

Cross-boundary Evolution of Urban Planning and Urban Drainage Towards the Water Sensitive “Sponge City”



Meiyue Zhou, Stephan Köster, Jian’e Zuo, Wu Che, and Xianping Wang

Abstract To counter its high urban pluvial flood vulnerability, China has been promoting Sponge City Development, a critical urban transition that requires cross-boundary evolution, particularly among the urban planning and urban drainage sectors. This article analyzes the relevant causes of high urban pluvial flood vulnerabilities in Chinese cities and the enormous gaps between the status quo and the ambitious targets. To bridge the gaps, a three-tier solution system is proposed and is supported by a broad range of approaches, know-how, techniques, examples, concepts, and policies. Firstly, water-sensitive urban planning can minimize macroscale damage on the local hydrological cycle. For example, it is illustrated here how cities can preserve critical ecological infrastructure effectively while developing resiliently, compactly, and habitably, for example, through spatial development criteria, urban growth boundaries and multifunctional urban poly-centers. Furthermore, implementations of low-impact development (LID) facilities can ameliorate local hydrology and reduce runoff pollution. This research thoroughly analyzes the relevant risks and challenges while customizing solutions, e.g., LID

The original version of this chapter was revised: author group was corrected. The correction to this chapter is available at https://doi.org/10.1007/978-3-030-01488-9_24

M. Zhou (✉)
Project Engineer Pabsch & Partner, Hildesheim, Germany

S. Köster
Institute of Sanitary Engineering and Waste Management, Leibniz University Hannover,
Hanover, Germany
e-mail: koester@isah.uni-hannover.de

J. Zuo
School of Environment, Tsinghua University, Beijing, China
e-mail: jiane.zuo@mail.tsinghua.edu.cn

W. Che
School of Environment and Energy Engineering, Beijing University of Civil Engineering
and Architecture, Beijing, China
e-mail: chewu812@vip.163.com

X. Wang
Jiaxing Planning & Design Research Institute Co., LTD, Jiaxing, China

planning, based on improved hydrology – hydraulic and water quality simulations, management train, and separated treatment. Lastly, urban sewer system can be improved cost-efficiently via improving top-level designs and also via fully releasing, utilizing, and activating the existing sewer system's drainage and detention potential. Although the lessons and recommendations reviewed here are customized for Chinese cities, they can also be a reference for other fast-developing cities endangered by urban pluvial flooding.

1 Introduction

Due to economic reform, China has been experiencing unprecedented economic growth and rapid urbanization. Till 2016 its urbanization ratio reached 57.35% with 792.98 million urban dwellers living in 656 cities and counties (NBS, 2017). However, its ultra-urbanization in the past decades also caused substantial urban environmental problems, such as severe ecological damage, air pollution, urban climate problems, water deterioration, and water scarcity. Urban pluvial flooding is a notorious threat in particular for most Chinese cities and has led to billions of euros lost on average each year (Yu and Liu 2003; State Flood Control and Drought Relief Headquarters and PRC Ministry of Water Resources 2012). Within the years 2008–2010, pluvial floods swept over 218 Chinese cities (Lv and Zhao 2013).

Future urban pluvial flooding scenarios will be exacerbated due to the impacts of climate change and its synergy with the urban microclimate caused by land sealing. A series of researchers have indicated that climate change will on one hand accelerate China's urbanization via surging the risks for rural populations (Chen et al. 2005; Huang et al. 2007) while on the other hand concentrating urbanization and immigration to Central, Southern, and Eastern China in the middle and long term, due to the predicted worsening climatic and geological disasters in Northern and Western China than the rest of China. However, even Central, Southern, and Eastern China also expect to face serious climate change challenges such as rising sea levels, storm surges, extreme rainfall, flooding, seasonal droughts, and heat waves (Chen et al. 2005; Xu et al. 2005; Zhang et al. 2008; Zhai et al. 2011a; Shi et al. 2012). Furthermore, urban microclimate, esp. UHIE (urban heat island effects) and URIE (urban rain island effects), can escalate extreme weather esp. drought and heavy rainfall (Zhai et al. 2011b). UHIE and URIE together with the nationwide fiercer and more frequent heavy rainfall can intensify urban flooding risks. Hence, it is foreseen that climate change will put more urban populations under the enduring risks of urban stormwater flooding along with greater damages and higher economic losses than before (Weng et al. 2013).

With the advancing urbanization of China, urban infrastructure construction esp. municipal engineering development will continue to thrive. On one hand, large cities need to retrofit and improve their existing infrastructure. On the other hand, a large number of small- and medium-sized cities will experience large-scale urban infrastructure development esp. in water supply and drainage services (Xinhua News Agency 2014). Yet, urban infrastructure construction esp. in medium- and

small-sized cities faces serious funding shortages and therefore requires robust and cost-effective solutions in the long term (Koizumi et al. 2008).

This article is targeted at reducing China's urban flooding vulnerabilities and resolves urban planning and urban drainage problems. This article also seeks to explore and customize the state-of-the-art practices and concepts as future-oriented solutions.

2 Materials and Methods

This article is based on a broad range of literature reviews covering major topics such as urbanization, land-use planning, climate change, flood control, urban drainage, politics, administration, and finance. On one hand, we have integrated information from relevant research results, policies, and reports from China and additionally from international experiences. On the other hand, this research article is practice-oriented, thanks to practical inputs from plenty expert interviews, stakeholder workshops, and site visits. Though Chinese cities are the main focus, other fast-developing regions could also refer to the experiences, principles, concepts, and techniques summarized here due to the integrated inputs.

3 Results and Discussions

3.1 Cause Analysis

3.1.1 Low-Efficiency Urban Expansion

The most evident symbol for China's urbanization is the vast land use and land cover changes (LULCC), esp. sealing natural land with impervious surfaces, which has been particularly swift since the year 2000 (Kuang et al. 2013). Massive urban expansion and construction often encroach over farmland and water bodies. For instance, Shanghai has usurped 1158 km² of farmland in the last 20 years (Miao et al. 2011), while Wuhan City has preserved only 27 of 147 lakes since 1949 (Di Liu 2009). Such massive construction has also led to the unreasonable positioning and arrangement of urban settlements. The construction of towns and cities is located in many cases in low-lying areas, sometimes even in flood zones without protection (Dai and Cao 2012).

Researchers have acknowledged that increasing imperviousness causes dramatically higher stormwater runoff in addition to higher and earlier peak discharge (Livingston and McCarron 1992; Schueler et al. 1992; Wijesekara et al. 2010; Yang 2013). It is no wonder that most of China's big cities integrated runoff coefficients reach as high as ca.0.4–0.8 (MOHURD 2011). For example, Shanghai, with over 80% imperviousness, has 50–80% precipitation becoming runoff (Wang and Rao 2004).

Moreover, impervious surfaces also damage the urban hydrologic system. The massive LULCC during China's urbanization has not only eliminated lots of water

bodies but has also split, blocked, and impaired the natural hydraulic circulation of the remaining urban water systems. These arbitrary disturbances increase the instability of natural water bodies' hydrological processes, impair natural water bodies' ecological security, and therefore aggravate urban water safety problems (Cuo et al. 2008; Liu 2009; Bao 2011; Kuang et al. 2013).

In addition, impervious urban LULCC also exacerbates the flooding pressure through escalating the UHIE and the accompanying URIE. Under URIE, urban areas tend to receive more precipitation than suburbs during flooding seasons but less than suburbs during dry seasons. In any case, URIE makes cities more susceptible to high-intensity rainstorms, therefore aggravating the risk of urban flooding (Zhai et al. 2011b). As Chinese cities feature especially severe UHIE (Tang et al. 2009; Zhai et al. 2011b; National Aeronautics and Space Administration 2013), one can safely infer their strong URIE and hence predominantly high heavy rainfall possibilities.

3.1.2 Infrastructure Planning and Construction

The ultra-rapid urbanization has left Chinese cities with a huge gap between the fast aboveground development and the overdue underground urban infrastructure development, such as the poor-quality urban drainage pipeline system (Koizumi et al. 2008). Nationwide surveys show that even the drainage capacities in provincial cities have about only 1y return period, while more than 70% of all the urban drainage systems have only less than 1y design return periods (IWHR 2013). Such low urban drainage pipeline capacities originate from the following facts:

- (a) Though improved, China's urban drainage standards have been set as very low, e.g., ranging between 0.5 and 3y before 2014 and between 2 and 5y since 2014 for ordinary areas (MOHURD 2011, 2014a).
- (b) The common application of flow attenuation coefficient for storm sewer design until 2014 made the capacity of a 1y design return period storm sewer in China only equal to a 0.5–0.8y abroad (Gong et al. 2012; MOHURD 2014a).
- (c) Local decision-makers tend to adopt the lower limits of the already very low urban drainage standards (IWHR 2013).
- (d) The relevant weak monitoring, operation, and maintenance culture excessive sewer misconnections, blockage, and damages. Meanwhile the common “lowest unique bid” and subcontracting during government procurement may not guarantee the due quality either (Robert Rothery 2003; Weisheng et al. 2013; Ye et al. 2013).
- (e) Plenty of the urban drainage pipeline systems in Chinese cities are already heavily loaded even in dry seasons, due to the ever-increasing service area and the higher stormwater runoff coefficients.

To sum up, massive LULCC surge Chinese cities' pluvial flood risk via causing higher and more rapid peak discharge and boosting URIE (Di Liu 2009). Meanwhile the vanished natural drainage capacity fails to be compensated under the absence of a robust and systematic drainage system (Wu and Zhai 2012). Consequently, in the

event of heavy rainfall, large impervious urban areas intensely escalate and concentrate stormwater runoff in a short time. On one hand, the weak municipal sewer system becomes a bottleneck for transferring floodwaters to the receiving water bodies; on the other hand, the impaired inland water system not only fails to buffer the intense stormwater runoff inflow but also poses an extra flooding risk. Take the typical pluvial flood process in Wuhan City as example: after urbanization, its flooding durations were squeezed from ca. 20 h to ca. 10 h; flood peak occurred 3–4 h earlier, and the flood peak runoff turned significantly higher, severely surging the shock on drainage system (Di Liu 2009). Evidently, should such low-efficiency urbanization development continue, high urban flooding vulnerability will always be an attribute of Chinese cities.

3.1.3 Regulative and Administrative Reasons

A critical driver behind the scenes of massive urban LULCC is the Chinese taxation system and ideology about urbanization. On one hand, local governments heavily depend on releasing land via land market to raise governmental revenue to fund local urban infrastructure and public services (Ding 2007; Koizumi et al. 2008; Wang 2013). By 2008, 60% of all local government finances originated from land-releasing (Wong 2005). On the other hand, sealed land surfaces and high-rise buildings have been for a long time the dominating symbols of urbanization and modernization and critical criteria for evaluating political performances. Local governments have consequently spared no efforts to release more land, to promote “huge” projects, esp. by developing undeveloped land into commercial and residential uses, even at the price of demolishing and replacing existing developments (Koizumi et al. 2008; Li 2012; Wang 2013).

Furthermore, China’s broad, complex, and transiting framework of laws, regulations, and standards on urban planning and construction, though contributive, was not fully prepared to helm China’s swift urbanization processes. Firstly, the Soviet “population speculation-land use-infrastructure layout” approach dominated China’s urban planning for decades and failed to cope with the swift urbanization and sustainability issues (Yu et al. 2011). Secondly, relevant regulations and standards often lose power in practice due to the lack of supportive details and requirements and due to lack of pertinence and justification (Wang 2013). For example, it was not until 2002 and 2005 that China first issued administrative measures (*ban fa*) for urban green lines and urban blue lines (MOHURD 2002, 2005a). However, it is still not rare in practice to destroy the natural green and blue space first and then artificially create “green lines” and “blue lines” for cities, due to the insufficient legislations safeguarding urban natural infrastructures.

Lastly, China’s top-down planning decision-making, although it directed the overall trend of its large and rapid urbanization, failed to effectively attend to details (Yin 2008). On one hand, this is caused by the complex, sometimes overlapping sometimes split administrative system, e.g., the fragmented and discontinuous urban river landscape planning, administration, supervision, and maintenance (Bao 2011). On the other hand, the common information silos among various departments and

regions put Chinese cities in a vulnerable situation, esp. during emergencies such as heavy rainfall or malfunction of critical infrastructure (Fang 2009).

3.2 China's Countermeasures in Urban Planning and Urban Drainage

The emerging urban environmental problems and the aggravating urban flooding pressures have pushed Chinese authorities to ameliorate the urban planning system and urban drainage system for its new era of urbanization.

China's urban planning system is under transition. At the national scale, a long-term blueprint "the National Major-Function-Oriented-Zoning (NMFOZ)" categorizes different regions as optimized, prioritized, restricted, or prohibited for spatial development (State Council 2010). At the regional scale, central government has plotted urban clusters to develop both coordinately and synergistically. At the city scale, recent years have seen the authorities repeatedly emphasizing enhancing the spatial and environmental quality of urbanization; advocating principles such as compact development, inventory planning, urban expansion control, and natural space protection; constructing the underground infrastructure before the above-ground infrastructure; and enhancing the role of water such as the official slogan "water-oriented city" (State Council 2010). To realize the above principles, urban planning and construction are required to follow the zoning construction (suitable, restricted, or prohibited) and the control boundary lines, such as urban yellow lines (for urban infrastructure, including drainage facilities, flood-control facilities, etc.), urban blue lines (for the prescribed urban surface water bodies), the urban green lines (for various, prescribed urban green spaces), and the urban purple lines (protection scope for historical and cultural blocks and buildings) (State Council 1992; MOHURD 2002, 2003, 2005b, 2005c; State Council 2010; Xinhua News Agency 2014; Jie Fan 2015).

China's urban drainage system is entering a new era as well. Since 2014 the central government requires cities to upgrade from two-level to a three-level urban drainage system. The conventional two-level drainage system comprised only of the municipal-level drainage system with low-return periods (i.e., drainage sewer and pump stations) and the hydraulic-level drainage system with high-return periods (i.e., the flood control system against fluvial flood, ocean tide, torrential flood, and debris flow), leaving a huge drainage gap in between (Huang 2009). The newly founded three-level drainage system introduces a gap-bridging level, i.e., the local flooding prevention and control system, whose design recurrence intervals for megacities, large cities, and smaller cities are correspondingly 50–100 years, 30–50 years, and 20–30 years (MOHURD 2014a). Furthermore, the design standards of the municipal drainage system and the hydraulic drainage system were

significantly enhanced. Since 2006, storm sewer design standards were upgraded twice, and the design return period increased from 0.5–3 years to 2–5 years for ordinary urban areas, from 3–5 years to 3–10 years for important downtown areas, and even 10–50 years for downtown underground spaces (MOHURD 2011, 2014a). Meanwhile, the revision of rainfall intensity equations and the abolishment of flow attenuation coefficients since 2014 have led to a giant leap in the practical drainage capacities of storm sewers, for which cities have to gradually catch up (MOHURD 2011, 2014a). Taking a southern city as an example, its 1-year return period storm sewer design for rainfall intensity rose from 33 mm/day to 43 mm/day.

How to realize the newly founded local flooding prevention and control system? Since 2014, China's central government has been strongly promoting "Sponge City," a modern urban stormwater management system that is designed to maintain, restore, and maximize the urban capacity for stormwater infiltration, detention, retention, purification, utilization, and discharge, thereby effectively controlling stormwater runoff (esp. total runoff, peak volume, and peak time) (MOHURD 2014b). The central government encourages cities to regain such functions via flexibly customizing and combining natural and artificial approaches, ranging from protecting the existing ecological system to restoring damaged water bodies and other natural environments and to promoting low-impact development (LID). A Sponge City should comprise the following three interactive and interconnected elemental systems:

- (a) LID system: to reduce, decelerate, and treat stormwater runoff via infiltration, storage, regulation, conveyance, interception, and treatment. The LID under China's Sponge City context covers a broad range of facilities, e.g., pervious pavements, green roof, first-flush diversion, perforated pipe, infiltration trench, rain barrels, low-lying green space, bio-retention, grass swale, vegetated filter strips, detention ponds, regulation chambers, retention ponds, stormwater wetlands, infiltration basin, and infiltration wells (MOHURD 2014b).
- (b) Drainage sewer system: to collect, transport, and discharge stormwater runoff within its design capacity.
- (c) Excess runoff discharge system: comprising retention water bodies, flood way, deep tunnels, etc.

Evidently, the Sponge City campaign will last for decades. Ambitious targets such as reducing the stormwater runoff coefficient to maximum 0.3 should be reached by at least 80% of urban built area by 2030. To facilitate the enforcement, the central government not only assigned batches of pilot cities but also added stormwater runoff control ratios as mandatory control criteria for the urban master plan, the regulatory plans, and the special plans for roads, water, and green space, and set Sponge City as prerequisites of urban planning permission and project construction (State Council 2015).

3.3 Recommendations for Urban Planning and Urban Drainage

3.3.1 Challenges to Solve

The coming decades will witness huge progress to China's urban drainage and urban planning systems if the following challenges and deficiencies can be effectively tackled.

First of all, Sponge City covers various sectors, disciplines, and industries (e.g., urban planning, geology, hydrology, meteorology, civil engineering, landscape planning, ecology, and botany). Its scales range from site to drainage zone, to city, and to watershed. However, due to administrative reasons, most Chinese cities are not ready for such systematic, cross-regional, cross-sector, and cross-profession cooperation yet, not only for the phases of planning but also during the phases of construction, operation, and maintenance. For example, due to lack of cooperation and coordination between different urban sectors, it was not a rare case in the first 3 years of Sponge City Development that the silts from urban greening construction block the freshly finished pervious pavements.

Secondly, China's current experience and talent reserve for Sponge City might be insufficient to achieve the ambitious targets set above in the short term. Despite plenty of LID research and demonstrations in China, there is seldom reliable, long-term operational, and maintenance experience available. Moreover, local practitioners and industries seriously lack LID expertise, since it is often the research institutions that carry out LID projects. As a consequence of the lack of data, experience, and talent, the relevant administrations don't dare yet to compel Sponge City Development in practice; the practice of Sponge City Development can at last differ a lot from the beautiful top-level design as well; despite the national campaign of Sponge City Development, cities rather cautiously demonstrate it in small regions rather than spoil it via large-scale constructions. In the coming years, how successfully researchers, sectors, practitioners, and industries can build up and disseminate relevant experiences will directly influence how well China can cope with the many realistic challenges in the relevant standard making, design, construction, operation, and maintenance issues.

Thirdly, the drainage pipeline sector faces perhaps the trickiest challenge, namely, how to upgrade to higher and stricter drainage standards, and for higher flexibility and resilience toward changes in population, land use, and climate, while causing the least disturbance to urban operations.

Fourthly, a huge challenge is how to deal with the current level of heavy storm-water runoff contamination and hence the risks of siltation and blockage for LID facilities and groundwater contamination.

Lastly, how to persistently finance Sponge City, which requires thousands of billions of RMB investment (Ren 2015)? The central government promotes public-private partnerships (PPP) to bridge the huge financial gap, namely, on the one hand including Sponge City projects into governmental procurement and on the other

hand encouraging auxiliary financial support such as loans, bonds, and securities (State Council 2015). However, PPP won't be able to prop up Sponge City smoothly and effectively in the long run, unless the Chinese authorities can coordinate the risks to PPP stakeholders and reasonably reduce the numerous hurdles from laws, regulations, supervision, water tariffs and financial frameworks, etc. (Choi et al. 2010; Cheung and Chan 2011).

3.3.2 How to Enhance Urban Planning

Urban planning and construction is not only the source but also the cure for China's high urban pluvial flood vulnerabilities. Here the authors would like to firstly emphasize solidifying the base, namely, the role and mechanisms of the urban planning system, and then suggest land uses and land cover in detail, i.e., where not to develop and where and how to develop.

Multidisciplinary Urban Planning and Local Water Boards

First of all, urban planning can only direct urbanization and prevent and solve urban environmental problems at the very source, if the approved regulatory plans become statutory and the urban planning sector gets authorized to exercise certain urban planning-related environmental protection on behalf of the environmental sectors (Yin 2008). Moreover, the new era of urbanization, not only featured with Sponge City but also inventory planning, compact development, smart city, etc., requires reducing pressure from the top-down decision-making system and opening urban planning for more independent, multidisciplinary, cross-sector, and multi-stakeholder participations. This means not only to develop harmonized and cooperative sector policies between the urban planning sector, water sector, environmental sector, urban climatic sector, and traffic sector, etc. (Ellis et al. 2002) but also to simplify the know-how of the relevant sectors and research fields, to develop user-friendly toolboxes to enhance the feasibility of multidisciplinary urban planning (Ng 2012). However, the water sector itself needs to become more united, in order to develop a stronger voice in urban development. Despite years of debate around reforming China's dispersed and overlapping water-relevant ministry framework, Chinese cities badly need a better coordinated water sector within the existing framework. Learning from the EU and Singapore (Check 1997; Liefferink et al. 2011; Watson 2014; Hüesker and Moss 2015), it is recommended that each level of Chinese government should form, lead, and coordinate a corresponding level water board comprised of the critical local water stakeholders, e.g., water supply and drainage, flood control, water resource, river and lake administrations, agriculture, and fisheries. An efficient water board requires not only a well-designed network management but also a clear empowerment to coordinate, participate, supervise, and impact the water-related issues throughout urban planning and construction, e.g., ensuring the safety of drainage pipelines during underground construction,

restricting the development of low-lying areas, and safeguarding water bodies from development (Check 1997). In this respect, Zhejiang Province is a pioneer by promoting the “Five Water Comprehensive Control Office” (五水共治) to coordinate wastewater treatment, flood control, pluvial flood discharge, water supply security, and water saving (Chun 2015). However, huge potential still exists for Chinese cities to develop effective downscaling, e.g., assuring and authorizing the effective water administration to drainage-zone levels (Check 1997), to introduce and customize bottom-up approaches to the conventional top-down approach (Watson 2014).

Such cross-sector and multidisciplinary cooperation is not only necessary for the urban planning phase but also critical for improving the urban management. In fact, a key for achieving Sponge City Development would be, via multidisciplinary conversation, input, and cooperation, to optimize the construction schedules, to supervise the construction process, and to achieve integrated operation and maintenance for the road, urban landscape, urban drainage infrastructure, and urban water bodies.

Where Not to Develop: Critical Ecological Infrastructure

The biggest lesson for China from the decades of massive urban construction is not about what to develop but rather where not to develop. The urban planning sector needs to take the lead in preserving, restoring, and maintaining urban critical ecological infrastructure (CEI), i.e., the critical natural elements and structures formed by natural green spaces and water bodies, acting as ecological calming buffers between urban zones (Yin 2008; Yu et al. 2011; Laforteza et al. 2013). When well arranged, CEI brings tremendous benefits to cities, e.g., improving urban resilience against pluvial flooding, maintaining natural water cycles, improving the urban microclimate, and relieving air pollution (Pretty et al. 2007; Forest Research 2010; Laforteza et al. 2013). Within the context of Chinese urban planning systems, the most practical approach to realize and remedy CEI directs to the urban green lines (UGL) and urban blue lines (UBL), both of which are mandatory for Chinese cities master planning, regulatory planning, and detailed planning. However, the following deficits of the current UGL and UBL need to be solved; otherwise CEI and its beneficial effects cannot be scaled up: on one hand, the passive and affiliated roles of UGL and UBL make them always compromised for other urban special plans, e.g., roads and utility lines. On the other hand, such a high-footprint approach still prevails, as using UBL and UGL for conquering nature rather than working with nature, e.g., landfilling natural rivers somewhere and excavating artificial ponds elsewhere, “building a valid green space but destroying the ecological environment” (Saunders and Yu 2012).

In order to retain and restore more CEI, we recommend the following approaches. Firstly, the urban planning sector needs multidisciplinary cooperation to rectify, identify, classify, and upgrade UGL and UBL according to their CEI potentials and

hence to set corresponding protection buffers and protection measures, as well as to initiate relevant guidelines and directives. The core criteria of identifying CEI potentials should include, for instance, soil and water preservation, low maintenance, climate change resilience, ecological diversity, biodiversity, and a low overall carbon footprint. Due to limited urban natural spaces, brownfield restoration will become a major source for CEI development, e.g., restoring abandoned industrial parks into wetland parks (Turenscape 2016). Secondly, as continuity and connectivity can synergize the beneficial effects of CEI, it is recommended to plan CEI as an overall ecological system and to hierarchically connect the different tiers of CEI via spatial planning ranging from site and neighborhood scales to the district and city scales and to the city-region and regional scales (Benedict and McMahon 2002; Weber et al. 2006; Wickham et al. 2010; EEA 2011; Laforteza et al. 2013). Thereby, even if only for CEI, the scope of urban planning and the relevant land investigation and database development needs to expand from the urban built area and urban plan-to-build area to the whole urban planning area or even to the whole administrative region of a city. In this respect, Shenzhen City undeniably foreruns via enforcing the “basic ecological control line” (基本生态控制线) since 2005 (People’s government of Shenzhen 2013; Xiao and Xie 2014; Peng 2014).

As to UGL particularly, it is time to enhance the quality of UGL as solely quantitative control tools (viz., the mandatory criteria of the green rate and the green space per capita) at certain levels connived the unsustainable urban greening mentioned before. Therefore, we recommend that relevant authorities customize obligatory guidelines and eco-design directives to preserve/restore/optimize/create the mature urban green space esp. for the high flood risk areas and ecologically sensitive areas. Particularly, considering the well-proven contributions of urban forests in pluvial flood control and stormwater purification, it is recommended to delineate the critical root zone as protection zone for the preserved trees and native forest remnants and to include more mature trees into preservation lists rather than only for “ancient and famous trees” and over 50-year-old trees (Brabec et al. 2002; Yin 2008; MOHURD 2012; Stone Environmental Inc. 2014). Stakeholders could also use tools like the Urban Forest Effect Model to evaluate the benefits of UGL (Jayasooriya and Ng 2014). As for the artificial landscape, eco-design in comparison with the conventional landscape can significantly enhance the CEI potentials of a landscape, e.g., the multi-advantages of the customized native polyculture over conventional turf (Mark Simmons 2013).

As to UBL, an overall watershed view is highly recommended for the local planning board including esp. the water resource sector and the flood control sector to plan UBL, namely to coordinate and customize short-term, middle-term, and long-term UBL plans for the overall targets of gradually restoring the hydrological network of the local watershed by reconnecting and restoring disturbed rivers while conserving remnant water bodies and undeveloped floodplains and restricting further development of developed riverine floodplains (Ellis et al. 2002; Rong et al. 2009; Liao 2012; Yang and Li 2014).

How to Develop: Urban Built-Up Area

How to make cities more resilient against unending challenges such as climate change, population fluctuation, economy transition, and deteriorating environments and resources? China needs more resilient urban structures, as the severe urban environmental and resource problems have already proven the obsolescence of the extensive, passive economy-driven and population-driven urban construction and expansion. Nowadays compact city is quite often counted as a solution. However, if compact city is merely limited to the pursuit of always higher-density living, it may neither bring a healthier city nor curb urban expansion (Neuman 2005; Wei and Zhang 2012). The authors believe that the way toward urban resilience and sustainable urban spatial development lies in organized, controlled, and moderate decentralization. To put it into a scenario, it is the urban clustering formed ploy centers featured with urban growth boundaries, compact and mixed-land use, and multi-functional and relatively independent urban operation, buffered by traffic routes and ecological land in between (Geng 2008; Chiu. 2012; Xinli et al. 2013; U.S. Department of Energy 2014). Rather than a fixed blueprint, this is a process-oriented direction (Neuman 2005). Hereafter illustrated in details about its spatial development features.

1. Urban Growth Boundary

Urban growth boundary (UGB) is a well-known tool for curbing urban expansion. Despite Chinese central government's call for UGBs since 2006, the UGB practice of several pilot megacities and large cities failed to substantially control urban expansion due to (1) the deficiencies of the methodologies for setting UGBs, including the commonly adopted constrained cellular automata-based methodologies, (2) the nonenforcement characteristic of UGB, and (3) the incomplete coverage of development permits and hence large amount of unofficial development outside of the UGB (Li 2011; Wan et al. 2013; Long et al. 2015). Therefore, it is recommended to effectively control urban sprawl with UGB as follows. Firstly, authorities should summarize and evaluate the existing UGB experiences and provide clear guidelines for UGB determination. Environmental capacity analysis and flood risk analysis should particularly be taken as mandatory toolbox elements for UGB determination to secure the bottom line of local environmental quality and urban security. Planners can use different levels of environmental quality standards such as surface water quality to infer the corresponding upper limits of population, industrial allocation, construction land, and hence the scales of UGB (Fu et al. 2009). The urban planning sector should integrate flood risk as a mandatory concern and add interacting hydrological risk simulations into its daily toolbox, therefore delineating the high-risk flood zones as construction-limited or even as construction-forbidden areas (van Sebastiaan et al. 2011; Xu et al. 2013). Therefore, it would be promising for determining UGB to develop spatial models that couple Constrained Cellular Automata Model with Green Infrastructure Assessment Model and Soil Conservation Service Model or with hydrologic and hydraulic framework (Li 2011; Xu et al. 2013; Giacomoni et al. 2014). Moreover, Chinese authorities may have to

set UGB as mandatory or even statutory requirements for all cities, not only for the megacities and large cities, since small-medium cities and towns will become the major contributors for the growth of construction land (State Council 2016). Furthermore, it is necessary to fully enforce development permits without exception and to strictly monitor land use with technologies such as remote sensing. Meanwhile, cities should be authorized to moderately adjust UGB with sufficient demonstration on the premise of not breaking the critical bottom lines mentioned above.

2. Multifunctional Poly-center with Mixed Land Use

Depending on the scale of the cities, poly-center can refer to multipolar cities and satellite towns. Besides, based on the fragmentation analysis of built-up land, cities can delineate new poly-centers by uniting the construction-land fragments with high defragmentation potentials (Wei and Zhang 2012). Spatial planning for multifunctional poly-centers, beyond the simple high density and intensity of industrial and residential land uses, requires mixed land use, multimodal transportation, and high degrees of accessibility in order to activate urban operation even within small spatial scopes (Neuman 2005). Such multiple urban function allocation largely depends upon the political and economic decisions, housing policies, employment-decentralization, and industrial allocations which are beyond the context of this article (Gilli 2009). But in order to ease such transitions, China's urban planning sector should soon revise its still mutually exclusive land classification system for more compatibility capacities (Yin 2008).

Urban open spaces are particularly great sites for multifunctional planning. When well designed with integrated approaches and multidisciplinary involvement, they can safely augment the urban stormwater detention and retention capacity without using extra land, hence significantly reducing the peak runoff and protecting surface water via reducing CSOs and stormwater tank overflow (Fu et al. 2009; Michael et al. 2011). There are many such examples worldwide, such as the SMART tunnel in Kuala Lumpur and the squares, streets, parks, and even playgrounds also used for stormwater detention in Hamburg and Rotterdam (Kannapiran 2005). However, this also poses more requirements of the upstream stormwater management processes for sure.

3. Space Development Criteria

The interpretations of compact city, which are based on the idea against urban sprawl, have gradually evolved over years. Researchers have gradually agreed that compact city rather than fixed blueprints is the evolving process toward more efficient and habitable urban land uses. Namely, construction density and intensity, including the population density, building density, traffic density, plot ratio, etc., should be neither too low due to the efficiency nor too high due to the habitability (Neuman 2005; Yan et al. 2013; Martilli 2014). Despite the will from Chinese authorities for more compact land use, the existing construction density indexes are criticized as incomplete, unspecific, lacking of technical proof, susceptible to changes, and lacking of enforcement (Zhou and Zou 2004; Ban et al. 2007; Yin

2008). The mandatory construction density and intensity control criteria as required by the national codes include construction land area, population capacity, land-use type, plot ratio, building height, green rate, green space allocation, and underground space development layout (Ministry of Construction 2002, 2005). However, only few mandatory construction density limits are available in the national codes, e.g., for residential areas, maximum building density of 30% and minimum plot ratio of 1.0. Consequently, urban construction compactness in practice is out of control along with the tremendous extensive land use. For example, in campus cities and development zones, there are plenty of hyper-dense urban areas afflicted with poor habitability, overloaded drainage infrastructure, and hence high risk of pluvial flooding. Such construction density disorder results in not only the wasting of land resource and land sealing but also urban decay (Geng 2008). Therefore, we recommend updating the construction density indexes as follows:

- (a) To add an open space ratio as another mandatory criteria to form a three-dimensional construction density index combination including plot ratio, site coverage, building height, and open space ratio, which can effectively describe urban density and simulate the possible urban morphologies (Haupt et al. 2004; Dong 2012). As urban open space offers a great platform for various multifunctional stormwater controls (US NAP 2009), the open space ratio will be another important Sponge City criterion in addition to the plot ratio and low-lying green space ratio.
- (b) We also suggest that the central authority specifies the lower and upper limits for the various development density and intensity criteria of the different land uses at the different urban zones of various scales of cities that are located in different climatic zones. They should provide basic revision formulas for the local cities to further customize the development density and intensity limits according to the coefficient factors such as plot area, traffic capacity, runoff control, and the distance to CEI. One can find density zoning experience from the forerunner Chinese cities such as Shanghai, Guangzhou, and Shenzhen (Zhou and Zou 2004; People's government of Shenzhen 2014). As for the existing hyper-compact urban areas, local government should focus on its step-by-step redevelopment toward safer and better environments and higher resource and energy efficiency, instead of even higher construction densities (Geng 2008).

3.3.3 How to Realize Low-Impact Development

Sponge City Development opens a huge platform and market for LID facilities in China. However, China must overcome the following challenges to implement LID effectively. Firstly, there is a lack of high-resolution data that are crucial for LID planning such as land use, land cover, geologic and hydraulic data, empirical cost, and performance data. Secondly, the stormwater runoff of most Chinese cities can be heavily contaminated and poses a high risk of causing a fast defect of LID units

and of groundwater pollution. For example, Beijing roof runoff (COD 123–328 mg/L) was even more contaminated than German road runoff (COD 582 mg/L) (Che et al. 2003). Thirdly, uneven rainfall distribution and limited urban land resources make it difficult to search for cost-effective scales and placements of LID units. We therefore suggest the following routes for the coming age of LID implementations:

Firstly, cities should accelerate the relevant monitoring and high-resolution database construction and sharing. Cities can meanwhile customize local stormwater management models such as SWMM for the LID selection, placement, and assessment with limited data as follows: (1) Carry out LID on several high-resolution, well-gauged urban catchments; calibrate and validate each high-resolution model. (2) Regionalize the model for large-scale low-resolution urban areas with reasonable efforts including surface discretization and processing the high-resolution models calibrated parameter sets. Such regionalized low-resolution models can accurately simulate runoff volume although they tend to over-simulate peak runoff (Krebs et al. 2014).

Secondly, effective pollution prevention measures can significantly reduce the contamination load and hence increase the life span of LID facilities, e.g. enhancing urban waste management; public education; disconnecting stormwater hotspots from LID facilities; controlling the application of fertilizers and pesticides especially nearby LID infiltration facilities, for example, via slow-release fertilizer, maximum dosing limits, fertilizer-free zones and fertilizer-free seasons (EP Florida 2015); and limiting toxic construction material such as galvanized roofing materials (Foerster 1996; Clark et al. 2008).

Thirdly, LID design should follow the stormwater management process (also called as treatment train), selectively combining LID units in series to reduce the overall land use of LID and the effectiveness of both runoff control and runoff pollution control (Liu et al. 2015a). A full LID management process includes source control, site control, regional control, and conveyance control in between, each comprised of various possible LID units with different functions such as stormwater absorption, pretreatment, filtration, infiltration, detention, storage, retention, conveyance, treatment, etc. (susdrain, 2012; MPCA 2015b). Optimal combinations can be found by evaluating project targets, site conditions, the runoff reduction and pollutant removal performance of various LID units, and other critical concerns of stakeholders such as amenity, ecological service, and costs. There are various tools developed to assist with the selection of a management train, such as the runoff quality scoring system in Germany (DWA 2007), the Minimal Impact Design Standards (MIDS) Calculator in Minnesota (MPCA 2015a), and various models such as SWMM, SUSTAIN, MUSIC, and L-THIA LID in the USA and Australia (Jayasooriya and Ng 2014; Liu et al. 2015b). In order to control stormwater runoff as close to the source as possible, source control is of primary importance, namely, to reduce runoff formation and to separate differently contaminated runoff. The coming years will see huge growth of green roof and pervious pavements in Chinese cities due to the authorities demands for an increase in perviousness. Yet, green roofs and pervious pavement are no universal cure and need to be taken with

precautions, e.g., allowing pervious pavements only for low-traffic load roads to avoid pavement deformation and groundwater pollution and selecting extensive/intensive green roofs according to local climate and the site water balance. Separating differently contaminated runoff at the source can significantly enhance the cost-effectiveness of runoff control via avoiding treating large amount of low-concentrated mixed runoff (Ellis et al. 2002). For example, the management trains of roof runoff and road runoff should have as few overlaps as possible. Since the first-flush concentration of most runoff pollutants is within a short-time period, it is highly recommended for Chinese cities to customize the split-flow control volume according to the local land use and runoff pollution load and to divert first flush to wastewater sewer or separate treatment facilities. For instance, the split-flow volume in Beijing is recommended for the first 1–3 mm rainfall for roof runoff, 4–5 mm for neighborhood runoff, and 6–8 mm for downtown road runoff (Che et al. 2007). Another critical concern for designing a LID treatment train is to base LID processes on the pollutant particle sizes (Wong et al. 2002). As most of the runoff pollutants are adsorbed to suspended solids (Gooré Bi et al. 2015), TSS removal facilities and designs can significantly reduce the pollutant load and increase the lifespan of LID, such as a vortex separator, vegetation buffers, forebays, and design for sufficient hydraulic residence time.

Sufficient support and attention should be invested upon improving stormwater management modeling. China's current local stormwater models still have huge upgrading potential in terms of accuracy, water quality simulation, universal applicability, and user experience (Wu et al. 2010). Yet, even the universal model SWMM, which is a sophisticated, common tool for Chinese researchers and designers, also has many gaps to fill, e.g., to accurately address a broad range of the LID practices rather than only for green roofs, rain gardens, infiltration, and bio-retention practices (Jayasooriya and Ng 2014). It must be able to simulate the outflow-inflow connection between the LID practices to simulate the distribution of pervious surface's runoff to LID practices in a single sub-catchment (Rosa et al. 2015). China's Sponge City Development will accelerate the trend of LID simulations, such as to promote stakeholder participation, cyber infrastructure, web-based models, model coupling, real-time monitoring and modeling, etc.

Lastly, the following factors will also decide the success or failure of LID practices. A prerequisite is the sustaining funding and management mechanisms. We recommend officially assigning LID practices such as stormwater utility, to clearly define the ownership-duty-and-benefit distribution and balance among the LID facilities, storm sewer pipelines, wastewater sewers, and treatment facilities, to adopt stormwater runoff discharge fees, to allocate funding from the municipal finance according to multi-services of LID practices, and to explore various tax and insurance incentives for the LID campaign. Moreover, proper maintenance of LID is crucial but also seems difficult and tedious for local municipalities. Therefore, it is worthwhile for Chinese cities to customize clear LID operation and maintenance guidelines, to issue maintenance certificates to certified companies, and to implement mandatory and regular third-party inspections (Michael et al. 2011). LID authorities should also never overlook the risk management of stormwater reuse and

should regulate the reuse application, reuse scale, and reuse treatment to minimize the risk of public infection, particularly considering the relatively highly contaminated stormwater runoff quality and the high population density in Chinese cities.

3.3.4 How to Upgrade the Sewer System?

Recent central government policies clearly point out the development trend of the conventional urban drainage system (including drainage pipelines, pump stations, and drainage ditches), namely, increased drainage pipeline design standards, separated sewer systems, utility tunnels, deep tunnels, and digital management. Admittedly, these new era urban drainage infrastructures, if properly carried out, will improve the urban drainage capability. However, it can take decades to complete such a national infrastructure revolution due to the enormous investment requirement, the limitations from built urban space, and conflicts with urban operations. However, the most urgent, practical, and cost-efficient solutions should be to fully utilize the drainage capacity and storage capacity of existing drainage infrastructure. It is not rare for Chinese cities to have a significant amount of silted or damaged drainage pipelines and drainage ditches and hence huge loss of its drainage and storage capacities. The direct causes for such avoidable losses include a massive number of illicit sewer connections (i.e., storm sewers often convey combined wastewater), poor site management of construction sites (i.e., a lot sand and silt flow into drainage pipelines), and illegal wastewater dumping (especially oily wastewater discharge from restaurants and slurry discharge from construction sites) (Huang et al. 2007; Li et al. 2014; Wang 2014). The indirect causes can originate from the sewer design, construction, pipeline material, engineering supervision, quality control, and operation and maintenance (O&M). Most Chinese cities have not yet developed scientific, systematic, and stable O&M mechanisms for drainage pipelines. The sewer O&M approaches still feature low efficiency, high labor intensity, high risk potential, and low technology (e.g., sewer dredging mainly depends on human labor), due to a lack of attention and finance. The following approaches are recommended to fully activate the drainage and storage capacity of conventional drainage infrastructure.

First of all, the relevant top-level designs should be improved and made more explicit to reduce, avoid, and remedy the problems damaging the drainage infrastructure's capacity as mentioned above. Contributing efforts would be to develop explicit national technical guidelines, standards, and liability mechanisms to direct and regulate the relevant survey, consensus, design, construction, materials, engineering supervision, operation, and maintenance and to develop a training-certification-supervision system for the relevant practitioners (Xue and Song 2014). The conventional drainage infrastructure will benefit from more attention, support, and organization via a more efficient institutional setting with a clear duty-power-finance structure for integrating drainage infrastructure, wastewater treatment plants, and flood control. The top-level financing design should esp. consider the long-term, stable finance for regular and qualified drainage infrastructure operation

and maintenance. Some of the other critical top-level design efforts include to effectively forbid the “lowest unique bid” behaviors, to prioritize and advance drainage infrastructure planning before land trade with developers in order to gain sufficient time and support for the qualified planning and reliable construction of drainage infrastructure (Ellis et al. 2002), to promote full-scale coverage of connection permission for public drainage pipelines, to enhance the monitoring and punishment of illegal wastewater dumping, to enhance construction site management criteria, etc.

Furthermore, the conventional drainage system can release, utilize, and activate its drainage and storage capacity via a three-step innovation and improvement, in order to reduce the costly burden of building inline or offline tanks, tunnels, and basins. Firstly, fitting hydrodynamic sewer self-cleaning technologies into drainage infrastructures can release the capacity inhabited by silt. Such self-cleaning facilities, based on a preset hydrodynamic mechanism, automatically detain upstream stormwater or wastewater and form an adequate flush wave from the impounded water to remove silt. With neither intensive labor nor external powers, self-cleaning sewers can create an easy and approachable physical sewer base for other critical sewer O&M tasks, such as online monitoring, video inspection, and trenchless repair. Secondly, urban drainage infrastructure can further exert its inline storage potential via embedding flow control technology such as weirs and vortex valves. Flow control devices restrict the flow rate from its upstream sewer to its downstream sewer, utilizing the otherwise unused volume of the upstream drainage pipeline, storage tank, and road space, attenuating peak flow, and protecting downstream drainage and treatment facilities (Richard et al. 1994; Andoh et al. 2009).

Lastly, to fully activate the capacity of the whole drainage network, measures to increase its connectivity, flexibility, and resilience are necessary. To increase the drainage network connectivity, it is recommended to add connection pipes to increase the drainage pipeline density esp. for high flood risk urban catchments (Peng et al. 2015). The enhancement of sewer network flexibility and resilience depends on the promotion of decentralized systems, flexible design alternatives, and smart sewer technologies. Therefore, new constructions and infrastructure retrofits should prioritize the decentralized system at the planning phase over the conventional centralized system, due to the prior’s integrated advantages in terms of flexibility, sustainability, and security (Dong et al. 2012). At the early design phase, designers need to select local suitable flexible design alternatives rather than the conventional rigid design, such as the “robust design, phased design, modular design, modular/component platform design, and design for remanufacturing” (Spiller et al. 2015). Intelligent sewer technologies, including smart metering, smart control (smart valves, pumps), intelligent processing and analysis, and decision-making tools, can fully activate the overall capacity of drainage network by allotting drainage water among the differently loaded drainage pipelines. However, modern intelligent sewer technologies are still only viable for developed cities due to the relatively expensive investment requirement.

4 Conclusions

Decades of massive urban construction not only wins China high urbanization and economy growth but also causes severe urban environmental problems, particularly the widespread high urban pluvial flood vulnerabilities. Since 2014, China has been promoting Sponge City Development 海绵城市建设, a Chinese version of Water Sensitive Cities, to alleviate this high urban pluvial flood problem and meanwhile to improve the urban water system.

The causes for Chinese cities' high urban pluvial flood risk are a complicated cluster, which is related to several urban sectors and various urban development phases, especially urban planning; the planning, construction, operation and maintenance of drainage infrastructure; the relevant regulations and administrations of water bodies and green infrastructure. This review analyzes the causes and classifies the complicated causes into the following three categories:

Firstly, the low-efficiency urban expansion, which is featured with massive growth of impervious land use and land covers, caused higher and more intensive stormwater runoff, severely damaged urban hydrologic system, and escalated urban heat island effects and urban rain island effects.

Secondly, the planning, construction, and maintenance of urban drainage infrastructure severely lag behind the overground development. Urban drainage infrastructure becomes a bottleneck of drainage, due to the following reasons: low drainage standards; use of flow attenuation coefficient; common "lowest unique bid"; weak engineering supervision; poor operation and maintenance; excessive sewer misconnections, blockage, and damages; ever-increasing service area and high runoff coefficient; and low water tariff and high dependence on governmental subsidies.

Last but not the least are the regulative and administrative reasons. For example, both the taxation mechanism and the political fever for a sealed urban image encouraged local governments' overdependence on land releasing. Moreover, the relevant laws, regulations, and standards on urban planning and construction are not cutting-edge and agile enough for China's very swift urbanization, such as the insufficient legislations and shallow enforcements for safeguarding urban natural infrastructure. Also necessary to mention are the typical problems of top-down planning decision system: the complex, sometimes overlapping sometimes split administrative system and their information silos.

As analyzed in this article, Chinese authorities have started series of countermeasures in the urban planning sector and urban drainage sector. Sponge City Development, as one of the most systematic evolution, set series of ambitious targets yet needs to solve the following challenges and problems: from cross-boundary cooperation experience to the capacity of relevant talents, to the not well-separated drainage system, to the power distribution, to more efficient administration, to long-term finance, to effective legislation, etc.

Just as the high urban pluvial flood vulnerabilities are caused systematically, it requires also cross-boundary efforts, evolution, and cooperation to develop into a

water-sensitive, climate change-resilient Sponge City. We customize for Chinese cities series of recommendations for their urban planning, low-impact development and urban sewer system. Here briefly summarizes some of the key points.

There is a lot that urban planning sector can improve to avoid and to solve the urban pluvial flood problems and urban water system problems from the beginning:

Firstly, in order to keep urban construction relatively in control, the authority should authorize and support the urban planning sector to exert the function of environmental and ecological protection. Particularly the dispersed water sectors should get better streamlined, coordinated, and integrated and actively participate in all the phases of urban planning and construction, to protect and to optimize the urban water system from the very beginning.

A most preliminary concern of urban planning should be to firstly preserve the valuable critical ecological infrastructures free from development. The urban green lines and urban blue lines of current urban planning system, if well enforced, can serve this means, if only the multidisciplinary contributions can be introduced to rectify, identify, classify, and upgrade the urban green lines and urban blue lines according to their potentials of critical ecological infrastructures.

While planning for urban developed land, we think, cities can gain more climate change resilience via organized, controlled, and moderate urban decentralization and clustering, formed ploy centers featured with urban growth boundaries, compact and mixed-land use, and multifunctional and relatively independent urban operation, buffered by traffic routes and ecological land in between.

In order to curb urban fragmentation, we recommend Chinese authorities to fully promote urban growth boundary and strictly enforce the development permits nationwide. Yet more efforts still need to be invested in developing methodologies for scientifically setting urban boundaries, considering, for example, not only environmental capacities but also flood risks.

It is also recommended to revise China's still mutually exclusive land classification system for more compatibility capacities, so that to encourage more multifunctional and mixed land use of urban area. This can activate cities efficiently. For example, multifunctional open spaces, if properly designed, can safely augment the urban stormwater detention and retention capacity without using extra land.

Compact city development can at the source limit urban imperviousness and the impacts on hydrological cycle. To balance between land use efficiency and habitability, we recommend the central authority to specify the lower and upper limits for the various development density and intensity criteria accordingly and to form a three-dimensional construction density index combination including plot ratio, site coverage, building height, and open space ratio.

Low-impact development, as core element of China Sponge City Development, can very well connect the urban planning sector and the drainage sector. We firstly analyzed the challenges for LID, such as lack of high-resolution data, heavy stormwater runoff contamination, uneven rainfall distribution, limited urban land

resources, and critical gaps in modelling. Based on that this technical review customized recommendations about how to accelerate relevant monitoring and high-resolution database construction and sharing, how to customize local stormwater management models, how to effectively prevent stormwater runoff pollution and hence to increase the life span of LID facilities, and how to customize stormwater management process. Besides, we also listed some critical points to improve the stormwater management simulation tools and shared some insights about sustaining, funding, and management mechanisms for LID.

As to the sewer system, the most urgent, practical, and cost-efficient solutions should be to fully utilize the drainage capacity and storage capacity of existing drainage infrastructure.

Hereto this article customized recommendations for improving the relevant top-level design, in such as national technical guidelines, standards and liability mechanisms, more efficient institutional setting, long-term reliable financing design, prohibition of “lowest unique bid,” and prioritization of drainage infrastructure before land trade.

Technically, this technical review described a three-step innovation and improvements to release, utilize, and activate the drainage and storage capacity of sewer system: to fit hydrodynamic sewer self-cleaning technologies into drainage infrastructures, to embed flow-control technology such as weirs and vortex valves, and to promote measures for enhancing sewer connectivity, flexibility, and resilience, such as connection pipes, decentralized systems, flexible design alternative, and smart sewer technologies.

In its first 3 years, 2015–2017 Sponge City Development has been taking over more expectations, not only urban pluvial flood control but also improvement of the whole urban water environment. For both expectations, this decades-long national mega project and evolution requires mind-opening cross-boundary evolution and cooperation especially among urban planning, drainage system, and urban natural infrastructure. This review, based on the past lessons and cutting-edge trends, summarizes the relevant causes and recommendations and serves as an introduction for the beginning of this cross-boundary evolution. In the coming years, China’s Sponge City Development will bring the world lots of technical and administrative innovations and breakthrough and lively demonstrate how to evolve toward water-sensitive cities with cross-boundary efforts.

Acknowledgments We highly appreciate the support from the German Federal Ministry of Education and Research. We thank our colleagues, Ms. Jing GAN from Tongji University, Ms. Mingli XIE from Jiaying Planning & Design Research Institute, Mr. Xiang Zhou from HKL Architects, and further research partners from Beijing, Jiaying, Wuxi, Shanghai, and Shenzhen for sharing insights and expertise that greatly assisted this review, although they may not agree with all the interpretations of this paper. We also thank Mr. Kelly Stanley for assistance with proofreading that greatly improved the manuscript.

References

- Andoh RY, Faram MG, Osei K (2009) Vortex flow controls in integrated Stormwater management for urban environments. The 6th international water sensitive Urban Design Conference and Hydropolis 3:617–627
- Ban M, Fang C, Song J (2007) Study on intensive land utilization of industrial zone and its enlightenment 国内外开发区土地集约利用的途径及其启示 (Chinese) 16(3):45–50
- Bao W (2011) 城市河道景观的修复 Restore urban river landscape (Chinese). 知识经济 Knowl Based Econ 2:143
- Benedict MA, McMahon ET (2002) Green infrastructure: smart conservation for the 21st century. *Renew Resour J* 20:12–17
- Brabec E, Schulte S, Richards PL (2002) Impervious surfaces and water quality: a review of current literature and its implications for watershed planning (EN). *J Plan Lit* 16(4):499–514
- Bulletin of flood and drought disasters in China (2012) China Water Power Press
- Che W, Liu Y, Li J (2003) Urban rainwater and its pollution control 国内外城市雨水水质及污染控制. *Water Wastewater Eng* 29(10):38–41
- Che W, Zhang W, Li J, Meng G, Wang H (2007) Initial Split-flow control of urban rainwater runoff pollution (Chinese). *China Water Wastewater* 23(6):1–5
- Check LM (1997) Drainage planning and control in the urban environment the Singapore experience. *Environ Monit Assess* 44(1/3):183–197
- Chen Y, Ding Y, She Z, Lin E, Pan J, Zhou G, Wang S, Zhou D, Li C, Zhang J, Xu G, Liu C, Wu Z (2005) Assessment of climate and environment changes in China (II): measures to adapt and mitigate the effects of climate and environment changes: advances in *Climate Change Research* (Chinese) 1(2):51–57
- Cheung E, Chan APC (2011) Risk factors of public-private partnership projects in China: comparison between the water, power, and transportation sectors. *J Urban Plann Dev* 137(4):409–415
- Chiu RLH (2012) Urban sustainability and the urban forms of China's leading mega cities: Beijing, Shanghai and Guangzhou. *Urban Policy Res* 30(4):359–383
- Choi J-h, Chung J, Lee D-J (2010) Risk perception analysis: participation in China's water PPP market. *Int J Proj Manag* 28(6):580–592
- Chun G (2015) 五水共治浙江会就美丽画卷 (Chinese). *People's Daily*, October 9
- Clark SE, Steele KA, Spicher J, Siu CY, Lalor MM, Pitt R, Kirby JT (2008) Roofing materials' contributions to storm-water runoff pollution. *J Irrig Drain Eng* 134(5):638–645
- Cuo L, Lettenmaier DP, Mattheussen BV, Storck P, Wiley M (2008) Hydrologic prediction for urban watersheds with the distributed hydrology-soil-vegetation model. *Hydrol Process* 22(21):4205–4213
- Dai S, Cao K (2012) Countermeasure of urban flood and drainage in China. *Mod Urban Res* (01), 21, 22, 28
- Di Liu (2009) The impacts of urbanization on stormwater flood runoff, Wuhan case study 城市化对雨洪径流的影响-以武汉市为例 (Chinese). *Pioneering with science & technology monthly 科技创业月刊* 1, 66/71
- Ding C (2007) Policy and praxis of land acquisition in China. *Land Use Policy* 24(1):1–13
- Dong C (2012) Density and urban morphology 密度与城市形态 (Chinese). *Archit J* (7):22–27
- Dong X, Zeng S, Chen J (2012) A spatial multi-objective optimization model for sustainable urban wastewater system layout planning (eng). *Water Sci Technol J Int Assoc Water Pollut Res* 66(2):267–274
- DWA (2007) DWA-M 153 recommended actions for dealing with Stormwater. German Association for Water, Wastewater and Waste
- EEA (2011) Green infrastructure and territorial cohesion. The concept of green infrastructure and its integration into policies using monitoring systems. Copenhagen, Denmark
- Ellis JB, D'Acry BJ, Chatfield PR (2002) Sustainable urban-drainage systems and catchment planning. *J Chart Inst Water Environ Manag* 16(4):286–291

- EP Florida (2015) model ordinance for Florida-friendly fertilizer use on urban landscapes. Florida department of environmental protection. http://ffl.ifas.ufl.edu/fert_ordinances.html
- Fan J (2015) Draft of major function oriented zoning of China (Chinese). *Acta Geograph Sin* 70(2):186–201
- Fang C (2009) Report on urbanization and its guarantee for resources and eco-environment in China (Chinese). Science Press
- Foerster J (1996) Patterns of roof runoff contamination and their potential implications on practice and regulation of treatment and local infiltration. *Water Sci Technol* 33(6):39–48
- Forest Research (2010) Benefits of green infrastructure. Report by Forest research: report by Forest research, contract no. WC0807, 42
- Fu G, Butler D, Khu S-T (2009) The impact of new developments on river water quality from an integrated system modelling perspective. *Sci Total Environ* 407(4):1257–1267
- Geng H (2008) Compact without crowd: application of Compact City theory in China (Chinese). *City Plann Rev* 32(6):48
- Giacomoni MH, Gomez R, Berglund EZ (2014) Hydrologic impact assessment of land cover change and STORMWATER management using the hydrologic footprint residence. *J Am Water Resour Assoc* 50(5):1242
- Gilli F (2009) Sprawl or Reagglomeration? The dynamics of employment Deconcentration and industrial transformation in greater Paris. *Urban Stud* 46(7):1385–1420
- Gong Y, Li J, Shi H, Li W (2012) Discussion on several key questions about urban Stormwater management techniques. *China Water Wastewater* 28(22):50–53
- Gooré Bi E, Monette F, Gasperi J (2015) Analysis of the influence of rainfall variables on urban effluents concentrations and fluxes in wet weather. *J Hydrol* 523:320–332
- Haupt P, Pont MB, Moudon AV (2004) Spacemate: the spatial logic of urban density. Delft University Press, Delft, 103 S
- Huang C (2009) Discussion on urban flood prevention and waterlogging drainage standards 城市防洪排涝标准探讨 (Chinese). *Hydraul Sci Technol* 4:60–61
- Huang D-B, Bader H-P, Scheidegger R, Schertenleib R, Gujer W (2007) Confronting limitations: new solutions required for urban water management in Kunming City. *J Environ Manag* 84(1):49–61
- Hüesker F, Moss T (2015) The politics of multi-scalar action in river basin management: implementing the EU water framework directive (WFD). *Land Use Policy* 42:38–47
- IWHR PR (2013) Urban flood control status quo, problems and solutions 城市防洪工作现状、问题及其对策: document no.: China major water project WH2012013. Institute of Water Resources and Hydropower Research
- Jayasooriya VM, Ng AW (2014) Tools for modeling of Stormwater management and economics of green infrastructure practices: a review. *Water Air Soil Pollut* 225(8)
- Kannapiran RK (2005) A study and evaluation on SMART project, Malaysia. Bachelor thesis
- Koizumi A, Wang JH, Liu X (2008) Advancing sustainable urban development in China. *Proc ICE - Munic Eng* 161(1):3–10
- Krebs G, Kokkonen T, Valtanen M, Setälä H, Koivusalo H (2014) Spatial resolution considerations for urban hydrological modelling (English). *J Hydrol* 512:482–497
- Kuang W, Liu J, Zhang Z, Lu D, Xiang B (2013) Spatiotemporal dynamics of impervious surface areas across China during the early 21st century (Chinese). *Sci China Press* 58(5–6):465–478
- Lafortezza R, Davies C, Sanesi G, Konijnendijk CC (2013) Green infrastructure as a tool to support spatial planning in European urban regions. *iForest* 6(2):102–108
- Li Y (2011) Method of determining urban growth boundary from the view of ecology: a case study of Hangzhou 生态视角下的城市增长边界划定方法-以杭州市为例 (Chinese). *City Plan Rev* (12):83–90
- Li J (2012) Land development rights trading concerning preserving farmland: commenting on housing with minor property rights 论保护农田的土地开发权交易政策 (Chinese). *J Soc Sci* 12:40–45

- Li T, Zhang W, Feng C, Shen J (2014) Performance assessment of separate and combined sewer systems in metropolitan areas in southern China (eng). *Water Sci Technol J Int Assoc Water Pollut Res* 69(2):422–429
- Liao K-H (2012) A theory on urban resilience to floods—a basis for alternative planning practices (English). *Ecol Soc* 17(4):48
- Liefferink D, Wiering M, Uitenboogaart Y (2011) The EU water framework directive: a multi-dimensional analysis of implementation and domestic impact. *Land Use Policy* 28(4):712–722
- Liu C (2009) Environmental protection info express (Chinese). *Chutian Metropolis Daily*
- Liu W, Chen W, Peng C (2015a) Influences of setting sizes and combination of green infrastructures on community's stormwater runoff reduction. *Ecol Model* 318:236–244
- Liu Y, Bralts VF, Engel BA (2015b) Evaluating the effectiveness of management practices on hydrology and water quality at watershed scale with a rainfall-runoff model (eng). *Sci Total Environ* 511:298–308
- Livingston EH, McCarron E (1992) *Stormwater management: a guide for Floridians*. Florida Department of Environmental Regulation, Tallahassee
- Long Y, Han H, Lai S (2015) Implementation evaluation of urban growth boundaries: an analytical framework for China and a case study of Beijing 城市增长边界实施评估:分析框架及其在北京的应用 (Chinese). *Urban Plan Forum* (1)
- Lv Z, Zhao P (2013) 170城市不设防,340城市不达标首份中国城市内涝报告:风险正在加剧. *Southern Weekly*. <http://www.infzm.com/content/92491>. Accessed 6 Jan 2015
- Martilli A (2014) An idealized study of city structure, urban climate, energy consumption, and air quality. *Urban Clim* 10:430–446
- Miao L, Cui X, Luan H (2011) Similarities and differences of Beijing and Shanghai's land use changes induced by urbanization. *J Meteorol Sci* 31(4):398–404
- Michael LC, Robert GT, Shirley EC, Shannon L, Keith L, Michael AP, Aaron P (eds) (2011) *Low impact development technology: implementation and economics*. American Society of Civil Engineers, Reston
- Ministry of Construction (2002) Interim provisions on the mandatory content of urban planning 城市规划强制性内容暂行规定 (Chinese)
- Ministry of Construction (2005) Measures for formulating city planning 城市规划编制办法 (Chinese)
- MOHURD (2002) Measures for the administration of urban green lines (CN)
- MOHURD (2003) Measures for the administration of city purple lines (Chinese)
- MOHURD (2005a) Measures for the administration of urban blue line (CN)
- MOHURD (2005b) Measures for the administration of urban blue lines (Chinese)
- MOHURD (2005c) Measures for the administration of urban yellow line (Chinese)
- MOHURD (2011) Code for design of outdoor wastewater engineering: GB 50014-2006 (Chinese)
- MOHURD (2012) 住房城乡建设部关于促进城市园林绿化事业健康发展的指导意见
MOHURD's guiding opinion on promoting sustainable development of urban greening and urban landscaping (Chinese)
- MOHURD (2014a) Code for design of outdoor wastewater engineering: GB 50014-2006
- MOHURD (2014b) Sponge city construction guidance-develop low impact development stormwater System 海绵城市建设技术指南-低影响开发雨水系统构建. http://www.mohurd.gov.cn/zcfg/jsbwj_0/jsbwjcsjs/201411/t20141102_219465.html. Accessed 5 Oct 2015
- MPCA (2015a) MIDs Calculator. Minnesota Pollution Control Agency. <http://stormwater.pca.state.mn.us/index.php/Calculator>. Accessed 21 Mar 2016
- MPCA (2015b) Using the treatment train approach to BMP selection. Minnesota Pollution Control Agency. http://stormwater.pca.state.mn.us/index.php/Using_the_treatment_train_approach_to_BMP_selection. Accessed 17 Mar 2016
- National Aeronautics and Space Administration (2013) Heat Wave in China. <http://climate.nasa.gov/news/969/> (Accessed 9 Feb 2014)

- NBS (National Bureau of Statistics of the People's Republic of China) (2017) 中华人民共和国2016年国民经济和社会发展统计公报. online accessed from: http://www.stats.gov.cn/tjsj/zxfb/201702/t20170228_1467424.html. Accessed 2 Nov 2017
- Neuman M (2005) The Compact City fallacy. *J Plan Educ Res* 25(1):11–26
- Ng E (2012) Towards planning and practical understanding of the need for meteorological and climatic information in the design of high-density cities: a case-based study of Hong Kong. *Int J Climatol* 32(4):582–598
- Peng Y (2014) Shenzhen will build the database of ecological line 深圳将建生态线信息数据库. *Shenzhen Economic Daily*, October 10
- Peng Y, Zuo J, Gan L, Liu G, Meng X (2015) Analysis on construction and operation of combined interceptor sewer in karst topography regions with high External River levels. *China Water & Wastewater* 31(2)
- People's government of Shenzhen (2013) Shenzhen basic ecological control line-optimized plan (2013) 深圳市基本生态控制线优化调整方案(2013)
- People's government of Shenzhen (2014) Shenzhen urban planning standards and principles 深圳市城市规划标准与准则
- Pretty J, Peacock J, Hine R, Sellens M, South N, Griffin M (2007) Green exercise in the UK countryside: effects on health and psychological Well-being, and implications for policy and planning. *J Environ Plan Manag* 50(2):211–231
- Ren X (2015) 海绵城市建设催生万亿元投资盛宴四领域10只概念股迎上涨良机. *证券日报*, October 20
- Richard F, Michael PB, William V (1994) Stormwater pollution abatement technologies (English). EPA/600/SR-94/129 Project Summary, Cincinnati, OH
- Rong B, Sun Y, Deng H, Wu G (2009) On connotation and planning method of protection line & control line for water environmental management under watershed scale: 流域水环境管理保护线与控制线及其规划方法 (Chinese). *China Acta Ecologica Sinica* 29(2):924–930
- Rosa DJ, Clausen JC, Dietz ME (2015) Calibration and verification of SWMM for low impact development. *J Am Water Resour Assoc* 51(3):746–757
- Rothery R (2003) China's legal framework for public procurement. *J Public Procurement* 3(3):370–388
- Saunders WS, Yu K (eds) (2012) Designed ecologies: The landscape architecture of Kongjian Yu, 1 online resource (255)
- Schueler TR, Kumble PA, Heraty MA (1992) A current Assessment of urban best management practices: techniques for reducing non-point source pollution in the coastal zone. Metropolitan Washington Council of Governments, Washington, D.C
- Shi J, Wu S, Zhang Y, Wang T (2012) Integrated landslide mitigation strategies study for global change in China (Chinese). *Geol Rev* 58(2):309–318
- Simmons M (2013) The lawn is dead – long live the lawn. American Society of Landscape Architects. <https://www.asla.org/2013awards/083.html>
- Spiller M, Vreeburg JHG, Leusbrock I, Zeeman G (2015) Flexible design in water and wastewater engineering--definitions, literature and decision guide (eng). *J Environ Manag* 149:271–281
- State Council (1992) Regulation on urban greening 城市绿化管理条例
- State Council (2010) National Major-Function-Oriented Zoning: NMFOZ (Chinese)
- State Council (2015) Guiding opinions of the general Office of the State Council on advancing the construction of sponge Cities 国务院关于推进海绵城市建设的指导意见 (Chinese)
- State Council (2016) Several opinions of the state council on further promoting neo-urbanization 国务院关于深入推进新型城镇化建设的若干意见 (Chinese)
- Stone Environmental Inc (2014) Stormwater management benefits of trees-final report
- Susdrain (2012) SuDS management train. [susdrain.org. http://www.susdrain.org/delivering-suds/using-suds/suds-principles/management-train.html](http://www.susdrain.org/delivering-suds/using-suds/suds-principles/management-train.html). Accessed 21 Mar 2016
- Tang L, Li Z, Yan C, Sun C, Xu X, Xiang H (2009) Mitigative effects of different vegetations on heat island effect in Nanjing (Chinese). *Ecol Environ Scis* 18(1):23–28

- Turenscape (2016) Turenscape sponge city project index, online available from: <https://www.turenscape.com/en/project/index/4.html>
- U.S. Department of Energy (2014) Climate change and infrastructure, Urban Systems, and vulnerabilities: technical report for the US Department of Energy in support of the National Climate Assessment
- US NAP (2009) Urban stormwater management in the United States. National Academies Press, Washington, D.C., 1 online resource (xii, 598)
- van Sebastiaan H, Chris Z, Richard A, Jeroen R (2011) Learning and action alliances for the integration of flood risk management into urban planning: a new framework from empirical evidence from the Netherlands. *Environ Sci Pol* 14:543–554
- Wan Y, Cheng X, Zhao W (2013) Urban growth boundary study: Dingzhou case 城市空间增长边界(UGB)制定方法研究-以定州中心城区UGB的制定为例 (Chinese). *Planner* 29(9):113–117
- Wang J (2013) China's dilemma on controlling urban sprawl: planning regulations, evaluation, and prospects for revision. *Pol J Environ Stud* 22(3):915–924
- Wang Y (2014) 浅谈排水管网的养护管理与安全运行 (CN). *Science & Technology Information* 12(22):86
- Wang B, Rao Y (eds) (2004) 透水性铺装与城市热岛效应 Pervious pavements and urban heat island Effects. 中国建筑工业出版社, 4 pp
- Watson N (2014) IWRM in England: bridging the gap between top-down and bottom-up implementation. *Int J Water Resour Dev* 30(3):445–459
- Weber T, Sloan A, Wolf J (2006) Maryland's green infrastructure assessment: development of a comprehensive approach to land conservation. *Landsc Urban Plan* 77(1–2):94–110
- Wei Y, Zhang Z (2012) Assessing the fragmentation of construction land in urban areas: an index method and case study in Shunde, China. *Land Use Policy* 29:417–428
- Weisheng, L., M.M. Liu, A., Hongdi, W., Zhongbing, W., 2013. Procurement innovation for public construction projects. *Eng Const and Arch Manage* 20 (6), 543–562
- Weng Y, Xing L, Zhao J (2013) On urbanization and waterlogging disasters (Chinese). *Shanxi Architecture* 39(17)
- Wickham JD, Riitters KH, Wade TG, Vogt P (2010) A national assessment of green infrastructure and change for the conterminous United States using morphological image processing. *Landsc Urban Plan* 94(3–4):186–195
- Wijesekara GN, Gupta A, Valeo C, Hasbani JG, Marceau DJ (eds) (2010) Impact of landuse changes on the hydrological processes in the Elbow river watershed in southern Alberta, 8 pp
- Wong MH (2005) The financial analysis of land releasing revenue (Chinese). *The finance forum magazine* 4, 15
- Wong THF, Fletcher TD, Duncan HP, Coleman JR, Jenkins GA (2002) A model for urban stormwater improvement: conceptualization, pp 8–13
- Wu H, Zhai G (2012) China's urban stormwater management and flood resources use (Chinese). *Mod Urban Res* 01:23–28
- Wu W, He W, Huang G, Feng J (2010) Review of urban storm water simulation techniques (Chinese). *Adv Water Sci* 21(1):137–144
- Xiao W, Xie Q (2014) Ecological red line-development's control rather than obstacles. *Southern Daily*, February 28
- Xinhua News Agency (2014) China's national urbanization plan (2014–2020) (Chinese)
- Xinli KE, Feng WU, Caixue M (2013) Scenario analysis on climate change impacts of urban land expansion under different urbanization patterns: a case study of Wuhan metropolitan. *Adv Meteorol* 2013
- Xu Y, Huang X, Zhang Y, Lin W, Lin E (2005) Statistical analyses of climate change scenarios over China in the 21st century (Chinese). *Adv Clim Chang Res* 1(2)
- Xu K, Wu S, Chen D, Dai L, Zhou S (2013) The urban growth boundary determination based on hydrology effects: taking Xinminzhou as an example 基于水文效应的城市增长边界的确定-以镇江新民洲为例. *Sci Geogr Sin* 33(8):979–985

- Xue T, Song Y (2014) Blue book 52: issues about the operation and management of urban drainage pipeline 蓝皮书52:探讨城市排水管网的运营管理问题 (Chinese)
- Yan Y, Chen S, Li G, Yu C (2013) Urban compactness index and its application: compactness of built-up areas in. *Nanjing and Suzhou* 32(5)
- Yang X (2013) On influence of non-constructed areas in natural water areas in urban areas on urban stormwater management (Chinese). *Shanxi Archit* 39(10):12–13
- Yang P, Li J (2014) Ecology oriented blue line planning compilation innovation: Liuxi River, Conghua, Guangzhou: 生态导向下河流蓝线规划编制创新-以广州流溪河(从化段)蓝线规划编制为例 (Chinese). *Planners* (7)
- Ye K, Li B, Shen L (2013) Key factors considered in compiling tender prices for China's public works projects. *J Manag Eng* 29(3):206–215
- Yin C (2008) Comparative research of spatial control in urban detailed planning in China and Germany (EN). Doktor thesis, Stuttgart, Germany
- Yu J, Liu F (2003) Research on urbanization and modern urban flood control and disaster reduction problems (Chinese). 城市化与现代城市防洪减灾问题研究 *Haihe Water Resour* (2):33–34
- Yu K, Wang S, LI D (2011) The negative approach to urban growth planning of Beijing, China. *J Environ Plan Manag* 54(9):1209–1236
- Zhai J, Zeng X, Jiang T (2011a) Evolution of drought and flood pattern and its effect on water resources in China from 1961 to 2050 (Chinese). *J Trop Geogr* 31(3):237–242
- Zhai J, Zhao Y, Pei Y (2011b) Drive mechanism of urbanization on regional water cycle (Chinese). *Water Resour Hydropower Eng* 42(11):6–9
- Zhang J, Wang G, Yang y, He R, Liu J (2008) The possible impacts of climate change on water security in China (Chinese). *Adv Clim Chang Res* 4(5):290–295
- Zhou L, Zou B (2004) Research of methodology on control of city density 探讨多层次控制城市密度的技术方法: Reasonings for the Shenzhen economic zone density zoning study 《深圳经济特区密度分区研究》的主要思路. *City Plan Rev* (12)