

# Challenges in urban stormwater management in Chinese cities: A hydrologic perspective

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First published 2020

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2 **hydrologic perspective**

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23 **Abstract:** For managing the worsening urban water disasters in China, the  
24 Government of China proposed the concept of “*Sponge City*” in 2013 and initiated the  
25 strategy in 30 pilot cities from 2015. Despite the promise of the concept, there have  
26 been many challenges in implementing the “Sponge City” program (SCP). In this  
27 manuscript, we discuss the hydrology-related challenges in implementing the SCP. In  
28 particular, we consider two key challenges: (1) Determination of the “*Volume Capture*  
29 *Ratio of Annual Rainfall*” (VCRAR), as controlling urban stormwater runoff is one of  
30 the core targets of the SCP; and (2) Estimation of a proper rainfall threshold, which  
31 influences the layout of green-infrastructures in the SCP to achieve the core VCRAR  
32 target. To discuss these challenges, we consider the city of Beijing, the capital of  
33 China, as a case study. Our analysis shows that the trade-offs between the investment  
34 for the SCP and its potential economic benefits should be considered by undertaking a  
35 proper determination of VCRAR. The VCRAR estimated for Beijing from the present  
36 analysis is 0.73. This value is more reasonable than the empirical value of 0.80 that is  
37 presently used, as it can guarantee the positive rate of return on the investment. We  
38 also find that the nonstationary characteristics of rainfall data and their spatiotemporal  
39 differences are important for the estimation of the rainfall threshold in SCP. For  
40 instance, even using the daily rainfall data over a period of 30 years (1983–2012) in  
41 Beijing, as required by the National Assessment Standard, the estimated rainfall  
42 threshold of 27.3 mm underestimates the reasonable rainfall threshold that should at  
43 least be larger than 30.0 mm. Thus, the former cannot ensure the VCRAR target of

44 0.80. Based on these results, we offer proper approaches and key suggestions towards  
45 useful guidelines for delivering better SCP in the Chinese cities.

46 **Keywords:** Urban stormwater management; Sponge city; Low impact development;  
47 Nonstationary rainfall; Volume capture ratio of annual rainfall

48

## 49 **1. Introduction**

50 The increasing threats from rapid urbanization and climate change on urban  
51 rainstorms and urban floods as well as the associated socioeconomic losses  
52 (Winsemius et al., 2016; Wang et al., 2018; Blöschl et al., 2019) are raising serious  
53 scientific and public concerns worldwide. Evaluating and mitigating the risks of urban  
54 flood disasters is a key issue in urban stormwater management, which is also a major  
55 challenge for sustainable urban development (Jiang et al., 2018; Zhang et al., 2016;  
56 Zhang et al., 2019). Many concepts, including best management practices (BMPs),  
57 low impact development (LID), green infrastructures (GIs), water sensitive urban  
58 design (WSUD), and resilient cities, have been proposed to address the many issues  
59 associated with urban water management (Chui et al., 2016; Chui and Trinh, 2016; Li  
60 et al., 2019a; Zevenbergen et al., 2018; Haghightafshar et al., 2019).

61 The BMPs were first proposed in the 1970s in North America to control stormwater  
62 pollution. Following these, the LID was developed in the 1990s and have been widely  
63 adopted in North America and New Zealand (USEPA, 2000). With the concept for  
64 source control of stormwater management, the LID promotes and advocates various  
65 small and separate ecological facilities (bio-retention measures, green roofs, pervious

66 pavements, grass swales, etc.) to control stormwater pollution, reduce runoff volume,  
67 and relieve combined sewer overflow (Li et al., 2016). However, the stormwater  
68 problems encountered in many mega cities around the world are too complex to be  
69 solved only depending on those source control facilities. In 2000, the GIs were  
70 proposed as a strategic framework for environmental, social, and economic  
71 sustainability of cities (Benedict, 2000). Presently, the WSUD is gaining popularity. It  
72 is an integrated concept for urban planning and designs based on water environments,  
73 for balancing different land use types and for protecting the water cycle, so that the  
74 city will be sustainable and ecologically friendly (Coombes et al., 2000). Apart from  
75 these concepts, many other new city concepts and ideas have also been proposed,  
76 including “sustainable cities”, “livable cities”, “intelligent cities”, “eco cities”, “low  
77 carbon cities” and even their combinations (De Jong et al., 2015).

78 With proper consideration of these concepts and relevant experiences gained  
79 around the world, the Chinese Government proposed the concept of “*Sponge City*” in  
80 2013 to tackle the worsening urban water disasters in China (Sang & Yang, 2016;  
81 Nguyen et al., 2019). The basic idea of the “*Sponge City*” concept is to enhance the  
82 rainwater-regulation and storage capacity of the underlying surfaces in urban areas. It  
83 considers not only the source control facilities, such as the LID, but also the midway  
84 and terminal control measures for urban stormwater management. Thus, it functions  
85 to detain the stormwater with small-medium return periods to recharge groundwater  
86 that aims at improving the urban resilience (like resilient sponge structures) and  
87 controlling stormwater (Xia, 2017; Li et al., 2019b; Zhu et al., 2019).

88 To begin implementing the “Sponge City” concept, the Government of China chose  
89 30 cities (16 cities in 2015 and 14 cities in 2016, as shown in Figure 2) for the  
90 tentative promotion of the “*Sponge City*” program (SCP), with an annual investment  
91 of US \$60~90 million for each pilot city (Jia et al., 2017). These 30 cities are  
92 generally called as “pilot cities” of the SCP. Up to now, many measures and  
93 technologies have been developed under the guidance and implementation of the SCP,  
94 where all the public acceptance, financial issues, overall legal framework,  
95 environmental risks, and benefit evaluation have been taken into consideration (Xu et  
96 al., 2018; Hu et al., 2019).

97 The outcomes of such studies are certainly encouraging, especially considering the  
98 early stage of the SCP. However, there also remain many challenges and barriers that  
99 affect the effectiveness and delivery of the SCP, as the program has not worked as  
100 well as expected in reducing urban flood disasters (e.g. waterlogging) in many pilot  
101 cities (Chan et al., 2018; Jiang et al., 2018; Nguyen et al., 2019; Liu et al., 2020). This  
102 inevitably raises questions on the functions and effects of the program. Among such  
103 challenges are several key hydrology-related ones, including detection of  
104 spatiotemporal variability of rainstorms, estimation of key urban hydrological  
105 indicators for designing the SCP, and urban hydrological modeling.

106 In this study, we address two key hydrology-related challenges, which play vital  
107 roles and, hence, are top priorities in designing the SCP. The first is concerned with  
108 the determination of the “*Volume Capture Ratio of Annual Rainfall*” (VCRAR), as the  
109 core target of the SCP; and the second is the estimation of a proper rainfall threshold,

110 which influences the layout of Green-infrastructures (GIs) to achieve the above core  
111 VCRAR target (Randall, 2019). As shown in Figure 1, we denote the total rainwater  
112 of a region as  $R_0$  (sum of all blue (or red) rainfall intensities in Figure 1) and denote  
113 the rainwater magnitude that can be controlled (through infiltration, storage, and  
114 evaporation) by the SCP as  $R_1$  (the part below the rainfall threshold,  $T^*$ (blue) (or  
115  $T^*$ (red)), in Figure 1); a VCRAR target requires that the ratio between  $R_1$  and  $R_0$   
116 should be no smaller than VCRAR, and thus it is the core target of the SCP. To  
117 achieve this, a proper rainfall threshold  $T^*$  should be estimated. To be specific, the  
118 suitable layout of GIs (green roofs, bio-retention cells, permeable pavements, *etc.*)  
119 should be designed and implemented, based on which all the rainfall intensities below  
120  $T^*$  should be controlled, and their sum should be no smaller than  $R_1$ , to achieve the  
121 above core VCRAR target. However, in the current implementation of the SCP in  
122 Chinese cities the VCRAR is empirically determined, which lacks reliable scientific  
123 basis. Furthermore, the nonstationary variability of rainfall is not given adequate  
124 consideration in the estimation of proper rainfall threshold. For example, the  
125 estimated rainfall threshold to ensure the same VCRAR target is different when using  
126 the two rainfall samples (blue and red) in Figure 1.

127 **<Figure 1>**

128 To address the above two issues here, we consider the city of Beijing, the capital of  
129 China and one of the 30 pilot cities implementing the SCP, as the case study. Our  
130 main objective is to offer, based on the outcomes of our analysis, proper approaches  
131 and solutions that can provide useful guidelines for improving the implementation of



132 the SCP in Chinese cities and for urban stormwater management in other cities  
133 worldwide.

## 134 **2. Sponge City program in Beijing**

135 The capital city of the People’s Republic of China, Beijing, is chosen as one of the  
136 30 pilot cities implementing the SCP, and their locations are shown in Figure 2.  
137 Beijing frequently encounters serious rainstorms (with intensity higher than 70 mm/h)  
138 and flood events. Over the last two decades, more than 50 rainstorm-flood disasters  
139 have occurred in the region (Yang et al., 2016), directly causing many human deaths  
140 and annual average economic losses of more than US \$100 million. For example, the  
141 rainstorm and floods occurred on 21 July 2012 claimed at least 79 human lives and  
142 caused economic losses equivalent to about US \$1.6 billion (Sang and Yang, 2012).  
143 For tackling the worsening urban water disasters in Beijing, the SCP has been  
144 officially implemented in the urban areas (see Figure 2) since 2016. Up to now, more  
145 than 3,000 stormwater collection and flood control projects (called SCP projects, as  
146 shown in Figure 2) have been built in Beijing, which are now playing important roles  
147 in the stormwater interception, local flood control, non-point source pollution  
148 reduction, and stormwater utilization (Zhang et al., 2018).

149 Following the requests by the Ministry of Housing and Urban-Rural Development  
150 of the People’s Republic of China, the VCRAR was empirically set as “0.80” in the  
151 early stage of the implementation of the SCP in Beijing, which is also continued even  
152 now. Furthermore, according to the “Construction Guideline of Sponge City in  
153 China-Low Impact Development of Stormwater System (Trail)” (Ministry of Housing

154 and Urban-Rural Development, 2014), the VCRAR target is also empirically  
155 determined nationwide, with a value ranging from 0.60 to 0.90 (Li et al., 2017), by  
156 considering the hydrological characteristics and the socio-economic importance of  
157 different cities. However, such empirical determination lacks objective and effective  
158 method for tackling the underlying issue and, therefore, more reliable scientific basis  
159 needs to be established.

160 **<Figure 2>**

161 Following the above Construction Guideline, the rainfall threshold to ensure the  
162 VCRAR target of 0.80 in Beijing was estimated as 27.3 mm, by using the daily  
163 rainfall data measured during 1983–2012 at the Guanxiangtai meteorological station  
164 (shown in Figure 2). The Guanxiangtai meteorological station is usually taken as a  
165 representative station that reflects the climatic conditions in Beijing. However, the  
166 value of “27.3 mm” may have large bias against a rainfall threshold that may be  
167 considered proper (or at least reasonable), as it does not consider the nonstationary  
168 variability of rainfall. It is important to note, however, that due to the influences of  
169 climate variability and rapid urbanization, rainfall in Beijing has been exhibiting  
170 significant nonstationarity over the last six decades or so, as in most other places in  
171 China and elsewhere around the world. For instance, the Mann-Kendall test indicates  
172 that rainfall at the Guanxiangtai station exhibited two abrupt changes since 1951  
173 (Yang et al., 2019), one in 1965 and the other in 1996. Indeed, at the most basic level,  
174 the statistical characteristics (especially the mean value) of rainfall have obvious  
175 differences when different periods are considered, as clearly shown in Table 1.

176 Therefore, the choice of the data period (or record length) would inevitably influence  
177 the estimation of a proper, or at least a reasonable, rainfall threshold, leading to a  
178 biased rainfall threshold that cannot ensure the VCRAR target. More details on this  
179 will be discussed in Section 4.

180 <Table 1>

### 181 **3. Volume Capture Ratio of Annual Rainfall (VCRAR)**

182 The VCRAR is the core target in the design of the SCP, and a key index to  
183 quantify its hydrological effects (from rainfall). Therefore, determination of a proper  
184 VCRAR is a vital issue in the implementation of the SCP. Presently, the VCRAR is  
185 only empirically assigned by considering the requirements of urban stormwater  
186 management and the degree of urbanization. However, it lacks an objective scientific  
187 basis (Guo et al., 2019). Generally, the VCRAR target directly determines the  
188 investment required and its potential benefits. Considering, for example, the need for  
189 waterlogging control, a higher (lower) VCRAR target requires more (less) rainwater  
190 to be controlled, which can thus ensure lower (higher) occurrences of flooding and  
191 waterlogging disasters, yielding higher (lower) benefits; however, this also requires a  
192 larger (smaller) rainfall threshold and thus stronger (weaker) designs and  
193 implementation of GIs, meaning larger (smaller) financial investment (Mei et al.,  
194 2018). Therefore, the trade-offs between the investment for the SCP and its potential  
195 benefits should be quantitatively assessed. This can be a dependable basis for  
196 determining a proper VCRAR.

197 In this study, we propose the following approach for the determination of the  
198 proper VCRAR by considering these trade-off issues:

- 199 (1) estimate the total investment of the SCP under different VCRAR targets;
- 200 (2) use historical hydrological and natural disasters data, and establish the  
201 economic loss curve of urban stormwater disasters in the concerned study area;
- 202 (3) use the above curve to estimate the annual economic losses without the SCP;
- 203 (4) use the same curve to estimate the annual economic losses under different  
204 VCRAR targets and compare their differences with and without the SCP, aimed at  
205 identifying the annual economic benefits from the SCP;
- 206 (5) normalize the total investment for the SCP and its annual economic benefits and  
207 calculate the change rates for analyzing the trade-offs (The normalization is needed,  
208 since the investment and benefits cannot be directly compared); and
- 209 (6) identify the VCRAR value below which the increased rates of annual economic  
210 benefits stay higher than the total investment. This is regarded as the proper VCRAR  
211 value (This is reasonable, since a higher benefit with lower investment is always  
212 desirable and the expectation).

213 For the city of Beijing, considered here as a case study, the economic loss curve of  
214 urban stormwater disasters is obtained from *Yang et al. (2016)*. Based on this, the  
215 trade-offs between the investment for the SCP and its potential benefits in Beijing are  
216 analyzed using the above approach. Figure 3(a) indicates that with an increase in the  
217 VCRAR target, the total financial investment continues to increase and the annual  
218 economic loss continues to decrease in this urban area, as expected, corresponding to

219 the increase in its annual economic benefits. It also shows that the change rate of the  
220 total investment exponentially increases with an increase in the VCRAR target. This  
221 is different from the change rates of its annual economic benefits.

222 Figure 3(b) shows, after normalization, that the change rate of the investment  
223 continues to increase with an increase in the VCRAR value. However, it also shows  
224 that the change rate of the annual economic benefits increases and then decreases with  
225 an increase in the VCRAR target, with the peak change rate of 5.94 achieved at  
226  $VCRAR = 0.65$ . Their change rates have the same values as that obtained at  $VCRAR$   
227  $= 0.73$ , before (after) which the increased rate of the annual economic benefits stays  
228 larger (smaller) than the investment. Thus, a VCRAR target of 0.73 is selected as the  
229 best value by the proposed approach.

230 It is important to note that in the present implementation of the SCP in Beijing, the  
231 VCRAR is empirically set at 0.80. With a VCRAR target of 0.80, there is a 41.0%  
232 increase in investment when compared to that with a VCRAR target of 0.73, which is  
233 obtained from the present study. At the same time, there is only a 20.3% increase in  
234 the overall annual economic benefit with a VCRAR target of 0.80 when compared to  
235 the benefit obtained with a VCRAR target of 0.73. Thus, it is suggested that a value of  
236 0.73 is a more suitable VCRAR target for the implementation of the SCP in Beijing,  
237 for guaranteeing the positive rate of return on the investment.

238 <Figure 3>

239

240 **4. Rainfall threshold**

241 For achieving the VCRAR target determined from the approach proposed above,  
242 estimation of a proper rainfall threshold is important. That is, through a rational layout  
243 of GIs (green roofs, bio-retention cells, permeable pavements, etc.) and their  
244 constructions, rainfall intensities below a certain rainfall threshold are required to  
245 intercept and control, based on which the VCRAR target is expected to achieve (as  
246 shown in Figure 1).

247 The National Assessment Standard for sponge city construction effect (GB/T  
248 51345-2018, [http://www.mohurd.gov.cn/wjfb/201904/t20190409\\_240118.html](http://www.mohurd.gov.cn/wjfb/201904/t20190409_240118.html)) was  
249 issued by the *Ministry of Housing and Urban-Rural Development of the People's*  
250 *Republic of China* in 2018. According to this, the rainfall threshold is recommended  
251 to be estimated using the following approach:

252 (1) select the daily rainfall data samples (denoted as  $X_0$ ) with more than 30 years  
253 and remove those data samples with the intensities smaller than 2 mm/day. Then, take  
254 the residual as the effective rainfall data samples (denoted as  $X$  and denoted its total  
255 amount as  $R$ );

256 (2) set a small rainfall threshold  $T_j$  and divide the effective rainfall data samples  $X$   
257 into two parts (above and below  $T_j$ ), with the amount  $R_j^a$  and  $R_j^b$  (i.e.,  $R = R_j^a + R_j^b$ ),  
258 respectively, in order to evaluate the ratio  $S_j = R_j^b/R$ ;

259 (3) increase the value of  $T_j$  and repeat the above steps to obtain the time series  $S_j$ ;  
260 and

261 (4) the  $T^*$  when its  $S_j$  is equal to the determined VCRAR is the estimated rainfall  
262 threshold.

263 There are two major drawbacks in the above approach. First, it does not consider  
264 the influence of data period (and also record length) of the rainfall data samples used.  
265 Note that the record length always has some influence, even if it is longer than 30  
266 years; in general, the longer the data, the better and more reliable are the outcomes.  
267 Second, it does not consider the influence of time-resolution of the rainfall data  
268 samples used. Considering the climatic variability and change (Loo et al., 2019), it is  
269 generally known that rainfall variations usually indicate nonstationary characteristics,  
270 such as the oscillations and trends at multi-temporal scales (Sang, 2013; Lin et al.,  
271 2019). Therefore, rainfall data samples with a “30-year” record, as required by the  
272 National Assessment Standard, may not be sufficient to accurately represent the  
273 statistical characteristics of its population, and the rainfall threshold estimated may  
274 vary with the length and period of the data records used (as shown in the example in  
275 Figure 1). In addition, proper consideration of the temporal resolution of the rainfall  
276 data is also important. For instance, use of daily rainfall data may likely lead to  
277 numerical bias, because a large proportion of extreme rainfall events occur in  
278 durations shorter than 24 hours, especially those that occur in Northern China. Thus,  
279 the rainfall threshold estimated also varies with the temporal resolution considered.

280 These problems can be explained with the case study of the city of Beijing. Figure  
281 4 shows the results for two different scenarios at the Guanxiangtai meteorological  
282 station: one with rainfall data over different time periods (Figure 4(a)) and the other  
283 with rainfall data at different temporal resolutions (Figure 4(b)). More specifically,  
284 five different time periods (1951–1965, 1966–1996, 1997–2016, 1966–2016, and

285 1951–2016) and five different temporal resolutions (1-hr, 2-hr, 6-hr, 12-hr, and 24-hr)  
286 are considered. As seen from Figure 4(a), the estimated rainfall thresholds for a given  
287 VCRAR are different for the five periods, due to the nonstationary characteristics of  
288 rainfall variability (as shown in Table 1). Furthermore, the rainfall thresholds  
289 corresponding to a given VCRAR also differ for different temporal resolutions of  
290 rainfall data samples (see Figure 4(b)). These different rainfall thresholds require  
291 different layouts of GIs and their distinct construction standards, for guaranteeing the  
292 VCRAR targeted.

293 The rainfall threshold used in the present implementation of the SCP in Beijing was  
294 estimated as 27.3 mm (as explained in Section 2), to ensure the VCRAR target of 0.80  
295 that is presently used. However, a reasonable rainfall threshold should at least be  
296 larger than 30.0 mm, no matter considering longer data periods (see Figure 4(a),  
297 except the results in 1997-2016) or other temporal resolutions (as clearly shown in  
298 Figure 4(b)). By using the above threshold of 27.3 mm, the stormwater in the urban  
299 areas cannot be controlled enough and, thus, the VCRAR target cannot be achieved.  
300 This implies that more efforts are needed to improve the SCP in Beijing and to  
301 improve the urban water management in the region.

302 **<Figure 4>**

303 By further considering the spatial heterogeneity of statistical characteristics of  
304 extreme rainfall events, rainfall thresholds should also have spatial changes (Sang and  
305 Yang, 2016), which cannot easily be estimated by the uniformed approach from the  
306 National Assessment or Guidance standard of the SCP. Indeed, the rainfall threshold



307 estimated from the uniformed approach would have large numerical bias or errors,  
308 influencing the layout of the GIs, and causing inaccurate investment budget and low  
309 effects for the SCP.

310 For obtaining more explicit and precise estimation of the rainfall threshold, it is  
311 important to analyze the nonstationary characteristics of rainfall by considering the  
312 influences of the above two factors, even though rainfall data over long periods and at  
313 high temporal resolutions are not easily available in China, and globally more broadly.  
314 It is suggested, therefore, that a set of rainfall thresholds be estimated to reflect  
315 different rainfall situations, with at least the maximum, average, and minimum rainfall  
316 thresholds estimated, for supporting the rational layout of green-infrastructures and  
317 the estimation of investment budget for the SCP.

318

## 319 **5. Closing Remarks**

320 The Sponge City program (SCP), which is based on an accurate understanding of  
321 hydrological characteristics, is an important direction of development in urban  
322 stormwater management in China. However, there are some key issues in the present  
323 implementation of the SCP in different Chinese cities. This study discussed two key  
324 hydrology-related issues, which are also common problems in the current SCP  
325 implementation in Chinese cities, that need to be considered prior to the design and  
326 implementation of the SCP: (1) determination of Volume Capture Ratio of Annual  
327 Rainfall (VCRAR); and (2) estimation of a proper rainfall threshold. With a case study  
328 of the city of Beijing, the present study proposed new approaches to address the above

329 two issues. The results from the proposed approaches are certainly encouraging.  
330 Application of the approaches to other Chinese cities (as shown in Figure 2), where  
331 similar situations and many other complex problems exist, would help realize their  
332 suitability for the SCP, and urban stormwater management, more broadly.

333 It is important to note, at this point, that approaches for estimation of proper  
334 VCRAR and rainfall threshold are still in their early stages. There is still a long way  
335 to go in our efforts to mitigate the problems associated with urban stormwater  
336 management (e.g. waterlogging) in Chinese cities, which continues to be a very  
337 complex and challenging issue. With the anticipated impacts of climate change, the  
338 increasing trend (i.e. more frequent and greater magnitude) of regional hydroclimatic  
339 extremes (especially floods) is very likely to continue, and even accelerate in the  
340 future. Therefore, their potential risks and influences should be further evaluated in  
341 the implementation of the SCP and the design of the SCP infrastructures and measures.  
342 As a result, more meticulous and rational actions and policies should be developed  
343 and undertaken, for achieving the targets of the SCP and further development for  
344 improving the sustainable urban stormwater management in Chinese cities, and cities  
345 around the world more broadly.

346

#### 347 **Acknowledgments**

348 This project was financially supported by the National Key Research and  
349 Development Program of China (No. 2019YFA0606903), Beijing Municipal Natural  
350 Science Foundation (No. 8194061), National Natural Science Foundation of China

351 (No. 41971040), the Youth Innovation Promotion Association CAS (No. 2017074),  
352 and the Major Science and Technology Program for Water Pollution Control and  
353 Treatment (No. 2017ZX07103-002). The authors would like to thank the four  
354 anonymous reviewers for their constructive comments and useful suggestions on an  
355 earlier version of this manuscript, which led to significant improvements.

356

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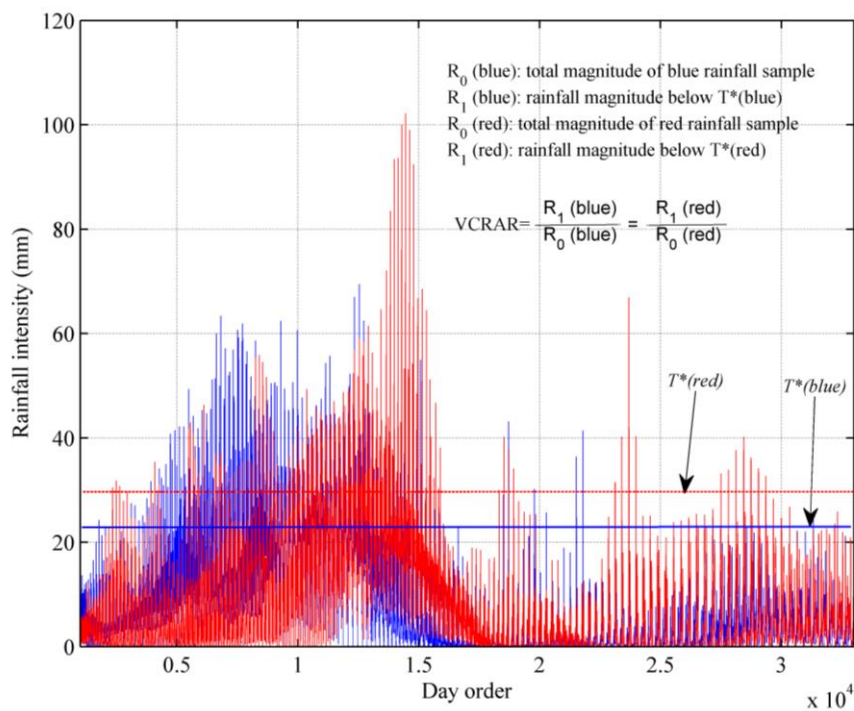
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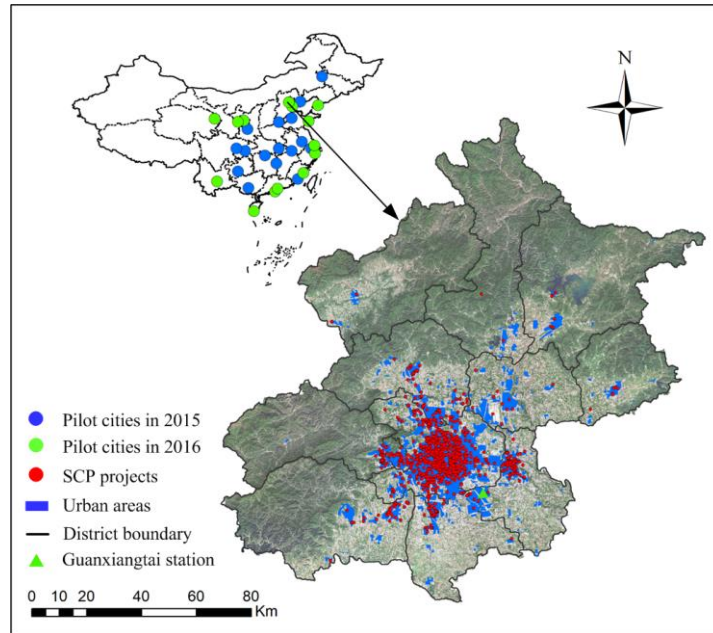
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471 **Captions of Figures**

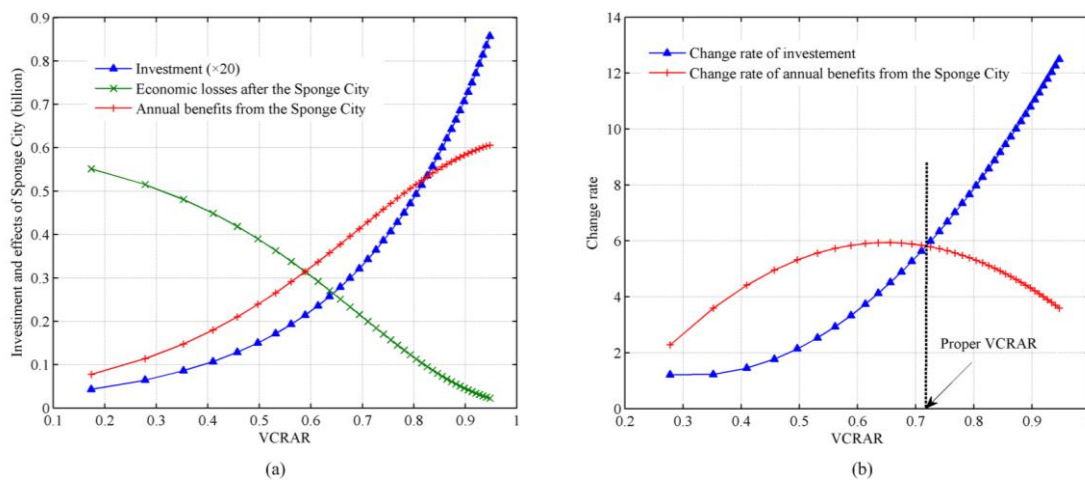




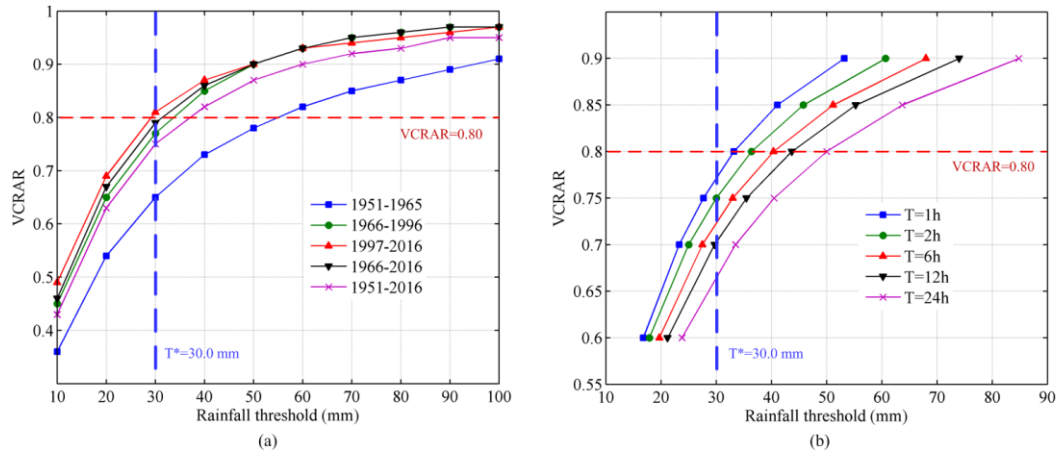
473 **Figure 1.** Schematic diagram showing the definition of the volume capture ratio of  
 474 annual rainfall (VCRAR) and the rainfall threshold ( $T^*$ ) to ensure the VCRAR target.  
 475 Here, the blue and red time series represent two rainfall samples. Using the two  
 476 rainfall thresholds based on these samples to ensure the same VCRAR are different.  
 477



478  
 479 **Figure 2.** Locations of 30 pilot cities for the implementation of the Sponge City  
 480 program (SCP) in China, and the spatial distribution of the SCP projects that have  
 481 been built since 2016 in the city of Beijing.  
 482



483  
 484 **Figure 3.** (a) Relationship between the volume capture ratio of annual rainfall  
 485 (VCRAR) and the total investment, and the annual economic losses and benefits by  
 486 considering the effects of the SCP in Beijing. (b) Relationship between the VCRAR  
 487 and the change rates of the normalized investment and its annual economic benefits.  
 488 Here, the daily rainfall data measured at the representative Guanxiangtai station in  
 489 Beijing, with the measured period from 1951 to 2016, are used for the calculation.



490

491 **Figure 4.** Relationship between the rainfall threshold and the volume capture ratio of  
 492 annual rainfall (VCRAR) in Beijing. (a) Their relationship curves obtained from the  
 493 daily rainfall data over different time periods; and (b) their relationship curves at  
 494 different temporal resolutions. Here, it shows that a reasonable rainfall threshold  
 495 should at least be larger than 30.0 mm (i.e., the abscissa values of all curves (except  
 496 that in 1997-2016) are larger than 30.0 mm when their ordinate values equal 0.80), to  
 497 ensure the VCRAR target of 0.80 that is presently used in Beijing.

498

499 **Tables in the manuscript**

500

501 **Table 1.** Statistical characteristics of annual rainfall measured at the representative  
 502 Guanxiangtai meteorological station in Beijing over different periods.

Statistic	Period				
	1951-1965	1966-1996	1997-2016	1966-2016	1951-2016
Mean (mm)	709.17	594.07	531.73	569.62	603.21
Coefficient of variation	0.37	0.26	0.27	0.27	0.34
Coefficient of skewness	0.49	0.21	0.65	0.39	0.97

503