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6 # Impacts of future climate change on urban flood volumes in Hohhot City

7 ## in Northern China: benefits of climate mitigation and adaptations

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Contents

67

Abstract

69   The author would like to thank all reviewers for their dedicated time reviewing the manuscript

70   and for their useful and constructive suggestions. All comments by the reviewers were carefully

71   addressed and the manuscript has substantially benefited from the proposed changes. Here

72   below, the author would like to clarify the changes regarding all comments, which are repeated

73 in grey boxes. The following convention is applied to denote modification in the original
74 manuscript: new text.

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1 Reviewer #1

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Reviewer #1 Comment 1

I see that the authors made a substantial revision of the article by addressing most of my
previous comments. I think the article can become suitable for publication, provided that the
comments below are adequately addressed.

80 **Response**

81 We greatly appreciates the reviewer for the thoughtful and encouraging comments on this
82 manuscript. In the revision, we have tried our best to address the comments. More details of
83 response to each specific comment are provided below.

84

Reviewer #1 Comment 2

Line 154: As I said in the previous review, please remove "all", as there are more than five
GCMs in CMIP5.

85 **Response**

86 Thanks for your suggestion. We have removed "all" in the revision.

87

Reviewer #1 Comment 3

Line 227: There is currently no information nor figures/tables on the outcomes of the
goodness of fit tests, hence I suggest to mention at least some quantitative results in the text.

88 **Response**

89 Thanks for your comments. Please note that our test returns a decision for the null hypothesis of

90 an extreme value distribution rather than a quantitative value, based on MATLAB tool

91 (https://www.mathworks.com/help/stats/adtest.html). Results show that our test fails to reject the

92 null hypothesis at the 5% significance level, suggesting that the fitted extreme value distribution

93 could be used to describe the extreme precipitation distribution in the study region.

94 In the revision, the sentence "The goodness-of-fit was tested by calculating the Kolmogorov–

95 Smirnov and Anderson–Darling statistics" was revised to

96 Kolmogorov–Smirnov and Anderson–Darling statistics show that the hypothesis regarding

97 the extreme value distribution is not rejected. That is, the fitted distribution could be well

98 used to describe the extreme precipitation distribution in the study region.

99

> ### Reviewer #1 Comment 4
>
> Line 381: "boundary bars" are commonly referred to as "whiskers".

100 **Response**

101 Thanks for your comments. In the revision, we have changed "boundary bars" to "whiskers".

102

> ### Reviewer #1 Comment 5
>
> Figure 3: In this figure it is not clear which lines/bars refer to TFV and which other to the
> percent increase. Please clarify in the legend (and/or in the caption).

103 **Response**

104 Thanks for your comments. We have re-plotted the figure and added more descriptions in the

105 figure caption. Please check the updated figure and caption below.

106
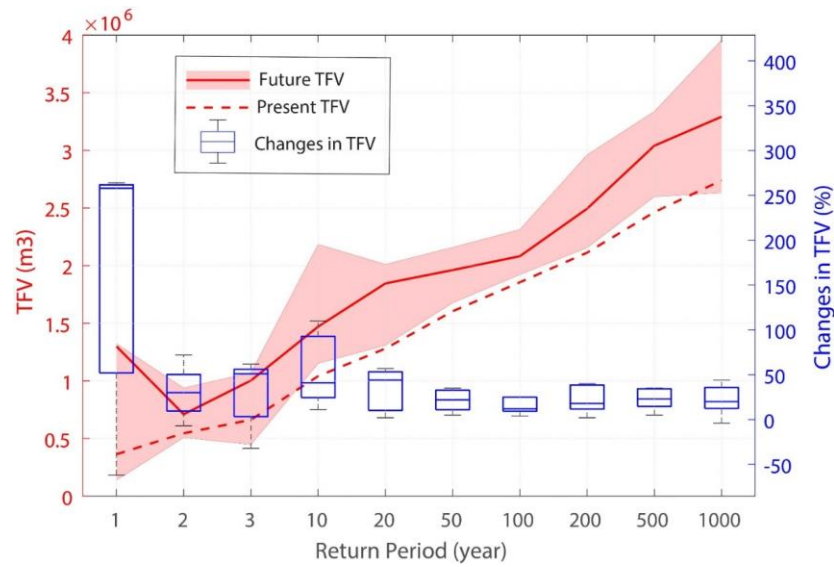
Figure 3 Changes in total flood volume (TFV) as a function of precipitation intensity at various return periods under RCP8.5 scenario without mitigation and adaptations. Red solid line represents the multi-model ensemble median TFV with shaded areas denoting the ensemble range. Red dashed line is the TFV under present condition. Box plots show the relative changes in TFV by 2020–2040 relative to present condition. Box edges illustrate the 25th and 75th percentile, the central mark is the median and whiskers mark the 5th and 95th percentiles.

129
130 **2 Reviewer #2**
131

Reviewer #2 Comment 1

In this paper, the authors assessed the benefits of mitigating climate change by reducing greenhouse gas emissions and locally adapting to climate change by modifying drainage systems to reduce urban flooding under various climate change scenarios through a case study conducted in Northern China. As the authors commented, this study accounted for the effects of both climate change mitigation and adaptation together in a consistent framework different from previous studies related to this issue. It would be the most important research outcome of this paper.

Now, the paper presents specific and easily identifiable advance in knowledge, which can be usefully applicable to the profession. With the subject within the scope of the journal, the authors describe the paper's research purpose, main findings, and conclusions in a more concise way. However, I have still several concerns about the paper's method, data, results and conclusions, which need to be modified for final publication.

132 **Response**

133 We greatly appreciates the reviewer for the thoughtful and encouraging comments on this

134 manuscript. In the revision, we have tried our best to address the comments. More details of

135 response to each specific comment are provided below.

136

137 Note: line numbers in the response refer to those in the cleaned version of manuscript.

6

138

Reviewer #2 Comment 2

Cost-effectiveness Issue: The authors compared the reduced total flood volumes by climate change mitigation and drainage system adaptation as functions of return period in Figure 7. From this result, the authors highlight the effectiveness of system adaptations in reducing future flood volumes and comment that this has important implications for the research community and decision-makers involved in urban flood management in the 'Summary and Conclusions' part. Because this study only focused on the future changes in urban flood volume followed by the applied different scenarios, there still remains a limitation of this study related to 'cost-effectiveness issue'. In the 'Uncertainties and Limitations' part, the authors added a sentence in lines 453-454 but it seems not enough to explain the limitation of this study. Of course, there are already many meaningful discussions in the 'Uncertainties and Limitations' part but I think the main discussion issue of this part should be 'cost effectiveness' with valuable references.

139 **Response**

140 Thanks for your comments. We agree that a limitation of this study is lack of assessment of costs
141 and benefits of adaptation measures from the economic perspective. In the revision, we have
142 added the following discussions in lines 454-465.

143 In particular, the cost-effectiveness of the proposed adaptation measures should be
144 accounted for. Indeed, a major limitation of this study is lack of assessment of costs and
145 benefits of adaptation measures from the economic perspective. In fact, besides the
146 effectiveness of proposed adaptation measures in reducing flood volume, assessment of the
147 associated economic costs is essential for flood risk management (Rojas et al., 2013; Veith
148 et al., 2003; Hinkel et al., 2014; Aerts et al., 2014; Ward et al., 2017). For example, Ward
149 et al. (2017) showed that investments in urban flood protections with dykes are not
150 economically attractive everywhere. Higher investment and maintenance costs may
151 prohibit the implementation of adaptation strategies as proposed in this study. Future
152 efforts should therefore be devoted to building a framework for assessing the costs and
153 benefits of urban flood reduction measures and examine whether the reduced losses are
154 higher than the costs of investments and maintenance of these measures.

155

Reviewer #2 Comment 3

Introduction: The authors need to clarify each condition for other researchers' outcomes. Please pay careful attention to the summary of other researchers' outcomes. For example,

Lines 64-66: For example, in Danish design guidelines for urban drainage, a 30% and 40% increase in the precipitation intensity is expected for the 10-and 100-year return periods, respectively (Arnbjerg-Nielsen, 2012). I read this reference, Arnbjerg-Nielsen (2012). but there were research outcomes about the delta change for Denmark. It seems hard to figure out where this sentence is originated from.

156 **Response**

157 Thanks for your comments. We have revised this sentence to:

158 For example, Arnbjerg-Nielsen (2012) reported that the design intensities in Denmark are

159 projected to increase by 10-50% for return periods ranging from 2 to 100 years."

160

Reviewer #2 Comment 4

Lines 75-77: For example, Ashley et al. (2005) showed that flooding risks may increase by almost 30 times in comparison to current situations, and effective adaptation measures are required to cope with the increasing risks in the UK. Please refer to any information about flooding risks and current situations.

161 **Response**

162 Thanks for your comments. We have revised this sentence to:

163 For example, Ashley et al. (2005) showed that flood risk (i.e., occurrence of pluvial

164 flooding) in four UK catchments may increase by almost 30 times by 2080s compared to

165 current conditions around the year 2000, and effective adaptation measures are required to

166 cope with the increasing risks.

167

Lines 77-79: Larsen et al. (2009) estimated that future extreme one-hour precipitation will increase by 20%~60% throughout Europe. Please refer to more specific information about the future year.

168 **Response**

169 Thanks for your comments. We have revised this sentence to:

170 Larsen et al. (2009) estimated that future extreme one-hour precipitation will increase by

171 20%~60% throughout Europe by 2071–2100 relative to 1961–1990

172

Materials and Methods – a. Study region: The authors need to re-organize the structure of this part for helping readers understand the contents clearly (For example, 1) General comments; 2) Major flood event on 11 July 2016; 3) Necessity for adaptation policies; 4) Plan for the year 2020).

173
174 **Response**

175 Thanks for your comments. We have re-organized the structure of this sector following your

176 suggestions. Please check the revision in lines 121-146.

177

Materials and Methods – c. Urban drainage modeling: The authors need to summarize only important points, which are directly used for urban drainage modeling in the Storm Water Management Model. Please move several parts to the 'Supplementary Materials' or 'Appendix' part such as Table 1, Equations 1-4 and the related explanations?

178
179 **Response**

180 Thanks for your comments. In the revision, we have refined the methodology section and moved
181 Table 1, Equations 1-4 and related explanations to the Supplementary Materials following your
182 suggestion.
183

Reviewer #2 Comment 8

4-hour rainfall time series: Do the authors have any reasons for selecting 4-hour rainfall
time series in this study? In lines 223-224, the authors commented that the annual maximum
daily precipitation was determined for both historical and future periods.

184
185 **Response**

186 Thanks for your comments. In this study, a 4-hour rainfall time series was generated for each
187 return period at 10-minute interval. The duration of design rainfalls (i.e. 4-hour rainfall) is
188 selected based on the time of concentration (ToC) of the watershed in the study region, according
189 to the design principles as outlined in [Butler and Davies, 2010; Chow et al., 2013]. In the
190 revision, we have added the following explanations in Lines 197-200.
191 A 4-hour rainfall time series was generated for each return period at 10-minute intervals.
192 The duration of design rainfalls (i.e., 4-hour rainfall) is selected based on the time of
193 concentration (ToC) of the watershed in the study region, according to the design
194 principles as outlined in Butler and Davies (2010) and Chow et al. (2013).
195

196 Yes, the annual maximum daily precipitation was determined for both historical and future
197 periods. In this study, we used the delta change factor to derive future climate scenarios as inputs
198 into our flood drainage model. Specifically, for each year, the annual maximum daily
199 precipitation was determined for both historical and future periods. The generalised extreme
200 value (GEV) distribution was then fitted separately to the two sets of daily values (Coles 2001;
201 Katz et al. 2002). The goodness-of-fit was tested by calculating the Kolmogorov–Smirnov and
202 Anderson–Darling statistics. The value corresponding to each return period was estimated based
203 on the GEV distribution and the changes between future and historical periods were calculated as
204 the change factors. The derived change factor for each return period was then multiplied by the
205 historical design CDS rainfall time series to derive future climate scenarios as inputs into our

206 urban drainage model. This approach was adopted due to two reasons: 1) Future hourly rainfall
207 data is not readily available; 2) the relative climate change signal simulated by GCMs are argued
208 to be more reliable than the simulated absolute values (Ho et al. 2012).
209
210 More details can be found in the revised methodology section and supplementary materials.
211 Discussions on the methodology can also be found in the section "Uncertainties and Limitations"
212 in the revision.
213

Reviewer #2 Comment 9

Figure 2: The authors need to revise the explanation about Figure 2 (lines 236-245) and the
title of the Figure 2 for helping readers understand the contents in a more concise way.

214 **Response**
215 Thanks for your comments. We have added the following descriptions about Figure 2 in Lines
216 226-231, and the figure caption was also revised accordingly.
217   A log-linear relationship is assumed to characterize the changes in flood volume with the
218   increase in precipitation intensity as indicated by return periods (Figure 2a) following
219   Zhou et al. (2012) and Olsen et al. (2015). Generally, more TFV (i.e., system overloading)
220   is expected with increase in rainfall intensity. In Figure 2b, the TFVs were linked to their
221   specific occurrence probabilities. The total grey area under the curve denotes the TFVs
222   integrated across various return periods and represents the total expected TFVs per year.
223   The contribution of an individual flood event to total average TFVs is dependent not only
224   on the flood volume, but also its corresponding probability of occurrence.
225

Reviewer #2 Comment 10

Abbreviation: Please carefully use the word abbreviation. For example, Line 236: The TFV
-> The total flood volume (TFV); Line 282: climate change -> climate change (CC).

226 **Response**

227   Thanks for your comments. We have added the full names for these abbreviations in the revision.
228

> ### Reviewer #2 Comment 11
>
> Weighted mean imperviousness (WMI): Please define how to calculate the WMI.

229   **Response**

230   Thanks for your suggestion. The WMI of a subcatchment is calculated as the average of
231   impervious factors of all landuse types in the subcatchment, weighted by the area of landuse type
232   as follows:

233
$$\text{WMI} = \sum_i \text{IF}_i \times A_i \Big/ \sum_i A_i$$

234   Where IF_i and A_i are the impervious factor and area for land use type i, respectively.

235

236   In the revision, we have added the equation and explanations for calculating WMI in Lines 255-
237   261.

238

> ### Reviewer #2 Comment 12
>
> Figure 3: The authors need to revise the explanation about Figure 3 (lines 282-292) for
> helping readers understand the contents in a more concise way (for example, 1) max; 2)
> median; 3) min; 4) multi-model ensemble median). ☐ 1yr -> 1

239   **Response**

240   Thanks for your comments. In the revision, we have re-plotted figure 3 and added more details in
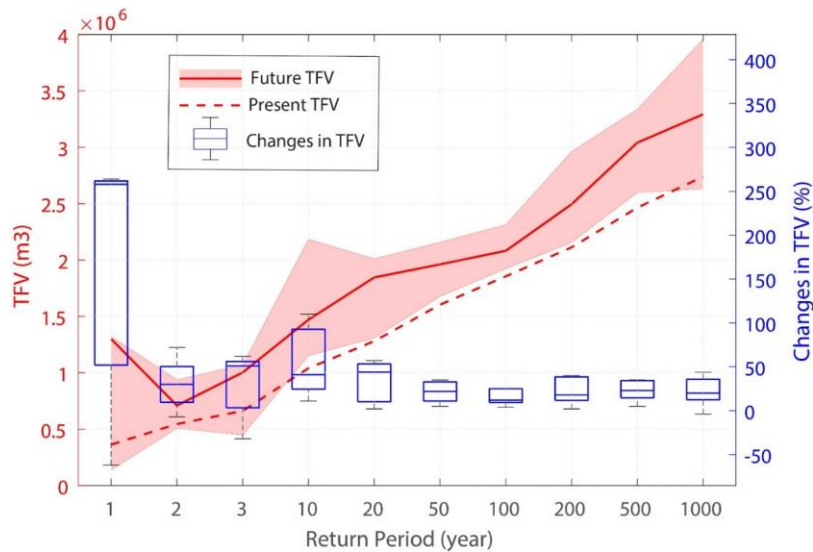241   the figure caption. Please check the updated figure below.

242

243

Figure 3 Changes in total flood volume (TFV) as a function of precipitation intensity at various

return periods under RCP8.5 scenario without mitigation and adaptation. Red solid line

represents the multi-model ensemble median TFV with shaded areas denoting the ensemble

range. Red dashed line is the TFV under present condition. Box plots show the relative changes

in TFV by 2020–2040 relative to present condition. Box edges illustrate the 25th and 75th

percentile, the central mark is the median and whiskers mark the 5th and 95th percentiles.

250

Reviewer #2 Comment 13

Figure 4: Please add the x-axis title

251 **Response**

252 Thanks for your suggestion. We have added the x-axis title in the revision.

253
254
255
256

Reviewer #2 Comment 14

Ratio of flood volume (RFV) in Figure 5: Please define how to calculate the RFV.

257 **Response**

258 Thanks for your suggestion. The RFV is defined as the ratio of flooded volume from overloaded

259 manholes to input rainfall volume. We have added the definition in the revision (Lines 304-305)

260 and revised the figure caption accordingly.

261

> #### Reviewer #2 Comment 15
>
> TFV reduction (%): Please define how to calculate the TFV reduction. In Figures 4 and 7,
> the readers can see the related results, mainly composed of negative and positive numbers,
> respectively. Especially, in Figure 7, the authors need to explain about the negative values
> for the return periods of 100 and 200 years.

262
263 **Response**

264 Thanks for your comments. The TFV reduction is calculated as the percentage difference in TFV

265 with mitigation or adaptation compared to that without mitigation or adaptation (i.e., $100 *$

266 $(TFV_{wo} - TFV_w)/TFV_{wo}$). Here, three scenarios including two adaptation strategies (i.e., Pipe

267 and Pipe+LID) and one climate mitigation are considered and the reduced TFV are inter-

268 compared among the three scenarios in Figure 7 to demonstrate that the proposed adaptation

269 strategies are more effective than climate mitigation in reducing future flooded volume.

270

271 In Figure 7, the grey, blue and red bars indicate the TFV reductions with two adaptation

272 strategies and climate mitigation, respectively. Positive values indicate that climate mitigation

273 and/or local adaptation are effective in reducing the system overloading, namely the TFVs, and

274 vice versa. It is shown that climate mitigation can lead to reduction of flood volume ranging

275 from 10 to 40% compared to the scenario without mitigation. Importantly, local adaptations are

276 more effective than climate mitigation in reducing flood volume, as indicated by the much larger

277 values of TFV reductions. As noted by the reviewer, there are minor negative values of TFV

278 reductions for the return period of 100 and 200 years under climate mitigation scenario. The

279 negative value is attributed to the slightly higher increase in precipitation intensity under climate

280 mitigation scenario (RCP26) than the scenario without mitigation (RCP85) as simulated by two

281 of five climate models (i.e., GFDL-ESM2m and NorESM1-M, see Table 1), which translates to a

14

282 slight increase in flood volume under climate mitigation scenario. This climate internal
283 variability is partly cancelled by other three climate models, thus leading to very minor negative
284 value when considering the multi-model ensemble mean. This calls for the improvement of
285 climate model performance and the use of more climate models (GCMs) to derive more robust
286 climate projections in the future.
287
288 In the revision, we have added relevant explanations and discussions in Lines 351-361.
289   Overall, climate mitigation can lead to a reduction of flood volume by 10-40% compared
290   to the scenario without mitigation. Notably, there are minor negative values of TFV
291   reductions for the return period of 100 and 200 years under climate mitigation scenario.
292   The negative value is attributed to the slightly higher increase in precipitation intensity
293   under climate mitigation scenario (i.e. RCP26) than the scenario without mitigation (i.e.
294   RCP85) simulated by two of five climate models (i.e., GFDL-ESM2m and NorESM1-M,
295   see Table 1), which translated to slightly larger flood volume under climate mitigation
296   scenario. This climate internal variability is partly cancelled by other three climate models,
297   thus leading to very minor negative value by the multi-model ensemble mean. This calls
298   for the use of more climate models (GCMs) to derive more robust projections in the future
299   studies.
300

Reviewer #2 Comment 16

Lines 83-85: There are already many journal papers related to this issue. The authors revise
the 'Introduction' part to emphasize the novelty of this study.

301
302 **Response**
303 Thanks for your comments. In the revision, we have revised the introduction to emphasize the
304 novelty of this study in Lines 85-93.
305   However, previous studies on the effects of climate change mitigation and adaptation are
306   typically conducted separately, and it is unclear which strategy is more effective in
307   reducing urban floods. This study aims to advance our understanding on urban floods
308   within the context of change climate, through investigating the benefits of climate change
309   mitigation (by reducing greenhouse gas emissions [GHG]) and local adaptation (by

310   improving drainage systems) in reducing future urban flood volumes in a consistent

311   framework.

312

Reviewer #2 Comment 17

Lines 122-123: Please add the related reference here.

313
314   **Response**

315   Thanks for your comments. We have added the related reference in the revision.

316

Reviewer #2 Comment 18

Lines 134-136: Please add the related reference here.

317
318   **Response**

319   Thanks for your comments. We have added the related reference in the revision.

320

Reviewer #2 Comment 19

Lines 200-202: Please add the related reference here.

321
322   **Response**

323   Thanks for your comments. We have added the related reference in the revision. Please note that

324   this paragraph is moved to supplementary materials following your suggestion #7.

325

Reviewer #2 Comment 20

Lines 251-255: If this explanation is about the adaptation plan for the year 2020, please
clarify the plan for the year 2020 in the 'Introduction' part and this part to help readers
understand the contents in a more concise way.

326
327   **Response**

328 Thanks for your comments. We have added relevant descriptions on this in Lines 113-115.

329 We then designed two plausible adaptation strategies for the study region and investigated

330 how much urban flood volume can be reduced with the adapted systems by 2020s. We also

331 compared the benefits of global-scale climate change mitigation and local adaptation in

332 reducing urban flood volumes to advance our understanding of the effective measures for

333 coping with future urban floods.

334

Reviewer #2 Comment 21

Lines 260-261: It seems better to start this paragraph with the explanation about the second adaptation scenario. The authors need to re-organize this paragraph.

335
336 **Response**

337 Thanks for your comments. We have added the following text in Lines 246-251.

338 The second adaptation scenario was designed to increase the permeable surfaces (e.g.,

339 green spaces) and reduce the regional imperviousness in the study region on the basis of

340 pipe capacity enhancement. This scenario is referred to as the Low Impact Development

341 (LID) scenario, and it was used to explore the effectiveness of urban green measures, such

342 as the use of permeable pavements, infiltration trenches, and green roofs. Changes in land

343 imperviousness in LID scenario have direct impacts on the performance of drainage system

344 in managing surface runoff.

345

Reviewer #2 Comment 22

Lines 269-272: Please give additional information on this part. It is hard to understand the meaning of this sentence.

346
347 **Response**

348 Thanks for your comments. We have added more details on this in Lines 255-262.

349 Due to a lack of detailed information about the permeable soil and coverage rates in the

350 study region, the effects of these specific measures cannot be modelled individually. Here,

351   we used a simplified approach by altering the subcatchment imperviousness to reflect the

352   combined effects of infiltration-related measures. We derived such information by

353   calculating the difference in land use type and imperviousness between the current and

354   planned city maps using a geographical information system (GIS). Figure 1d shows the

355   difference in weighted mean imperviousness ($WMI = \sum_i (IF_i \times A_i)/\sum_i A_i$, Where IF_i and

356   A_i is the impervious factor and area for land use type i, respectively.) for each

357   subcatchment in the current and planned maps, using the commonly applied impervious

358   factors (Pazwash, 2011; Butler and Davies, 2004) for each land use type. The difference in

359   WMI was used to indicate the potential for adaptation based on the city plan.

360

Reviewer #2 Comment 23

Lines 305-308: Please explain the main reason of these results with discussions.

361
362 **Response**

363 Thanks for your comments. We have added the following explanations and discussions in Lines

364 289-296.

365   Notably, the peak of the total TFV curve was projected to shift from the 1-year event under

366   the RCP8.5 scenario to the 3-year event under the RCP2.6 scenario (Figure 4b), indicating

367   a substantial reduction in the TFVs (especially at the 1-year return period) (Figure 4c). The

368   lower total TFVs under RCP2.6 scenario could be attributed to the smaller magnitude of

369   rainfall intensity than RCP8.5 scenario (Table 1), demonstrating the important role of

370   climate mitigation in reducing urban flood volumes. Overall, climate change mitigation

371   can reduce future flood volumes by 13% compared to the scenario without mitigation, as

372   indicated by the multi-model ensemble median.

373

Reviewer #2 Comment 24

Line 315: Please clarify where the historical flood points are.

374
375 **Response**

18

376 Thanks for your comments. The historical flood points are included in Figure 5a. We have

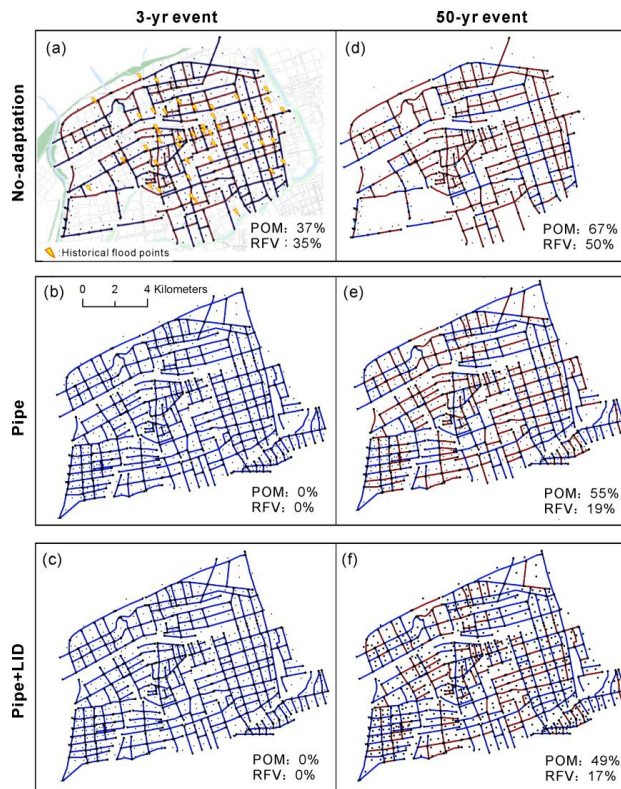377 revised the figure and clarified their locations in the figure caption.

378
379 **Figure 5** Spatial distribution of overloaded pipelines (red colour) induced by the 3-year (left
380 column) and 50-year extreme events (right column) without and with adaptations. The total
381 percentage of overloaded manholes (POM) and ratio of flood volume (RFV) to input rainfall
382 volume are summarised for each scenario. Historical flood points and local land use, mainly the
383 traffic network and green spaces, are shown in (a).

384
385
386
387 **Reference**

388 Aerts, J. C., Botzen, W. W., Emanuel, K., Lin, N., de Moel, H., & Michel-Kerjan, E. O. (2014).

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Impacts of future climate change on urban flood volumes in Hohhot City

in Northern China: benefits of climate mitigation and adaptations

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458 **Abstract**

459 As China has become increasingly urbanised, flooding has become a regular occurrence in its

460 major cities. Assessing the effects of future climate change on urban flood volumes is crucial to

461 informing better management of such disasters given the severity of the devastating impacts of

462 flooding (e.g., the 2016 flooding across China). Although recent studies have investigated the

463 impacts of future climate change on urban flooding, the effects of both climate change mitigation

464 and adaptation have rarely been accounted for together in a consistent framework. In this study,

465 we assess the benefits of mitigating climate change by reducing greenhouse gas emissions and

466 locally adapting to climate change by modifying drainage systems to reduce urban flooding

467 under various climate change scenarios through a case study conducted in Northern China. The

468 urban drainage model—Storm Water Management Model—was used to simulate urban flood

469 volumes using current and two adapted drainage systems (i.e., pipe enlargement and low-impact

470 development), driven by bias-corrected meteorological forcing from five general circulation

471 models in the Coupled Model Intercomparison Project Phase 5 archive. Results indicate that

472 urban flood volume is projected to increase by 52% in 2020–2040 compared to the volume in

473 1971–2000 under the business-as-usual scenario (i.e., Representative Concentration Pathway

474 (RCP) 8.5). The magnitudes of urban flood volumes are found to increase nonlinearly with

475 changes in precipitation intensity. On average, the projected flood volume under RCP 2.6 is 13%

476 less than that under RCP 8.5, demonstrating the benefits of global-scale climate change

477 mitigation efforts in reducing local urban flood volumes. Comparison of reduced flood volumes

478 between climate change mitigation and local adaptation (by improving the drainage system)

479 scenarios suggests that local adaptation is more effective than climate change mitigation in

480 reducing future flood volumes. This has broad implications for the research community relative

481 to drainage system design and modelling in a changing environment. This study highlights the

482 importance of accounting for local adaptation when coping with future urban floods.

483

484 **Keywords:** Climate change, urban floods, mitigation, adaptation, drainage systems

485

486 1.　　Introduction

487 Floods are one of the most hazardous and frequent disasters in urban areas and can cause

488 enormous impacts on the economy, environment, city infrastructure, and human society (Chang

489 et al., 2013; Ashley et al., 2007; Zhou et al., 2012). Urban drainage systems have been

490 constructed to provide carrying and conveyance capacities at a desired frequency to prevent

491 urban flooding. TheHowever, the design of drainage systems is generallyoften based on

492 historical precipitation statistics for a certain period of time, without considering the potential

493 changes in precipitation extremes for the designed return periods (Yazdanfar and Sharma, 2015;

494 Peng et al., 2015; Zahmatkesh et al., 2015). For example, in Danish design guidelines for urbanIt

495 is likely that drainage, a 30% and 40% increase in the precipitation intensity is expected for the

496 10- and 100-year return periods, respectively (Arnbjerg-Nielsen, 2012). The systems are,

497 however, likely towould be overwhelmed by additional runoff effects induced by climate change,

498 which may lead to increased flood frequency and magnitude, disruption of transportation

499 systems, and increased human health risk (Chang et al., 2013; Abdellatif et al., 2015). For

500 example, Arnbjerg-Nielsen (2012) reported that the design intensities in Denmark are projected

501 to increase by 10-50% for return periods ranging from 2 to 100 years. Therefore, it is important

502 to investigate the performance of drainage systems in a changing environment and to assess the

23

503 potential urban flooding under various scenarios to achieve better adaptations (Mishra, 2015;

504 Karamouz et al., 2013; Yazdanfar and Sharma, 2015; Notaro et al., 2015).

505

506 Impacts of climate change on extreme precipitation and urban flooding have been well

507 documented in a number of case studies. For example, Ashley et al. (2005) showed that flooding

508 risks (i.e., occurrence of pluvial floods) in four UK catchments may increase by almost 30 times

509 in comparisonby 2080s compared to current situationsconditions around the year 2000, and

510 effective adaptation measures are required to cope with the increasing risks in the UK. Larsen et

511 al. (2009) estimated that future extreme one-hour precipitation will increase by 20%~60%

512 throughout Europe. by 2071–2100 relative to 1961–1990. Willems (2013) found that in Belgium

513 the current design storm intensity for the 10-year return period is projected to increase by 50%

514 by the end of this century. Several studies have also investigated the role of climate change

515 mitigation andor adaptation in reducing urban flood damages and risks under climate change

516 scenarios (Alfieri et al., 2016; Arnbjerg-Nielsen et al., 2015; Moore et al., 2016; Poussin et al.,

517 2012). To date, however, limited work has been done to investigate theThe relationship between

518 changes in precipitation intensity and flood volume has also been well explored to provide

519 additional insights into drainage design strategies. More importantly, investigations (Olsson et al.,

520 2009; Willems et al., 2012; Zahmatkesh et al., 2015). However, previous studies on the effects of

521 climate change mitigation and adaptation are typically conducted separately, and it is unclear

522 which strategy is more effective in reducing urban floods. This study aims to advance our

523 understanding on urban floods within the context of change climate, through investigating the

524 benefits of climate change mitigation (by reducing greenhouse gas emissions [GHG]) and local

24

525 adaptation (by improving drainage systems) in reducing future urban flood volumes ~~are typically~~

526 ~~conducted separately, rather than within~~in a consistent framework.

527

528 As China has become increasingly urbanised, flooding has become a regular occurrence in its

529 cities; 62% of Chinese cities surveyed experienced floods and direct economic losses of up to

530 $100 billion between 2011 and 2014 (China Statistical Yearbook 2015). The 2016 flooding

531 affected more than 60 million people—more than 200 people were killed and $22 billion in

532 losses were suffered across China. Hence, assessing future changes in urban flooding is very

533 important for managing urban floods by designing new and re-designing existing urban

534 infrastructures to be resilient in response to the impacts of future climate change. While urban

535 floods are speculated to increase in the future (Yang 2000; Ding et al., 2006), their magnitudes

536 are hard to assess because of uncertainties associated with future climate change scenarios, as

537 well as the under-representation of plausible climate change mitigation and adaptation strategies

538 in the models.

539

540 In this study, we chose a drainage system in a typical city in Northern China to illustrate the role

541 of climate change mitigation and local adaptation in coping with future urban flood volumes.

542 Such an investigation of the performance of the present-day drainage system also has important

543 implications for local governments responsible for managing urban flood disasters in the study

544 region. Specifically, we first quantified the effects of future climate change on urban flood

545 volumes as a result of extreme precipitation events for various return periods using the present-

546 day drainage system. We then designed two plausible adaptation strategies for the study region

547 and investigated how much urban flood volume can be reduced ~~by~~with the adapted systems by

548   2020s. We also compared the benefits of global-scale climate change mitigation and local

549   adaptation in reducing urban flood volumes to advance our understanding of the effective

550   measures for coping with future urban floods.

551

552   2.   Materials and Methods

553   a.   Study region

554   The study region (Hohhot City) is located in the south-central portion of Inner Mongolia, China.

555   It lies between the Great Blue Mountains to the north and the Hetao Plateau to the south, which

556   has a north-to-south topographic gradient. The region is in a cold semi-arid climate zone,

557   characterised by cold and dry winters and hot and humid summers. The regional annual mean

558   precipitation is approximately 396 mm with large intra-seasonal variations. Most rain storms fall

559   between June and August, a period that accounts for more than 65% of the annual precipitation.

560   The drainage area in year 2010 was about 210.72 km^2 and it served a residential population of

561   1.793 million (Figure 1a). The land use types in the region can be classified into five categories:

562   agricultural land (8%), residential areas (38%), industrial land (13%), green spaces (7%), and

563   other facilities (34%, including municipal squares, commercial districts, institutions). The

564   planned drainage area in 2020 is about 307.83 km^2, which is 50% larger than the current

565   drainage area. The land use categories and distribution are shown in Figure 1b.

566
567   The region is in a cold semi-arid climate zone, characterised by cold and dry winters and hot and

568   humid summers. The regional annual mean precipitation is approximately 396 mm and it

569   exhibits large intra-seasonal variations. Most rain storms fall between June and August, a period

570 ~~that accounts for more than 65% of the annual precipitation.~~ According to local water authorities,

571 the major soil type of the area is a mixture of loam and clay.

572

573 The current drainage system can be divided into three large sub-basins (Figure 1c) and 326 sub-

574 catchments with a total pipeline length of 249.36 km. The drainage network has a higher pipeline

575 cover rate in the central part, but a rather low design standard for extreme rainfall events with a

576 return period of less than 1 year. Historical records of stormwater drainage and flood damage

577 indicate that the region has experienced an increase in flood frequency and magnitude within the

578 context of climate change and urbanisation (Zhou et al., 2016). During the major flood event on

579 11 July 2016, the city, especially the western portion of the watershed, was hit by an extreme

580 rainfall event that featured more than 100 mm of rain in 3 hours. The flood event led to the

581 cancellation of at least 8 flights and 17 trains, and delays of several transportation systems. In

582 particular, in the central area, the flood event caused severe traffic jams on major streets and

583 resulted in a number of flooded residential buildings. A new drainage system is therefore

584 required to cope with increasing urban flood volumes and frequencies in the future. The planned

585 drainage area for 2020s is about 307.83 km^2, which is 50% larger than the current drainage area

586 (Zhou et al., 2016). The land use categories and distribution are shown in Figure 1b.

587

588 b. Climate change scenarios

589 Climate projections by five general circulation models (GCMs) from Phase 5 of the Coupled

590 Model Intercomparison Project (CMIP5) archive were obtained from the Inter-Sectoral Impact

591 Model Intercomparison Project (ISI-MIP) (Warszawski et al., 2014). The CMIP5 climate

592 projections were bias-corrected against observed climate for the overlapping period 1950–2000

593   using a quantile mapping method (Piani et al., 2010; Hempel et al., 2013). The bias-corrected

594   CMIP5 climate projections represent a complete climate change picture that includes both the

595   mean property and variation of future climate. Several studies have demonstrated the value of the

596   bias-corrected climate projections in quantifying climate change impacts on global and regional

597   hydrology (e.g., Piontek et al., 2014; Elliott et al., 2014; Haddeland et al., 2014; Leng et al.,

598   2015a,b). In this study, we used the bias-corrected climate from~~all~~ five GCMs (HadGEM2-ES,

599   GFDL-ESM2M, IPSLCM5A-LR, MIROC-ESM-CHEM, and NorESM1-M) under two

600   Representative Concentration Pathways (RCPs) (i.e., RCP 2.6 and RCP 8.5). The projected

601   urban flood volumes under the business-as-usual scenario RCP 8.5 are compared with those

602   under the climate change mitigation scenario RCP 2.6 to explore the benefits of climate change

603   mitigation in reducing regional urban flood volumes. The possible land-surface-atmosphere

604   interactions that would indirectly affect rainfall and flooding are not considered in this study.

605

606   c.   Urban drainage modelling

607   The Storm Water Management Model (SWMM 5.1) developed by the U.S. Environmental

608   Protection Administration is a widely used urban stormwater model that can simulate rainfall-

609   runoff routing and pipe dynamics under single or continuous events (Rossman and Huber, 2016).

610   SWMM can be used to evaluate the variation in hydrological and hydraulic processes and the

611   performance of drainage systems under specific mitigation and adaptation scenarios in the

612   context of global warming. The hydrological component requires inputs of precipitation and

613   subcatchment properties including drainage area, subcatchment width, and imperviousness. The

614   pipe network requires inputs from manholes, pipelines, outfalls, and connections to sub-

615   catchments (Zahmatkesh et al., 2015; Chang et al., 2013). Basic flow-routing models include

28

616   steady flow, kinematic, and dynamic wave methods. Infiltration can be described by the Horton,

617   Green-Ampt, or Curve Number (SCS-CN) methods. The dynamics of pipe flow are calculated

618   based on the continuity equation and Saint-Venant equations (Rossman and Huber, 2016).

619   Overflow occurs once the surface runoff exceeds the pipe capacity and is expressed as the value

620   of total flood volume (TFV) at each overloaded manhole; i.e., the excess water from manholes

621   after completely filling the pipe system without taking into account the outlet discharges. Other

622   types of model outputs include catchment peak flows, maximum flow rates of pipelines, and

623   flooded hours of manholes. It should be noted that SWMM is not capable of simulating surface

624   inundation dynamics and cannot provide accurate estimation of the inundated zones and depths.

625   The TFV value is thus used to approximately reflect the flood condition and drainage system

626   overloading status. Nevertheless, surface inundation models (e.g., Apel et al., 2009; Horritt and

627   Bates, 2002; Vojinovic and Tutulic, 2009) are applicable if more accurate information about

628   overland flow characteristics is available. In this study, the kinematic wave routing and the

629   Horton infiltration model are used for model simulations. The infiltration capacity parameters for

630   the category of "Dry loam soils with little or no vegetation" are used in the hydrological model to

631   be consistent with the local soil type (Akan, 1993; Rossman and Huber, 2016) (~~Table~~

632   ~~1~~Supplementary Materials, ST1).

633

634   Rainfall inputs are calculated based on the regional storm intensity formula (SIF) using historical

635   climatic statistics (Zhang and Guan, 2012) (~~see Equation 1). Application of the SIF is a standard~~

636   ~~practice for determining design rainfalls in urban drainage modelling in China, and is well~~

637   ~~documented in the National Guidance for Design of Outdoor Wastewater Engineering~~

638   ~~(MOHURD, 2011). In fact, the SIF represents an Intensity-Duration-Frequency (IDF)~~

29

639   relationship, which is a common approach in literature for estimating design rainfall hydrographs

640   using the Chicago Design Storms (CDS) approach (Berggren et al., 2014; Willems et al., 2012;

641   Zhou et al., 2013).

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

642   where q is the average rainfall intensity, and P and t are the design return period and duration of

643   storm, respectively. The typical temporal resolution considered in SIF for urban drainage

644   modelling is minutes. A, b, c, and D are regional parameters governing the IDF relationship

645   among rainfall intensity, return period, and storm duration. For the study region, the values of A,

646   b, c, and D were obtained from the local weather bureau and are equal to 635, 0, 0.61, and 0.841,

647   respectively.

648

649   The procedure for applying SIF to obtain CDS is outlined in the National Technical Guidelines

650   for Establishment of Intensity-Duration-Frequency Curve and Design Rainstorm Profile

651   (MOHURD, 2014; Zhang et al., 2008; Zhang et al., 2015). Specifically, for a given return period,

652   the SIF is fitted into the Horner's equation as:

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

653

654   The synthetic hyetograph based on the Chicago method is computed using Equation 2 and an

655   additional parameter r (where 0< r <1), which determines the relative time step of the peak

656   intensity, $t_p = r*t$. The time distribution of rainfall intensity is then described after the peak $t_a =$

657    $(1-r)*t$ and before the peak $t_b = r*t$ using Equations 3 and 4, respectively, where i_b and i_a are the

658   instantaneous rainfall intensity before and after the peak:

30

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

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

659 Supplementary Materials, Equation 1-4). In this study, we considered 10 return periods, i.e., the

660 1-, 2-, 3-, 10-, 20-, 50-, 100-, 200-, 500-, and 1000-year events. A 4-hour rainfall time series was

661 generated for each return period at 10-minute intervals based on Equations 1–4. The duration of

662 design rainfalls (i.e., 4-hour rainfall) is selected based on the time of concentration (ToC) of the

663 watershed in the study region, according to the design principles as outlined in Butler and Davies

664 (2010) and Chow et al. (2013). We assumed that the SIF was constant without considering the

665 non-stationary features in a changing climate. That is, the Intensity-Duration-Frequency (IDF)

666 relationships for estimating design rainfall hydrographs were assumed to remain stable in the

667 future and only changes in the daily mean intensity were considered because of the limited data

668 availability in future sub-hourly climate projections from which to derive the parameters.

669

670 As for future climate, the projected changes (i.e., change factors) in precipitation intensity at

671 various return periods were calculated for each GCM-RCP combination (Table 21). Specifically,

672 for each year, the annual maximum daily precipitation was determined for both historical and

673 future periods. The generalised extreme value (GEV) distribution was then fitted separately to

674 the two sets of daily values (Coles 2001; Katz et al. 2002). The goodness-of-fit was tested by

675 calculating the Kolmogorov–Smirnov and Anderson–Darling statistics show that the hypothesis

676 regarding the extreme value distribution is not rejected. That is, the fitted distribution could be

677 well used to describe the extreme precipitation distribution in the study region. The value

31

678 corresponding to each return period was estimated based on the GEV distribution and the

679 changes between future and historical periods were calculated as the change factors. The derived

680 change factor for each return period was then multiplied by the historical design CDS rainfall

681 time series to derive future climate scenarios. We acknowledge that the estimation of changes in

682 extreme precipitation events involves inevitable uncertainties and therefore caution should be

683 exercised when interpreting the relevant results.

684

685 d. Flood volume assessment

686 The total flood volume (TFV) values of given rainfall events were simulated by the SWMM. A

687 log-linear relationship is assumed to characterize the changes in flood volume with the increase

688 in precipitation intensity as indicated by return periods (Figure 2a) following Zhou et al. (2012)

689 and Olsen et al. (2015). Generally, more ~~intense~~TFV (i.e., system overloading) is expected with

690 increase in rainfall ~~will induce higher TFVs. The~~ intensity. In Figure 2b, the TFVs were ~~further~~

691 linked to their specific occurrence ~~frequencies to derive the expected flood volume for a flood~~

692 ~~event at a specific probability (Figure 2b). The~~ probabilities. The total grey area under the curve

693 denotes the TFVs integrated across various return periods and represents the ~~average~~ total

694 expected TFVs per year ~~for all floods at various return periods.~~. The contribution of an

695 individual flood event to total average TFVs is dependent not only on the flood volume, but also

696 its corresponding probability of occurrence. Intensified precipitation is expected to increase the

697 magnitude of system overflow, resulting in an upward trend in the TFV-return period

698 relationship and increased total TFVs. ~~Mitigation and adaptation are aimed at reducing or~~

699 ~~preventing the impacts of global warming on flood volumes.~~

700

701   e. Design of adaptation scenarios

702   In this study, two adaptation scenarios were designed to explore the role of adaptation in

703   reducing urban flood volume within the context of climate change by 2020s. The first scenario

704   ~~adapted~~ was designed to update the drainage system as planned by ~~the~~local water authorities to

705   cope with the ~~designed~~ standard ~~of a~~ 3-year design event. It involved two main improvements of

706   the current drainage system—enhancing the pipeline diameter and expanding the pipe network.

707   The design was implemented in the SWMM model as shown in Figure 1c. The number of

708   pipelines of the present-day and adapted systems was 323 and 488, with a total pipe length of

709   251.6 km and 375.4 km, respectively. In the adapted scenarios, the mean pipeline diameter was

710   about 1.73 m, which increased by 53% compared to that of the present-day system.

711

712   ~~A variety of site-specific factors, such as the imperviousness of land area in the drainage basin,~~

713   ~~can also influence the performance of a drainage system in managing surface runoff.~~ The second

714   adaptation scenario was designed to increase the permeable surfaces (e.g., green spaces) and

715   reduce the regional imperviousness in the study region on the basis of pipe capacity enhancement.

716   This scenario is referred to as the Low Impact Development (LID) scenario, and it was used to

717   explore the effectiveness of urban green measures, such as the use of permeable pavements,

718   infiltration trenches, and green roofs. Changes in land imperviousness in LID scenario have

719   direct impacts on the performance of drainage system in managing surface runoff. Due to a lack

720   of detailed information about the permeable soil and coverage rates in the study region, the

721   effects of these specific measures cannot be modelled individually. Here, we used a simplified

722   approach by altering the subcatchment imperviousness to reflect the combined effects of

723   infiltration-related measures. We derived such information by ~~comparing~~calculating the

33

724 difference in land use type and imperviousness between the current and planned ~~land use~~city

725 maps using a geographical information system (GIS~~) and incorporated the changes in land use~~

726 ~~and imperviousness into the designed LID scenarios.~~). Figure 1d shows the difference in

727 weighted mean imperviousness (~~WMI) calculated~~ $WMI = \sum_i(IF_i \times A_i)/\sum_i A_i$, Where IF_i and

728 A_i is the impervious factor and area for land use type i, respectively.) for each subcatchment in

729 the current and planned maps, using the commonly applied impervious factors (Pazwash, 2011;

730 Butler and Davies, 2004) for each land use type. The difference in WMI was used to indicate the

731 ~~area~~ potential for adaptation based on the city plan. For example, a subcatchment with higher

732 positive changes in the WMI indicates that the area is planned to have a land use type with lower

733 imperviousness and therefore is assumed to be more suitable for LID planning, and vice versa.

734

735 3.   Results

736 a.   Impacts of future climate change on urban flood volumes

737 Figure 3 shows the projected climate change (CC) impacts on urban flooding using the present-

738 day drainage system of the near future (i.e., 2020–2040) under the RCP 8.5 scenario. Without

739 climate change mitigation or adaptation, the TFV was projected to increase significantly with the

740 increase of extreme rainfall events for most of investigated return periods (Table 2). Note that the

741 lower bounds for return periods of 1, 3, and 1000 years fall below the current TFV curve due to

742 the decrease in precipitation intensities. Despite the large uncertainty associated with climate

743 projections, in particular with the 1-, 10-, and 1000-year return periods, the poor service

744 performance of the current system in coping with urban flooding was evident. Overall, the urban

745 flood volume was projected to increase by 52% on average by the multi-model ensemble median

746   by 2020–2040; the largest increase (258%) was projected for the 1-year event and the smallest

747   increase (12%) for the 100-year event.

748

749   b.   Benefits of climate change mitigation in reducing urban flood volumes

750   Figure 4 shows the comparison of TFVs under the RCP 8.5 scenario (i.e., a business-as-usual

751   scenario) and the RCP 2.6 scenario (i.e., a climate change mitigation scenario). Although large

752   uncertainties exist arising from climate models, it is clear that the simulated TFVs are much

753   smaller under the RCP 2.6 scenario than under the RCP 8.5 scenario, demonstrating the benefits

754   of climate mitigation in reducing local urban flood volumes. Such benefits are especially evident

755   for floods for smaller return periods. For example, an increase of 936 m^3 in flood volume is

756   projected with the increase in 1-year extreme rainfall under the business-as-usual climate change

757   scenario (i.e., RCP 8.5), 52% of which would be reduced if climate change mitigation is in place

758   (i.e., under RCP 2.6). ~~Overall, climate change mitigation can reduce future flood volumes by 13%~~

759   ~~compared to the scenario without mitigation, as indicated by the multi-model ensemble median.~~

760   Notably, the peak of the total TFV curve was ~~even~~ projected to shift from the 1-year event under

761   the ~~RCP 8~~RCP8.5 scenario to the 3-year event under the ~~RCP 2~~RCP2.6 scenario (Figure 4b~~).~~

762   ~~Such~~), indicating a ~~shift~~substantial reduction in the ~~peak toward~~ TFVs (especially at the 1-year

763   return period) (Figure 4c). The lower total TFVs under RCP2.6 scenario could be attributed to

764   the smaller ~~return periods combined with a flatter curve demonstrates~~magnitude of rainfall

765   intensity than RCP8.5 scenario (Table 1), demonstrating the important role of climate mitigation

766   in ~~regulating local~~reducing urban flood volumes. Overall, climate change mitigation can reduce

767   future flood volumes by 13% compared to the scenario without mitigation, as indicated by the

768   multi-model ensemble median.

35

769

770   c.   Benefits of adaptation in reducing urban flood volumes

771   Figure 5 shows the overloaded pipelines (red colour) with and without adaptation. The simulated

772   results under the present 3-year event (recommended service level) and 50-year event (one

773   typical extreme event) were selected to illustrate the role of adaptation in coping with floods in

774   the historical period. As shown in Figure 5a, the simulated locations of overloaded pipelines are

775   in good agreement with historical flood points as recorded by local water authorities. Overall, the

776   percentage of overloaded manholes (POM) and the ratio of flood volume (RFV) to input rainfall

777   volume are up to 37% and 35% in the current drainage system (Figure 5a), respectively. When

778   experiencing a 50-year extreme rainfall, the POM and RFV increase to 67% and 38%,

779   respectively. This indicates that current pipe capacities are insufficient to cope with extreme

780   rainfall events (Figure 5b). Spatially, the central portion of the city is the most affected region

781   due to the low service level in the area. With proposed adaptations, urban floods can be reduced

782   to zero under a 3-year flood event. Such benefits of local adaptations are also evident when

783   experiencing more intense precipitation events (e.g., 50-year events), for which the POM and

784   RFV reduced from 67% and 50% to 49% and 17%, respectively.

785

786   Figure 6 shows the future changes in urban flood volume (CTFVs) ($CTFV=(TFV_c - TFV_{nc})/TFV_{nc}$,

787   where c and nc represent the results with and without climate change, respectively) with changes

788   in extreme rainfall for various return periods. The performance of the current drainage system

789   (no adaptation) was found to be less sensitive to future climate change, as indicated by the flatter

790   slope in Figure 6. For example, a similar magnitude of changes in flood volume was projected

791   given changes in extreme rainfall for the return periods of 3, 50, and 500 years; the CTFV is 0.62,

792   0.32 and 0.35 for these periods, respectively. This is because the capacity of the current system is

793   too small to handle extreme rainfall events with return periods larger than 1 year—a condition

794   under which the current drainage system would be flooded completely, not to mention the

795   situations with increased rainfall intensity in the future. Mathematically, the low sensitivity of

796   the current drainage system to changes in extreme rainfall intensity could be attributed to the

797   large value of the denominator in the calculation of *CTFV*.

798

799   With adaptations in place, the flood volume becomes much smaller than that in the current

800   system due to capacity upgrading to hold more water. For example, when experiencing a 10-year

801   extreme rainfall event, the urban flood volumes for the present period (i.e., TFV_{nc}) are 1041,230,

802   274,650 and 180,610 m^3 in the current and two adapted systems, respectively, while in the future

803   period, the magnitude of flood volume (i.e., TFV_c) is relatively similar among the three drainage

804   systems. Therefore, future CTFVs relative to the historical period are much larger in the adapted

805   systems than in the current system. The larger CTFVs in the adapted systems do not mean a

806   worsened drainage system performance. Rather, they imply that the capacity (i.e., service level)

807   of adapted drainage systems tends to become lower with climate change, while the current

808   drainage system has already reached its peak capacity in handling extreme rainfall events in the

809   historical period and thus shows a low sensitivity to future increases in rainfall intensity under

810   climate change scenarios. Notably, the considerable increases in the CTFVs for return periods of

811   less than 10 years in the adapted systems imply that the designed adaptations can effectively

812   attenuate extreme rainfall events for small return periods. For more extreme rainfall events of

813   return periods $\geq$50 years, more consistent results were found for both adaptation scenarios. This

814   indicates that although the performances of adapted drainage systems are significantly improved

815 compared to that of the current system, the flood volume remains large when experiencing

816 extreme rainfall events with return periods larger than 50 years, because flooding in such cases

817 will push the adapted drainage systems to their upper limits.

818

819 d. Climate mitigation versus drainage adaptation

820 Figure 7 shows the reduced TFVs by climate change mitigation and drainage system adaptation

821 as functions of return period. It is evident that both mitigation and adaptation measures are

822 effective in reducing future urban flood volumes. However, such benefits are projected to

823 weaken gradually with the increase in rainfall intensity (i.e., larger return periods). Overall,

824 climate mitigation can lead to a reduction of flood volume by 10-40% compared to the scenario

825 without mitigation. Notably, there are minor negative values of TFV reductions for the return

826 period of 100 and 200 years under climate mitigation scenario. The negative value is attributed to

827 the slightly higher increase in precipitation intensity under climate mitigation scenario (i.e.

828 RCP26) than the scenario without mitigation (i.e. RCP85) simulated by two of five climate

829 models (i.e., GFDL-ESM2m and NorESM1-M, see Table 1), which translated to slightly larger

830 flood volume under climate mitigation scenario. This climate internal variability is partly

831 cancelled by other three climate models, thus leading to very minor negative value by the multi-

832 model ensemble mean. This calls for the use of more climate models (GCMs) to derive more

833 robust projections in the future studies.

834

835 Importantly, our results show that the two adaptation systems proposed in this study are found to

836 be more effective in reducing urban floods than climate change mitigation. In most cases, the

837 benefits of local adaptation are more than double those of mitigation. In extreme cases, the

38

838 reduction in TFV achieved by adaptation is five times more than that achieved by climate change

839 mitigation (i.e., for the return periods of 2–3 years). Such effectiveness of urban flood reduction

840 through drainage system adaptations has profound implications for local governments charged

841 with managing urban flooding in the future. Notably, the second scenario (LID+pipe) exhibited a

842 higher level of flood volume reduction than the pipe scenario in coping with extreme rainfall

843 events for all investigated return periods. This implies that implementation of LID measures to

844 augment drainage system capacity is more effective through reducing upstream loadings

845 compared to updating the pipe system alone.

846

847 It is noted that local soil characteristics could affect the performance of the designed adaptation

848 systems, in particular the LID measures. However, information about soil properties was not

849 available at the subcatchment level in the study region. Here, a set of sensitivity experiments

850 were conducted by adopting different parameters (e.g., infiltration values) associated with

851 possible soil conditions (i.e., dry sand, loam, and clay soils with little or no vegetation in ~~Table~~

852 ~~1~~Supplementary Materials, ST1) for the area. The ~~boundary bars~~whiskers in Figure 7 show the

853 uncertainty range arising from the representation of different soil conditions in the drainage

854 model. The benefits of the designed adaptation measures in reducing urban flood volumes were

855 found to be robust regardless of soil conditions, and such benefits exceeded those of climate

856 change mitigation, confirming our major conclusions found in this study.

857

858 4.   Uncertainties and Limitations

859 A number of uncertainties and limitations arise from the model structure, parameter inputs,

860 emission scenarios, GCMs, climate downscaling/bias-correction approaches, etc. Specifically,

861   climate projections by GCMs are subject to large uncertainties, in particular regarding

862   precipitation (Covey et al., 2003) at spatial scales, which are relevant for urban flood modelling.

863   An alternative approach is to simulate future climate using a regional climate model (RCM)

864   nested within a GCM. Such climate projections by RCMs have added value in terms of higher

865   spatial resolution, which can provide more detailed regional climate information. However,

866   various levels of bias would still remain in RCM simulations (Teutschbein and Seibert 2012) and

867   bias corrections of RCM projections would be required; e.g., the European project ENSEMBLES

868   (Hewitt and Griggs 2004; Christensen et al. 2008). To run a RCM was not within the scope of

869   this study; instead, we tended to use publicly available climate projections. Here, we obtained the

870   climate projections from the ISI-MIP (Warszawski et al. 2014), which provides spatially

871   downscaled climate data for impact models. The climate projections were also bias-corrected

872   against observations (Hempel et al. 2013) and have been widely used in climate change impact

873   studies on hydrological extremes such as floods and droughts (e.g., Dankers et al. 2014;

874   Prudhomme et al. 2014; Leng et al. 2015a). It should be noted that we used the delta change

875   factor to derive future climate scenarios as inputs into our drainage model instead of using GCM

876   climate directly. This is because the relative climate change signal simulated by GCMs is argued

877   to be more reliable than the simulated absolute values (Ho et al. 2012). Moreover, we used an

878   ensemble of GCM simulations rather than one single climate model in order to characterise the

879   uncertainty range arising from climate projections. However, disadvantages of this method are

880   that transient climate changes cannot be represented and that changes in intra-seasonal or daily

881   climate variability are not taken into account (Leng and Tang, 2014). Such sources of uncertainty

882   can be explored when improved climate models at finer scales become available (Jaramillo and

883   Nazemi 2017).

884

885   In addition, the SIF parameters were assumed to remain stable in the future and only changes in

886   the daily mean intensity were considered, because future sub-hourly climate projections were not

887   readily available. The full climate variability range would also be under-sampled, although we

888   used five climate models to show the possible range. Given the above limitations, we

889   acknowledge that the modelling results represent the first-order potential climate change impacts

890   on urban floods. Future efforts should be devoted to the representation of dynamic rainfall

891   changes at hourly time steps with consideration of non-stationary climate change.

892

893   Moreover, several assumptions had to be made due to limitations of the current modelling

894   structure and approach. For example, the conveyance capacities of the drainage system and flood

895   volume would largely depend on the state of drainage systems. Hence, a drainage system

896   obstructed by vegetation, waste, or artefacts (cables, pipes, temporary constructions) can make

897   the outcomes of the SWMM calculation significantly different from observations. However,

898   quantifying the impacts of drainage system states on urban flood volumes is not trivial because

899   of the difficulties involved in collecting field data and selecting and using appropriate methods

900   for reasonable assessment of pipe conditions (Ana and Bauwens, 2007; Fenner, 2000), and was

901   not within the scope of this study. With deterioration, such as ageing network, pipe deterioration,

902   blockage, and construction failures, drainage systems were shown to become more vulnerable to

903   extreme rainfalls as demonstrated in previous studies (Dawson et al., 2008; CIRIA, 1997; Davies

904   et al., 2001). It is very likely that our simulated urban flood volumes would be underestimated

905   without considering the changes in drainage conditions (Pollert et al., 2005).

906

907 Further, constrained by the one-dimensional modelling approach using SWMM, the

908 performances of LID measures were mainly evaluated according to their effects in reducing

909 water volume from overloaded manholes (Oraei Zare et al., 2012; Lee et al., 2013). That is, the

910 LID adaptation measure was mainly designed to reduce the amount of water rather than slowing

911 down the water speed, which has been demonstrated to be effective in reducing urban floods

912 (Messner et al., 2006; Ashley et al., 2007; Floodsite, 2009). However, it should be noted that

913 most LID measures can reduce runoff volume and flow speed at the same time, although some of

914 the LID measures are primarily designed to slow down the flow speed, i.e., vegetated swales. To

915 examine whether flood retention of a given event is induced by runoff volume or the internal

916 speed control function in the model is difficult and requires detailed data for model validations.

917 Specifically, the required information about surface roughness, soil conductivity, and seepage

918 rate were unavailable at the subcatchment scale in the study region. Therefore, a simplified

919 modelling approach was used to take advantage of existing data, especially for the design of LID

920 measures. With the aid of more detailed field data and planning documents, the design of LID

921 measures could be significantly improved by implementing more advanced approaches (Elliott

922 and Trowsdale, 2007; Zoppou, 2001).

923

924 Evaluation of other potential adaptation strategies, such as flood retention by rain gardens and

925 green roofs, can be explored in the future to gain additional insights into the performance of LID

926 systems. In particular, the cost-effectiveness of the proposed adaptation measures should be

927 accounted for. Indeed, a major limitation of this study is lack of assessment of costs and benefits

928 of adaptation measures from the economic perspective. In fact, besides the effectiveness of

929 proposed adaptation measures in reducing flood volume, assessment of the associated economic

930 costs is essential for flood risk management (Rojas et al., 2013; Veith et al., 2003; Hinkel et al.,

931 2014; Aerts et al., 2014; Ward et al., 2017). For example, Ward et al. (2017) showed that

932 investments in urban flood protections with dykes are not economically attractive everywhere.

933 Higher investment and maintenance costs may prohibit the implementation of adaptation

934 strategies as proposed in this study. Future efforts should therefore be devoted to building a

935 framework for assessing the costs and benefits of urban flood reduction measures and examine

936 whether the reduced losses are higher than the costs of investments and maintenance of these

937 measures.

938

939 Nevertheless, given these limitations, this study stands out from previous climate impact

940 assessment studies of urban flood volumes by having proposed two feasible adaptation strategies

941 and compared their benefits to those from global-scale climate change mitigations through GHG

942 reductions within a consistent framework. Depending on the progress on data collection and the

943 demands of local authorities, more advanced methods for pipe assessment (e.g., considering the

944 changing pipe conditions), LID measures (detailed modelling of LID control), and two-

945 dimensional surface flooding for assessment of flood damage and risk are planned in a future

946 study to provide a more comprehensive analysis of the adaptation measures.

947

948 5.   Summary and Conclusions

949 The potential impacts of future climate change on current urban drainage systems have received

950 increasing attention during recent decades because of the devastating impacts of urban flooding

951 on the economy and society (Chang et al., 2013; Zhou et al., 2012; Abdellatif et al., 2015).

952 However, few studies have explored the role of both climate change mitigation and drainage

953   adaptations in coping with urban flooding in a changing climate. This study investigated the

954   performance of a drainage system in a typical city in Northern China in response to various

955   future scenarios. In particular, we assessed the potential changes in urban flood volume and

956   explored the role of both mitigation and adaptation in reducing urban flood volumes in a

957   consistent manner.

958

959   Our results show significant increases in urban flood volumes due to increases in precipitation

960   extremes, especially for return periods of less than 10 years. Overall, urban flood volume in the

961   study region is projected to increase by 52% by the multi-model ensemble median in the period

962   of 2020–2040. Such increases in flood volume can be reduced considerably by climate change

963   mitigation through reduction of GHG emissions. For example, the future TFVs under 1-year

964   extreme rainfall events can be reduced by 50% when climate change mitigation is in place.

965   Besides global-scale climate change mitigation, regional/local adaptation can be implemented to

966   cope with the adverse impacts of future climate change on urban flood volumes. Here, the

967   adaptation measures as designed in this study were demonstrated to be much more effective in

968   reducing future flood volumes than climate change mitigation measures. In general, the reduced

969   flood volumes achieved by adaptation were more than double those achieved by climate change

970   mitigation.

971

972   Through a comprehensive investigation of future urban floods, this study provides much-needed

973   insights into urban flood management for similar urban areas in China, most of which are

974   equipped with highly insufficient drainage capacities. By comparing the reduction of flood

975   volume by climate change mitigation (via reduction of GHG emissions) and local adaptation (via

976 improvement of drainage systems), this study highlights the effectiveness of system adaptations

977 in reducing future flood volumes. This has important implications for the research community

978 and decision-makers involved in urban flood management. We emphasise the importance of

979 accounting for both global-scale climate change mitigation and local-scale adaptation in

980 assessing future climate impacts on urban flood volumes within a consistent framework.

981

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1181   ~~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~~	~~0.3~~	~~3~~	~~9~~

1182
1183
1184   ~~Table 2~~Table 1 Projected changes in precipitation intensity under return periods ranging from 1
1185   year to 1000 years by five Global Climate Models under two Representative Concentration
1186   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

1187

1188 **List of Figures**

1189 **Figure 1** Land use of the study region for the year 2010 (a) and 2020 (b). Pipe network
1190 description of current and planned drainage systems (c). Difference in Weighted Mean
1191 Imperviousness (WMI) between year 2010 and 2020 (d).
1192 **Figure 2** Illustration of ~~flood volume and average total expected~~ total flood volume (TFVs) as a
1193 function of return ~~period under a stationary drainage system. The grey area denotes the~~ periods (a)
1194 and estimation of average total expected TFVs per year ~~considering all kinds of floods.~~(i.e., the
1195 grey area in b) under a stationary drainage system.
1196 **Figure 3** ~~Projected TFV with changes in~~ Changes in total flood volume (TFV) as a function of
1197 precipitation intensity at various return periods under ~~the~~ RCP8.5 scenario ~~for~~without mitigation
1198 and adaptation. Red solid line represents the multi-model ensemble median TFV with shaded
1199 areas denoting the ~~period of~~ensemble range. Red dashed line is the TFV under present condition.
1200 Box plots show the relative changes in TFV by 2020–2040~~.~~ relative to present condition. Box
1201 edges illustrate the 25th and 75th percentile, the central mark is the median and whiskers mark
1202 the 5th and 95th percentiles.
1203 **Figure 4** Comparison of (a) flood volume, (b) total TFVs (i.e., the piece-wise integral of flood
1204 volume versus the expected frequency with changes in precipitation intensity of various return
1205 periods under RCP8.5 (blue) and RCP2.6 (red). (c) is ~~for~~ the ~~reduced TFVs in~~TFV reduction
1206 calculated as the percentage ~~(i.e.,~~difference in TFVs under RCP2.6 compared to RCP8.5 (i.e.,
1207 benefits of climate mitigation) ~~in RCP2.6 relative to RCP8.5~~ at various return periods.
1208 **Figure 5** Spatial distribution of overloaded pipelines (red colour) induced by the 3-year (left
1209 column) and 50-year extreme events (right column) without and with adaptations. The total
1210 percentage of overloaded manholes (POM) and ratio of flood volume (RFV) to input rainfall
1211 volume are summarised for each scenario.~~Descriptions of~~ Historical flood points and local land
1212 use, mainly the traffic network and green spaces, are ~~provided as the background image~~shown in
1213 (a).
1214 **Figure 6** Future changes in flood volumes (CTFVs) relative to historical conditions under the
1215 current drainage system (yellow) and two adaptation scenarios (i.e., Pipe in red and Pipe+LID in
1216 green) at various return periods.
1217 **Figure 7** Comparison of benefits of climate mitigation and two adaptation strategies in reducing
1218 urban flood volumes with changes in precipitation intensities for various return periods, and with
1219 related variations (boundary bars) as a result of uncertainty arising from local soil conditions.
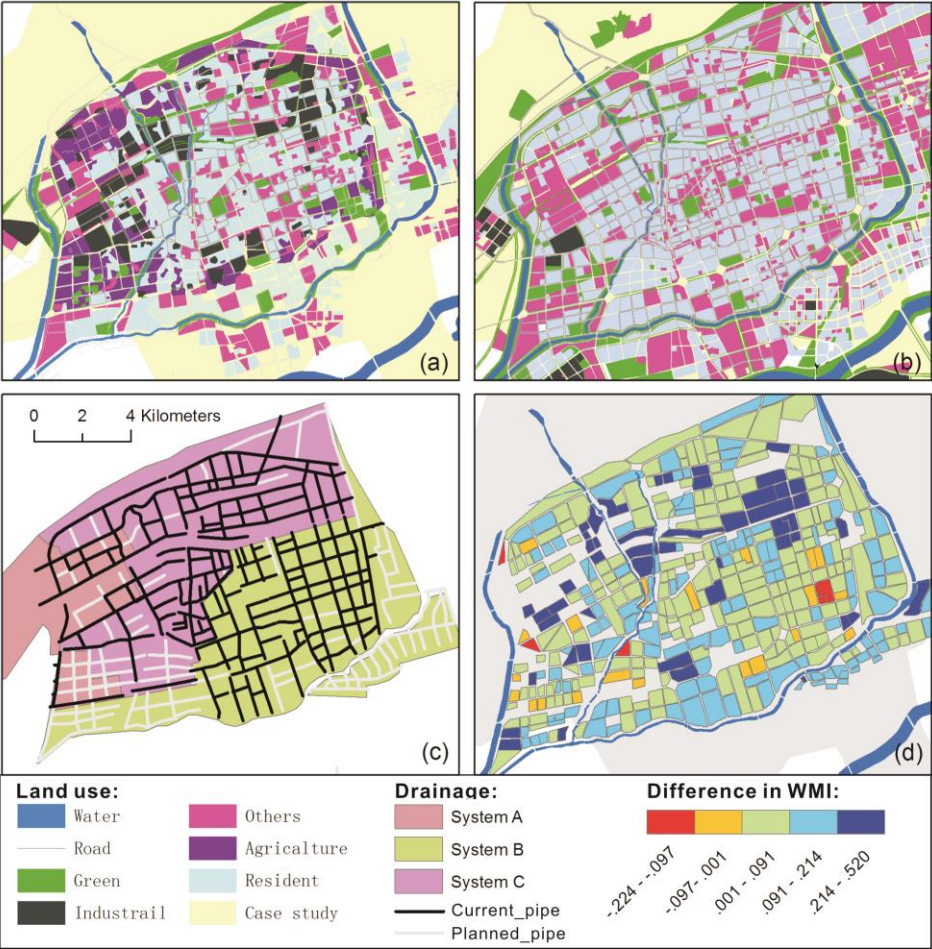1220

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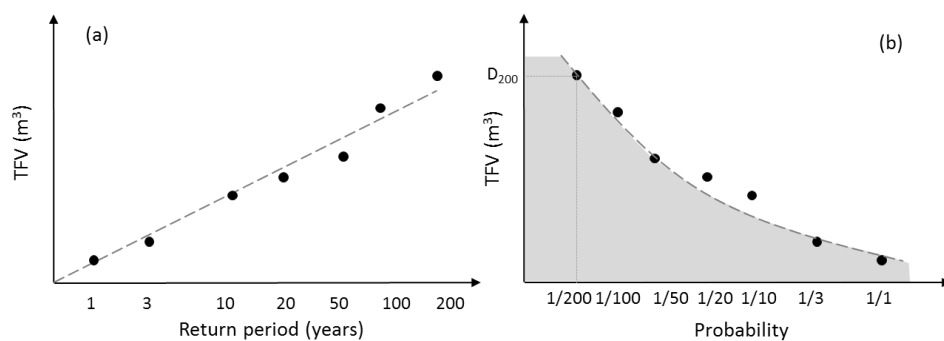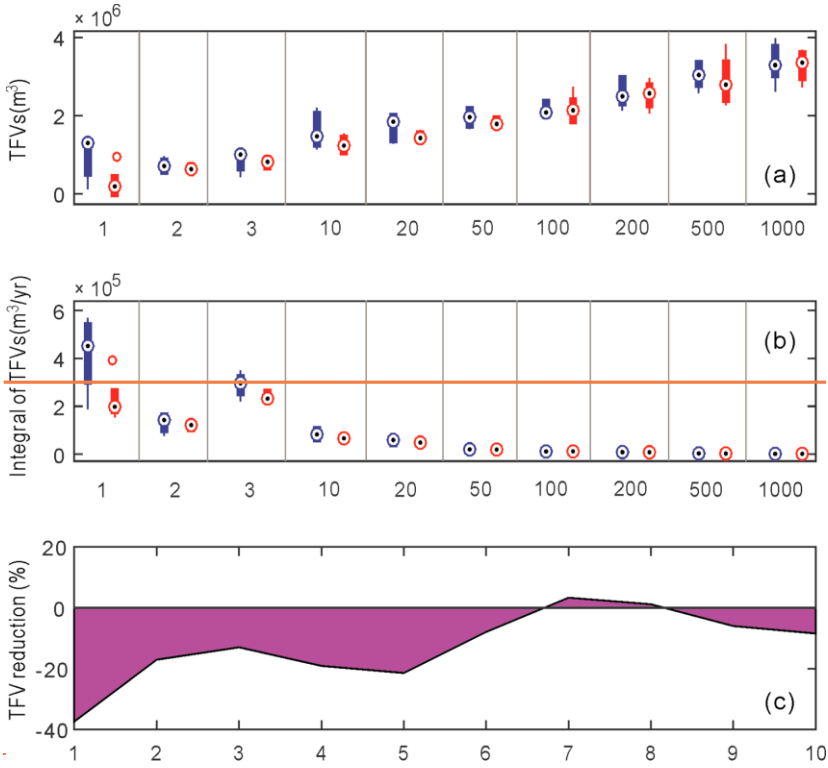Imperviousness (WMI) between year 2010 and 2020 (d).

Figure 2 Illustration of ~~total~~ 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~~
periods (a) and estimation of average total expected TFVs per year ~~considering all kinds of~~
~~floods~~(i.e., the grey area in b) under a stationary drainage system.
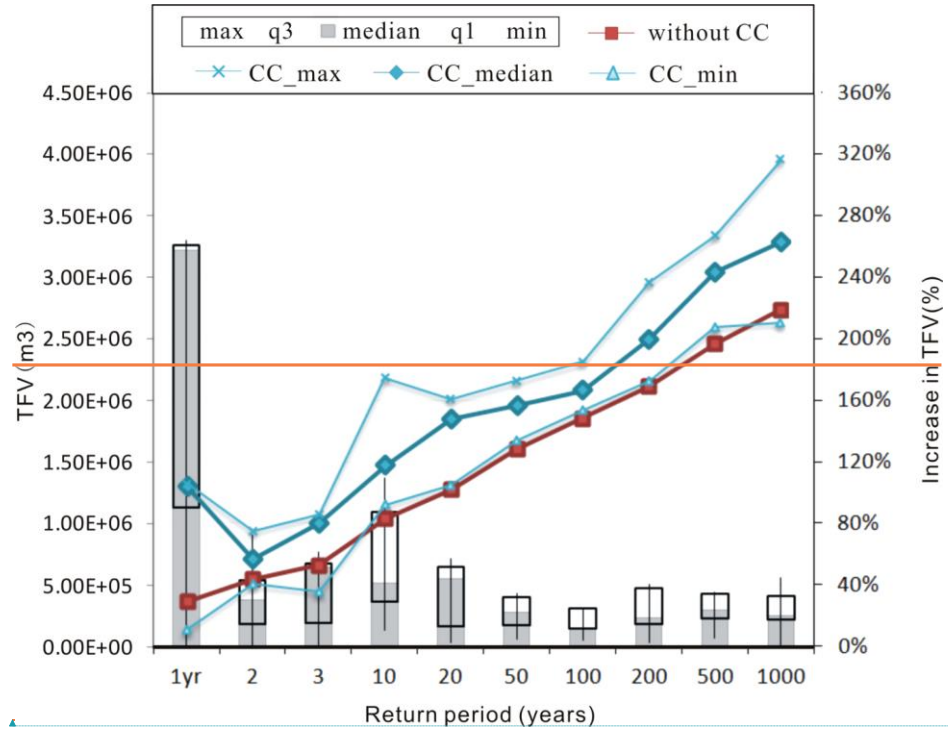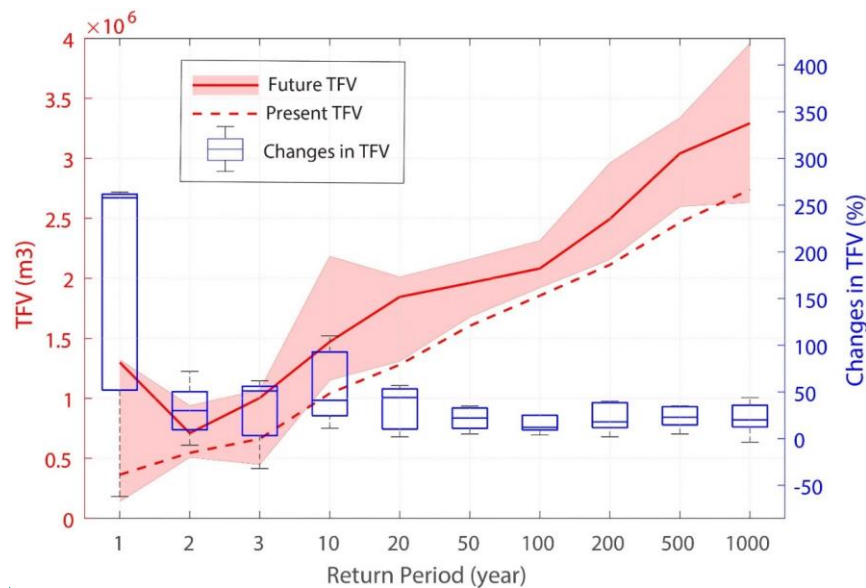
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Figure 3 ~~Projected TFV with changes in~~ Changes in total flood volume (TFV) as a function of precipitation intensity at various return periods under ~~the~~ RCP8.5 scenario ~~for~~without mitigation and adaptation. Red solid line represents the multi-model ensemble median TFV with shaded areas denoting ~~the~~ ~~period of~~ensemble range. Red dashed line is the TFV under present condition. Box plots show the relative changes in TFV by 2020–2040~~,~~ relative to present condition. Box edges illustrate the 25th and 75th percentile, the central mark is the median and whiskers mark the 5th and 95th percentiles.

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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~~ TFV reduction calculated as the percentage difference in TFVs under RCP2.6 compared to RCP8.5 (i.e., benefits of climate mitigation) ~~in RCP2.6 relative to RCP8.5~~ at various return periods.
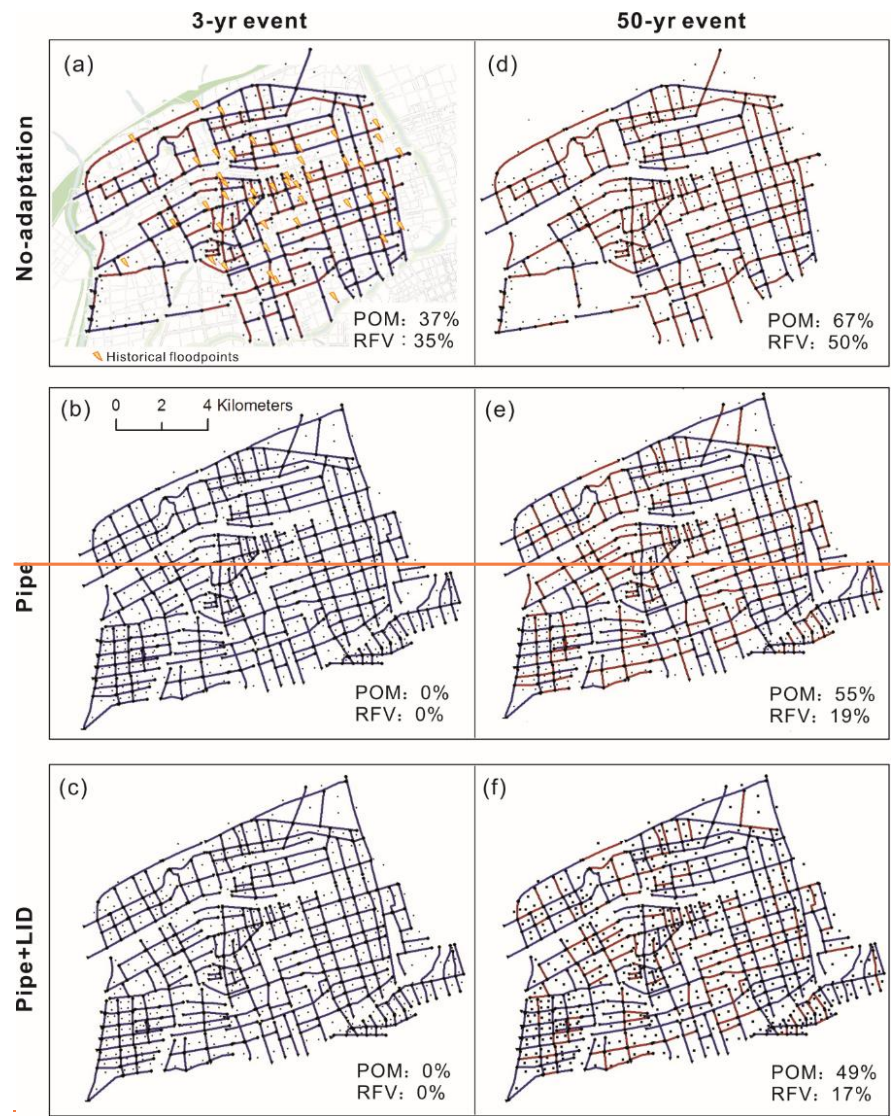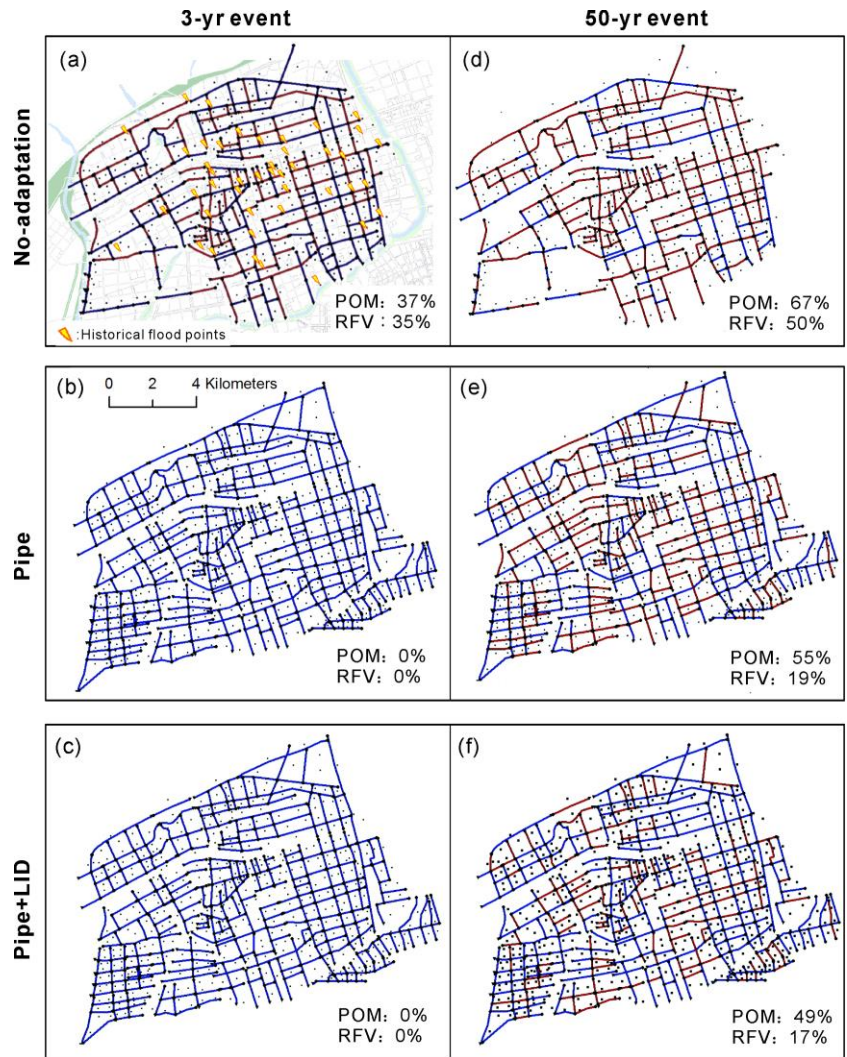
Figure 5 Spatial distribution of overloaded pipelines (red colour) induced by the 3-year (left column) and 50-year extreme events (right column) without and with adaptations. The total percentage of overloaded manholes (POM) and ratio of flood volume (RFV) to input rainfall volume are summarised for each scenario. ~~Descriptions of~~ Historical flood points and local land use, mainly the traffic network and green spaces, are ~~provided as the background image~~shown in (a).
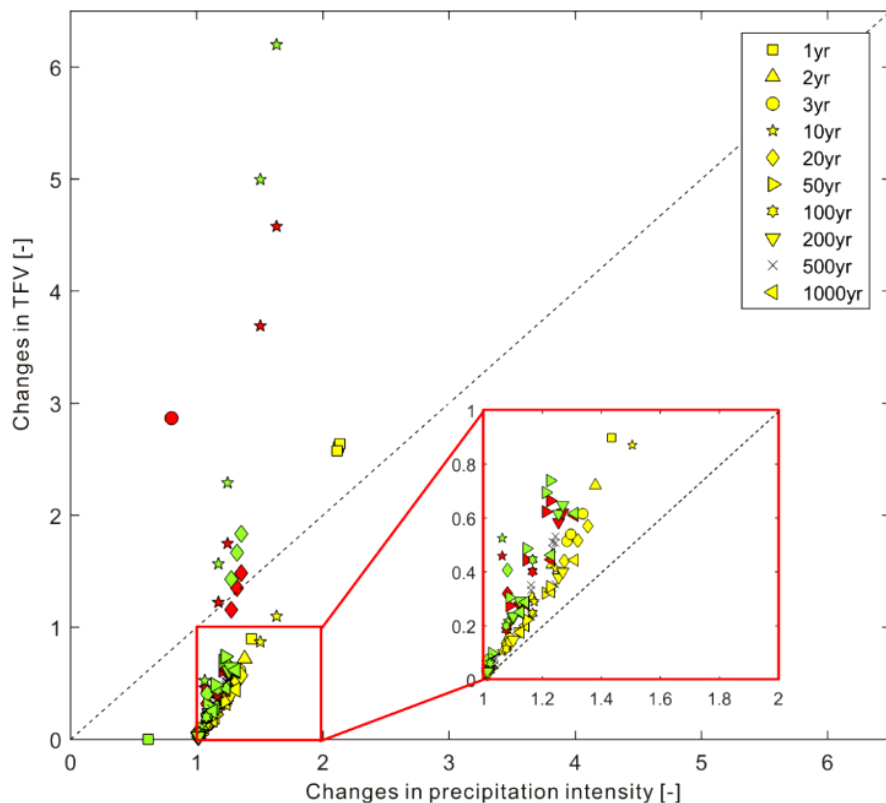
Figure 6 Future changes in flood volumes (CTFVs) relative to historical conditions under the current drainage system (yellow) and two adaptation scenarios (i.e., Pipe in red and Pipe+LID in green) at various return periods.
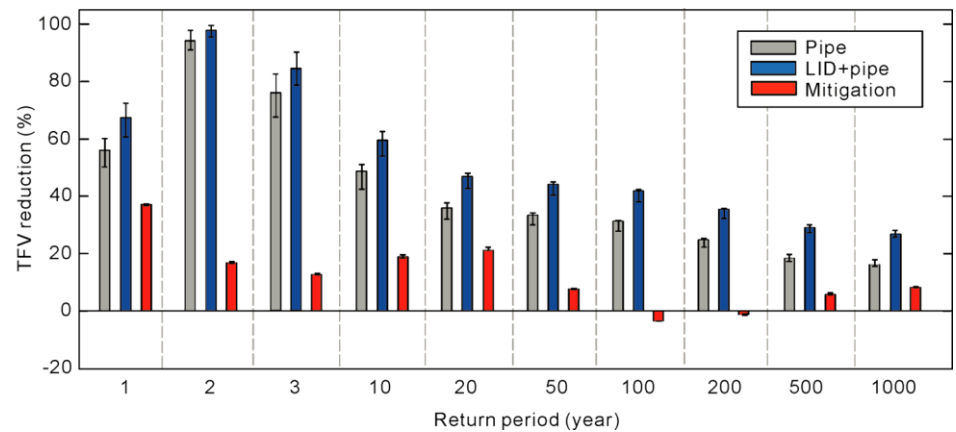
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1267 **Figure 7** Comparison of benefits of climate mitigation and two adaptation strategies in reducing
1268 urban flood volumes with changes in precipitation intensities for various return periods, and with
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