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Challenges in urban stormwater management in Chinese Cities: A hydrologic perspective

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

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

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

1. Introduction

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

The BMPs were first proposed in the 1970s in North America to control stormwater pollution. Following these, the LID was developed in the 1990s and have been widely adopted in North America and New Zealand (USEPA, 2000). With the concept for source control of stormwater management, the LID promotes and advocates various small and separate ecological facilities (bio-retention measures, green roofs, pervious pavements, grass swales, etc.) to control stormwater pollution, reduce runoff volume, and relieve combined sewer overflow (Li et al., 2016). However, the stormwater problems encountered in many mega cities around the world are too complex to be solved only depending on those source control facilities. In 2000, the GIs were proposed as a strategic framework for environmental, social, and economic sustainability of cities (Benedict, 2000). Presently, the WSUD is gaining popularity. It is an integrated concept for urban planning and designs based on water environments, for balancing different land use types and for protecting the water cycle, so that the city will be sustainable and ecologically friendly (Coombes et al., 2000). Apart from these concepts, many other new city concepts and ideas have also been proposed, including "sustainable cities", "livable cities", "intelligent cities", "eco cities", "low carbon cities" and even their combinations (De Jong et al., 2015).

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

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

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

In this study, we address two key hydrology-related challenges, which play vital roles and, hence, are top priorities in designing the SCP. The first is concerned with the determination of the “*Volume Capture Ratio of Annual Rainfall*” (VCRAR), as the core target of the SCP; and the second is the estimation of a proper rainfall threshold, which influences the layout of Green-infrastructures (GIs) to achieve the above core VCRAR target (Randall, 2019). As shown in Figure 1, we denote the total rainwater of a region as R_0 (sum of all blue (or red) rainfall intensities in Figure 1) and denote the rainwater magnitude that can be controlled (through infiltration, storage, and evaporation) by the SCP as R_1 (the part below the rainfall threshold, T^*(blue) (or T^*(red)), in Figure 1); a VCRAR target requires that the ratio between R_1 and R_0 should be no smaller than VCRAR, and thus it is the core target of the SCP. To achieve this, a proper rainfall threshold T^* should be estimated. To be specific, the suitable layout of GIs (green roofs, bio-retention cells, permeable pavements, *etc.*) should be designed and implemented, based on which all the rainfall intensities below T^* should be controlled, and their sum should be no smaller than R_1, to achieve the above core VCRAR target. However, in the current implementation of the SCP in Chinese cities the VCRAR is empirically determined, which lacks reliable scientific basis. Furthermore, the nonstationary variability of rainfall is not given adequate consideration in the estimation of proper rainfall threshold. For example, the estimated rainfall threshold to ensure the same VCRAR target is different when using the two rainfall samples (blue and red) in Figure 1.

<Figure 1>

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

2. Sponge City program in Beijing

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

Following the requests by the Ministry of Housing and Urban-Rural Development of the People's Republic of China, the VCRAR was empirically set as "0.80" in the early stage of the implementation of the SCP in Beijing, which is also continued even now. Furthermore, according to the "Construction Guideline of Sponge City in China-Low Impact Development of Stormwater System (Trail)" (Ministry of Housing and Urban-Rural Development, 2014), the VCRAR target is also empirically determined nationwide, with a value ranging from 0.60 to 0.90 (Li et al., 2017), by considering the hydrological characteristics and the socio-economic importance of different cities. However, such empirical determination lacks objective and effective method for tackling the underlying issue and, therefore, more reliable scientific basis needs to be established.

<Figure 2>

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

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

<Table 1>

3. Volume Capture Ratio of Annual Rainfall (VCRAR)

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

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

(1) estimate the total investment of the SCP under different VCRAR targets;

(2) use historical hydrological and natural disasters data, and establish the economic loss curve of urban stormwater disasters in the concerned study area;

(3) use the above curve to estimate the annual economic losses without the SCP;

(4) use the same curve to estimate the annual economic losses under different VCRAR targets and compare their differences with and without the SCP, aimed at identifying the annual economic benefits from the SCP;

(5) normalize the total investment for the SCP and its annual economic benefits and calculate the change rates for analyzing the trade-offs (The normalization is needed, since the investment and benefits cannot be directly compared); and

(6) identify the VCRAR value below which the increased rates of annual economic benefits stay higher than the total investment. This is regarded as the proper VCRAR value (This is reasonable, since a higher benefit with lower investment is always desirable and the expectation).

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

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

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

<Figure 3>

4. Rainfall threshold

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

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

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

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

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

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

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

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

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

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

<Figure 4>

By further considering the spatial heterogeneity of statistical characteristics of extreme rainfall events, rainfall thresholds should also have spatial changes (Sang and Yang, 2016), which cannot easily be estimated by the uniformed approach from the National Assessment or Guidance standard of the SCP. Indeed, the rainfall threshold estimated from the uniformed approach would have large numerical bias or errors, influencing the layout of the GIs, and causing inaccurate investment budget and low effects for the SCP.

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

5. Closing Remarks

The Sponge City program (SCP), which is based on an accurate understanding of hydrological characteristics, is an important direction of development in urban stormwater management in China. However, there are some key issues in the present implementation of the SCP in different Chinese cities. This study discussed two key hydrology-related issues, which are also common problems in the current SCP implementation in Chinese cities, that need to be considered prior to the design and implementation of the SCP: (1) determination of Volume Capture Ratio of Annual Rainfall VCRAR); and (2) estimation of a proper rainfall threshold. With a case study of the city of Beijing, the present study proposed new approaches to address the above two issues. The results from the proposed approaches are certainly encouraging. Application of the approaches to other Chinese cities (as shown in Figure 2), where similar situations and many other complex problems exist, would help realize their suitability for the SCP, and urban stormwater management, more broadly.

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

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References

Benedict, M.A., 2000. Green Infrastructure: A Strategic Approach to land conservation. American Planning Association. Chicago: Planning Advisory Service Memo.

Blöschl, G., et al., 2019. Changing climate both increases and decreases European river floods. Nature, 573, 108-111.

Chan, F.K.S., Griffiths, J.A., Higgitt, D., Xu, S., Zhu, F., Tang, Y.T., Xu, Y., Thorne, C.R., 2018. "Sponge City" in China—a breakthrough of planning and flood risk management in the urban context. Land Use Policy, 76, 772-778.

Chui, T.F.M., Liu, X., Zhan, W., 2016. Assessing cost-effectiveness of specific lid practice designs in response to large storm events. Journal of Hydrology, 533, 353-364.

Chui, T.F.M., Trinh, D., 2016. Modelling infiltration enhancement in a tropical urban catchment for improved stormwater management. Hydrological Processes, 30(23), 4405-4419.

Coombes, P.J., Argue, J.R., Kuczera, G., 2000. Figtree place: A case study in water sensitive urban development (WSUD). Urban Water, 1, 335-343.

De Jong, M., Joss, S., Schraven, D., Zhan, C., Weijnen, M., 2015. Sustainable-smart-resilient-low carbon-eco-knowledge cities; making sense of a multitude of concepts promoting sustainable urbanization. Journal of Cleaner Production, 109, 25-38.

Guo, X., Guo, Q., Zhou, Z., Du, P., Zhao, D., 2019. Degrees of hydrologic restoration by low impact development practices under different runoff volume capture goals. Journal of Hydrology, 578, 124069.

Haghighatafshar, S., Yamanee-Nolin, M., Klinting, A., Roldin, M., Gustafsson, L. G., Aspegren, H., Jönsson, K., 2019. Hydroeconomic optimization of mesoscale blue-green stormwater systems at the city level. Journal of Hydrology, 578, 124125.

Hu, M.C., Zhang, X., Li, Y., Yang, H., Tanaka, K., 2019. Flood mitigation performance of low impact development technologies under different storms for retrofitting an urbanized area. Journal of Cleaner Production, 222, 373-380.

Jia, H, Wang, Z, Zhen, X, et al., 2017. China's sponge city construction: A discussion on technical approaches. Frontiers of Environmental Science & Engineering, 11(4), 18.

Jiang, Y., Zevenbergen, C., Ma, Y., 2018. Urban pluvial flooding and stormwater management: A contemporary review of China's challenges and "Sponge Cities" strategy. Environmental Science & Policy, 80, 132-143.

Li, C., Peng, C., Chiang, P., Cai, Y., Wang, X., Yang, Z., 2019a. Mechanisms and applications of green infrastructure practices for stormwater control: A review. Journal of Hydrology, 568, 626-637.

Li, H., Ding, L., Ren, M., Li, C., Wang, H., 2017. Sponge city construction in China: A survey of the challenges and opportunities. Water, 9(9), 594.

Li, Q., Wang, F., Yu, Y., Huang, Z., Li, M., Guan, Y., 2019b. Comprehensive performance evaluation of LID practices for the sponge city construction: a case study in Guangxi, china. Journal of Environmental Management, 231, 10-20.

Li, X.N., Li, J.Q., Fang, X., Gong, Y.W., Wang, W.L., 2016. Case Studies of the Sponge City Program in China. World Environmental and Water Resources Congress 2016, 295-308. 10.1061/9780784479858.031.

Lin, C.C., Liou, K.Y., Lee, M., Chiueh, P.T., 2019. Impacts of urban water consumption under climate change: An adaptation measure of rainwater harvesting system. Journal of Hydrology, 572, 160-168.

Liu, J., Shao, W., Xiang, C., Mei, C., Li, Z., 2020. Uncertainties of urban flood modeling: Influence of parameters for different underlying surfaces. Environmental Research, 182, 108929.

Loo, Y.Y., Billa, L., Singh, A., 2015. Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia. Geoscience Frontiers, 6(6), 817-823.

Mei, C., Liu, J., Wang, H., Yang, Z., Ding, X., Shao, W., 2018. Integrated assessments of green infrastructure for flood mitigation to support robust decision-making for sponge city construction in an urbanized watershed. Science of the Total Environment, 639, 1394-1407.

Ministry of Housing and Urban-Rural Development, 2014. The construction guideline of sponge city in China-low impact development of stormwater system (trail).

Nguyen, T.T., Ngo, H.H., Guo, W., Wang, X.C., Ren, N., Li, G., Ding, J., Liang, H., 2019. Implementation of a specific urban water management-sponge city. Science of the Total Environment, 652, 147-162.

Randall, M., Sun, F., Zhang, Y., Jensen, M. B., 2019. Evaluating Sponge City volume capture ratio at the catchment scale using SWMM. Journal of environmental management, 246, 745-757.

Sang Y.F., 2013. A review on the applications of wavelet transform in hydrologic timeseries analysis. Atmospheric Research, 122, 8-15.

Sang, Y.F., Yang, M., 2016. Urban waterlogs control in China: more effective strategies and actions are needed. Natural Hazards, 85(2), 1291-1294.

Salas, J.D., Obeysekera, J., Vogel, R.M., 2018. Techniques for assessing water infrastructure for nonstationary extreme events: a review. Hydrological Sciences Journal, 63(3), 325-352.

United States Environmental Protection Agency (USEPA). 2000. Low impact development (LID): A literature review. EPA-841-B-00-005.

Wang, P., Deng, X., Zhou, H., Qi, W., 2018. Responses of urban ecosystem health to precipitation extreme: A case study in Beijing and Tianjin. Journal of Cleaner Production, 177, 124-133.

Winsemius, H.C., et al., 2016. Global drivers of future river flood risk. Nature Climate Change, 6, 381-385.

Xia, J., Zhang, Y., Xiong, L., He, S., Wang, L.F., Yu, Z., 2017. Opportunities and challenges of the Sponge City construction related to urban water issues in China. Science China Earth Sciences, 60, 652-658.

Xu, T., Engel, B.A., Shi, X., Leng, L., Jia, H., Yu, S.L., Liu, Y., 2018. Marginal-cost-based greedy strategy (MCGS): fast and reliable optimization of low impact development (LID) layout. Science of the Total Environment, 640-641, 570-580.

Yang, M.Y., Pan, X.Y., Liu, H.L., Yu, L., Di, S.C., Zhang, Y.H., 2019. Accurate calculation of the volume capture ratio of annual rainfall considering the field rainfall evolution (in Chinese with English Abstract). Journal of Hydraulic Engineering, 50(12), 1510-1517,1528.

Yang, P.G., Jin, J., Zhao, D.S., Li, J., 2016. An Urban Vulnerability Study Based on Historical Flood Data: A Case Study of Beijing (in Chinese with English Abstract). Scientia Geographica Sinica, 36(5), 733-741.

Zevenbergen, C., Fu, D., Pathirana, A., 2018. Transitioning to sponge cities: Challenges and opportunities to address urban water problems in China. Water, 10, 1230; doi:10.3390/w10091230.

Zhang, L.X., Yang, Z.F., Voinov, A., Gao, S.L., 2016. Nature-inspired stormwater management practice: The ecological wisdom underlying the Tuanchen drainage system in Beijing, China and its contemporary relevance. Landscape and Urban Planning, 155, 11-20.

Zhang, P.P., Zhang, L.X., Hao, Y., Liang, S., Liu, G.Y., Xiong, X., Yang, M., Tang, W.Z., 2019. Understanding the tele-coupling mechanism of urban food-energy-water nexus: Critical sources, nodes, and supply chains. Journal of Cleaner Production, 235, 297-307

Zhang, S., Li, Y., Ma, M., Song, T., Song, R., 2018. Storm water management and flood control in Sponge City Construction of Beijing. Water, 10, 1040.

Zhu, Z., Chen, Z., Chen, X., Yu, G., 2019. An assessment of the hydrologic effectiveness of low impact development (LID) practices for managing runoff with different objectives. Journal of Environmental Management, 231, 504-514.

Captions of Figures

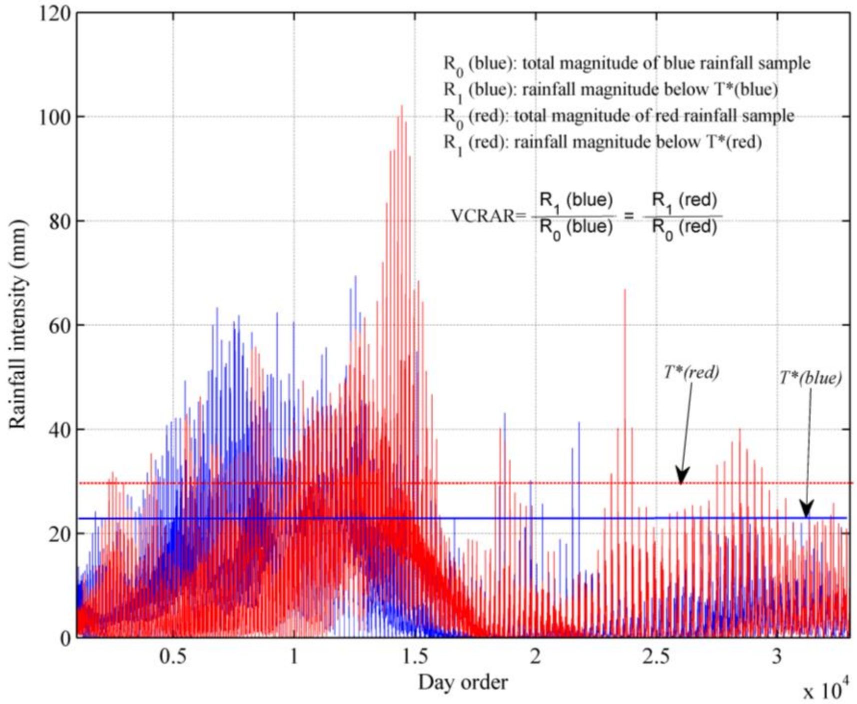

Figure 1. Schematic diagram showing the definition of the volume capture ratio of annual rainfall (VCRAR) and the rainfall threshold (T^*) to ensure the VCRAR target. Here, the blue and red time series represent two rainfall samples. Using the two rainfall thresholds based on these samples to ensure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

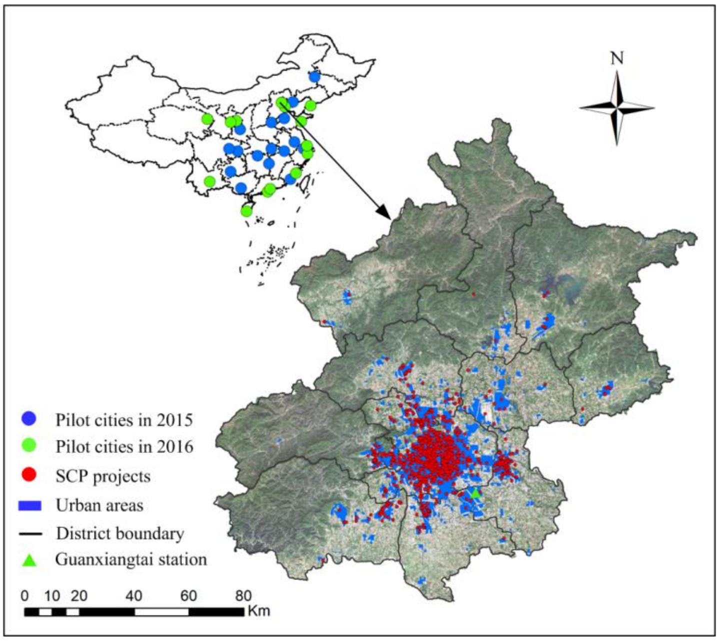

Figure 2. Locations of 30 pilot cities for the implementation of the Sponge City program (SCP) in China, and the spatial distribution of the SCP projects that have been built since 2016 in the city of Beijing.

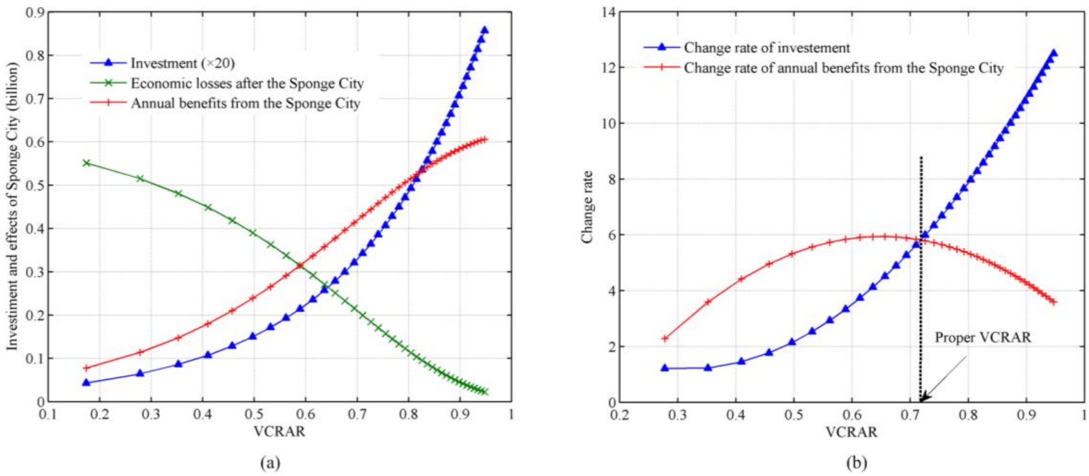

Figure 3. (a) Relationship between the volume capture ratio of annual rainfall (VCRAR) and the total investment, and the annual economic losses and benefits by considering the effects of the SCP in Beijing. (b) Relationship between the VCRAR and the change rates of the normalized investment and its annual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

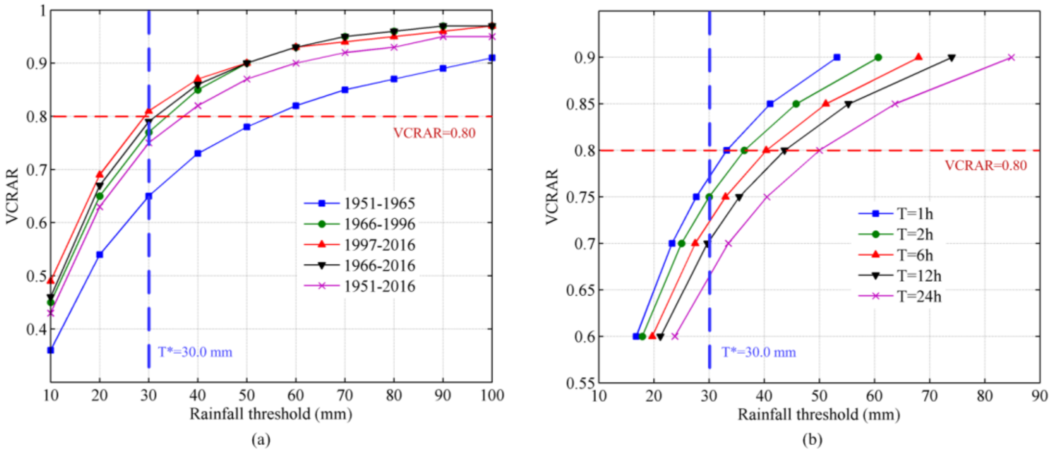

Figure 4. Relationship between the rainfall threshold and the volume capture ratio of annual rainfall (VCRAR) in Beijing. (a) Their relationship curves obtained from the daily rainfall data over different time periods; and (b) their relationship curves at different temporal resolutions. Here, it shows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

Tables in the manuscript

Table 1. Statistical characteristics of annual rainfall measured at the representative 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