdf.
MOHURD, 2016. Code for Design of Outdoor Wastewater Engineering (GB 50014—2006) (2016 Revised Version) (in Chinese). Ministry Of Housing And Urban-Rural Development and Ministry Of National Quality Standard Monitoring Bureau, Beijing, China.
Olsen, A., Zhou, Q., Linde, J., Arnbjerg-Nielsen, K., 2015. Comparing methods of calculating expected annual damage in urban pluvial flood risk assessments. Water 7, 255–270.
Panthou, G., Vischel, T., Lebel, T., Quantin, G., Molinie, G., 2014. Characterising the space-time structure of rainfall in the Sahel with a view to estimating IDAF curves. Hydrol. Earth Syst. Sci. 18, 5093–5107.
Pazwash, H., 2011. Urban Storm Water Management. CRC Press, Taylor and Francis, Boca Raton, FL.
PRPSDC. China Water Resources Pearl River Planning Surveying & Designing Co., LTD. Accessed in October 2018 from http://www.prpsdc.com/zszj/newweb/index.asp 2018.
Prudhomme, C., Wilby, R.L., Crooks, S., Kay, A.L., Reynard, N.S., 2010. Scenario-neutral approach to climate change impact studies: application to flood risk. J. Hydrol. 390, 198–209.
Pumo, D., Arnone, E., Francipane, A., Caracciolo, D., Noto, L.V., 2017. Potential implications of climate change and urbanization on watershed hydrology. J. Hydrol. 554, 80–99.
Qin, H.-P., Li, Z.-x., Fu, G., 2013. The effects of low impact development on urban flooding under different rainfall characteristics. J. Environ. Manag. 129, 577–585.
Rosbjerg, D., 2017. Optimal adaptation to extreme rainfalls in current and future climate. Water Resour. Res. 53, 535–543.
Rossman, L., Huber, W., 2016. Storm Water Management Model Reference Manual US EPA Office of Research and Development, Washington DC, EPA/600/R-15/162A.
Semadeni-Davies, A., Hernebring, C., Svensson, G., Gustafsson, L.G., 2008. The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: suburban stormwater. J. Hydrol. 350, 114–125.
Shi, J., Liu, K., He, W., Yan, C., 2007. Analysis on the characteristics of climate change in Hohhot, inner Mongolia in recent 40 years. J. Inn. Mong. Agric. Univ. 28, 39–43.
Teutschbein, C., Seibert, J., 2012. Bias correction of regional climate model simulations for hydrological climate-change impact studies: review and evaluation of different methods. J. Hydrol. 456–457, 12–29.
Thanvisitthpon, N., Shrestha, S., Pal, I., 2018. Urban flooding and climate change: a case study of Bangkok, Thailand. Environ. Urban. ASIA 9, 86–100.
Todd, C.E.D., Goss, A.M., Tripathy, D., Harbor, J.M., 2007. The effects of landscape transformation in a changing climate on local water resources. Phys. Geogr. 28, 21–36.
van Roosmalen, L., Christensen, J.H., Butts, M.B., Jensen, K.H., Refsgaard, J.C., 2010. An intercomparison of regional climate model data for hydrological impact studies in Denmark. J. Hydrol. 380, 406–419.
Vojinovic, Z., Tutulic, D., 2009. On the use of 1D and coupled 1D-2D modelling approaches for assessment of flood damage in urban areas. Urban Water J. 6, 183–199.
Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., Schewe, J., 2014. The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP): project framework. Proc. Natl. Acad. Sci. U. S. A. 111, 3228–3232.
Weng, Q.H., 2001. Modeling urban growth effects on surface runoff with the integration of remote sensing and GIS. Environ. Manag. 28, 737–748.
Whitehead, P.G., Jin, L., Macadam, I., Janes, T., Sarkar, S., Rodda, H.J.E., et al., 2018. Modelling impacts of climate change and socio-economic change on the Ganga, Brahmaputra, Meghna, Hooghly and Mahanadi river systems in India and Bangladesh. Sci. Total Environ. 636, 1362–1372.
Willems, P., 2000. Compound intensity/duration/frequency-relationships of extreme precipitation for two seasons and two storm types. J. Hydrol. 233, 189–205.
Willems, P., 2013. Revision of urban drainage design rules after assessment of climate change impacts on precipitation extremes at Uccle, Belgium. J. Hydrol. 496, 166–177.
Willems, P., Arnbjerg-Nielsen, K., Olsson, J., Nguyen, V.T.V., 2012. Climate change impact assessment on urban rainfall extremes and urban drainage: methods and shortcomings. Atmos. Res. 103, 106–118.
Wu, H.C., Huang, G.R., Meng, Q.Q., Zhang, M.Z., Li, L.C., 2016. Deep tunnel for regulating combined sewer overflow pollution and flood disaster: a case study in Guangzhou City, China. Water 8, 14.
Wu, X.S., Wang, Z.L., Guo, S.L., Liao, W.L., Zeng, Z.Y., Chen, X.H., 2017. Scenario-based projections of future urban inundation within a coupled hydrodynamic model framework: a case study in Dongguan City, China. J. Hydrol. 547, 428–442.
Xie, J.Q., Chen, H., Liao, Z.L., Gu, X.Y., Zhu, D.J., Zhang, J., 2017. An integrated assessment of urban flooding mitigation strategies for robust decision making. Environ. Model. Softw. 95, 143–155.
Yao, L., Wei, W., Chen, L.D., 2016. How does imperviousness impact the urban rainfall-runoff process under various storm cases? Ecol. Indic. 60, 893–905.
Yazdanfar, Z., Sharma, A., 2015. Urban drainage system planning and design-challenges with climate change and urbanization: a review. Water Sci. Technol. 72, 165–179.
Yin, J., Yu, D.P., Yin, Z., Liu, M., He, Q., 2016. Evaluating the impact and risk of pluvial flash flood on intra-urban road network: a case study in the city center of Shanghai, China. J. Hydrol. 537, 138–145.
Zahmatkesh, Z., Karamouz, M., Goharian, E., Burian, S.J., 2015. Analysis of the effects of climate change on urban storm water runoff using statistically downscaled precipitation data and a change factor approach. J. Hydrol. Eng. 20, 11.
Zare, S.O., Saghafian, B., Shamsai, A., 2012. Multi-objective optimization for combined quality-quantity urban runoff control. Hydrol. Earth Syst. Sci. 16, 4531–4542.
Zhang, D., Zhao, Dq, Chen, Jn, Wang, Hz, 2008. Application of Chicago approach in urban drainage network modeling. Water & Wastewater Eng. 34, 354–357.
Zhou, Q., Halsnæs, K., Arnbjerg-Nielsen, K., 2012a. Economic assessment of climate adaptation options for urban drainage design in Odense, Denmark. Water Sci. Technol. 66, 1812–1820.
Zhou, Q., Mikkelsen, P.S., Halsnaes, K., Arnbjerg-Nielsen, K., 2012b. Framework for economic pluvial flood risk assessment considering climate change effects and adaptation benefits. J. Hydrol. 414, 539–549.
Zhou, F., Xu, Y., Chen, Y., Xu, C.Y., Gao, Y., Du, J., 2013. Hydrological response to urbanization at different spatio-temporal scales simulated by coupling of CLUE-S and the SWAT model in the Yangtze River Delta region. J. Hydrol. 485, 113–125.
Zhou, Q., Ren, Y., Xu, M., Han, N., Wang, H., 2016. Adaptation to urbanization impacts on drainage in the city of Hohhot, China. Water Sci. Technol. 73, 167–175.
Zhou, Q.Q., Leng, G.Y., Huang, M.Y., 2018. Impacts of future climate change on urban flood volumes in Hohhot in northern China: benefits of climate change mitigation and adaptations. Hydrol. Earth Syst. Sci. 22, 305–316.