Impacts of future climate change on urban flood risks: benefits of climate mitigation and adaptations [MS No.: hess-2016-369]

Responses to reviewer comments

REFEREE REPORT(S):

Anonymous Referee #1:

The article by Zhou at al tackles a very topical issue in the field of flood risk assessment, which deals with climate change, mitigation and adaptation measures. The research questions that the authors investigate is sound and meaningful, and it is particularly interesting as the benefits of adaptation and mitigation measures are evaluated numerically through a modelling framework (though their associate cost is not assessed). Now the bad news: the structure of the article is sometimes not so clear, due to missing links, lack of details in the methods, questionable assumptions and unclear interpretation of results. Also, the use of English, although sufficient, is sometimes sub-optimal, and could do with a revision by a native speaker. Please pay careful attention to the use of prepositions and of the "s" for plurals. I found a number of mistakes and inappropriate use. Nonetheless, I think that the article had good potential for being published, provided that the following comments are adequately addressed. Please pay special attention to the general comments, where substantial work is needed to improve parts of the description of methods, assumptions and evaluation of results.

Response: *We greatly appreciate the reviewer for the constructive comments and suggestions to improve our manuscript. In the revision, we have 1) added more details on the datasets and methods, 2) added more discussions on the assumptions and limitations, 3) modified the relevant statements and figures which are unclear or inaccurate, 4) invited a native speaker to proof-read the paper. More details of our responses to each comment are provided as follows.*

Note: the line numbers as mentioned in the response below refer to those in the cleaned version of manuscript.

General comments

L 131-146: I would like to see some comments by the authors on the suitability of CMIP5 data for studies on urban flooding. Given the coarse resolution of CMIP5 (as they are global models), I'm sure that the entire study region is considerably smaller than 1 model grid cell. This poses some questions on how well extreme precipitation for modeling urban flooding is adequately represented by such datasets, given that such models are not able to represent local and short-lived storms commonly inducing flooding in small catchments. Intuitively one would say that downscaled projections with high resolution would be more suitable for this work, though that clearly depends on the data availability. Perhaps the authors can comment on that.

<u>Response</u>: *Thanks for the comments. As pointed out by the reviewer, bias would exist in global climate model (GCM) simulations especially at the local and regional scales. An alternative approach is to simulate the future climate using regional climate model (RCM) nested within a GCM. Such climate projections by RCM have added value in terms of higher spatial resolution which can provide more detailed regional information. However, various level of bias would still remain in RCM simulations (Teutschbein and Seibert 2012) and bias correction of RCM projections are required, e.g. the European project ENSEMBLES (Hewitt and Griggs 2004; Christensen et al. 2008). To run regional climate model is not within the scope of this study. Instead, we tend to use publicly available climate projection dataset. Here, we obtain climate projections from the ISI-MIP (Warszawski et al. 2014), which provides spatially-downscaled climate data for impact models. The climate projections were also bias-corrected against observations (Hempel et al. 2013) and have been widely used in climate change impact studies on hydrological extremes such as floods and droughts (e.g. Dankers et al. 2014; Prudhomme et al. 2014; Giuntoli et al. 2015; Leng et al. 2015).*

It should be noted that we used the delta change factor to derive the climate scenarios as inputs into our flood drainage model instead of using the climate projections directly. Specifically, we calculate the change factor between current and future climate projection simulated by GCMs and multiply them to observed time series to derive future climate scenario into our flood drainage model. This is because the relative climate change signal simulated by GCMs are argued to be more reliable than the simulated absolute values (Ho et al. 2012). What's more, we use an ensemble of GCM simulations rather than one single climate model in order to characterize the uncertainty range arising from climate projections.

In the revision, we have added more discussions on this (Lines 388-420).

Reference

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., & Schewe, J. (2014). The inter-sectoral impact model intercomparison project (ISI–MIP): project framework. Proceedings of the National Academy of Sciences, 111(9), 3228-3232.

Dankers, R., Arnell, N. W., Clark, D. B., Falloon, P. D., Fekete, B. M., Gosling, S. N., ... & Stacke, T. (2014). First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble. Proceedings of the National Academy of Sciences, 111(9), 3257-3261.

Prudhomme, C., Giuntoli, I., Robinson, E. L., Clark, D. B., Arnell, N. W., Dankers, R., ... & Hagemann, S. (2014). Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment. Proceedings of the National Academy of Sciences, 111(9), 3262-3267.

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Hempel, S., Frieler, K., Warszawski, L., Schewe, J., & Piontek, F. (2013). A trend-preserving bias correction–the ISI-MIP approach. Earth System Dynamics, 4(2), 219-236.

Christensen, J. H., Boberg, F., Christensen, O. B., & Lucas-Picher, P. (2008). On the need for bias correction of regional climate change projections of temperature and precipitation. Geophysical Research Letters, 35(20).

Hewitt, C. D., and D. J. Griggs (2004), Ensembles-based predictions of climate changes and their impacts, Eos Trans. AGU, 85, 566.

Ho, C. K., Stephenson, D. B., Collins, M., Ferro, C. A., & Brown, S. J. (2012). Calibration strategies: a source of additional uncertainty in climate change projections. Bulletin of the American Meteorological Society, 93(1), 21.

L 169-182: I suggest expanding this section as I think there are some unclear points which prevents the reader from understanding some modeling steps, underlying assumptions, as well as from making the approach reproducible. For example, is q in eq. 1 the peak intensity? Which is the temporal resolution considered? Most climate datasets have 1 day as highest temporal resolution, but that would probably be rather coarse for urban flooding applications. How are then the hyetographs calculated from the q? Is it a simple rescaling based on their peak, keeping the same shape? Also, I see a lack of information on how climatic data is handled statistically to estimate storms/volumes with selected return period between 1 and 1000 years. For example, I see that the considered period for assessing future scenarios is 2020-2040, hence 21 years of data. Does it mean that return periods in the order of 1000 years are estimated from 21 years of data? Could the authors clarify on this? Can they provide ranges of uncertainty due to the undersampling of the climate variability in such long periods? Also, this should be mentioned in Sect. 4 as a further uncertainty source. Final comment is about eq. 1: could you briefly comment on how the parameters A, b, c, D are valid under a non-stationary climate? 4 parameters and just 2 variables sounds a lot for an empirical formula.

Response: *Thanks for the comments. In this study, we adopt the storm intensity formula (SIF) to derive the precipitation input into our drainage model. Application of the SIF is a standard practice for determining design rainfalls in urban drainage modelling in China, and is well documented in the National Guidance for Design of Outdoor Wastewater Engineering (MOHURD, 2011). Specifically, the SIF represents an Intensity-Duration-Frequency (IDF) relationship, which is a common approach in literature for estimating design rainfall hydrographs using the Chicago Design Storms (CDS) approach (Berggren et al., 2014; Cheng and AghaKouchak, 2014; Panthou et al., 2014; Willems, 2000; Zhou et al., 2012). More details can refer to Smith (2004) for the derivation of CDS from an IDF relationship. 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) and have been well adopted for Chinese urban drainage designs (Wu et al., 2016; Yin et al., 2016; Zhang et al., 2008; Zhang et al., 2015). Therefore, the method for using the SIF to generate CDS design storms for our SWMM modelling study is reproducible and valid for drainage modelling.*

The technical details of SIF and derivation of CDS rainfall are given as follows. As shown in the Equation 1, the q is the average rainfall intensity, t is the storm duration and P is the design return period. The typical temporal resolution in SIF is minutes for urban drainage modelling. A, b, c and D are the regional parameters governing the IDF relations among rainfall intensity, return period and storm duration. For a given return period, the SIF can be fitted into the Horner's equation (2004) as shown in Equation 2:

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

$$i = \frac{a}{(t + b)^c} \qquad \textit{Eq. (2)}$$

The synthetic hyetograph based on the Chicago method is computed using Equation 2 and an additional parameter r (where 0< r <1) which determines the relative time step of the peak intensity, $t_p=r*t$*. The time distribution of rainfall intensity is described after the peak* $t_a = (1-r)*t$ *and before the peak* $t_b=r*t$ *by Equation (3) and (4), respectively. Specially,* i_b *is the instantaneous rainfall intensity before the peak, and* i_a *is the instantaneous rainfall intensity after the peak.*

$$i_a = \frac{a[\frac{(1-c)t_a}{(1-r)} + b]}{(\frac{t_a}{(1-r)} + b)^{1+c}} \qquad \text{Eq. (3)}$$

$$i_b = \frac{a[\frac{(1-c)t_b}{r} + b]}{(\frac{t_b}{r} + b)^{1+c}} \qquad \text{Eq. (4)}$$

In this study, we considered 10 return periods, i.e., the 1-, 2-, 3-, 10-, 20-, 50-, 100-, 200-, 500-, and 1000-year events. A 4-hour rainfall time series was generated for each return period at 10-minute intervals based on Equations 1−4. The A, b, c and D parameters governing the SIF shape were obtained from the local weather bureau, which fits the historical precipitation distribution for the study region. In the revision, we have added more details about the methods (Lines 189-220).

As for the generation of future climate scenarios, we first calculate the change factor for each return period. Specifically, for each year, the annual maximum daily precipitation was determined for both historical and future periods. Then, the generalized extreme value (GEV) distribution is 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. The value corresponding to each return period is derived based on the GEV distribution and the changes between future and historical periods are calculated as the change factors (as shown in Table 2 in the text). The change factor for each return period is then multiplied to the historical design CDS rainfall time series to derive future climate scenarios for the model. We acknowledge that to estimate the changes in extreme precipitation events involves inevitable uncertainties especially for return periods beyond the length of the data, e.g. 1000yrs as pointed by the reviewer. Hence, caution should be exercised when interpreting the results for return levels beyond the data length. However, we'd like to mention that "return period" is intrinsically a statistical measurement derived based on probability density function (PDF) of historical data in extended period. That is, it represents a recurrence interval which is an estimate of the likelihood of an event (in our case, a flood) indicated by the PDF. Depending on the historical period used, the return period could vary if the time series is not stationary. Nevertheless, a 1000-year return period can be derived from 21-year time series based on its definition by using a PDF. We have added discussions on *this in the revision. We agree that climate variability range would be under-sampled, although five climate models are used to show the possible ranges. In the revision, we have added discussions on this in the revision (Lines 222-233; 416-420).*

The parameters A, b, c, D are derived from sub-hourly rainfall data and provided by local weather bureau. The four parameters which describe the Intensity-Duration-Frequency (IDF) relationship in the study region are assumed to be constant without considering its non-stationary features in a changing climate. To derive the parameter in the future period requires hourly precipitation data, which are not readily available. Hence, the IDF relationship is assumed to remain stable in the future and only changes in the daily mean intensity are considered. Given the above limitations, we acknowledge that our modeling results mainly represent the first-order potential climate change impacts on urban floods. Future efforts should be devoted to the representation of dynamic rainfall changes at hourly time step taking into account of non-stationary climate change. We have added more discussions on this in the revised manuscript (Lines 414-420).

Reference:

Berggren, K., Packman, J., Ashley, R., and Viklander, M.: Climate changed rainfalls for urban drainage capacity assessment, Urban Water Journal, 11, 543-556, 10.1080/1573062X.2013.851709, 2014.

Cheng, L. Y., and AghaKouchak, A.: Nonstationary Precipitation Intensity-Duration-Frequency Curves for Infrastructure Design in a Changing Climate, Scientic Report, 4, 10.1038/srep07093, 2014.

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Katz RW, Parlange MB, Naveau P (2002) Statistics of extremes in hydrology. Adv Water Resour 25(8-12):1287–1304

MOHURD: AQSIQ. Code for Design of Outdoor Wastewater Engineering (GB 50014-2006), Ministry of Housing and Urban-Rural Development, General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China: Beijing, China (In Chinese), 2011.

MOHURD: 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 November 2016 from http://www.mohurd.gov.cn/wjfb/201405/W020140519104225.pdf, 2014.

Panthou, G., Vischel, T., Lebel, T., Quantin, G., and Molinie, G.: Characterising the space-time structure of rainfall in the Sahel with a view to estimating IDAF curves, Hydrology and Earth System Sciences, 18, 5093-5107, 10.5194/hess-18-5093-2014, 2014.

Smith, A. A.: MIDUSS Version 2, Reference Manual, Version 2.00 Rev2.00., Alan A. Smith Inc., Dundas, Ontario, Canada, 2004.

Willems, P.: Compound intensity/duration/frequency-relationships of extreme precipitation for two seasons and two storm types, Journal of Hydrology, 233, 189-205, http://dx.doi.org/10.1016/S0022-1694(00)00233-X, 2000.

Wu, H., Huang, G., Meng, Q., Zhang, M., and Li, L.: Deep Tunnel for Regulating Combined Sewer Overflow Pollution and Flood Disaster: A Case Study in Guangzhou City, China, Water, 8, 329, 2016.

Yin, J., Yu, D. P., Yin, Z., Liu, M., and He, Q.: Evaluating the impact and risk of pluvial flash flood on intra-urban road network: A case study in the city center of Shanghai, China, Journal of Hydrology, 537, 138-145, 10.1016/j.jhydrol.2016.03.037, 2016.

Zhang, Y.-q., Lv, M., and Wang, Q.-g.: Formula method design of drainage pipe network and analysis of model simulation, Water Resour. Power, 33, 105-107, 2015.

Zhang, D., Zhao, D. q., Chen, J. n., and Wang, H. z.: Application of Chicago approach in urban drainage network modeling, Water & Wastewater Engineering, 34, 354-357, 2008.

Zhou, Q., Mikkelsen, P. S., Halsnaes, K., and Arnbjerg-Nielsen, K.: Framework for economic pluvial flood risk assessment considering climate change effects and adaptation benefits, Journal of Hydrology, 414, 539-549, 10.1016/j.jhydrol.2011.11.031, 2012.

L235-250: Despite the authors' efforts to link the flood volume with flood risk and damage, I find inappropriate to call results in Figure 4 as "risk" and "damage". There is clearly a missing step in linking flood volume with some socio-economic indicator on the impact of floods. This also results in a biased evaluation of what is called "flood risk", which suggests in Figure 4 that the largest contribution is given by floods with 1-2 year return period. In reality, it may well be that a single 100-year flood induces a damage which is larger than 100 1-year floods. For this reason, I do not agree with the statement in lines 239-242. The authors should definitely clarify this part and spend some words on what are the consequences of their assumptions, if that is retained at all. In addition, the authors should clarify the relations between Fig 4a and 4b. I have the feeling that values in 4b are simply obtained by dividing numbers in 4a by their theoretical expected annual frequency indicated below each column. This would be incorrect as in this way you would be double counting all probabilities smaller than each considered class. You should instead apply the formula for piece-wise integral of flood damage versus the expected frequency of each class, hence considering the width of each bar (e.g., for the second column is 1/2-1/3, for the third one is 1/3 -1/10 and so forth).

Response: *Thanks for the comments. We agree with the reviewer that results in Figure 4 refer to the flood volume rather than "damage" or "risk" due to the missing linkage to the socio-economic conditions. We also agree that a single 100-year flood event could have larger impacts than 100 1-year floods. In the revision, we have deleted the word "damage" or "risk" throughout the manuscript and revised the statements and other relevant statements accordingly. The original Figure 2 which is used to illustrate the conceptual flood risks has also been revised.*

Following the suggestion by the reviewer, we have revised the Figure 4b to show the piece-wise integral of flood volume corresponding to each frequency class (e.g. the width of first class is 1/1-1/2 and so forth).

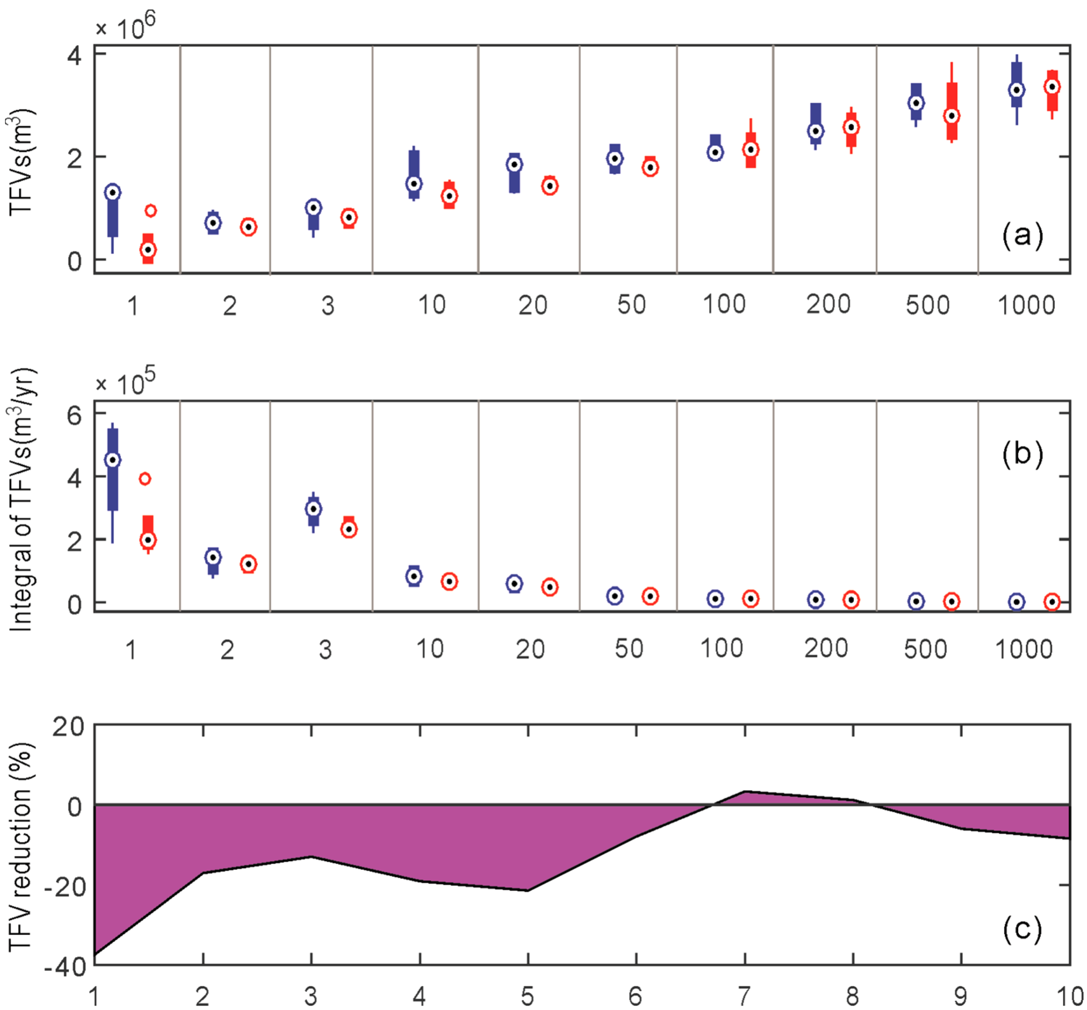

Figure 4 *Comparison of (a) flood volume, (b) total TFVs (i.e., the piece-wise integral of flood volume versus the expected frequency with changes in precipitation intensity of various return periods under RCP8.5 (blue) and RCP2.6 (red). (c) is for the reduced TFVs in percentage (i.e., benefits of climate mitigation) in RCP2.6 relative to RCP8.5 at various return periods.*

L 265-286: I find this part rather difficult to understand and suggest the authors to clarify some points and describe more thoroughly Figure 6 and its usefulness. First, the way changes (CTFV) are defined is not intuitive, as it is now defined as a multiplicative factor. Changes should be *CTFV=(TFVc-TFVnc)/ TFVnc*. Also, why the current system is less sensitive to climate change than the adapted system (l 268-269)? I'm a bit puzzled by seeing that small changes in the 10-year precipitation intensity lead up to a 7-fold increase in TFV under the case of adaptation. Does it mean 7 times worse conditions or simply that the adapted system can hold more water, also because the catchment area is larger? Then I get confused on the definition of TFV: is it the total volume or simply the excess volume after filling completely the pipes system? I thought it's the second option, but now I'm confused. Please clarify in sect. 2c. In both cases it's difficult to assess how worse the conditions (i.e., the damage) would be under larger TFV in the adapted system, though I think a graph with such information is currently missing and could be added. Finally, please avoid 4 decimals in numbers at lines 270-271; 2 decimal digits are surely enough.

<u>Response</u>: *Thanks for the comments. We are sorry for the confusion. The TFV is defined as the total volume flooded from manholes without taking into account the outlet discharges, i.e., excess water from manholes after completely filling the pipe system. As pointed out by the reviewer, the current drainage system is less sensitive to climate change. This is because the capacity of current drainage system is small, i.e. the excess water after filling completely the pipe system (i.e., TFVnc) is large. Given extreme rainfall events, the current system would be flooded completely, thus exhibiting less sensitivity to larger extreme rainfall events in the future. Therefore, the magnitude of changes in excess flood volume is smaller in the current system than the adapted system due to its large value of denominator in the calculation of CTFV (CTFV=(TFVc-TFVnc)/TFVnc).*

In order to better clarify this point, we have provided a table below summarizing the flood volumes of current and adapted drainage systems, with and without climate change. It is evident that for the present time, the flood volume of the adapted systems are much smaller than that in the current system due to capacity upgrades in the adapted systems to hold more water. For example, when experiencing a 10-year extreme rainfall event, the urban flood volumes for the present period (i.e., TFVnc) are 1041,230, 274,650 and 180,610 m3 in the current and two adapted systems(highlighted in blue), respectively, while in the future period, the magnitude of flood volume (i.e., TFVc, highlighted in yellow) is relatively similar among the three drainage systems. Therefore, future CTFVs relative to the historical period are much larger in the adapted systems than in the current system. Mathematically, the low sensitivity of the current drainage system to changes in extreme rainfall intensity could be attributed to the large value of the denominator in the calculation of CTFV.

In the revision (Lines 175-177, 326-357), we have 1) clarified the definition of TFV; 2) re-defined $CTFV=(TFV_c-TFV_{nc})/TFV_{nc}$ *following the suggestion, and updated Figure 6 accordingly (see Figure 6 below); 3) added more discussions on projected changes on TFV; 4) used 2 decimal digits for the numeric results throughout the text. Based on the suggested formula, the calculated CTFV for the three systems are 0.41, 1.75 and 2.29, respectively. The larger CTFVs in the adapted systems does not mean the worsened conditions. Rather, it indicates that the capacity (i.e., service level) of adapted system tends to become lower with climate changes while the current system has already reached its peak capacity in the present period and thus shows small sensitivity to climate change.*

Table S1*: TFVs of current and adapted systems with and without climate changes*

Return period		**1**	**2**	**3**	**10**	**20**	**50**	**100**	**200**	**500**	**1000**
Current system	*NC*	*363434*	*545594*	*662399*	*1041230*	*1280598*	*1604223*	*1855559*	*2113083*	*2464388*	*2740033*
	C1	*1311483*	*779030*	*1070807*	*1471180*	*1845707*	*2120890*	*2081960*	*2494516*	*3337794*	*3635804*
	C2	*138358*	*625172*	*763944*	*1151120*	*1309407*	*1676813*	*2313744*	*2916433*	*3302794*	*3292205*
	C3	*689945*	*710016*	*1003205*	*1343650*	*1447074*	*1819748*	*1922111*	*2424542*	*2907221*	*3224196*
	C4	*1322311*	*939202*	*1020153*	*1948310*	*1942896*	*2158862*	*2312024*	*2961595*	*3040893*	*3957185*
	C5	*1299874*	*508016*	*447533*	*2184984*	*2011414*	*1961587*	*2068387*	*2155563*	*2598096*	*2631549*
Pipe	*NC*	*0*	*0*	*0*	*274650*	*545548*	*902639*	*1191761*	*1454490*	*1825663*	*2107541*
	C1	*579100*	*66820*	*307628*	*754782*	*1177608*	*1465530*	*1424433*	*1853479*	*2753620*	*3048692*
	C2	*0*	*14683*	*58510*	*400927*	*576342*	*988731*	*1672038*	*2305916*	*2711960*	*2700636*
	C3	*30911*	*39643*	*236010*	*610572*	*720015*	*1151135*	*1260383*	*1791006*	*2295501*	*2631907*
	C4	*586820*	*175700*	*254039*	*1287942*	*1283153*	*1502586*	*1670054*	*2356962*	*2432769*	*3392554*
	C5	*564627*	*1288*	*647*	*1531861*	*1355232*	*1304201*	*1413665*	*1500109*	*1960429*	*1999834*
Pipe+ LID	*NC*	*0*	*0*	*0*	*180610*	*403742*	*735983*	*994636*	*1239575*	*1571403*	*1833913*
	C1	*435235*	*31853*	*205783*	*594395*	*981183*	*1247661*	*1207291*	*1602282*	*2407278*	*2683353*
	C2	*0*	*4374*	*27315*	*275503*	*432434*	*808381*	*1439073*	*2002787*	*2375242*	*2362011*
	C3	*10832*	*13901*	*152559*	*463675*	*568173*	*960769*	*1056741*	*1531386*	*1993485*	*2295640*
	C4	*442271*	*106856*	*165356*	*1082850*	*1077049*	*1280177*	*1437899*	*2042621*	*2123354*	*2966933*
	C5	*423441*	*723*	*536*	*1300494*	*1145087*	*1094680*	*1193045*	*1277930*	*1703625*	*1738962*

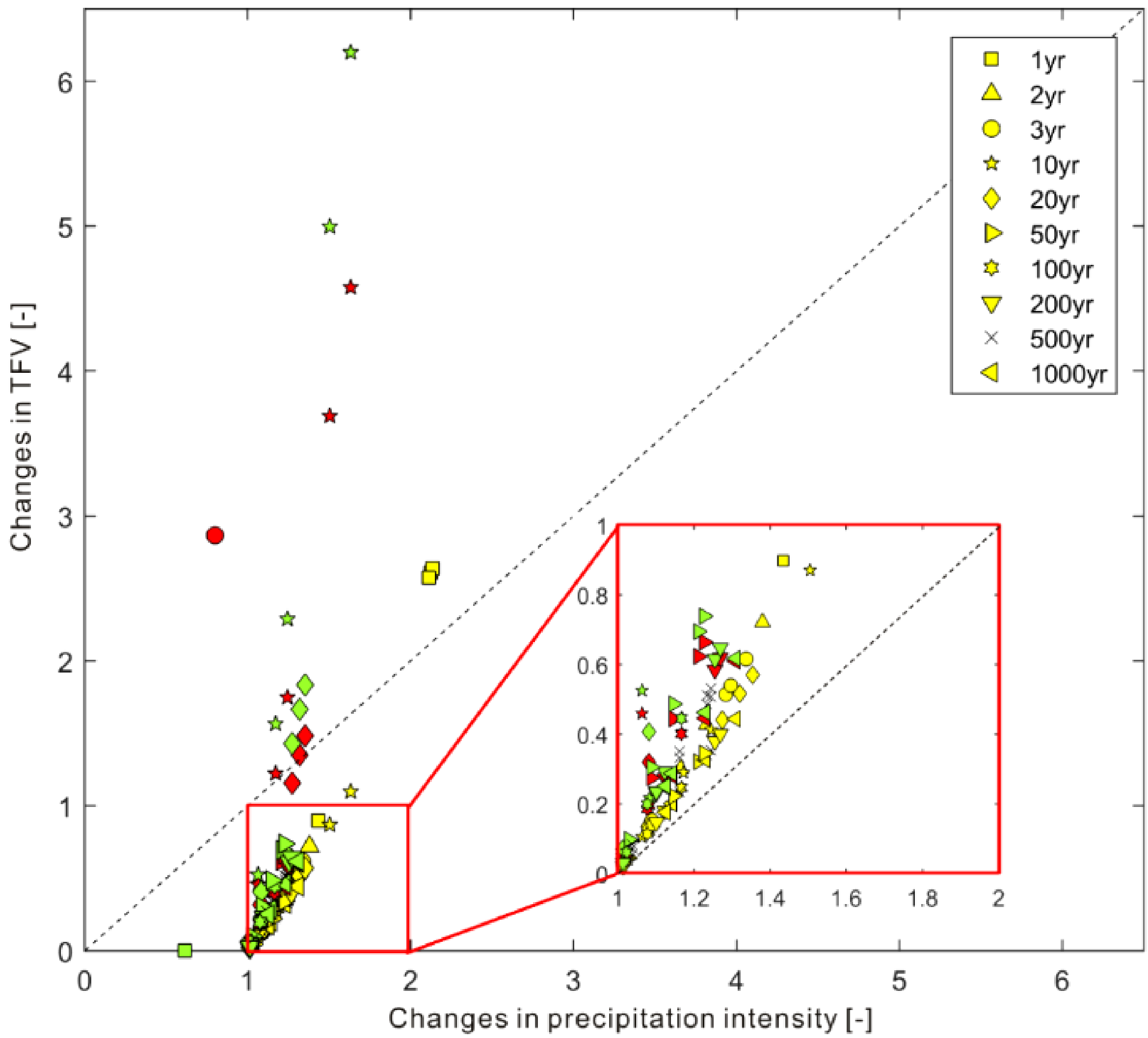

Figure 6 *Future changes in flood volumes (CTFVs) relative to historical conditions under the current drainage system (yellow) and two adaptation scenarios (i.e., Pipe in red and Pipe+LID in green) at various return periods.*

Specific comments

L 31: given the delay between submission and publishing I suggest removing "current" from the text. Same for line 81.

Response: *Done.*

L 32: I suggest removing "existing" in favor of "past", "recent," "literature" or similar

Response: *Done.*

L 40: "Based on the results" –> "Results indicates that"

Response: *Done.*

L45: This is an outcome of your research, hence I would not say it is “obvious” but rather something like “very likely” or “results clearly indicates::” or similar.

Response: *Thanks for the suggestion. We have revised it to “results clearly indicate”*

L 46: “greenhouse gas emissions”

Response: *Done.*

L 62: The sentence is not clear. Please specify units of the change and in relation to what (e.g., flood peak, precipitation intensity?)

Response: *Thanks for the suggestion. We have revised this sentence to "30% and 40% increase in the precipitation intensity is expected for the 10- and 100-year return periods" (Lines 64-66).*

L 66-69 is again not clear. E.g., non-stationary changes reads awkward. Also, what do you mean by future hydroclimate?

Response*: Thanks for the suggestion. We have revised this sentence to “Therefore, it is important to investigate the performance of drainage systems in a changing environment and to assess the potential urban flooding under various scenarios to achieve better adaptations" (Lines 69-72).*

L71-77: As the article has a strong focus on mitigation and adaptation I suggest adding some relevant references in those areas. See the work by (Alfieri et al., 2016; Arnbjerg-Nielsen et al., 2015; Moore et al., 2016; Poussin et al., 2012) among others. The few ones currently listed in the article are somehow hidden in the conclusions.

Response: *Thanks for the suggestion. We have expanded literature review and incorporated the suggested references in the revision (Lines 80-83).*

References

Alfieri, L., Feyen, L. and Baldassarre, G. D.: Increasing flood risk under climate change: a pan-European assessment of the benefits of four adaptation strategies, Clim. Change, 136(3), 507–521, doi:10.1007/s10584-016-1641-1, 2016.

Arnbjerg-Nielsen, K., Leonardsen, L. and Madsen, H.: Evaluating adaptation options for urban flooding based on new high-end emission scenario regional climate model simulations, Clim. Res., 64(1), 73–84, doi:10.3354/cr01299, 2015.

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Poussin, J. K., Bubeck, P., H. Aerts, J. C. J. and Ward, P. J.: Potential of semi-structural and non-structural adaptation strategies to reduce future flood risk: Case study for the Meuse, Nat. Hazards Earth Syst. Sci., 12(11), 3455–3471, doi:10.5194/nhess-12-3455-2012, 2012.

L136-137: the sentence is currently hard to read. Please reformulate.

Response: *Done.*

L 140-144: The sentence is rather misleading, first because there is now a wealth of studies using ensembles of several GCMs, and second because "all five GCMs" sounds like if there were only five, while CMIP5 includes way more than that.

Response: *Thanks for the suggestion. In the revision, we have deleted the statement "Unlike most previous studies that only used data from one or two GCM in climate change impact studies on urban floods".*

L 151: Rainfall is a climatic data. Please clarify.

Response: *Done.*

L 176: there are –> we considered

Response: *Corrected.*

L 181-182: This sentence should be supported by data, graphs or a reference to publications showing the validation work against historical records.

Response: *Thanks for the suggestion. In the revision, we have updated Figure 5a (attached below) by adding a graph on the city land use condition (e.g., green spaces and traffic network) and records of historical flood locations obtained from local water authorities. It is shown that the simulated locations of overloaded pipelines are in good agreement with historical records of flood points.*

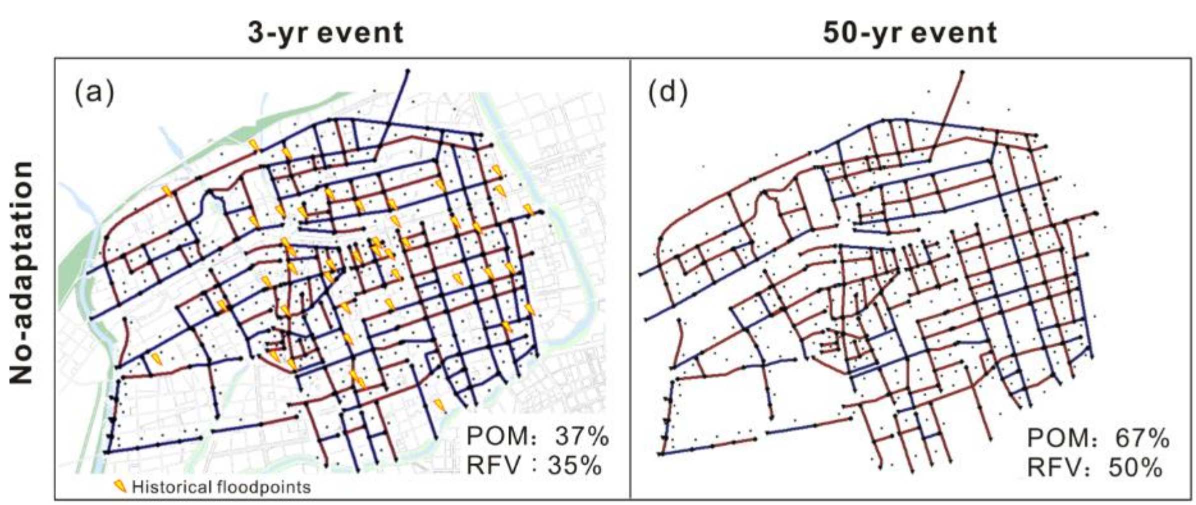


***Figure 5** Spatial distribution of overloaded pipelines (red colour) induced by the 3-year (left column) and 50-year extreme events (right column) without and with adaptations. The total percentage of overloaded manholes (POM) and ratio of flood volume (RFV) are summarised for each scenario.*

Descriptions of local land use, mainly the traffic network and green spaces, are provided as the background image in (a).

L 186-191: This part is difficult to read and understand. Please clarify and add some detail on how the TFV – return period relationship was derived. Figure 2 currently doesn't help a lot as it is too general, with no units nor tick marks. For example, if it the grey area is meant to indicate those events that contribute the most to the annual damage, then it should take at least 50% of the area under the curve in Figure 2, as its integral is proportional to the total flood risk.

Response: *Thanks for the suggestion. As responded to the third general comment, we have revised these sentences to make it clearer and concise (Lines 236-247). Figure 2 is also updated following the suggestions:*

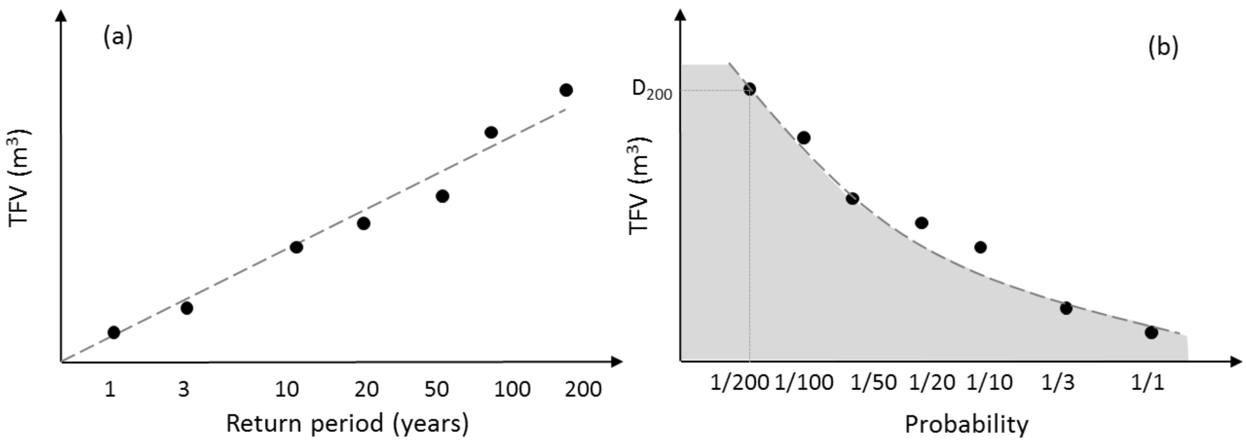


Figure 2 *Illustration of flood volume and average total expected total flood volumes (TFVs) as a function of return period under a stationary drainage system. The grey area denotes the average total expected TFVs per year considering all kinds of floods.*

L 191- 195: This statement indicates a strong assumption which is not justified at this stage and sounds like a speculation. Perhaps the authors want to introduce what is later on indicated by their findings, but I think at this point this is unjustified, unless the point is supported by stronger evidence and/or some references.

Response: *Thanks for the comment. In the revision, we have revised the relevant descriptions (Lines 242-247).*

L204-205: What is the extent of the enhancement of pipeline diameters in the adapted scenario? I couldn't find it anywhere in the text.

Response: *Thanks for the comment. The number of pipelines of the present-day and adapted systems was 323 and 488, with a total pipe length of 251.6 km and 375.4 km, respectively. In the adapted scenarios,* *the mean pipeline diameter was about 1.73 m, which increased by 53% compared to that of the present-day system. We have clarified this in the revision (Lines 255-258).*

L230-231: Is this 52% a simple average of the percent changes shown in Figure 3? Then I suggest to clarify, as it doesn't necessarily mean the overall projected change in flood risk.

Response: *Thanks for the comments. In the revision, we have added more details on the changes, rather than showing the overall average value (Lines 289-292).*

L 254: More correctly "10 magnitudes of rainfall events".

Response: *Corrected.*

L 263: 19% should be 49%.

Response: *Corrected.*

L 332-333: Not just uncertainties but modeling assumptions as well.

Response: *Thanks for the suggestion. We have added more discussions on the assumptions and limitations in the revision (Lines 414-462).*

L 328-329: That's true but perhaps out of the scope of this article, as anyways there is no real damage model to evaluate economic flood losses.

Response: *Thanks for the comment. Yes, flood damage is not addressed in this study. We have revised the relevant terms and descriptions in the revision.*

L 358-363: Following the discussions above one should be careful in calling these numbers "flood risk". Please adapt according to the indications in the discussion points above.

Response: *Thanks for the suggestion. We have changed "flood damage" or "flood risk" to "flood volume" throughout the text in the revision.*

L 605-606: I suggest including the period "2020-2040" in the caption for better understanding the graph.

Table 1: Which are the units in the table? Please specify units and the storm duration related to the precipitation intensity values listed (key parameter to understand such values).

Response: *Thanks for the suggestion. We have added the period "2020-2040" in the caption. This table shows the future change factor of precipitation at various return periods. It is dimensionless. The changes are multiplied to the present rainfall time series to obtain climate change scenarios as inputs to our model (see response to general comment 2).*

Figure 5: Please choose a more visible way of indicating overloaded pipelines, perhaps with a thicker line and/or a different color. Also the POM is currently mistakenly written as "NOM" in the 6 panels.

Response: *Thanks for the pointing out the typo. We have replaced "NOM" with POM. The illustration of overloaded pipelines is a direct output from the SWMM model. At present, it is not easy to highlight the pipelines given the hard-coded model user interface. Instead, we tried to update the figure with larger color contrast for better illustration. In addition, we have added city land use information (i.e., green spaces and traffic network) and records of historical flood pints obtained from the local water authorities in the updated figure.*

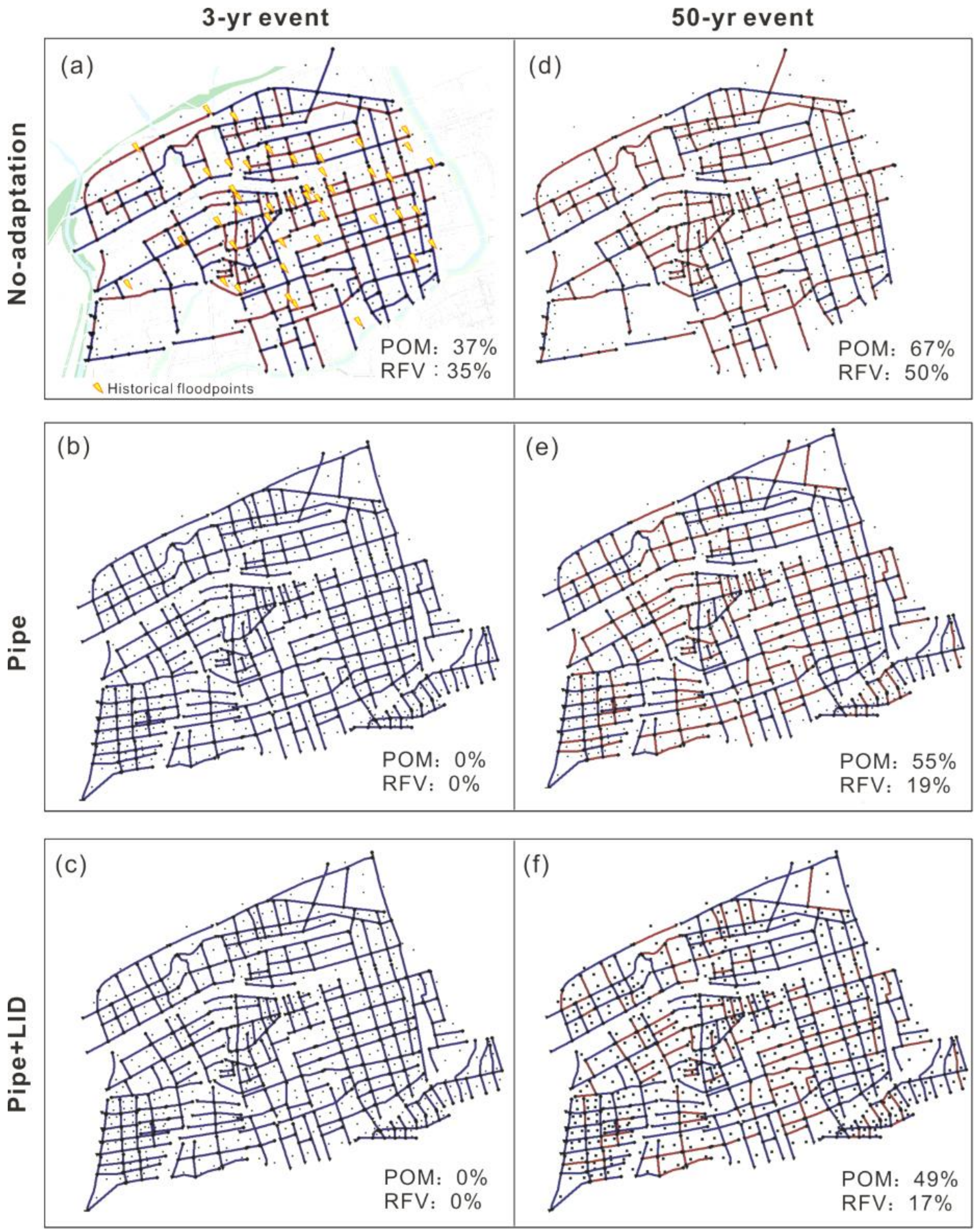


Figure 5 *Spatial distribution of overloaded pipelines (red colour) induced by the 3-year (left column) and 50-year extreme events (right column) without and with adaptations. The total percentage of overloaded manholes (POM) and ratio of flood volume (RFV) are summarised for each scenario.*

Descriptions of local land use, mainly the traffic network and green spaces, are provided as the background image in (a).

Figure 6: Add units in the axis labels. E.g.: “[-]” for dimensionless. Also, note the typo in the x-axis label.

<u>Response</u>: *Thanks for the suggestion. We have updated the figure in the revision.*

Figure 7: Negative values for risk reduction means increasing risk. Please reverse graphs with positive values (plus fix the typo rish -> risk)

<u>Response</u>: *Thanks for the suggestion. We have updated the figure and corrected the typo in the revision.*

Anonymous Referee #2:

SHORT COMMENTS IN THE JOURNAL STYLE

Scientific questions:

Adaptation effects on drainage performance in a context of climate change (CC) is relevant. Novel concepts. Try to quantify the impact adaptation measures is potentially new if appropriately developed in single case studies. Substantial conclusions. Not attended yet, due to insufficiently explained datasets and methods. Scientific methods and assumptions. Not clearly outlined. Results vs interpretations / conclusions. Unattended. Description. Pretty obscure. Authors proper credit. Ok! but not all is new. Title. OK! but to be revised in case of revision. Summary. Unbalanced on Climate trends when the most interesting part is adaptation. Overall presentation. Lacking of context outline. Language. To be revised by a mother tongue, that I am not. Formulae. Not expert enough to say. Parts to modify. Develop 1, 4 & 5, Clarify 2a & 2e, Reduce 2b, Delete 3b, Modify Fig. 1 & 5. References. Ok.

<u>Response</u>*:* *We greatly appreciate the reviewer for the constructive comments and suggestions to improve our manuscript. In the revision, we have 1) added more details on the datasets and methods, 2) added more discussions on the assumptions and limitations, 3) modified the relevant statements and figures which are unclear or inaccurate, 4) revised the specific sections as suggested, 5) invited a native speaker to proof-read the paper. More details of our responses to each comment are provided as follows.*

Note: the line numbers as mentioned in the response below refer to those in the cleaned version of manuscript.

EXTENDED COMMENTS

1 Introduction All key definitions should be provided here. Flood risk is the probability an hazard has to generate damages (UNISDR, ISO etc: : :), not a probability of a disastrous flood only (that is hazard occurrence). Should be wise to specify to whom this work is addressed, since very essential information of the case study is missing (see next sections).

<u>Response</u>*:* *Thanks for the comments. We agree with the reviewer that flood risk refers to the probability of a hazard to cause damage. In this study, we investigate the potential changes in flood volume (TFV) under various scenarios of climate changes and explore the role of adaptation and mitigation in regulating such changes. We acknowledge that the TFV is a hazard indicator, while flood damage is tightly linked to socio-economic conditions which is not addressed in this study. We have clarified this concept (Lines 239-247) and revised all relevant terms throughout the manuscript in the revision.*

This study investigates the performance of drainage system under climate change scenarios, which has great implications for adaptation and mitigation strategies for the study region, which has experienced increasing flood events (Lines 130-141). Comparing the reduction of flood volume by climate mitigation (via reduction of greenhouse gas emissions) and local adaptation (via improvement of the drainage system) indicates that local adaptations are more effective than climate mitigation in reducing future flood volumes. This study also has important implications for the research community on drainage system design and modeling in a changing environment. We emphasize the importance of considering adaptations in assessing climate change impacts on future urban floods. In the revision, we have provided more detailed information on the case study region, research background and the implications following the suggestions (Lines 102-112, 130-141, 488-496).

2. Material and Methods 2a) (i) A characterization of the hazard (rainfall) in Hohhot City is missing.

Response*: Thanks for the comments. In the study region, most rain storms fall between June and August, a period that accounts for more than 65% of the annual precipitation. In the revision, we have provided more descriptions on the rainfall characterizations and flood hazards in the study region (Lines 126-129 and 134-142).*

It should be noted that the input rainfall time series for the model are not the original historical observations. Rather, it is based on the storm intensity formula (SIF), which is used to estimate the design rainfall for each return period. The modeling practice mainly follows the standard procedure in urban drainage modeling in China, as documented in the national code for design of outdoor wastewater engineering (MOHURD, 2011). Specifically, the SIF represents an Intensity-Duration-Frequency (IDF) relationship, and is commonly used in the literature to estimate design rainfall hydrographs (Berggren et al., 2014; Cheng and AghaKouchak, 2014; Panthou et al., 2014; Willems, 2000; Zhou et al., 2012). Subsequently, the Chicago Design Storms (CDS) approach is applied to derive the design storms from the local SIF for the SWMM model as used in this study. The detailed procedures in using SIF to obtain the CDS design storms can be found in Chinese National Technical Guidelines for Establishment of Intensity-Duration-Frequency Curve and Design Rainstorm Profile (MOHURD, 2014) and have been well adopted in a number of Chinese urban drainage designs (Wu et al., 2016;Yin et al., 2016; Zhang et al., 2008; Zhang et al., 2015).

For the case study, the local rainfall is characterized by the SIF (q=635(1+0.841*lg(P))/t^0.61), which is obtained from local weather bureau. 10 return periods are considered in the paper and a 4-hour rainfall time series is generated for each return period at a 10-minute interval. The technical details in using SIF to derive the CDS rainfall are given in the following. As shown in the Equation 1, the q is the average rainfall intensity, t is the storm duration and P is the design return period. The typical temporal resolution considered in SIF for urban drainage simulations is minutes. A, b, c and D are regional parameters governing the IDF relations among rainfall intensity, return period and storm duration. For a given return period, the SIF is fitted into the Horner's equation as Eq.2:*

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

$$i = \frac{a}{(t + b)^c} \qquad \textit{Eq. (2)}$$

The synthetic hyetograph based on the Chicago method is computed using Eq. 2 and an additional parameter r (where 0< r <1) which determines the relative location of peak intensity (with respect to time), t_p*=r*t. The time distribution of rainfall intensity is described after the peak* t_a *= (1-r)*t and before the peak* t_b*=r*t by Eq. (3) and (4).* i_b *is the instantaneous rainfall intensity before the peak ,* i_a *is the instantaneous rainfall intensity after the peak.*

$$i_a = \frac{a[\frac{(1 - c)t_a}{(1 - r)} + b]}{(\frac{t_a}{(1 - r)} + b)^{1+c}} \qquad \textit{Eq. (3)}$$

$$i_b = \frac{a[\frac{(1 - c)t_b}{r} + b]}{(\frac{t_b}{r} + b)^{1+c}} \qquad \textit{Eq. (4)}$$

By following the above procedure, a 4-hour rainfall time series can be generated for each return period with the peak located in the center of the period. In the revision, we have added more details about the rainfall and methods in the revision (Lines 189-220).

Reference:

Berggren, K., Packman, J., Ashley, R., and Viklander, M.: Climate changed rainfalls for urban drainage capacity assessment, Urban Water Journal, 11, 543-556, 10.1080/1573062X.2013.851709, 2014.

Cheng, L. Y., and AghaKouchak, A.: Nonstationary Precipitation Intensity-Duration-Frequency Curves for Infrastructure Design in a Changing Climate, Scientic Report, 4, 10.1038/srep07093, 2014.

MOHURD: AQSIQ. Code for Design of Outdoor Wastewater Engineering (GB 50014-2006), Ministry of Housing and Urban-Rural Development, General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China: Beijing, China (In Chinese), 2011.

MOHURD: 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 November 2016 from http://www.mohurd.gov.cn/wjfb/201405/W020140519104225.pdf, 2014.

Panthou, G., Vischel, T., Lebel, T., Quantin, G., and Molinie, G.: Characterising the space-time structure of rainfall in the Sahel with a view to estimating IDAF curves, Hydrology and Earth System Sciences, 18, 5093-5107, 10.5194/hess-18-5093-2014, 2014.

Willems, P.: Compound intensity/duration/frequency-relationships of extreme precipitation for two seasons and two storm types, Journal of Hydrology, 233, 189-205, http://dx.doi.org/10.1016/S0022-1694(00)00233-X, 2000.

Wu, H., Huang, G., Meng, Q., Zhang, M., and Li, L.: Deep Tunnel for Regulating Combined Sewer Overflow Pollution and Flood Disaster: A Case Study in Guangzhou City, China, Water, 8, 329, 2016.

Yin, J., Yu, D. P., Yin, Z., Liu, M., and He, Q.: Evaluating the impact and risk of pluvial flash flood on intra-urban road network: A case study in the city center of Shanghai, China, Journal of Hydrology, 537, 138-145, 10.1016/j.jhydrol.2016.03.037, 2016.

Zhang, Y.-q., Lv, M., and Wang, Q.-g.: Formula method design of drainage pipe network and analysis of model simulation, Water Resource Power, 33, 105-107, 2015.

Zhang, D., Zhao, D. q., Chen, J. n., and Wang, H. z.: Application of Chicago approach in urban drainage network modeling, Water & Wastewater Engineering, 34, 354-357, 2008.

Zhou, Q., Mikkelsen, P. S., Halsnaes, K., and Arnbjerg-Nielsen, K.: Framework for economic pluvial flood risk assessment considering climate change effects and adaptation benefits, Journal of Hydrology, 414, 539-549, 10.1016/j.jhydrol.2011.11.031, 2012.

(ii) A detailed description of watershed soils is recommended. Rocky, lateritic, clay, sandy, or: : : soils perform differently in semi-arid contexts than in wet contexts. Even where infiltration seems possible some pervious looking soils after the first minutes turn into impervious. Context matter in this type of study.

Response*: Thanks for the comments. We agree with the reviewer that soil conditions matter in this type of study. In this study, three general soil categories are considered, i.e., the sand, loam and clay. According to the limited data on local soil conditions from local water authorities, the major soil type of* *the study region is a mixture of loam and clay. Based on the Horton's infiltration method (Rossman and Huber, 2016) and the values suggested by (Akan, 1993) as shown in the table below, we used the values under the category of "Dry loam soils with little or no vegetation" to represent the maximum infiltration capacity in the model. We have added more descriptions on this in the revision (Lines 129-130,185-187).*

Maximum (Initial) Infiltration Capacity (Akan, 1993)		
Soil Type	***(in/hr)***	***(mm/hr)***
Dry sandy soils with little or no vegetation	*5.0*	*127*
Dry loam soils with little or no vegetation	*3.0*	*76.2*
Dry clay soils with little or no vegetation	*1.0*	*25.4*
Dry sandy soils with dense vegetation	*10.0*	*254*
Dry loam soils with dense vegetation	*6.0*	*152*
Dry clay soils with dense vegetation	*2.0*	*51*
Moist sandy soils with little or no vegetation	*1.7*	*43*
Moist loam soils with little or no vegetation	*1.0*	*25*
Moist clay soils with little or no vegetation	*0.3*	*7.6*
Moist sandy soils with dense vegetation	*3.3*	*84*
Moist loam soils with dense vegetation	*2.0*	*5.1*
Moist clay soils with dense or no vegetation	*0.7*	*18*

To further address the concern, we have conducted a set of sensitivity experiments in the revision, see added Table 1 and revised Figure 7. Specially, we used three possible infiltration values corresponding to the first three soil types (i.e., dry sand, loam and clay soils with little or no vegetation) as listed in the above table. The parameters associated with each possible infiltration value are shown in the table below:

Table 1 Infiltration parameters for three categories of soil in the SWMM simulation

Infiltration parameters*	*MaxRate*	*MinRate*	*Decay rate*	*DryTime*
	[in/hr]	*[in/hr]*	*[1/hr]*	*[days]*
Dry loam with little or no vegetation	*3*	*0.5*	*4*	*7*
Dry sand with little or no	*5*	*0.7*	*5*	*5*

vegetation				
Dry clay with little or no vegetation	*1*	*0.3*	*3*	*9*

** To describe Horton infiltration method in SWMM, four basic infiltration parameters are required (Rossman and Huber, 2016) :*

- *MaxRate: Maximum infiltration rate on Horton curve*
- *MinRate: Minimum infiltration rate on Horton curve*
- *Decay: Decay rate constant of Horton curve*
- *DryTime: Time it takes for fully saturated soil to dry*

The original Figure 7 shows the comparison of benefits of climate mitigation and two adaptation strategies in reducing flood volume, based on the soil category 'Dry loam with little or no vegetation'. Here, we revised the Figure 7 by showing the uncertainty range (i.e. the error bar) arising from the representation of different soil conditions in the drainage model. It is shown that magnitudes of estimated benefits differ to some degree, nevertheless, the benefits of the designed adaptation measures in reducing urban flood volumes were found to be robust regardless of soil conditions, and such benefits exceeded those of climate change mitigation, confirming our major conclusions found in this study. We have included the relevant descriptions and results in the revised manuscript (Lines 376-385).

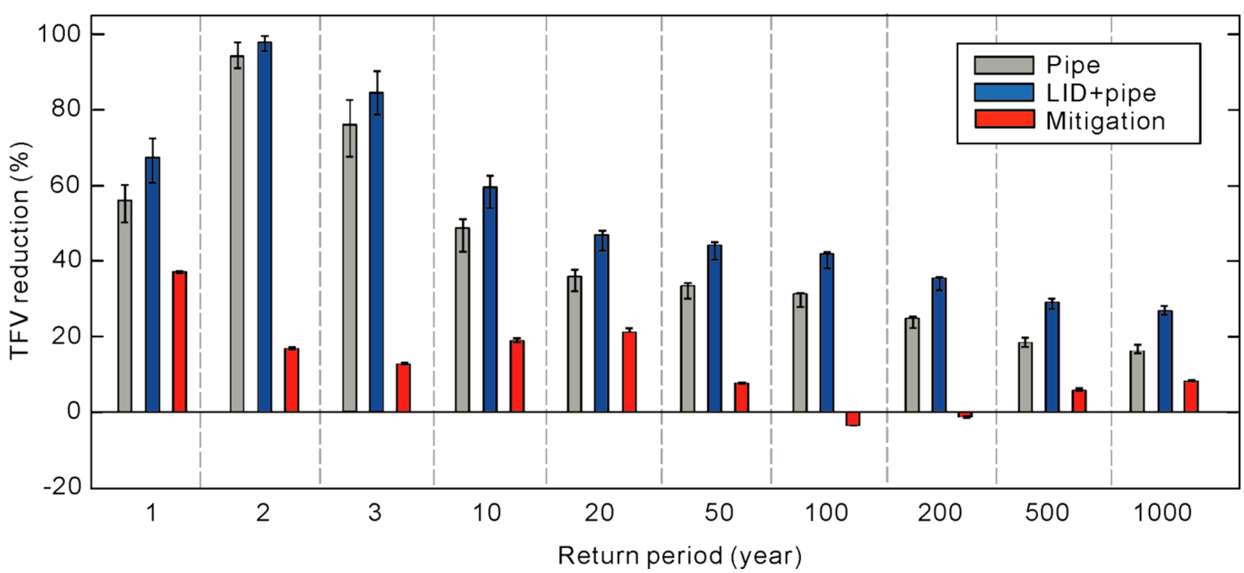


Figure 7 *Comparison of benefits of climate mitigation and two adaptation strategies in reducing urban flood volumes with changes in precipitation intensities for various return periods, and with related variations (boundary bars) as a result of uncertainty arising from local soil conditions.*

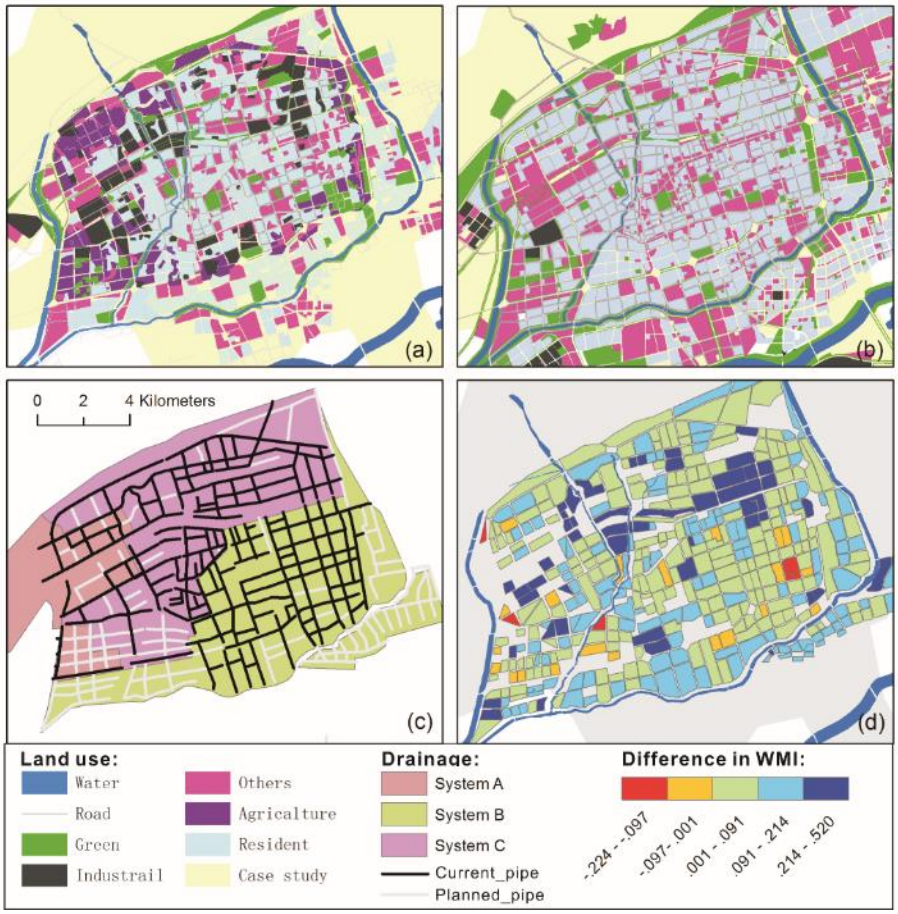
References:

Akan, O. A.: Urban stormwater hydrology: a guide to engineering calculations, CRC Press, 1993.

Rossman, L., and Huber, W.: Storm Water Management Model Reference Manual EPA/600/R-15/162A, 2016.

(iii) Authors consider permeable pavements, infiltration trenches and green roofs as possible adaptation measures. Which are the permeable soil and coverage rates in the different parts of the watershed considered?

Response*: Thanks for the comments. We agree that explicit consideration of permeable pavements, infiltration trenches and green roofs would make the designed adaptation measures more specific and realistic (Elliott and Trowsdale, 2007; Zoppou, 2001). However, there is no such detailed information on the permeable soil and coverage rates in the study region, which prevents us from representing these individual features/parameters in the model. Instead, the second adaptation scenario is designed to investigate the effects of increased permeable surfaces on flood volume, and is reflective of the combined effects of infiltration-related measures, including permeable pavements, infiltration trenches and green roofs. That is, a simplified approach by altering the subcatchment imperviousness was adopted due to the limitation of data availability in the study region. Specifically, we derived such information by comparing the current and planned landuse maps and incorporated the changes in landuse and imperviousness (see the updated Figure 1d) in the adaptation scenario. The figure 1d shows the difference in weighted mean imperviousness (WMI) calculated for each subcatchments (different parts of the watersheds) in the current and planned maps, which is used to indicate the area potential for adaptation based on the city plan. For example, a subcatchment with higher positive changes in the WMI indicates that the area is planned to have a land use type with lower imperviousness and therefore is assumed to be more suitable for LID planning, and vice versa. We have clarified this with more discussions in the revision (Lines 260-278).*



(iv) Can the authors provide some information about last disastrous floods in the case study? Areas affected the most, etc.

Response*: Thanks for the comment. During the major flood event on 11 July 2016, the city, especially the western portion of the watershed, was hit by an extreme rainfall event that featured more than 100 mm of rain in 3 hours. The local meteorological department issued the red warning of rainstorm. The flood event led to the cancellation of at least 8 flights and 17 trains, and delays of several transportation systems. In particular, in the central area, the flood event caused severe traffic jams on major streets (see the photos below) and resulted in a number of flooded residential buildings. We have added more descriptions on this in the introduction of the study region in the revision (Lines 136-142).*

(Photos: yjhlnews.com(left) and chinanews.com(right))

To provide more background information on historical flood events in the study area, we have included a map describing historical flood records and city traffic network in Figure 5a. It is obvious that the central portion of the city is the most affected region due to the low service level of its drainage system. We have updated the Figure 5 and added more descriptions in the revised manuscript (Lines 314-315).

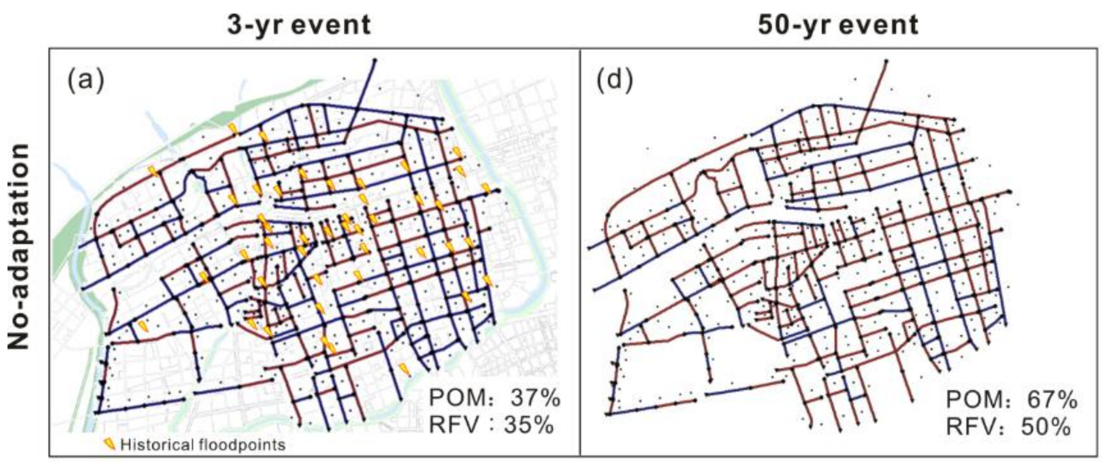


Figure 5*: Spatial distribution of overloaded pipelines (red colour) induced by the 3-year (left column) and 50-year extreme events (right column) without and with adaptations. The total percentage of overloaded manholes (POM) and ratio of flood volume (RFV) are summarised for each scenario. Descriptions of local land use, mainly the traffic network and green spaces, are provided as the background image in (a).*

2b) (i) It's quite normal to use more than one GCMs .

Response*: Agreed. We have deleted relevant statements in the revision.*

(ii) Reader expects to learn from the expected changes in rainfall (mm and in which month) but no information is provided on this topic.

Response*: Thanks for the comments. Readers can refer to the Table 2 which summarizes the change factors in extreme precipitation intensity of various return periods. It should be noted that the input rainfall time series for the model are not the original historical observations. Rather, it is based on the storm intensity formula (SIF), which is used to estimate the design rainfall for each return period. The modeling practice mainly follows the standard procedure in urban drainage modeling in China, as documented in the national code for design of outdoor wastewater engineering (MOHURD, 2011). Please see the response to comment 2 for details. We have added more details on this in the revision (Lines 189-233).*

2c) (i) Which rainfall information has been used to run SWMM [dataset length (years) and type (daily, three hourly, hourly, etc.)]?

Response*: Thanks for the comments. The rainfalls as inputs for the model are based on artificial rains in the format of Chicago Design storms derived from historical rainfall records following the standard by the local weather bureau and the national code for design of outdoor wastewater engineering (MOHURD, 2011). The rainfall period is 4 hours at sub-hour (i.e., 10 minute) time step. Please see the response to comment 2 for details. We have added more details on this in the revision (Lines 189-220).*

2e) (i) The adaptation measures considered are to reduce the amount of water that run off. This is one side of the problem. The other one is to slow down the water speed. And for this no measure is considered: there is a wide range of measures for semi-arid contexts commonly used for this. I recommend to consider it or explain why you don't.

Response*: Thanks for the comments. We agree that slowing down the water speed could be an alternative adaptation approach for attenuating runoff peak and reducing flood volume (Messner et al., 2006; Floodsite, 2009). We note that the water speed is influenced by, among others, the gradient and flow resistance of the bed of the water course (Ashley et al., 2007) and such information is not available at the sub-catchment scale in the study region.*

There are two main reasons that we did not consider the measures by attenuating the water speed in our designed adaptation approach. First of fall, although some of the LID measures are primarily designed to slow down the flow speed, i.e., vegetated swales, most of the LID measures can reduce both runoff volume *and flow speed at the same time. Constrained by the one-dimensional SWMM modelling approach in this study, the performances of LID measures were mainly evaluated according to their effects in reducing water volume from overloaded manholes (Oraei Zare et al., 2012;Lee et al., 2013). To examine whether flood retention of a given event is induced by runoff volume or the internal speed control function in the model is difficult and requires detailed data for model validations. Specifically, the required information about surface roughness, soil conductivity, and seepage rate were unavailable at the subcatchment scale in the study region. Based on the available datasets on current and future landuse maps, this study tends to apply and assess adaptation measures that mainly affect the surface imperviousness. We have added the discussions in the revised manuscript (Lines 436-449).*

Reference:

Ashley, R., Garvin, S., Pasche, E., Vassilopoulos, A., and Zevenbergen, C.: Advances in Urban Flood Management, in, edited by: Ashley, R., Garvin, S., Pasche, E., Vassilopoulos, A., and Zevenbergen, C., Taylor & Francis/Balkema, London, UK, 2007.

Floodsite: Flood risk assessment and flood risk management. An introduction and guidance based on experiences and findings of FLOODsite (an EU-funded Integrated Project), Deltares|Delft Hydraulics. ISBN 978 90 8 |4067|0, 2009.

Lee, J. M., Hyun, K. H., and Choi, J. S.: Analysis of the impact of low impact development on runoff from a new district in Korea, Water Science and Technology, 68, 1315-1321, 10.2166/wst.2013.346, 2013.

Messner, F., Penning-Rowsell, E., Green, C., Meyer, V., Tunstall, S., and Van der Veen, A.: Guidelines for Socio-economic Flood Damage Evaluation, Report Nr. T9-06-01, in, FLOOD site, HR Wallingford, UK, 2006.

Oraei Zare, S., Saghafian, B., Shamsai, A., and Nazif, S.: Multi-objective optimization using evolutionary algorithms for qualitative and quantitative control of urban runoff, Hydrol. Earth Syst. Sci. Discuss., 9, 777-817, 10.5194/hessd-9-777-2012, 2012.

(ii) How Authors have determined the impact of individual adaptation measures (permeable pavements, trenches, green roof) over run off reduction? This should be explained.

Response*: Thanks for the comments. As clarified in the response to 2a (iii), the second adaptation measure is mainly designed to investigate the impacts of increased permeable surfaces on flood volume reductions by altering the imperviousness of subcatchments to represent the infiltrated and detained water volume in the runoff-generation process. That is, the individual measures related to permeable pavements, trenches, green roof are not considered separately but represented in a combined and simplified approach. Thus, we are not able to explicitly assess the performance of these individual* *measures on flood reductions in details. We have added discussions on this in the revision (Lines 260-278).*

3) Results 3b) (i) I don't understand the approach: Mitigation is expected to impact on CC at long term (decades: : :). Drainage system is expected to reduce CC impacts at short-medium term (1-5 years). Is obvious that adapting we can't expect to see effects on rainfall: : :

Response*: Thanks for the comments. Mitigation refers to climate mitigations via reduction of greenhouse gas emissions. The mitigation effects are assessed here by comparing the results based on RCP8.5 emission scenario (which is a business-as-usual scenario) and RCP2.6 scenario (which considers the reduction of greenhouse gas emission). Climate mitigation via reducing greenhouse gas emissions is expected to influence precipitation characteristics and thus the subsequent flood hazards (i.e., flood volume in this study). Adaptation measures are localized and here refer to the specific design/update of drainage system. The possible land surface-atmosphere interactions which would indirectly affect the rainfall and floods are not considered in this study. We have clarified this in the revised manuscript (Lines 154-160).*

4) Uncertainties & Limitations (i) The consideration of the state of drainage system could be a limitation of this study? A drainage system obstructed by vegetation, waste or artefacts (cables, pipes, temporary constructions) can make the outcomes of the SWMM quite distant from the real world. And change also recommendations: : : that need to be extended to waste sector.

Response*: Thanks for the comments. We agree with the reviewer that the state of drainage system could affect its conveyance capacity and thus the system performance to various degrees. In some cases, floods are not induced by the exceedance of drainage capacity, but by the deterioration of drainage system itself, e.g., aging network, pipe deterioration, blockage, construction failures and local external factors (Dawson et al., 2008; CIRIA, 1997; Davies et al., 2001). Previous studies with a focus on sewer inspection and condition assessment, maintenance and rehabilitation strategies, have highlighted the need for labor-intensive field investigations for collecting information on the waste status and relocations, and such studies are often limited to certain areas (Ana and Bauwens, 2007; Fenner, 2000). In fact, assessment of drainage conditions requires detailed datasets, which has been recognized as a great challenge in applications. For example, in Europe, water service data collections mainly cover pipe length, age, material, diameter and location (Stone et al., 2002; Ana and Bauwens, 2007), while the assessment of pipe conditions are often managed by separate and specialized programs.*

Quantifying the impacts of drainage system states on urban flood volumes is not trivial, however, it was not within the scope of this study to take into account the actual state of the pipe system due to difficulties involved in collecting field data and selecting and using appropriate methods for reasonable assessment of pipe conditions. Such studies usually require comprehensive efforts on the material, data and method, (e.g., Dawson et al. 2008; Chae and Abraham 2001; Chughtai and Zayed 2008), which is not the focus of this paper. We acknowledge that the hydraulic performance may be overestimated without considering the drainage conditions and the waste section in the SWMM modeling approach (Pollert et al., 2005). In the revision, we have added more discussions on the impacts of pipe conditions on system performance, which should be addressed in the future study (Lines 422-434).

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Stone, S., Dzuray, E. J., Meisegeier, D., Dahlborg, A. S., and Erickson, M.: Decision-Support Tools for Predicting the Performance of Water Distribution and Wastewater Collection Systems., US EPA. 97pp., 2002.

5. Could the Authors consider to show us what is their way forward?

Response*: Thanks for the comments. As demonstrated in this study, local adaptation is found to be more effective in reducing future flood volumes than climate mitigation. However, several simplified approaches were adopted in the modeling and assessments as commented by the reviewer. Depending on the progress on data collection and the demands of local authorities, more advanced methods for pipe assessment (e.g., considering the changing pipe conditions), LID measures (detailed modelling of LID control), and two-dimensional surface flooding for assessment of flood damage and risk are planned in a future study to provide a more comprehensive analysis of the adaptation measures. We have added discussions on this in the revision (Lines 458-462).*

Figures 1 & 5: scale is not showed: how large are blocs contoured by drainage network?

Response*: Thanks for the comments. In the revision, relevant figures have been updated by including a scale bar (see the attached figures below).*

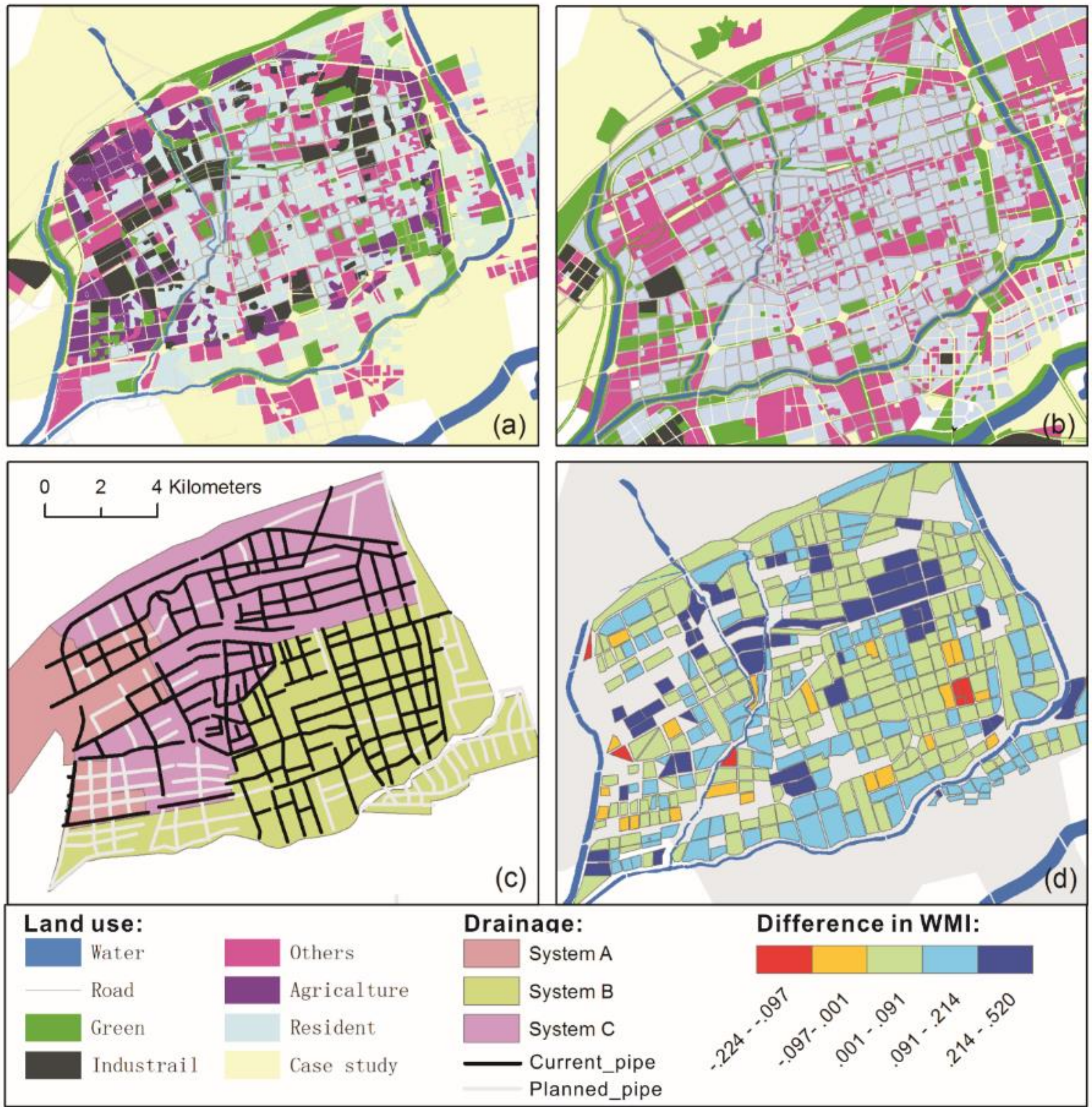

Figure 1 *Land use of the study region for the year 2010 (a) and 2020 (b). Pipe network description of current and planned drainage systems (c). Difference in Weighted Mean Imperviousness (WMI) between year 2010 and 2020 (d).*

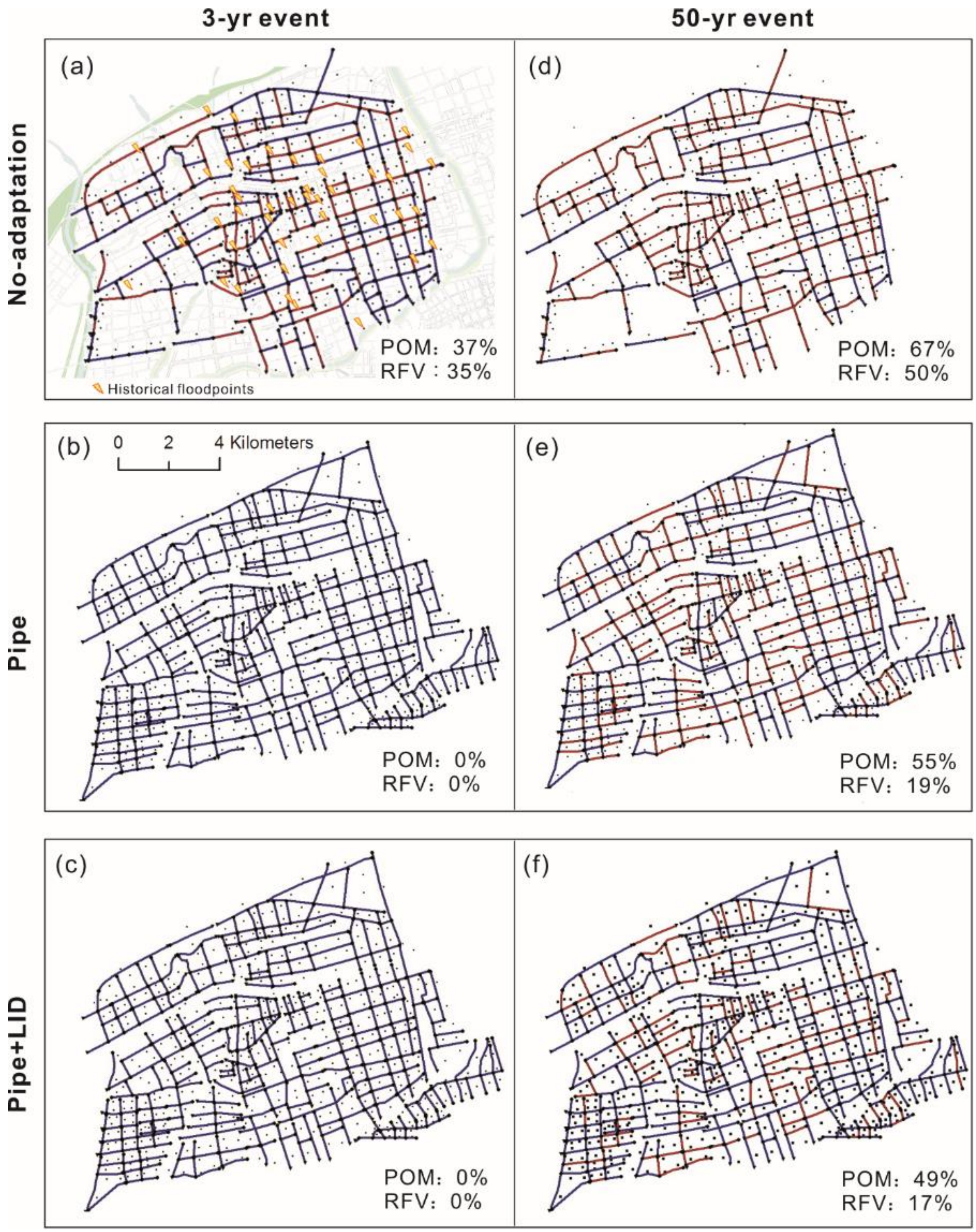

***Figure 5** Spatial distribution of overloaded pipelines (red colour) induced by the 3-year (left column) and 50-year extreme events (right column) without and with adaptations. The total percentage of overloaded manholes (POM) and ratio of flood volume (RFV) are summarised for each scenario. Descriptions of local land use, mainly the traffic network and green spaces, are provided as the background image in (a).*

6. Manuscript’s title Show the name of the case study and the country. Limit to Adaptation, delete mitigation, delete risk.

Response*: Thanks for the suggestion. In the revision, we replaced the “risk’ with “volume” and added the study region name and country. But we tend to keep “mitigation” in the title as we believe it is important although we emphasize the importance of considering adaptation in assessing climate change impacts on future urban floods. This is because the role of adaptation in reducing flood volume is highlighted through comparing with the reduced flood volume by climate mitigation. Indeed, comparing the reduction of flood volume by climate mitigation (via reduction of greenhouse gas emissions) and local adaptation (via improvement of the drainage system) indicates that local adaptations are more effective than climate mitigations in reducing future flood volume.*

Impacts of future climate change on urban flood ~~risks~~volumes in Hohhot City in Northern China: benefits of climate mitigation and adaptations

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Abstract

As China ~~is urbanized~~has become increasingly urbanised, flooding has become a regular ~~feature~~occurrence in its major cities. Assessing ~~potential urban flood risks under~~the effects of future climate change ~~has become~~on urban flood volumes is crucial ~~for~~to informing better ~~managing~~ management of such ~~risks~~disasters given the severity of the devastating ~~disasters~~ impacts of flooding (e.g., the ~~current~~ 2016 flooding across China). Although recent studies have investigated the impacts of future climate change on urban ~~flood risks have been investigated in many existing studies~~flooding, the effects of both climate change mitigation and ~~adaptations~~adaptation have rarely been accounted for together in a consistent framework. In this study, we assess the benefits of ~~(1) avoided~~ mitigating climate change by reducing greenhouse gas ~~(GHG)~~ emissions and ~~(2)~~locally adapting to climate change by modifying drainage systems ~~on urban flood risks within the context of global warming~~ to reduce urban flooding under various climate change scenarios through a case study conducted in ~~the~~ Northern China. The urban drainage model~~,~~ Storm Water Management Model ~~(SWMM),~~ was ~~employed~~used to simulate urban ~~floods under~~flood volumes using current ~~conditions~~ and two ~~feasible adaptation scenarios~~ adapted drainage systems (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~~. Results indicate that urban flood volume ~~of urban floods~~ is projected to increase by 52% in ~~the period of~~ 2020~~-~~–2040 ~~when~~ compared to ~~that~~the volume in 1971–2000 under the business-as-usual scenario (i.e., Representative Concentration ~~Pathways~~Pathway (RCP) 8.5). The magnitudes of urban ~~floods~~flood volumes 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~~flood volume under RCP 2.6 is 13% less than that under ~~RCP8~~RCP 8.5, demonstrating the ~~importance~~benefits of global-scale climate change mitigation efforts ~~on GHG emission reduction in regulating~~in reducing local ~~to regional hydrometeorological responses. Moreover, the two feasible~~ urban flood volumes. Comparison of reduced flood volumes between climate change mitigation and local adaptation (by improving the drainage system) scenarios ~~are shown to be able to further reduce risk associated with floods effectively~~suggests that local adaptation is more effective than climate change mitigation in reducing future flood volumes. This has broad implications for the research community relative to drainage system design and modelling in a changing environment. This study highlights the importance of accounting for local ~~climate~~ adaptation ~~efforts in assessing~~when coping with future urban ~~flood risks under a changing climate.~~ floods.

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

1. Introduction

Floods are one of the most hazardous and ~~common~~frequent 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 at a desired frequency to prevent urban flooding~~ at a desired frequency.~~. The design of ~~the~~ drainage ~~capacity~~systems is~~, however,~~ generally based on historical precipitation statistics ~~that are assumed to be stationary and thus do not incorporate~~ for a certain period of time, without considering the potential changes in precipitation extremes for the designed return periods (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~~30% and ~~0.4 are recommended~~40% increase in the precipitation intensity is expected for the 10- and 100-year return ~~period~~periods, respectively ~~with an anticipated technical life time of 100 years~~ (Arnbjerg-Nielsen, 2012). The systems are, however, likely to be overwhelmed by ~~the~~ additional runoff effects induced by climate change, which may lead to increased flood ~~damages, disruptions~~frequency and magnitude, disruption of transportation systems, and increased human health ~~risks~~risk (Chang et al., 2013; Abdellatif et al., 2015). ~~This necessitates examining~~Therefore, it is important to investigate the ~~system~~ performance ~~in response to non-stationary changes of future hydroclimate~~of drainage systems in ~~terms of both frequency and magnitude~~a changing environment and to assess the ~~consequent flood damages~~potential urban flooding under various scenarios to achieve better adaptations (Mishra, 2015; Karamouz et al., 2013; Yazdanfar and Sharma, 2015; Notaro et al., 2015).

Impacts of climate change on extreme ~~precipitations~~ precipitation and urban ~~floods were~~ flooding have been well documented in a number of case studies. For example, Ashley et al. (2005) showed that ~~floods~~flooding risks may increase by almost 30 times in comparison to current ~~situation~~situations, and effective ~~responses~~ adaptation measures are ~~necessary~~required to cope with the increasing risks in the UK. Larsen et al. (2009) estimated ~~the potential~~that future ~~increase in~~ extreme one-hour precipitation ~~events over~~will increase by 20%~60% throughout 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~~ in Belgium the current design storm intensity ~~in Belgium are projected~~ for the 10-year return period is projected to increase by 50% by the end of this century. Several studies have also investigated the role of climate change mitigation and adaptation in reducing urban flood damages and risks under climate change scenarios (Alfieri et al., 2016; Arnbjerg-Nielsen et al., 2015; Moore et al., 2016; Poussin et al., 2012). To date, however, limited work has been done to investigate the relationship between changes in precipitation intensity and flood volume to provide additional insights into drainage design strategies. More importantly, investigations of the benefits of climate change mitigation (by reducing greenhouse gas emissions [GHG]) and local adaptation (by improving drainage systems) in reducing future urban flood volumes are typically conducted separately, rather than within a consistent framework.

As China ~~is urbanized~~has become increasingly urbanised, flooding has become a regular ~~feature of~~ occurrence in its cities ~~with~~; 62% of Chinese cities surveyed ~~experiencing~~experienced floods and direct economic losses of 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 people were killed and $22 billion in losses were suffered across China. Hence, assessing future changes in urban flooding is very important for managing urban ~~flood risks through~~floods by designing new and re-designing existing urban infrastructures ~~that are~~to be resilient ~~to~~ in response to the impacts of future climate change. While ~~it is~~ urban floods are speculated ~~that urban flood damages will~~to increase in the future (Yang 2000~~ and~~; Ding et al., 2006), their magnitudes are hard to assess ~~due to~~because of uncertainties associated with future climate change scenarios, as well as the ~~lack of understanding~~under-representation of plausible climate change mitigation and adaptation strategies in the models.

In this study, we chose a drainage system in a typical city in Northern China to illustrate the role of climate change mitigation and local adaptation in coping with future urban flood volumes. Such an investigation of the performance of the present-day drainage system also has important implications for local governments responsible for managing urban flood disasters in the study region. Specifically, we first quantified the effects of future climate change on ~~plausible adaptations and mitigations strategies and their consequences~~urban flood volumes as a result of extreme precipitation events for various return periods using the present-day drainage system. We then designed two plausible adaptation strategies for the study region and investigated how much urban flood volume can be reduced by the adapted systems. We also compared the benefits of global-scale climate change mitigation and local adaptation in reducing urban flood volumes to advance our understanding of the effective measures for coping with future urban floods.

~~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 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~~. It lies between the Great Blue ~~Mountain~~Mountains to the north and the Hetao

~~plateau~~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 it 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~~, which is 50% larger than the ~~detailed description of the~~current drainage area. The land use ~~category~~categories and distribution ~~is~~are shown in Figure 1b.

The region is ~~within~~in a cold semi-arid climate zone, ~~characterized~~characterised by cold and dry winters and hot and humid summers. The regional annual mean precipitation is approximately 396 mm ~~with large intra-seasonal variations.~~and it exhibits large intra-seasonal variations. Most rain storms fall between June and August, a period that accounts for more than 65% of the annual precipitation. According to local water authorities, the major soil type of the area is a mixture of loam and clay. 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~~km. The drainage network has a higher pipeline cover rate in the central part, but ~~with~~ a rather low design standard for extreme rainfall events with a return period of less than ~~one~~1 year. Historical records ~~on storm water~~of stormwater drainage and flood ~~damages show~~damage indicate that the region has ~~been experiencing~~experienced an increase in flood ~~risks mainly due to~~ frequency and magnitude within the context of climate change and ~~urbanization~~urbanisation. During the major flood event on 11 July 2016, the city, especially the western portion of the watershed, was hit by an extreme rainfall event that featured more than 100 mm of rain in 3 hours. The flood event led to the cancellation of at least 8 flights and 17 trains, and delays of several transportation systems. In particular, in the central area, the flood event caused severe traffic jams on major streets and resulted in a number of flooded residential buildings. A new drainage system is therefore required ~~by the regional water authorities~~ to cope with ~~the~~ increasing urban flood ~~risks~~volumes and frequencies in the future.

b. Climate change scenarios

Climate projections by five general circulation models (GCMs) from ~~phase~~Phase 5 of the Coupled Model Intercomparison Project (CMIP5) archive ~~are~~were obtained from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) (Warszawski et al., 2014). The CMIP5 climate projections were bias-corrected against ~~reference dataset of the WATCH forcing data (WFD)~~ observed climate for the overlapping period 1950–2000 using ~~parametric~~a quantile mapping method (Piani et al., 2010; Hempel et al., 2013). ~~This dataset represents~~The bias-corrected CMIP5 climate projections represent a complete climate change picture ~~in~~ that ~~it~~ includes both the mean ~~properties~~property and variation of future ~~climates~~climate. Several studies have demonstrated the value of ~~this~~the bias-~~correction~~corrected climate projections in quantifying ~~the impacts of~~ climate change impacts 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~~In this study, we used the bias-corrected climate ~~data~~ from all five GCMs (HadGEM2-ES, GFDL-ESM2M, IPSLCM5A-LR, MIROC-ESM-CHEM, and NorESM1-M) under two Representative Concentration Pathways (RCPs) (i.e., ~~RCP2~~RCP 2.6 and ~~RCP8~~RCP 8.5~~) for our analysis.~~). The ~~impacts~~projected urban flood volumes under the business-as-usual scenario ~~RCP8~~RCP 8.5 are compared with ~~that in~~those under the climate change mitigation scenario ~~RCP2~~RCP 2.6 to explore the benefits of climate change mitigation ~~on~~in reducing regional urban flood ~~risks~~volumes. The possible land-surface-atmosphere interactions that would indirectly affect rainfall and flooding are not considered in this study.

c. Urban drainage modelling

The Storm Water Management Model (SWMM 5.1) developed by the ~~United State~~U.S. Environmental Protection Administration ~~(EPA) is one of the well-known~~is a widely used urban ~~storm water models for simulating~~stormwater model that can simulate rainfall-runoff routing and pipe dynamics under ~~either~~ single or continuous events (Rossman and Huber, 2016).~~ With climatic and rainfall inputs,~~ SWMM ~~is applied~~can be used to evaluate ~~variations~~the variation in hydrological and hydraulic processes and the performance of ~~the~~ drainage ~~system~~systems under ~~selected~~specific mitigation and adaptation scenarios in the context of global warming. The hydrological component requires inputs of precipitation~~, sub-catchment~~ and subcatchment properties~~, such as the~~ including drainage area, subcatchment width~~ reflecting the time of concentration,~~, and imperviousness. The pipe network requires inputs ~~of~~from 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~~The 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~~as the ~~parameter~~value of ~~Total Flood Volume~~total flood volume (TFV) at each overloaded manhole; i.e., the excess water from manholes after completely filling the pipe system without taking into account the outlet discharges. Other types of ~~results~~model outputs include ~~the~~ catchment peak flows, maximum flow ~~rate~~rates 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 condition and ~~system overloading of the~~ drainage system overloading status. 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.~~about overland flow characteristics is available. In this study, the kinematic wave routing and the Horton infiltration model are used for model simulations. The infiltration capacity parameters for the category of "Dry loam soils with little or no vegetation" are used in the hydrological model to be consistent with the local soil type (Akan, 1993; Rossman and Huber, 2016) (Table 1).

Rainfall inputs are calculated ~~from~~based on the regional storm ~~intensify~~intensity formula (SIF) using historical climatic statistics (Zhang and Guan, 2012~~), as shown in~~) (see Equation 1~~.~~). Application of the SIF is a standard practice for determining design rainfalls in urban drainage modelling in China, and is well documented in the National Guidance for Design of Outdoor Wastewater Engineering (MOHURD, 2011). In fact, the SIF represents an Intensity-Duration-Frequency (IDF) relationship, which is a common approach in literature for estimating design rainfall hydrographs using the Chicago Design Storms (CDS) approach (Berggren et al., 2014; Willems et al., 2012; Zhou et al., 2013).

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

where q is the average rainfall intensity~~; A, b, c and D are constants to describe the regional parameters of design flow.~~, and P and t are the design return period and duration of storm, respectively. ~~For this~~The typical temporal resolution considered in SIF for urban drainage modelling is minutes. A, b, c, and D are regional parameters governing the IDF relationship among rainfall intensity, return period, and storm duration. For the study region, the values of A, b, c, and D were obtained from the local weather bureau and are equal to 635, 0, 0.61, and 0.841, respectively.

~~The Chicago~~

The procedure for applying SIF to obtain CDS is outlined in the National Technical Guidelines for Establishment of Intensity-Duration-Frequency Curve and Design ~~Storms (CDS) approach is then employed to estimate~~ Rainstorm Profile (MOHURD, 2014; Zhang et al., 2008; Zhang et al., 2015). Specifically, for a given return period, the SIF is fitted into the Horner's equation as:

$$i = \frac{a}{(t+b)^c} \qquad \text{Eq. (2)}$$

The synthetic ~~rainfall hyetographs for a number of prescribed return periods,~~hyetograph based on the ~~parameters~~Chicago method is computed using Equation 2 and an additional parameter r (where $0< r <1$), which determines the relative time step of the ~~derived SIF (Zhang et al., 2008).~~ peak intensity, $t_p=r*t$. The time distribution of rainfall intensity is then described after the peak $t_a = (1-r)*t$ and before the peak $t_b = r*t$ using Equations 3 and 4, respectively, where i_b and i_a are the instantaneous rainfall intensity before and after the peak:

$$i_a = \frac{a\left[\frac{(1-c)t_a}{(1-r)} + b\right]}{\left(\frac{t_a}{(1-r)} + b\right)^{1+c}} \qquad \text{Eq. (3)}$$

$$i_b = \frac{a\left[\frac{(1-c)t_b}{r} + b\right]}{\left(\frac{t_b}{r} + b\right)^{1+c}} \qquad \text{Eq. (4)}$$

In this study, ~~there are in total~~we considered 10 return periods~~ of interest~~, i.e~~.~~., the 1~~,~~-, 2~~,~~-, 3~~,~~-, 10~~,~~-, 20~~,~~-, 50~~,~~-, 100~~,~~-, 200~~,~~-, 500~~-~~, and 1000-year events. ~~The ~~A 4-hour rainfall time series was generated for each return period at 10-minute intervals based on Equations 1−4. We assumed that the SIF was constant without considering the non-stationary features in a changing climate. That is, the IDF relationships were assumed to remain stable in the future and only changes in the daily mean intensity were considered because of the limited data availability in future sub-hourly climate projections from which to derive the parameters.

As for future climate, the projected changes (i.e., change factors) in precipitation intensity at various return periods ~~are~~were calculated ~~based on the climate projection ~~for each GCM-RCP combination (Table ~~1). The derived change ratios are~~2). Specifically, for each year, the annual maximum daily precipitation was determined for both historical and future periods. The generalised extreme value (GEV) distribution was 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. The value corresponding to each return period was estimated based on the GEV distribution and the changes between future and historical periods were calculated as the change factors. The derived change factor for each return period was then multiplied ~~to~~by the ~~synthetic~~historical design CDS rainfall ~~hyetographs~~time series to ~~drive the~~derive future ~~precipitation intensity~~climate scenarios. ~~The kinematic wave routing and the Horton infiltration model are used for model simulations. The model~~We acknowledge that the estimation of changes in extreme precipitation events involves inevitable uncertainties and therefore caution should be exercised when interpreting the relevant results~~, especially the overloaded manholes, are validated against historical records of flood events.~~.

d. Flood ~~risk~~volume assessment

The TFV values ~~corresponding to each~~of given rainfall ~~event at various return periods are~~events were simulated by the SWMM. ~~The TFV – return period relationship, as a proxy for flood damage illustration (~~A log-linear relationship is assumed to characterize the changes in flood volume with the increase in precipitation intensity as indicated by return periods (Figure 2a) following Zhou et al~~.,~~ . (2012~~;~~) and Olsen et al~~., 2015), is established to reflect the changes in flood consequence as a function of return period.~~. (2015). Generally, more intense rainfall ~~inputs will induce higher TFVs. Similarly, for~~ will induce higher TFVs. The TFVs were further linked to their occurrence frequencies to derive the expected flood volume for a flood event at a specific probability (Figure 2b). The total grey area under the curve represents the average total TFVs per year for all floods at various return periods. The contribution of an individual 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~~TFVs is dependent not only on the flood volume, but also its corresponding probability of occurrence. ~~It~~Intensified precipitation is expected ~~that climate change will~~to increase the magnitude of system overflow~~ and lead to~~, resulting in 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~~TFV-return period relationship and increased total TFVs. Mitigation and adaptation~~, on the contrary,~~

are aimed ~~to reduce~~at reducing or ~~prevent those~~preventing the impacts of global warming on flood ~~damage and risks~~volumes.

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~~were designed to explore the ~~effects~~role of adaptation ~~on~~in reducing urban flood ~~risks induced by~~volume within the context of climate change. The first scenario ~~adapts~~adapted the drainage system as planned by the water authorities to cope with the designed standard of a 3-year design event. It ~~involves~~involved two main improvements of the current drainage~~, by~~ system—enhancing the pipeline ~~diameters~~diameter and expanding the pipe network. The design ~~is~~was implemented in the SWMM model as shown in Figure 1c. The number of pipelines of the present-day and adapted systems was 323 and 488, with a total pipe length of 251.6 km and 375.4 km, respectively. In the adapted scenarios, the mean pipeline diameter was about 1.73 m, which increased by 53% compared to that of the present-day system.

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, can also influence the performance of a drainage system in managing surface runoff. The second adaptation scenario ~~is~~was to increase the permeable surfaces (e.g~~.~~., green spaces) and reduce the regional imperviousness in the study region on the basis of pipe capacity enhancement. This scenario is referred to as~~ to~~ the Low Impact Development (LID) scenario~~ that aims~~, and it was used to explore the ~~potential~~effectiveness of ~~decentralized and~~urban green measures, such as the use of permeable pavements, infiltration trenches, and green roofs. ~~Using the~~Due to a lack of detailed information about the permeable soil and coverage rates in the study region, the effects of these specific measures cannot be modelled individually. Here, we used a simplified approach by altering the subcatchment imperviousness to reflect the combined effects of infiltration-related measures. We derived such information by comparing the current and planned land use maps using a geographical information system (GIS~~), we select sub-catchments that are amendable for~~) and incorporated the changes in land use and imperviousness into the designed LID ~~adaptation based on~~scenarios. Figure 1d shows the difference ~~between the current and planned land use types. Specifically, the~~ in weighted mean imperviousness (WMI) ~~is~~ calculated for each ~~sub-catchment polygons~~subcatchment in the ~~two~~current and planned 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~~ land use type. The difference in WMI was used to indicate the area potential for adaptation based on the city plan. For example, a subcatchment with higher positive ~~change~~changes in the WMI indicates that the area is ~~expected~~planned to ~~experience decreased regional mean~~have a land use type with lower imperviousness ~~in designed adaptation scenarios~~and therefore is assumed to be more suitable for LID planning, and vice versa.

3. Results

a. Impacts of future climate change on urban ~~floods~~flood volumes

Figure 3 shows the ~~predicted impacts of future~~ projected climate change impacts on urban ~~floods~~flooding using the ~~current~~present-day drainage system ~~by~~of the near future ~~period~~(i.e., 2020~~-~~–2040 ~~as compared to~~) under the ~~historical period. It is found that without~~RCP 8.5 scenario. Without climate change mitigation or adaptation ~~(i.e., RCP8.5 and~~, the ~~current drainage system),~~

~~climate change is~~TFV was projected to ~~lead to significant~~ increase ~~in~~significantly with the ~~total flood volume (TFV)~~increase of extreme rainfall events for ~~various~~most of investigated return periods~~. We note~~ (Table 2). Note that ~~a small proportion of~~ the ~~projected TFVs (i.e.~~ lower ~~bound at~~bounds for return periods of 1, 3, and 1000 years~~)~~ fall below the current TFV curve~~. Under such circumstance, climate change will lead to decreased~~ due to the decrease in precipitation intensities~~ and so that the TFVs drop accordingly~~. Despite the large uncertainty associated with climate ~~models~~projections, in particular with the 1~~,~~-, 10-, and 1000~~ years~~-year return periods, the poor service performance of the current system ~~is~~ in coping with urban flooding was evident. Overall, the urban ~~flooding is~~flood volume was 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~~ by 2020~~-~~–2040~~, with~~; the largest increase (258%) ~~associated with~~was projected for the 1-~~yr events~~year event and the smallest increase (12%) ~~associated with~~for the 100-~~yr events~~year event.

b. Benefits of climate change mitigation ~~on~~in reducing urban ~~floods~~flood volumes

Figure 4 shows the ~~avoided flood risks due to GHG mitigations (i.e.~~ comparison of TFVs under the ~~difference between RCP2.6 and RCP8~~RCP 8.5 scenario (i.e., a business-as-usual scenario) and the ~~related uncertainties.~~RCP 2.6 scenario (i.e., a climate change mitigation scenario). 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~~arising from climate models, it is clear that ~~future~~ the simulated TFVs are much smaller under the RCP 2.6 scenario than under the RCP 8.5 scenario, demonstrating the benefits of climate mitigation in reducing local urban flood ~~management would benefit most from the global GHG mitigation~~volumes. Such benefits are especially evident for floods ~~with~~for smaller return periods. For example, an increase of 936~~.44 m^3 in~~ m^3 in flood volume is projected with the increase in 1-year extreme rainfall under the business-as-usual climate change scenario (i.e., RCP 8.5), 52% of which would be reduced if climate change mitigation is in place (i.e., under RCP 2.6). Overall, climate change mitigation can reduce future flood volumes by 13% compared to the scenario without mitigation, as indicated by the multi-model ensemble median. Notably, the peak of the total ~~flood volume is~~TFV curve was even projected ~~for~~to shift from 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~~under the RCP 8.5 scenario to the 3-year event under the RCP 2.6 scenario (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~~). Such a shift in ~~risks towards less frequent~~the peak toward smaller return periods~~,~~ combined with a flatter ~~risk~~ curve~~,~~ demonstrates the ~~benefits~~important role of climate mitigation in ~~reducing the~~regulating local urban 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.~~volumes.

c. Benefits of adaptation ~~on~~in reducing urban ~~floods~~flood volumes

~~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 and without ~~adaptations~~adaptation. The simulated results under the present ~~climate conditions, with the~~ 3-~~yr~~year event (recommended service level) and 50-~~yr~~year 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~~were selected to illustrate the role of adaptation in coping with floods in the historical period. As shown in Figure 5a, the simulated locations of overloaded pipelines are in good agreement with historical flood points as recorded by local water authorities. 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.~~ are up to 37% and 35% in the current drainage system (Figure 5a), respectively. When experiencing a 50-year extreme rainfall, the POM and RFV increase to 67% and 38%, respectively. This indicates that current pipe capacities are insufficient to cope with extreme rainfall events (Figure 5b). Spatially, the central portion of the city is the most affected region due to the low service level in the area. With proposed ~~adaptation scenarios, such risks~~adaptations, urban floods can be reduced to zero~~. The~~ under a 3-year flood event. Such benefits of local adaptations are also evident when experiencing more intense precipitation ~~(i.e. 50-yr~~ events~~), by reducing~~ (e.g., 50-year events), for which the POM and RFV reduced from 67% and 50% to ~~19~~49% and 17%, respectively.

~~In the context of climate change, we first assessed the correlation between the projected~~ Figure 6 shows the future changes in ~~precipitation intensity with the changes in TFVs (i.e.,~~ urban flood volume (CTFVs) ($CTFV\cancel{=}=(TFV_c\cancel{/}-TFV_{nc})/TFV_{nc}$, where c and nc represent the results with and without climate change~~ impacts~~, respectively) with ~~and without adaptations. It is found~~changes in ~~Figure 6 that~~extreme rainfall for various return periods. The performance of the current drainage system (no adaptation) ~~is~~ was found to be less sensitive to future climate change~~ (i.e., with a~~, as indicated by the flatter slope~~).~~ in Figure 6. 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~~ a similar magnitude of changes in ~~precipitation intensity.~~

~~For both adaptation scenarios, a considerable increase in the ratio between the CTFV and~~ flood volume was projected given changes in ~~precipitation intensity is observed~~extreme rainfall for the return periods ~~below 10~~of 3, 50, and 500 years; the CTFV is 0.62, 0.32 and 0.35 for these periods, respectively. This ~~implies that the designed adaptation can effectively attenuate~~ is because the capacity of the current system is too small to handle extreme rainfall 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~~return periods larger than 1 year—a condition under which the current drainage system would be flooded completely, not to mention the situations with increased ~~precipitation~~rainfall intensity in the future. Mathematically, the low sensitivity of the current drainage system to changes in extreme rainfall intensity could be attributed to the large value of the denominator in the calculation of *CTFV*.

With adaptations in place, the flood volume becomes much smaller than that in the current system due to capacity upgrading to hold more water. For example, when experiencing a 10-year extreme rainfall event, the urban flood volumes for the present period (i.e., *TFVnc*) are 1041,230, 274,650 and 180,610 m^3 in the current and two adapted systems, respectively, while in the future period, the magnitude of flood volume (i.e., *TFVc*) is relatively similar among the three drainage systems. Therefore, future CTFVs relative to the historical period are much larger in the adapted systems than in the current system. The larger CTFVs in the adapted systems do not mean a worsened drainage system performance. Rather, they imply that the capacity (i.e., service level) of adapted drainage systems tends to become lower with climate change, while the current drainage system has already reached its peak capacity in handling extreme rainfall events in the historical period and thus shows a low sensitivity to future increases in rainfall intensity under climate change~~. For intense precipitation~~ scenarios. Notably, the considerable increases in the CTFVs for return periods of less than 10 years in the adapted systems imply that the designed adaptations can effectively attenuate extreme rainfall events ~~with~~for small return ~~period ≥50 years, however, more~~ periods. For more extreme rainfall events of return periods >50 years, more consistent results ~~are~~were found for both adaptation scenarios. This ~~result implies~~indicates that although the performances of adapted 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~~ the flood volume remains large when experiencing extreme rainfall events with return periods larger than 50 years, because flooding in such cases 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~~reduced TFVs by climate change mitigation and drainage system adaptation as functions of ~~the~~ return period. It is evident that ~~the designed local-scale adaptation and global-scale GHG~~ both mitigation and adaptation measures are effective in reducing future urban flood ~~risks, but the~~ volumes. However, such 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~~in rainfall intensity (i.e~~.~~., larger return periods). Importantly, our results show that the two ~~proposed~~ adaptation ~~strategies~~systems proposed in this study are found to be more effective in reducing urban floods than ~~the global~~climate change mitigation ~~of GHG emissions for the study region~~. In most cases, the benefits of local adaptation are more than double ~~the level that can be~~ those of mitigation. In extreme cases, the reduction in TFV achieved by ~~mitigation. In extreme cases, the reduction in urban flood risks through adapting the drainage system is found to be~~ adaptation is five times more than that ~~through~~achieved by climate change mitigation (i.e., for the return periods of 2~~-10~~–3 years). ~~-~~Such effectiveness of ~~reducing~~ urban ~~floods~~flood reduction through ~~the designed adaptation measures~~drainage system adaptations has ~~great~~profound implications for ~~the~~ local ~~authority in~~governments charged with managing urban ~~flood risks~~flooding in the future. Notably, the second scenario (LID+pipe) ~~achieves~~exhibited a higher level of ~~risk~~flood volume reduction than the pipe scenario ~~across all~~in coping with extreme rainfall events for all investigated return periods. This implies that implementation of LID measures to augment drainage system capacity is more effective ~~from the hydrological perspective by~~through reducing upstream loadings ~~when~~ compared to ~~adapting~~updating the pipe system alone.

~~Uncertainty~~It is noted that local soil characteristics could affect the performance of the designed adaptation systems, in particular the LID measures. However, information about soil properties was not available at the subcatchment level in the study region. Here, a set of sensitivity experiments were conducted by adopting different parameters (e.g., infiltration values) associated with possible soil conditions (i.e., dry sand, loam, and clay soils with little or no vegetation in Table 1) for the area. The boundary bars in Figure 7 show the uncertainty range arising from the representation of different soil conditions in the drainage model. The benefits of the designed adaptation measures in reducing urban flood volumes were found to be robust regardless of soil conditions, and such benefits exceeded those of climate change mitigation, confirming our major conclusions found in this study.

4. Uncertainties and Limitations

~~There are a~~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~~ and limitations arise from the model structure~~/parameters of the drainage model~~, parameter inputs, emission scenarios, GCMs, climate downscaling/bias-correction approaches, etc. Specifically, climate projections by GCMs are subject to ~~significant~~large uncertainties, in particular regarding precipitation (Covey et al., 2003~~). Precipitation from~~) at spatial scales, which are relevant for urban flood modelling. An alternative approach is to simulate future climate using a regional climate model (RCM) nested within a GCM. Such climate projections by RCMs have added value in terms of higher spatial resolution, which can provide more detailed regional climate information. However, various levels of bias would still remain in RCM simulations (Teutschbein and Seibert 2012) and bias corrections of RCM projections would be required; e.g., the European project ENSEMBLES (Hewitt and Griggs 2004; Christensen et al. 2008). To run a RCM was not within the scope of this study; instead, we tended to use publicly available climate projections. Here, we obtained the climate projections from the ISI-MIP (Warszawski et al. 2014), which provides spatially downscaled climate data for impact models. The climate projections were also bias-corrected against observations (Hempel et al. 2013) and have been widely used in climate change impact studies on hydrological extremes such as floods and droughts (e.g., Dankers et al. 2014; Prudhomme et al. 2014; Leng et al. 2015a). It should be noted that we used the delta change factor to derive future climate scenarios as inputs into our drainage model instead of using GCM climate directly. This is because the relative climate change signal simulated by 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~~ is argued to be more reliable than the simulated absolute values (Ho et al. 2012). Moreover, we used an ensemble of GCM simulations rather than one single climate model in order to characterise the uncertainty range arising from ~~GCMs to the observed time series. Then, changes in urban flood risks are investigated using observed and adjusted climate data. Disadvantages~~climate projections. However, disadvantages of this method ~~lie in~~are 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). Such sources of uncertainty can be explored when improved climate models at finer scales become available (Jaramillo and Nazemi 2017).

~~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~~

In addition, the SIF parameters were assumed to remain stable in the future and only changes in the daily mean intensity were considered, because future sub-hourly climate projections were not readily available. The full climate variability range would also be under-sampled, although we used five climate models to show the possible range. Given the above limitations, we acknowledge that the modelling results represent the first-order potential climate change impacts on urban floods. Future efforts should be devoted to the representation of dynamic rainfall changes at hourly time steps with consideration of non-stationary climate change.

Moreover, several assumptions had to be made due to limitations of the current modelling structure and approach. For example, the conveyance capacities of the drainage system and flood volume would largely depend on the state of drainage systems. Hence, a drainage system obstructed by vegetation, waste, or artefacts (cables, pipes, temporary constructions) can make the outcomes of the SWMM calculation significantly different from observations. However, quantifying the impacts of drainage system states on urban flood volumes is not trivial because of the difficulties involved in collecting field data and selecting and using appropriate methods for reasonable assessment of pipe conditions (Ana and Bauwens, 2007; Fenner, 2000), and was not within the scope of this study. With deterioration, such as ageing network, pipe deterioration, blockage, and construction failures, drainage systems were shown to become more vulnerable to extreme rainfalls as demonstrated in previous studies (Dawson et al., 2008; CIRIA, 1997; Davies et al., 2001). It is very likely that our simulated urban flood volumes would be underestimated without considering the changes in drainage conditions (Pollert et al., 2005).

Further, constrained by the one-dimensional modelling approach using SWMM, the performances of LID measures were mainly evaluated according to their effects in reducing water volume from overloaded manholes (Oraei Zare et al., 2012; Lee et al., 2013). That is, the LID adaptation measure was mainly designed to reduce the amount of water rather than slowing down the water speed, which has been demonstrated to be effective in reducing urban floods (Messner et al., 2006; Ashley et al., 2007; Floodsite, 2009). However, it should be noted that most LID measures can reduce runoff volume and flow speed at the same time, although some of the LID measures are primarily designed to slow down the flow speed, i.e., vegetated swales. To examine whether flood retention of a given event is induced by runoff volume or the internal speed control function in the model is difficult and requires detailed data for model validations. Specifically, the required information about 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~~roughness, soil conductivity, and seepage rate were unavailable at the subcatchment scale in the study region. Therefore, a simplified ~~modeling~~modelling approach was used to take advantage of existing data~~. In a situation where~~, especially for the design of LID measures. With the aid of more detailed ~~case study~~field data and planning documents~~ are accessible~~, the design of LID ~~modeling should~~measures could be significantly improved by implementing more advanced approaches (Elliott and Trowsdale, 2007; Zoppou, 2001). Evaluation of ~~additional~~ other potential adaptation strategies, such as flood retention by rain gardens and green roofs, ~~needs to~~can be explored in the future to gain ~~a more comprehensive understanding~~additional insights into the performance of LID systems. In particular, the cost-effectiveness of the proposed adaptation measures ~~needs to~~should be ~~examined to better understand the feasibility of different adaptation scenarios~~accounted for. Nevertheless, given these limitations, this study stands out from previous climate impact assessment studies ~~on~~of urban ~~floods~~flood volumes by ~~proposing~~having proposed two feasible ~~adaptations~~adaptation strategies and ~~compare~~compared their benefits to ~~that~~those from ~~the~~ global-scale climate change mitigations through GHG ~~mitigation~~reductions within a consistent framework. Depending on the progress on data collection and the demands of local authorities, more advanced methods for pipe assessment (e.g., considering the changing pipe conditions), LID measures (detailed modelling of LID control), and two-dimensional surface flooding for assessment of flood damage and risk are planned in a future study to provide a more comprehensive analysis of the adaptation measures.

5. Summary and Conclusions

~~In~~The potential impacts of future climate change on current urban drainage systems have received increasing attention during recent ~~year, more~~decades because of the devastating impacts of urban flooding on the economy and ~~more studies on the improvement/adaptation of existing drainage systems in response to climate change have emerged~~society (Chang et al., 2013; Zhou et al., 2012; Abdellatif et al., 2015). ~~Despite these efforts on examining the~~ However, few studies have explored the role of both 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~~ drainage adaptations in coping with urban flooding in a changing climate. This study ~~assesses potential urban flood risks~~investigated the performance of a drainage system in a typical city in Northern China in response to various future ~~climate change in a typical urban area (Hohhot City), North of China~~scenarios. In particular, we ~~focus on~~assessed the potential changes in ~~future~~ urban flood ~~risks under various~~volume and explored the role of both mitigation and adaptation ~~scenarios~~in reducing urban flood volumes in a consistent ~~evaluation framework~~manner.

~~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,~~

Our results show significant increases in urban flood ~~risks are projected~~volumes due to ~~intensified~~increases in precipitation ~~for all investigated return periods~~extremes, especially for return periods ~~lower~~of less than 10 years. Overall, ~~floods risks are~~ urban flood volume in the study region is projected to increase by 52% ~~under~~by 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~~volume can be reduced considerably by climate ~~mitigations~~ change mitigation through ~~reducing~~reduction of GHG emissions. For example, the ~~risks for 1-yr~~future TFVs under 1-year extreme rainfall events can be reduced by 50% ~~by switching the climate scenario from RCP8.5 to RCP2.6, demonstrating the benefits of GHG mitigations.~~

when climate change mitigation is in place. Besides ~~the~~ global-scale ~~efforts of GHG mitigations~~climate change mitigation, regional/local ~~adaptations~~adaptation can be implemented to ~~reduce~~cope with the adverse impacts of future climate change on ~~local floods~~urban flood volumes. Here, ~~we~~the adaptation measures as designed in this study were demonstrated ~~the value~~

~~of adaptation measures by designing two alternative scenarios and compare their effectiveness to that of GHG mitigation. We found that the designed adaptation scenarios are~~to be much more effective in reducing future flood ~~risks, through which the achieved risk reduction is~~ volumes than climate change mitigation measures. In general, the reduced flood volumes achieved by adaptation were more than double ~~the level that can be~~those 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~~by 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.~~ change mitigation.

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~~provides much-needed insights into urban flood management for similar urban areas in China, most of which are equipped with highly insufficient drainage capacities. By comparing the reduction of flood volume by climate change mitigation (via reduction of GHG emissions) and local adaptation (via improvement of drainage systems), this study highlights the effectiveness of system adaptations in reducing future flood volumes. This has important implications for the research community and decision-~~making for better managing urban floods and emphasize~~makers involved in urban flood management. We emphasise the importance of accounting for both global-scale ~~GHG~~climate change mitigation and local-scale adaptation in assessing future climate impacts on urban flood ~~risks in~~volumes within a consistent framework.

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Table 1 Infiltration parameters for three categories of soil in the SWMM simulation

Soil category	Infiltration parameters			
	MaxRate	MinRate	Decay rate	DryTime
	[in/hr]	[in/hr]	[1/hr]	[days]
Dry loam with little or no vegetation	3	0.5	4	7
Dry sand with little or no vegetation	5	0.7	5	5
Dry clay with little or no vegetation	1	~~2~~0.3	3	~~10~~9

Table 2 Projected changes in precipitation intensity under return periods ranging from 1 year to 1000 years 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	1.2	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	1.1	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
MIROC-ESM-CHEM	RCP8.5	2.13	1.38	1.3	1.51	1.32	1.23	1.17	1.27	1.16	1.31
	RCP2.6	0.71	1.12	1.14	1.18	1.1	1.07	1.01	1.09	1.01	1.09
NorESM1-M	RCP8.5	2.11	0.96	0.8	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	1.1	1.18	1.09	1.2

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Figure 4 Comparison of (a) flood ~~damage (a) and risk~~volume, (b) total TFVs (i.e., the piece-wise integral of flood volume versus the expected frequency with changes in precipitation intensity of various return periods under RCP8.5 (blue) and RCP2.6 (red~~), and~~). (c) is for the ~~avoided impacts~~reduced TFVs in percentage (i.e., benefits of climate mitigation) in ~~terms of risk reductions under~~ RCP2.6 relative to RCP8.5 ~~(c).~~at various return periods.

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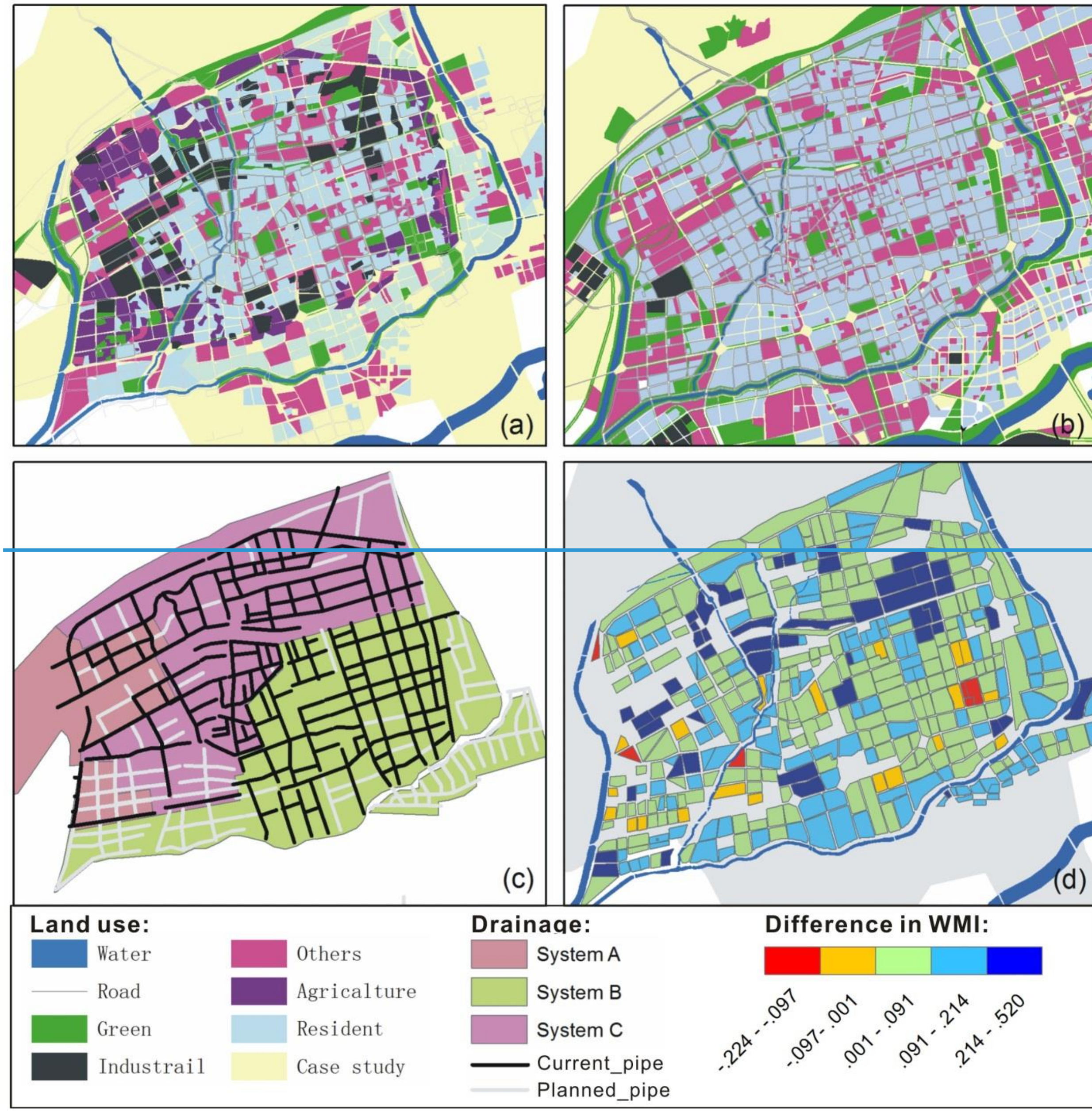
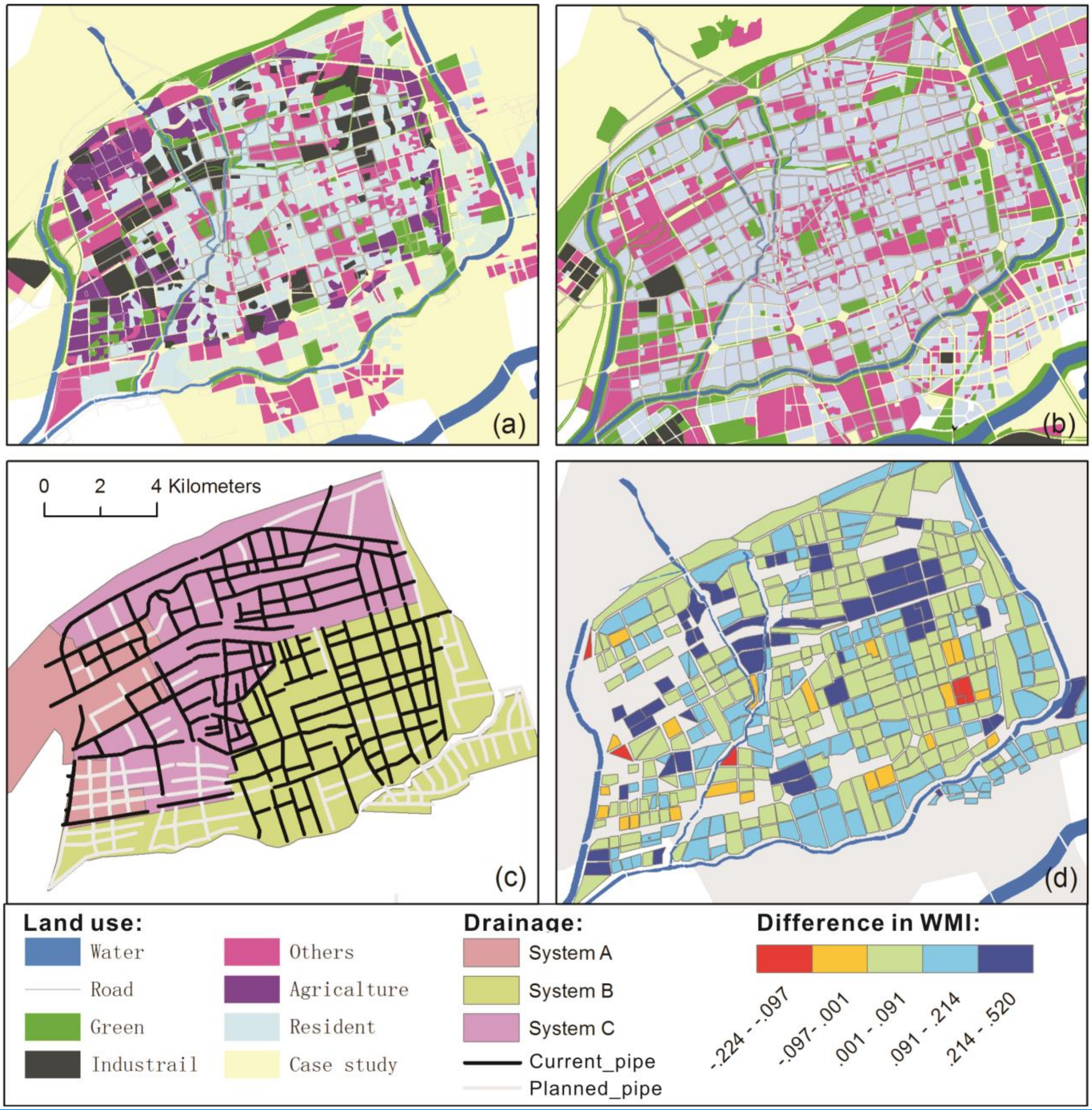

(a)
(b)
(c)
(d)
Land use:
Water
Road
Green
Industrail
Others
Agricalture
Resident
Case study
Drainage:
System A
System B
System C
Current_pipe
Planned_pipe
Difference in WMI:
-.224 - -.097
-.097- .001
.001 - .091
.091 - .214
.214 - .520



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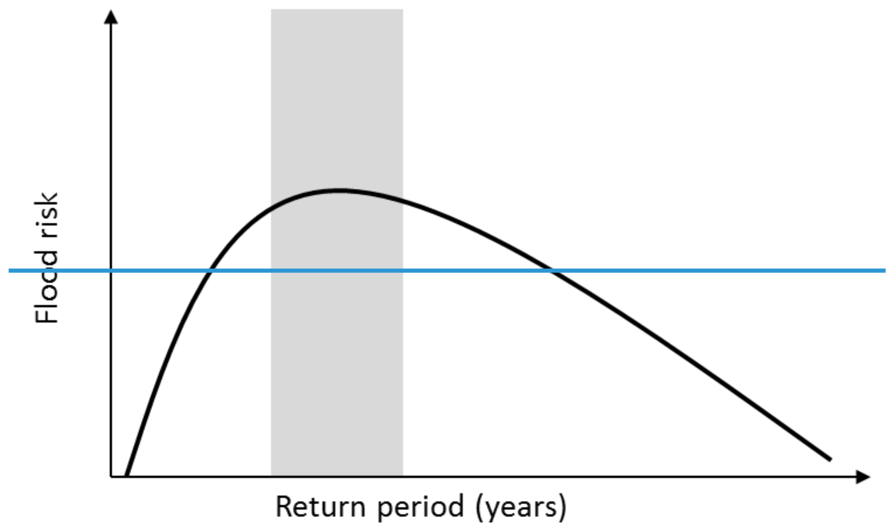

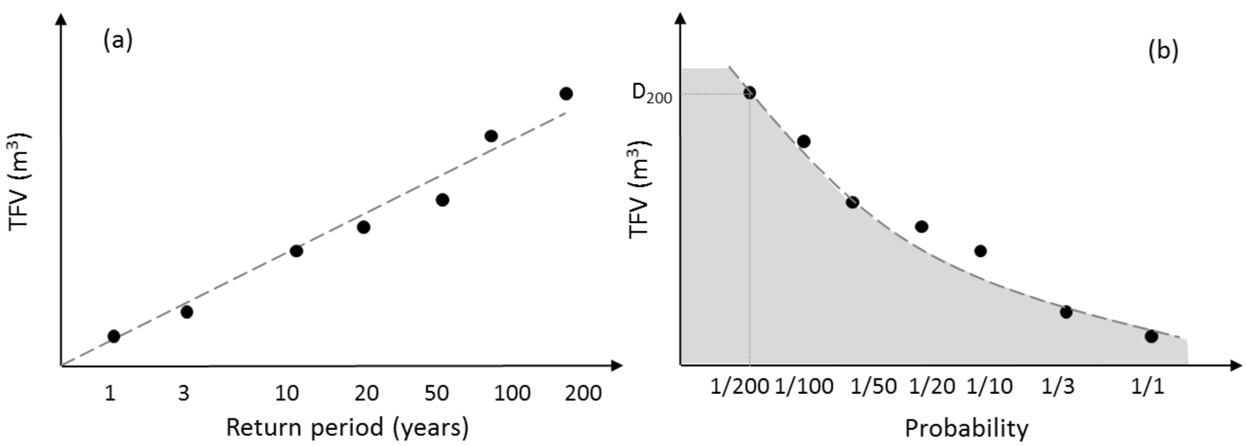

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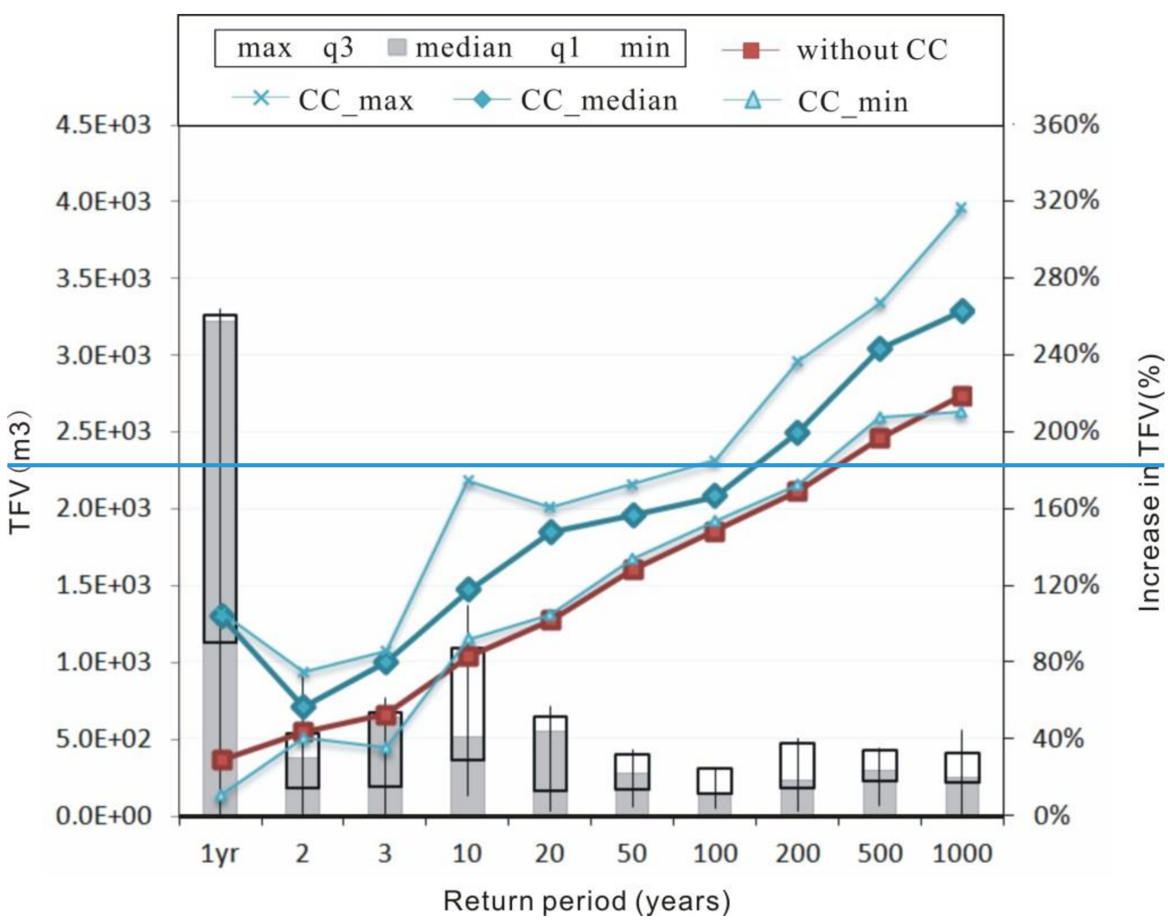
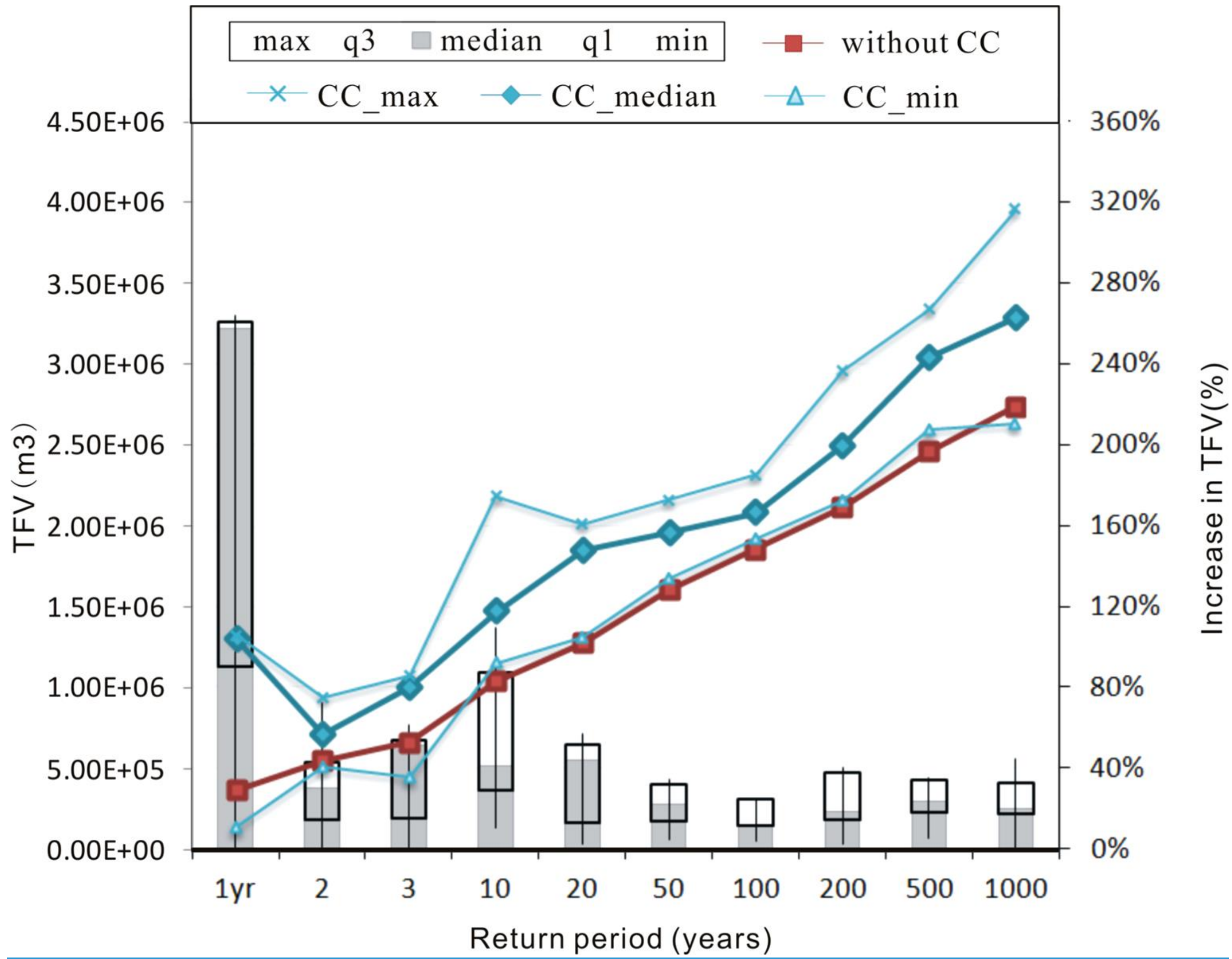

max q3 median q1 min
without CC
CC_max
CC_median
CC_min
TFV (m3)
Increase in TFV(%)
Return period (years)
4.5E+03
4.0E+03
3.5E+03
3.0E+03
2.5E+03
2.0E+03
1.5E+03
1.0E+03
5.0E+02
0.0E+00
360%
320%
280%
240%
200%
160%
120%
80%
40%
0%
1yr
2
3
10
20
50
100
200
500
1000



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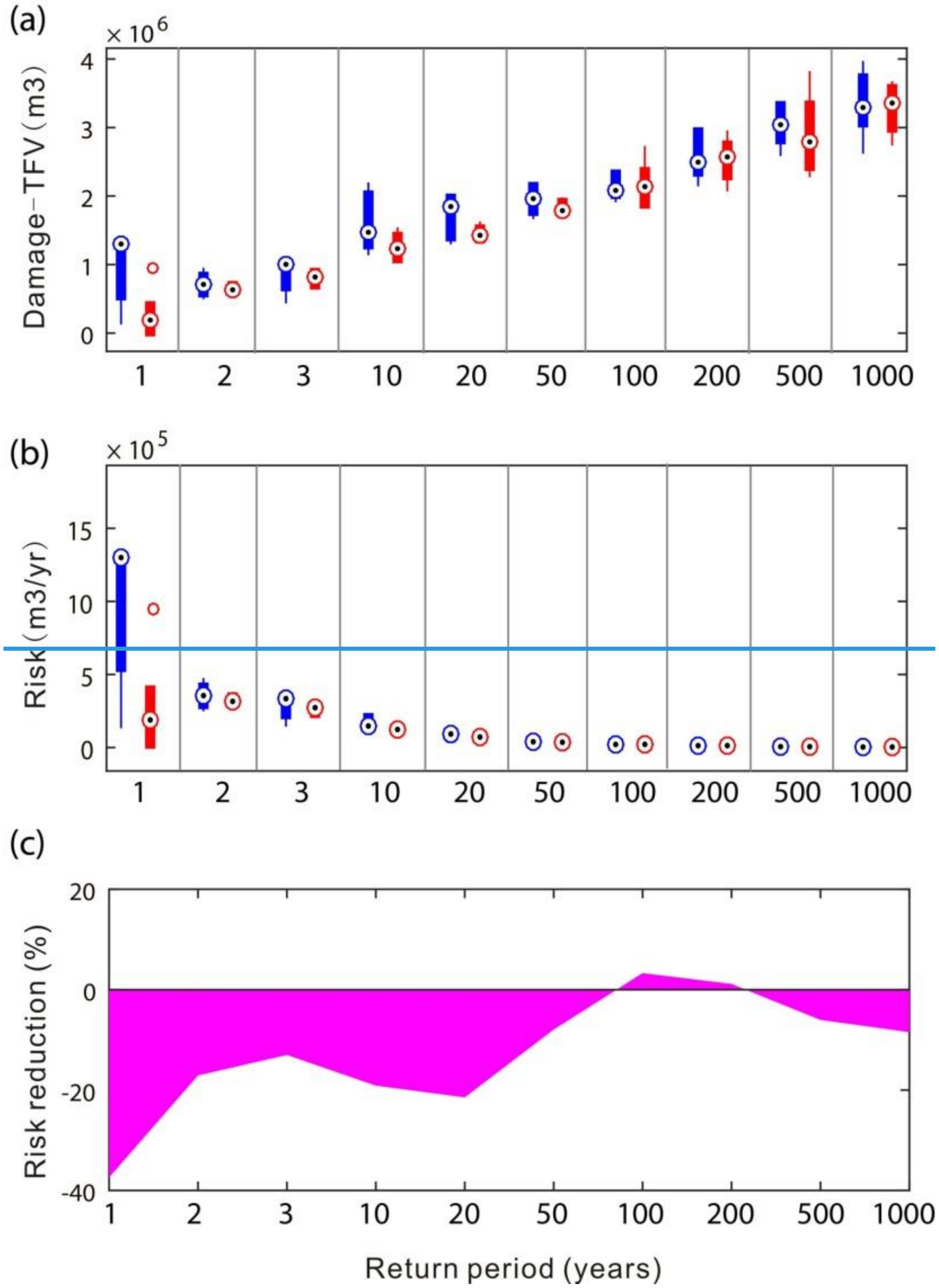
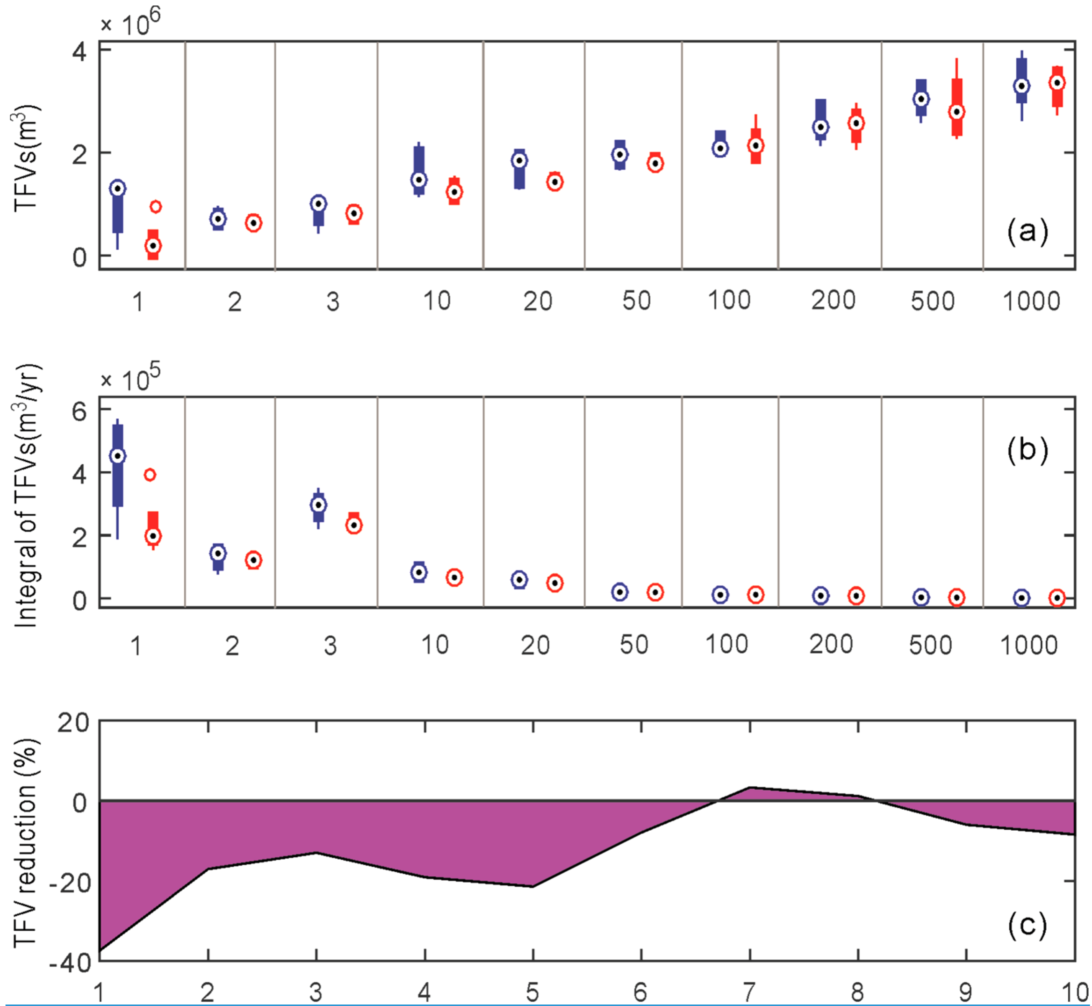

(a)
× 10^6
Damage−TFV（m3)
0
1
2
3
4
1
2
3
10
20
50
100
200
500
1000
(b)
× 10^5
Risk（m3/yr)
0
5
10
15
1
2
3
10
20
50
100
200
500
1000
(c)
Risk reduction (%)
20
0
-20
-40
1
2
3
10
20
50
100
200
500
1000
Return period (years)



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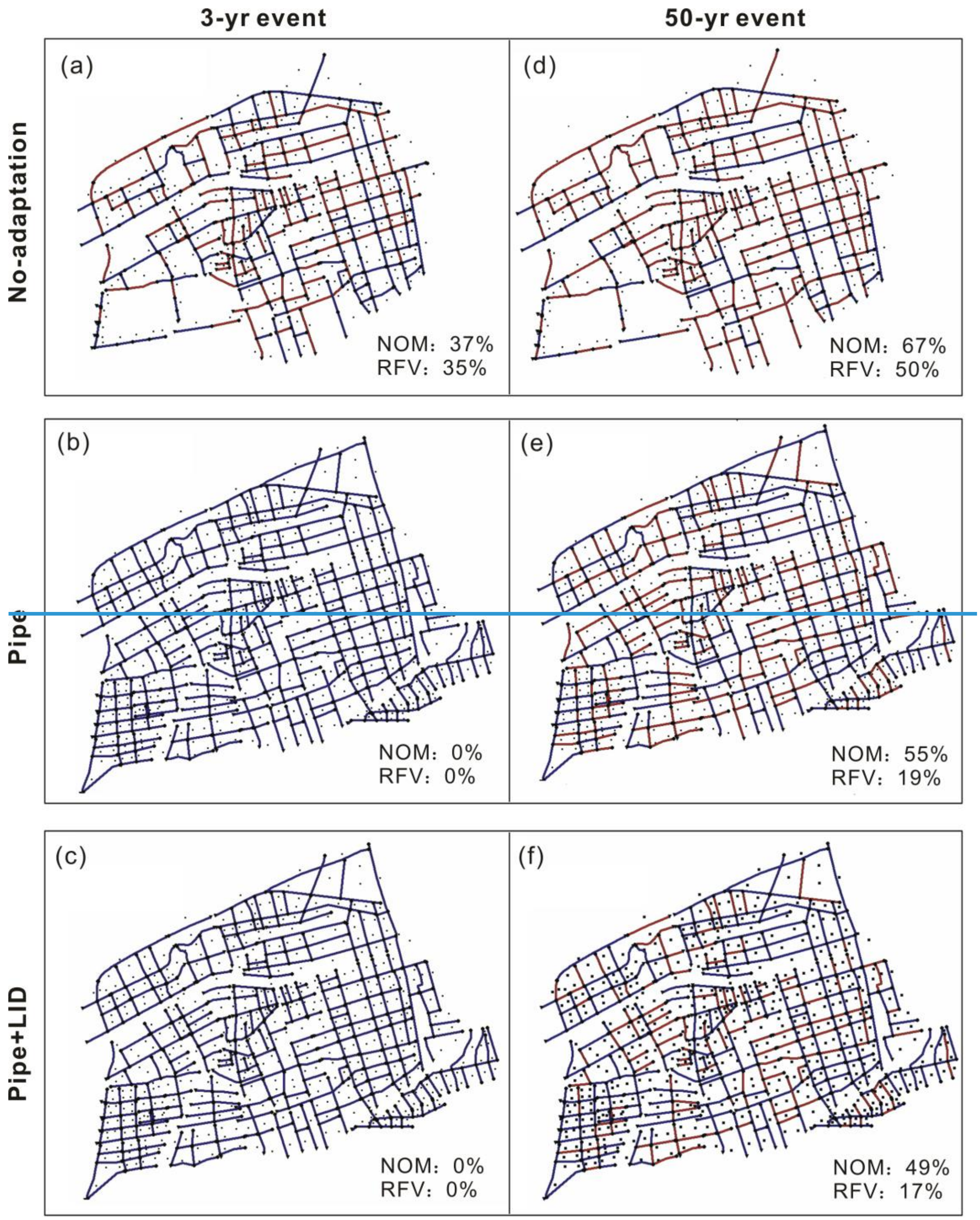
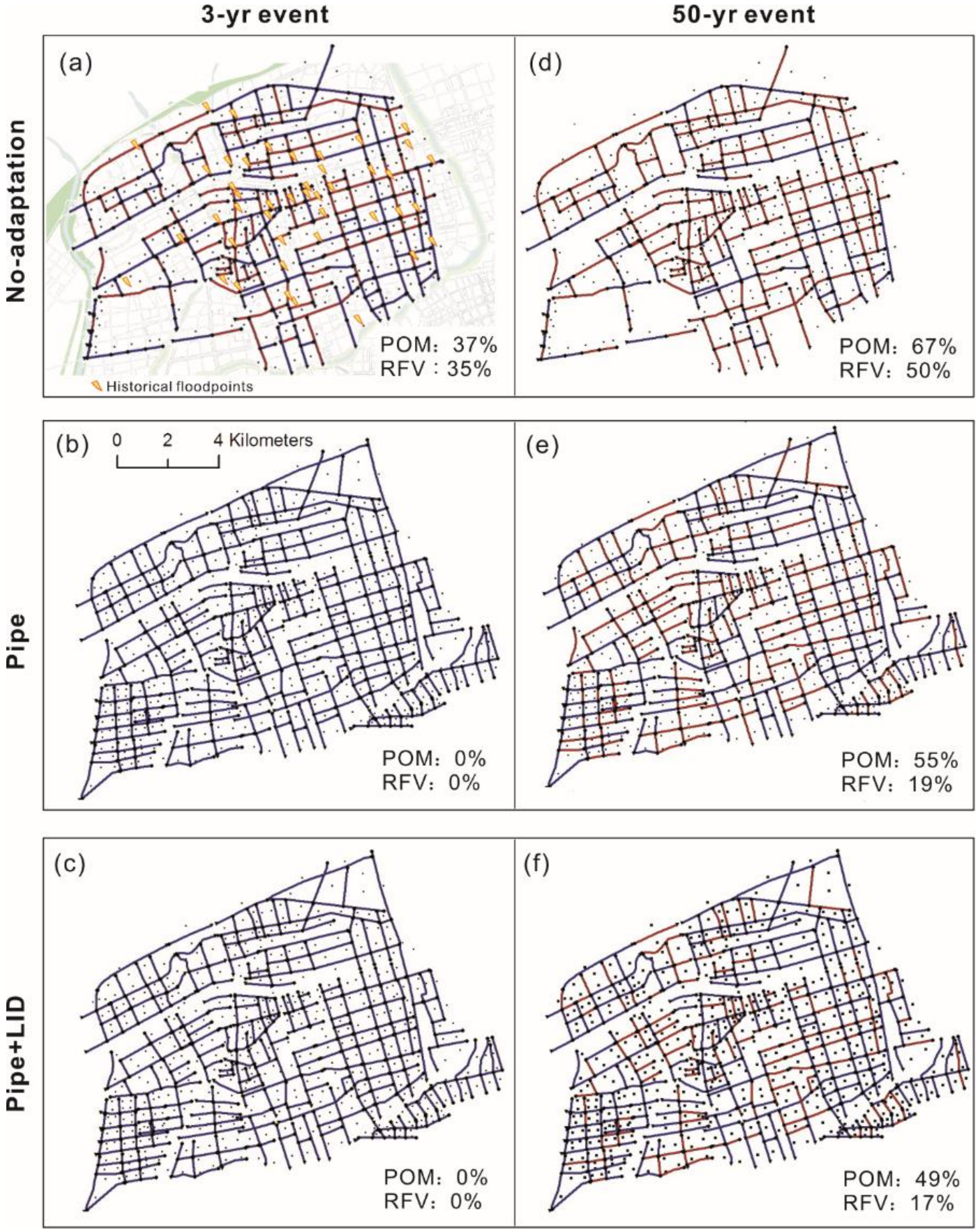

3-yr event
50-yr event
No-adaptation
Pipe
Pipe+LID
(a)
NOM：37%
RFV：35%
(b)
NOM：0%
RFV：0%
(c)
NOM：0%
RFV：0%
(d)
NOM：67%
RFV：50%
(e)
NOM：55%
RFV：19%
(f)
NOM：49%
RFV：17%



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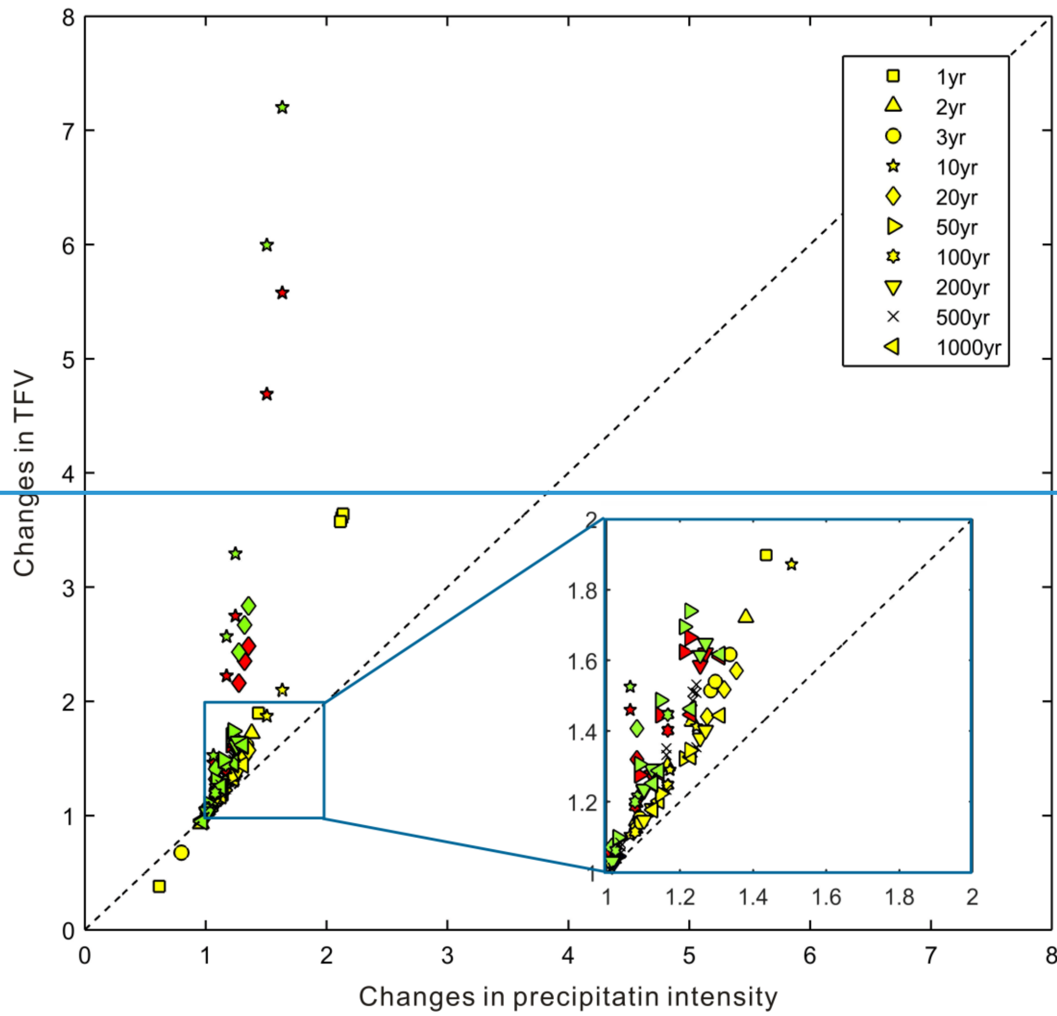
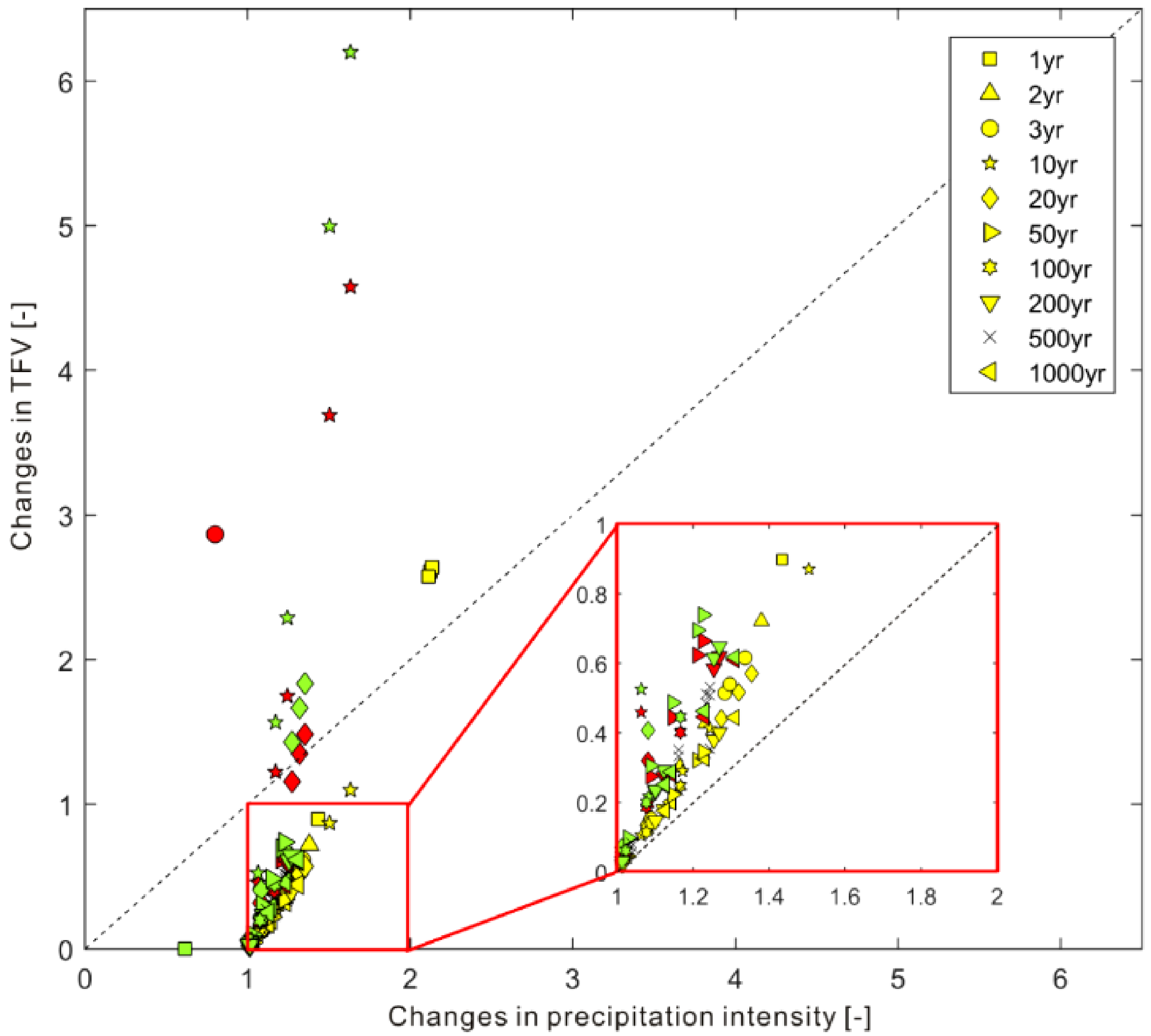

Changes in TFV
Changes in precipitatin intensity
1yr
2yr
3yr
10yr
20yr
50yr
100yr
200yr
500yr
1000yr



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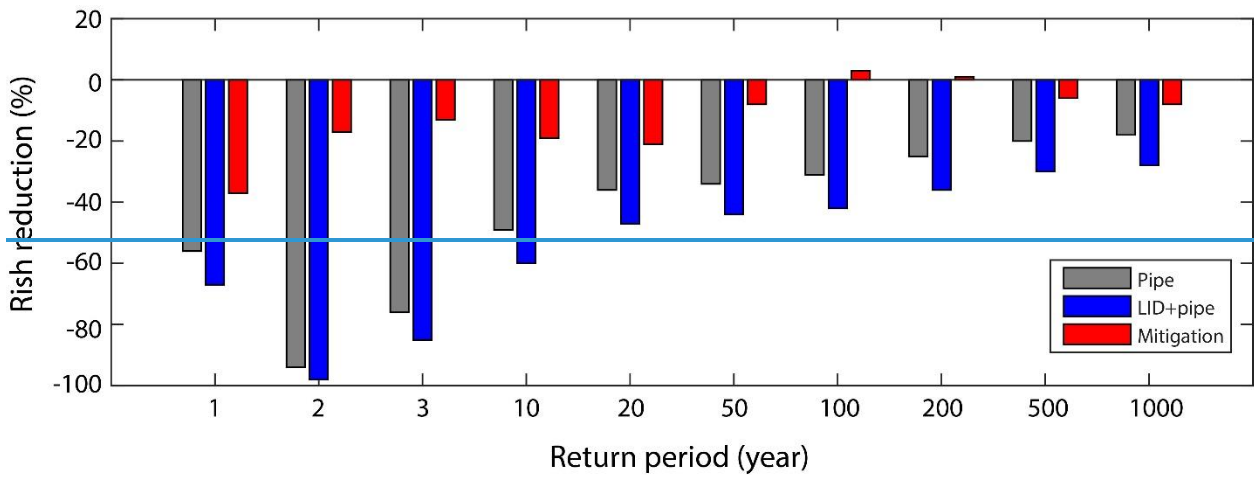
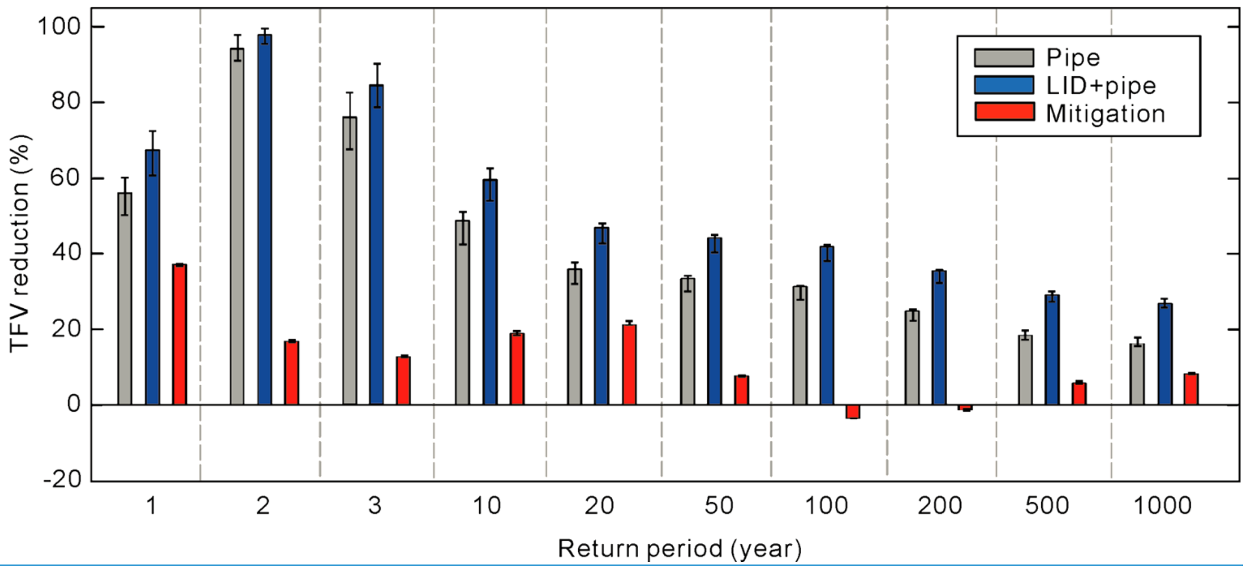

Rish reduction (%)
Return period (year)
Pipe
LID+pipe
Mitigation
20
0
-20
-40
-60
-80
-100
1
2
3
10
20
50
100
200
500
1000



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