Received: 19 August 2020 | Revised: 27 February 2021 | Accepted: 13 March 2021

DOI: 10.1111/wej.12705

FULL LENGTH ORIGINAL RESEARCH PAPER

Water and Environment Journal
Promoting Sustainable Solutions
CIWEM WILEY

# China's 'Sponge Cities': The role of constructed wetlands in alleviating urban pluvial flooding

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## Abstract

Research examined constructed wetlands (CWs) in piloting the 'Sponge City', a Chinese initiative designed, in part, to curtail extensive urban pluvial flooding. In Yangzhou a small number of exploratory qualitative interviews with relevant professionals elucidated key issues. The interviewees supported the concept of CWs but were uniformly sceptical about their viability. A possible CW in the city was also modelled, quantifying its effects and limitations. Results show that CWs can help attenuate urban flooding but there are important caveats concerning their implementation. These concern their size and capacity, sufficiency of urban space, and their economic sustainability. The political dimension of the Sponge City concept, including support from President Xi Jinping, suggests that CWs may be a distraction from more widespread urban flooding, which CWs may well not alleviate. Piloting is continuing and results will need to be more positive if Sponge Cities can be a strategically important flood attenuation measure.

KEYWORDS
flood, flood defence, flood management, drainage, modelling, risk management, urban, wetlands

## 1 | INTRODUCTION

Urban flooding is attracting increasing attention in China, particularly after the devastating Beijing flooding in July 2012 when the water-scarce Chinese capital, after a single rainstorm, experienced 79 deaths and more than CNY 11 billion in damages (~1.6 billion US$) (Christensen & Ma, 2020). As Chinese cities continue to experience this type of flooding, frustration and anger has grown among their residents (The Economist, 2015).

On the global scale there are similar concerns. Cities are becoming more exposed to flooding (Leal et al., 2019) and the IPCC Fifth Assessment Report records very high confidence that flooding and other climate-related risks are increasing in urban areas and sees their impacts as widespread (Revi et al., 2014). Even if global warming is limited to +1.5°C, flood hazard and risk would still increase in some regions compared to present day levels (Hoegh-Guldberg et al., n.d.). Although floods from coastal and fluvial systems are the most prominent among the different flood types (Jongman et al., 2012), urban floods are expected to increase with increasing heavy or extreme precipitation (Handmer et al., 2012; O'Donnell & Thorne, 2020). Cities are also facing greater flood risks because of the increased exposure of their populations and assets with continued urbanisation (Kundzewicz et al., 2014). These types of urban floods can be particularly challenging, moreover, since some remedial actions can threaten to undermine the very features which keep urban centres economically vibrant, including concentrated populations, dense development and highly productive use of all available land.

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Urban flooding is usually attributed to the replacement of natural drainage systems with artificial measures in the urbanisation process (Lashford et al., 2019), further exacerbated by land cover change accelerating runoff, the concentration of population and property, and possible local climate change (GWP & WMO, 2012; Tucci & Villanueva, 2005; Zhang et al., 2016). In China, the recent rapid urban growth is also judged to be directly responsible (World Bank & DRC, 2014). The frequency and impact of China's urban flooding are correlated with local rainfall (Liu et al., 2018), but the considerable Chinese investment in flood control since disastrous floods in the late 1990 s has not benefited many cities suffering from pluvial events, as that investment has focused almost exclusively on fluvial flooding (Ding et al., 2016).

In response to extensive pluvial flooding in cities, the Chinese government developed in 2013 its own initiative called the ‘Sponge City’ (Zhang et al., 2016). Sponge cities are straightforwardly conceptualised as ‘sponge-like cities that naturally accumulate, filter and purify rainwater’ (Sidner, 2018). Largely informed by Low Impact Development (LID) (Lashford et al., 2019), the initiative aims at retaining 70% of rainwater locally (State Council, 2015), aligned with the principles of enhancing infiltration, promoting storage and exploring the use of rainwater (Zevenbergen et al., 2018). Heavily subsidised by the central government, large scale Sponge City piloting has unfolded in 30 cities across the country since 2015, while takeup in other municipalities is also encouraged and occasionally subsidised by local governments (Li et al., 2018). The costs are large; the piloting is estimated to cost 15-22 million US$/km$^2$ (Liang, 2018), yet its effectiveness has been questioned because 19 of the 30 cities were flooded again in summer 2016 (Wang, 2016).

Constructed wetlands (CWs) are among the measures included in the official Sponge City technical guide (MoHURD, 2014), and are gaining growing attention although they have been introduced in China since the 1980 s (Zhang et al., 2012). CWs are carefully engineered systems to deliver the functional service(s) provided by natural wetlands (Metcalfe et al., 2018). Some wetlands, as on floodplains, have substantial flood storage capacity, but not all wetlands share such capacity (Bullock & Acreman, 2003), as it is highly dependent on their geomorphic features, soil properties, and other local conditions both before and during flood events (Williams et al., 2012).

Extensively applied to wastewater treatment (Shao et al., 2014; Zhang et al., 2012), the potential of CWs in attenuating floods has been less well reported, with only a few successful cases in Europe, North America and Asia (Gülbaz & Kazezyılmaz-Alhan, 2017; Williams et al., 2012). CWs could be disadvantageous owing to their need for substantial land area, for costly maintenance and for purposeful community support (Metcalfe et al., 2018; Zhang et al., 2009). Incompatibility can occur between the services provided and benefits generated (Williams et al., 2012). For example, creating attractive scenery desirable for tourism development may not necessarily be the outcome of CWs designed for wastewater treatment or even for flood storage.

Constructed wetland projects are nevertheless very commonly planned into Sponge City piloting. For example, Shenzhen, one of the piloting cities, planned to construct or restore 39 wetlands by 2020, with a total area of 10 km$^2$ and an estimated storage of 70 million m$^3$ of stormwater (MGS, 2016). With additional benefits such as enhanced aesthetic values in ‘greening’ urban areas (Skrzypiecbcef & Gajewskaad, 2017), CW projects are often further justified by the economic importance of creating attractive cities for promoting tourism.

However, significant issues and questions remain to be tackled, including what the expectations and rhetorics are around CWs in the piloting cities, how, when and where CWs could effectively attenuate pluvial flooding, and what are the policy implications of such effectiveness issues. This paper investigates these questions and related concerns with a case study research design (Yin, 2003) in a Chinese city (Yangzhou, in eastern China) where there appears to be the potential for feasible CW-based flood attenuation via a ‘Sponge City’ approach. The key research questions related to Sponge City piloting were (1) what are seen to be some of the merits and limitations of using CWs and (2) what are the likely effects of CWs on flood attenuation as revealed by modelling.

## 2 | METHODS

Research addressed these questions in two complementary ways, first seeking information about Sponge City and CW use from key informants in the city, and secondly modelling the effect of CW interventions under a range of different assumptions.

### 2.1 | Semi-structured exploratory qualitative interviews

To understand some of the expectations, rhetorics and likely realities of CWs in their piloting and to elucidate embedded CW issues, semi-structured interviews were conducted with local researchers and officials who are directly involved in the Sponge City initiative in Yangzhou, using the questions in Table 1.[1]

The interviewees were recruited through snowball sampling, taking advantage of the interviewees’ social networks to select participants (Frey, 2018). As is standard qualitative interviewing practice, sampling continued until repetitive ideas started to dominate (Brinkmann, 2013), justifying the small sample size. The seven interviewees were adult professionals (over 18 years old) employed by local government authorities or research organisations, who have first-hand information and understanding of the current policies and priorities of urban flood control and Sponge City piloting (Table 2). No attempt was made to investigate wider and public attitudes to CWs in the city; this would constitute a very different study, but would no doubt be valuable additional research.

The interviews took place in late June/July 2019 in the Chinese language, each lasting for 30–60 min. A comprehensive information sheet was provided to each interviewee beforehand, giving the purpose, inclusion criteria, risks, data protection issues and information

**TABLE 1** The topics explored in the semi-structured qualitative exploratory interviews

| No. | General topic areas |
|---|---|
| 1 | Qualitative comments on current implementation of 'Sponge City' initiatives |
| 2 | Understanding of sponge measures and their contribution |
| 3 | Understanding of flood risk management in the urban setting |
| 4 | Planning policies for flood risk mitigation |
| 5 | Understanding of nature-based solutions |
| 6 | Techniques employed in urban flood management |
| 7 | Understanding of the role of constructed wetlands in urban flood control |
| 8 | Institutional barriers to adopting sponge measures in urban flood control |
| 9 | Difficulties in adopting sponge measures for urban flood control |
| 10 | Values of adopting sponge measures in urban flood control |

**TABLE 2** The roles and backgrounds of the interviewees in the exploratory qualitative survey

| Interviewee | Roles and backgrounds |
|---|---|
| 1 | Policy advisor with a background in hydrology |
| 2 | Researcher specialised in hydraulics and flood management |
| 3 | Researcher specialised in ecological engineering |
| 4 | Senior researcher and policy advisor with a background in hydrology and climatology |
| 5 | Local official responsible for flood management and relief |
| 6 | Engineer specialised in river management |
| 7 | Engineer specialised in urban development |

on use of the research. Written or oral consents were obtained before each interview. Five of the interviews were audio recorded and later transcribed, and two were transcribed based on notes taken because the interviewees declined to be audio recorded.

Interview transcriptions were analysed to tag and group significant statements and ideas according to their key contents. Although the scope of questions was prepared beforehand, the content analysis conducted to yield the results did not attempt to force the interviewees' statements into the categories in that scope, since new ideas emerged during the interviews and new categories were thereby developed. Conclusions based on the categorised ideas were extracted and translated into English.

## 2.2 | Modelling of a CW in Yangzhou

To understand quantitatively some of the issues teased out in the interviews that were conducted, a physical-process based modelling exercise was conducted on an area in Yangzhou, a city with a population of ~2.3 million. The study area is in the southeast block of the city where its earliest industrialisation took place and drainage infrastructures are commonly outdated (BURD-GDY, 2018). Announced in 2017, an on-going regeneration programme incorporates a number of CW projects as priorities in water management and of economic significance for tourism in the city. One of the CWs takes the form of a park (~0.638 km$^2$) on the Qili River in the centre of the study area (Figure 1). Since the project is anticipated to bring value to the local environment and its scenery, this provides a suitable case in which to examine the potential and limitations of CWs in attenuating flooding.

The total study area is approximately 13.8 km$^2$, with a population of ~21,000 and is remarkably low-lying (elevations between −3 to 24 m vis-à-vis sea level) and flat (Terrain Ruggedness Indexes between 0 and 22.3, over 96% under 10; Figure 2). This is one of the typical polders in the lower reaches of the Yangtze catchment, which are enclosed areas hydraulically disconnected from the outer rivers (medium-sized water courses fringing the area). It relies heavily on artificial structures such as sluices and pumps to control water levels in the inner rivers (small watercourses within the area) owing to the lack of hydraulic gradient to allow natural drainage (Deng, 2014).

For such urbanised polders, a common strategy is to drain stormwater into the inner rivers and pump it out into the outer rivers (Zhu, 2018), the Yangzhou study area in this respect relying on four pumping stations (Figure 1). With sustained precipitation, these polders face significant flood risk as the resulting stormwater needs to be drained out very rapidly (Gao et al., 2012). Sufficient storage space in the inner rivers and in facilities such as CWs is crucial for effective drainage and thereby reducing flood risk.

This part of the research took advantage of a model originally developed by a local research institute with InfoWorks ICM for flood risk mapping of the Yangzhou Prefecture (Liu et al., 2016). The model was adapted for the southeast block of the city. The model was validated with historical observation data for two rainstorms in 2010 and 2015, giving a water level error range within 0.2 m (Figure 3). The original model was built with data provided by the municipal government agencies of Yangzhou, including topography and land-use (at

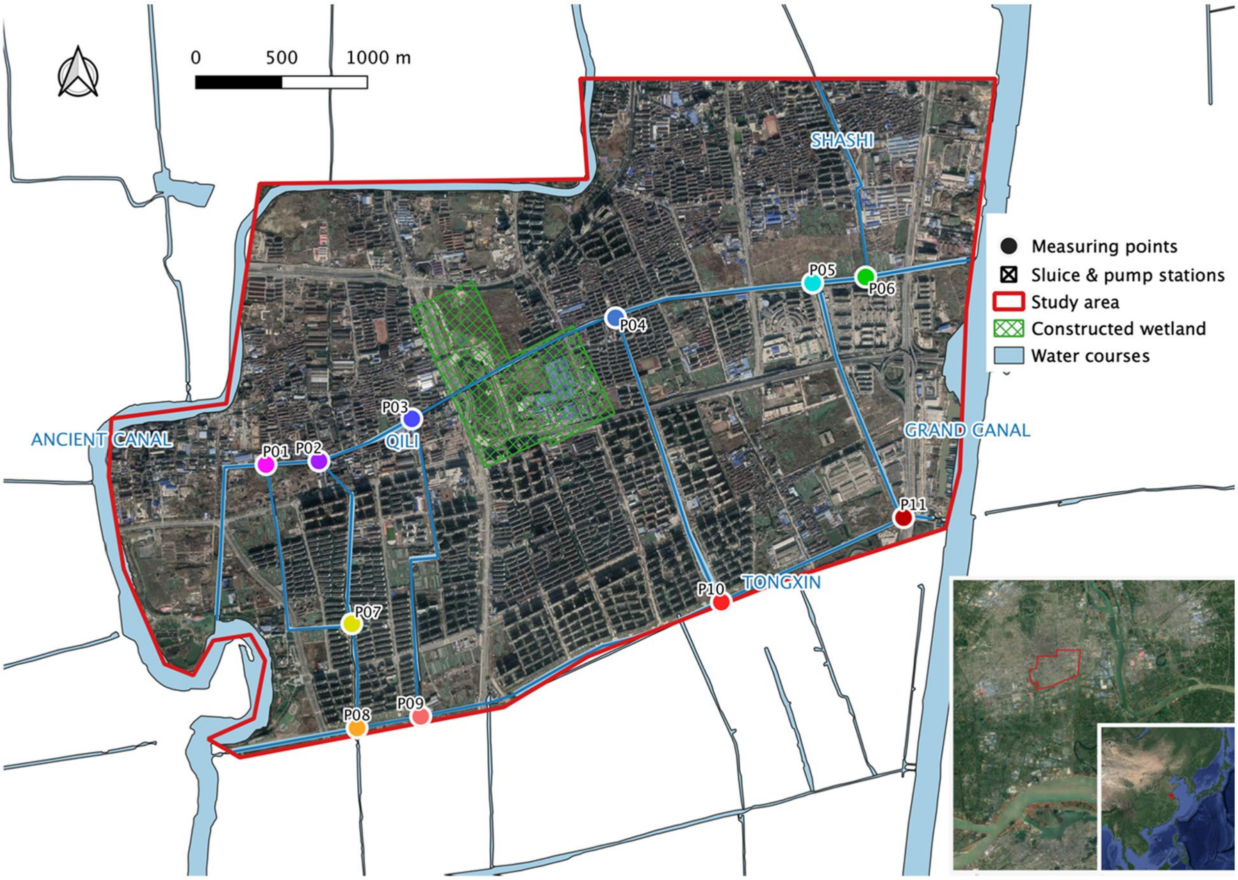


FIGURE 1 The study area located in the southeast block of Yangzhou city (see Table 3 for P01, PO3, etc.)

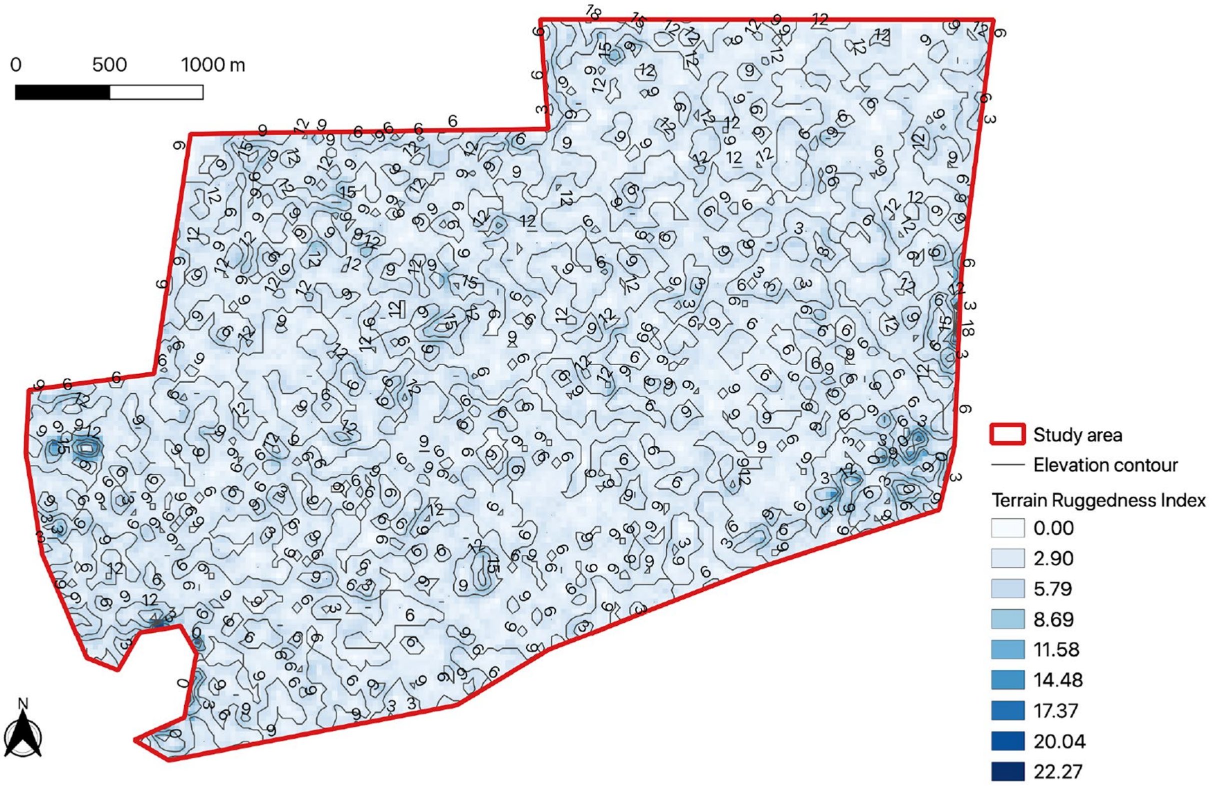


FIGURE 2 The flat and low-lying topography of the study area, making drainage problematic (data source: Shuttle Radar Topography Mission, plotted by the author)

1-m resolution), and key controlling infrastructures (such as sluices, pumping stations, bridges, conduits), and improved with other data from on-site measurements, including river cross-sections, dike and road elevations. Boundaries were set at the encircling rivers to the east, south and west of the study area, and a main through road to its north, so that the area forms a polder (Figure 1).

The design of CWs in China follows a national technical specification released by the former Ministry of Environmental Protection (MEP, 2010). To maximise the potential of the CW that was researched, a simplified scheme was developed in accordance with the specification's recommended slope ratio (Figure 4). As a minimum water depth (30 cm) should be maintained as recommended by MEP (2010), the substrate in the scheme is assumed to be fully saturated. Since the sewer system in the study area is fairly outdated with very limited capacity, and data on the system is classified, it is not taken into consideration in the simulation.

The rainfall-runoff process was simulated with the Storm Water Management Model (SWMM). Due to the lack of long-term observation records, precipitation data were based on an empirical equation widely used in China for estimating precipitation intensity:

$$i = \frac{A \cdot (1 + C \cdot lgP)}{167 \cdot (T + b)^n} \tag{1}$$

Here the average rainfall intensity (mm/min), $i$, is a function of the frequency, $P$, and duration, $T$, of the rainfall event, with $A$, $C$, $b$ and $n$ as location-specific parameters (Lou et al., 2018). The Chicago Method is recommended for the development of hyetographs in China (MoHURD, 2016), which consists of two analytical equations of rainfall intensity before and after the peak intensity (Silveira, 2016). Therefore, the rainfall intensity at $t$ (time since the start of rainfall) could be characterised as:

$$i_t = \frac{A \cdot (1 + C \cdot lgP)}{167} \cdot \frac{\frac{T \cdot \gamma - t}{\gamma} \cdot (1 - n) + b}{\left(\frac{T \cdot \gamma - t}{\gamma} + b\right)^{1+n}} \tag{2}$$

$$i_t = \frac{A \cdot (1 + C \cdot lgP)}{167} \cdot \frac{\frac{t - T \cdot \gamma}{1 - \gamma} \cdot (1 - n) + b}{\left(\frac{t - T \cdot \gamma}{1 - \gamma} + b\right)^{1+n}} \tag{3}$$

where $\gamma$ is the peak factor, ranging from 0 to 1, also known as *storm advancement coefficient*, to locate the peak intensity in the hyetograph over the duration ($T$) (Silveira, 2016). Qian (2013) studied the rainfall observational records of Yangzhou between 1985 and 2011, and formulated the following duration-frequency equation of Yangzhou:

$$i = \frac{182.503 \cdot (1 + 0.510 \cdot lgP)}{(t + 47.773)^{1.184}} \tag{4}$$

With Equations (2) and (3), and a storm advancement coefficient of 0.4 suggested by Lou et al. (2018), hyetographs could be developed (Figure 5). Based on a national technical guide (MoHURD, 2016), recurrence intervals of 1, 10, 20 and 50 years, and precipitation durations of 10 and 180 min, are used for comparison, making eight pairs of simulations with each pair consisting of two scenarios: with and without the proposed CW.

# 3 | RESULTS

## 3.1 | Opinions of Sponge Cities and constructed wetlands

### 3.1.1 | Differences and similarities

In the qualitative exploratory interviews, the respondents, familiar with or directly involved in the Sponge City piloting (Table 2), showed significant differences in their understanding of the concept. The urban development specialist saw this as not only the conservation and restoration of ecosystems, but also embracing the wider concept of low impact urban development (Interviewee 7; numbers in parentheses hereinafter refer to the list in Table 2). The water scientists appear to understand it literally as the attributes of a physical sponge—its capacity for holding water in its void space (1 and 4). Interviewee 2 indicated that the Ministry of Housing and Urban-Rural Development and the Ministry of Water Resources attempted a strict Sponge City definition between 2017 and 2018, but eventually gave up for fear of misleading the public. Those responsible for implementing the policy saw it as made up simply as collections of tangible elements such as rain gardens and constructed wetlands (6) rather than an overarching concept or design.

Nevertheless, there was also much agreement between the interviewees. No specific criteria could be recalled to distinguish a Sponge City from others. The most cited metric—70% runoff retention—is problematic because it is directly appropriated from US practices and not perfectly applicable here (1), and therefore is conveniently understood only in a statistical sense (2). The necessity for Sponge Cities was also unanimously supported, but it was recognised that only half of the expected funding has been delivered to some cities (4), so there is much uncertainty and it is difficult to generalise about the overall impact of scaling up. However, the interviewees stressed that it was already clear that coping with fluvial flooding from sources upstream of cities is impossible with just Sponge City measures.

### 3.1.2 | Scepticism and limitations

All the interviewees were sceptical about the effectiveness of Sponge measures such as green roofs and rain gardens as having a limited contribution in providing storage (3), as they could quickly get saturated (4). In contrast several interviewees considered that constructed wetlands are promising in attenuating pluvial floods (1, 2, 4 and 7), with extra benefits such as water quality improvement

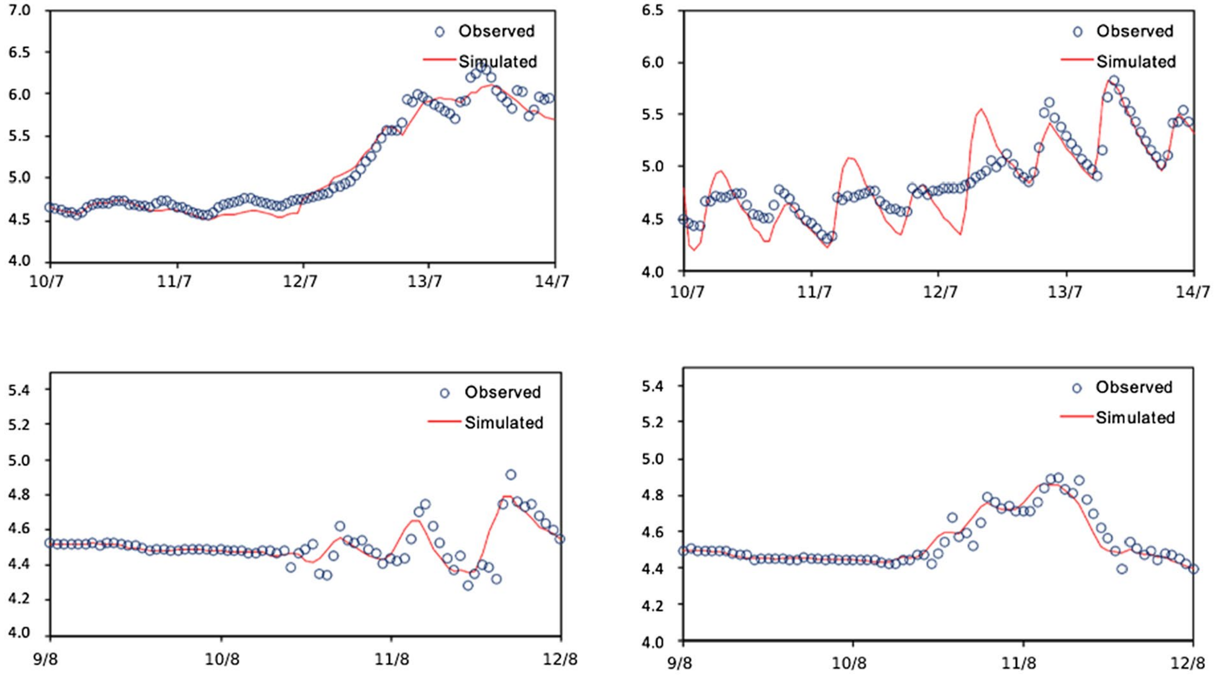


**FIGURE 3** Observed and simulated water levels (m) at two gauging stations of Yangzhou in two rainstorms (left: Siyuangou Sluice, right: Guazhou Sluice; top: July 2010, bottom: August 2015) (Liu et al., 2016)

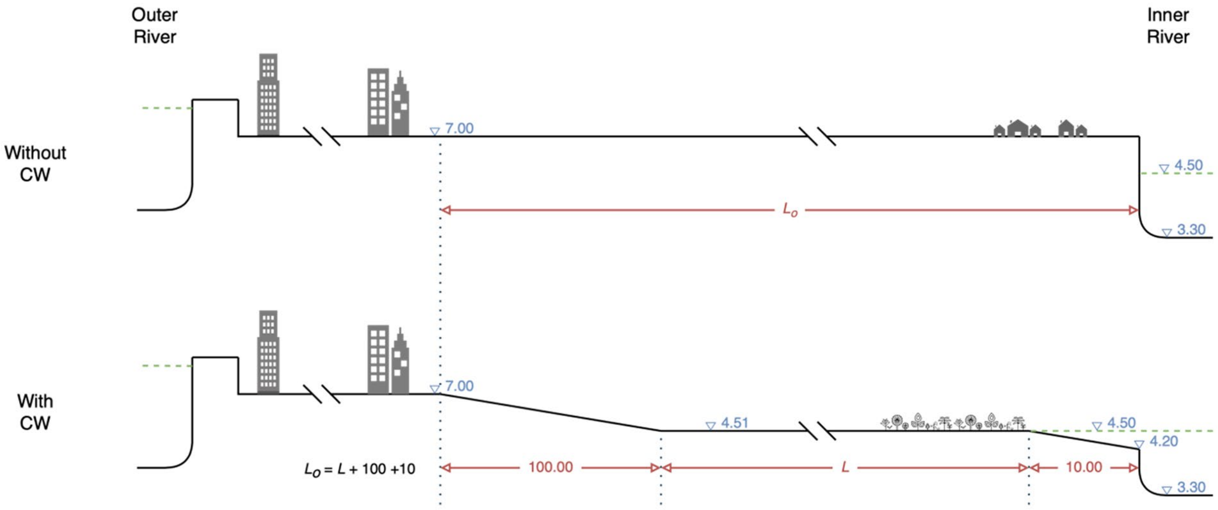


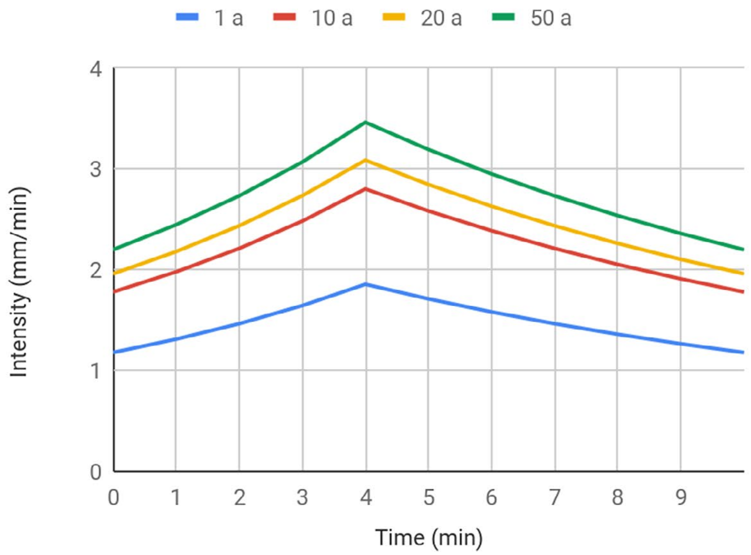
**FIGURE 4** Cross-sections before and after the installation of a constructed wetland (dimensions are in m and, for the purpose of demonstration, are not drawn to scale)

(4) and biodiversity conservation (6), and that there had been a small number of projects exploring the value of these wetlands (7).

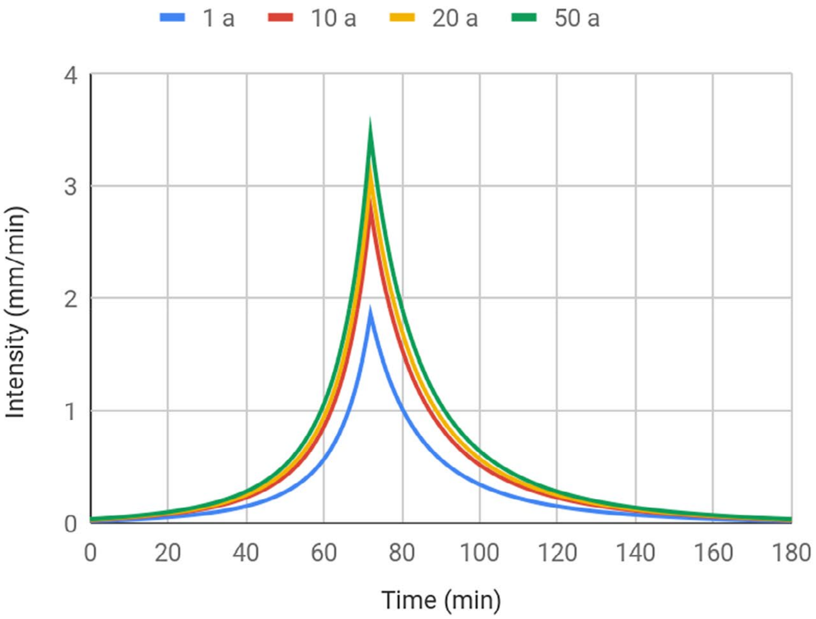
However, the interviewees also warned about the limitations of CWs because very few constructed wetlands are designed and optimised for attenuating flood flows (6 and 7) as the sponge concept implicitly suggests. The majority of CWs are for treating effluent from wastewater plants or river water. The most efficient schemes so far (6) involve the vertical flow design, consisting of aeration pipes with fillings such as gravel, and they therefore provide no capacity for flood storage (6). Other constructed wetlands are mostly for amenity purposes (2). Moreover, the interviewees also warned that competition between different uses of space in cities means priority is given in practice to more financially rewarding purposes such as real estate development, and therefore flood attenuation measures that require less land than CWs (such as deep storage tunnels) are always preferred (3).

**FIGURE 5** Hyetographs of design rainfalls for the study area with 10 (a) or 180 (b) min durations at recurrence intervals of 1/10/20/50a (years)

**(a)** 10 min rainfall events of 1/10/20/50 year recurrence



**(b)** 180 min rainfall events of 1/10/20/50 year recurrence



### 3.1.3 | Governance issues: Responsibilities and the locus of control

There were strong interviewee views about governance issues.

> In many developed western countries, [the management of] construction, water, transport and urban development might be under the responsibility of one single government department, which allows an integrated way [in planning]. In China, these are under different ministries and they see the problems from different perspectives. (3)

In China, moreover, the government's water departments are responsible for keeping the (inner and outer) rivers free from flooding, and development and housing administrations are supposed to drain the cities, with their sewer networks (Lu et al., 2007). However, different and not fully compatible standards are adopted between these inner and outer rivers and the drainage networks (2 and 6). Conversion between these standards requires a large amount of empirical studies and local knowledge (6). Cities in polders often find during flood events that the outer rivers have already flooded from upstream and therefore they have the almost impossible problem of finding storage within the cities (1). Constructed wetlands could have a part to play here.

A parallel issue concerns the locus of control: centralisation versus decentralisation. A risk-based approach to managing urban flooding calls for streamlining priorities while taking on an integrated perspective. The complexity of the integrated approach invites centralisation and a focus on technocracy in implementation, but bottom-up and participatory approaches need to work in an opposite direction (Wester & Warner, 2002).

All the interviewees credited the strong 'top-down' governmental leadership in the Sponge City piloting. This is valuable for master-planning ahead of constructed wetland initiation, for quick decision-making and better accountability (5 and 3). However, 'for implementation and application…, when the city has grown into a certain size, let's say a megacity, centralised ways might be too costly to afford' (3); Sponge City piloting should not be focusing only on a 'top-down' approach. But in a contested and highly political situation, less powerful stakeholders often protest against power asymmetry by pulling out from the agenda setting process (or threatening to) (Wester & Warner, 2002). From the perspective of the specialist on hydrology and climatology (4), such a protest manifests itself in the low-key way the Ministry of Water Resources participates:

> The Sponge City piloting …… is led by the Ministry of Housing and Urban-Rural Development with the Ministry of Water Resources being [merely] a partner …… [However] the latter is participating in a very passive manner … Yet the agencies for housing and urban development are only responsible for draining stormwater into rivers. Once that water is in the river, it becomes the responsibility of the water agencies. (4)

A common justification given for Sponge City implementation being dominantly top-down is the widespread technocratic belief that urban flooding control is better handled by professionals. In this context flood risk management therefore does not reject engaging the public, but neither does it encourage public participation (5). The lack of transparency among government agencies for managing floods is another factor here, as even where flood risk maps have been developed, they are not available for public use (6). Additionally, the lack of public participation could also be attributed to 'a widespread expectation of some sort of government omnipotence' (5), and therefore that the government should assume all flood-related responsibilities.

#### 3.1.4 | Governance issues: Financial unsustainability

The key to water management should be 'a tripod or stool, in which state, collective, and market institutions each play a role' (Meinzen-Dick, 2007). This has allowed water governance to be increasingly underpinned by approaches in which the water sector is run 'on a cost-recovery basis so that it becomes self-financing instead of relying on government budgetary allocations and subsidies' (Chikozho & Mapedza, 2017). This was seen as problematic for Sponge Cities by at least three of the interviewees (2, 3, 6).

The Sponge City piloting is subsidised by the central government but only for the first three years and local governments are supposed to secure additional funding. Therefore, financial sustainability was one of the top concerns of the locally based interviewees. The 'user pays' principle, which is widely accepted as a norm in water governance (Vörösmarty et al., 2015), seems to be considered less important in Sponge City implementation, largely because of 'public benefits' for the whole community.

> Currently many of the measures rely on government investment, with little evident economic benefits. Therefore, their sustainability depends highly on investments and subsidies from local and central governments. These projects cannot be seen as commercial ones from which [financial] benefits are expected. (3)

In the case of constructed wetlands, which involve high capital costs (Zhang et al., 2009), it seems that little attention has been paid to quantitatively justifying whether these projects are worthwhile or not.

> [Laughter] 'These projects are all for public benefits, which means the country should spend money on them. They don't come with economic benefits, but maybe environmental benefits. Perhaps only social environmental benefits, which are making people happy.' (6)

Therefore, although significant spillover benefits into local economies are expected from Sponge City measures such as constructed wetlands (2), for example, into the tourism sector, a neglect of quantifying and valuing the overall benefits of these developments is evident. This is making it seem somewhat doubtful to the interviewees whether there is a favourable economic case for their continuation and up-scaling.

### 3.2 | Simulating the constructed wetland for flood attenuation

The modelling of a CW in Yangzhou allows us to examine such infrastructure in a quantitative way. Not all the issues raised by the interviewees can be tackled by this modelling, but the necessary scale and the physical performance of these measures can be illuminated, and the CW judged in terms of both the potential and limitations for flood attenuation.

#### 3.2.1 | The potential of the CW in attenuating flooding

With combinations of different precipitation durations (10 or 180 minutes) and recurrence intervals (1, 10, 20 or 50 years), sixteen scenarios were simulated in eight pairs. Each pair consisted of

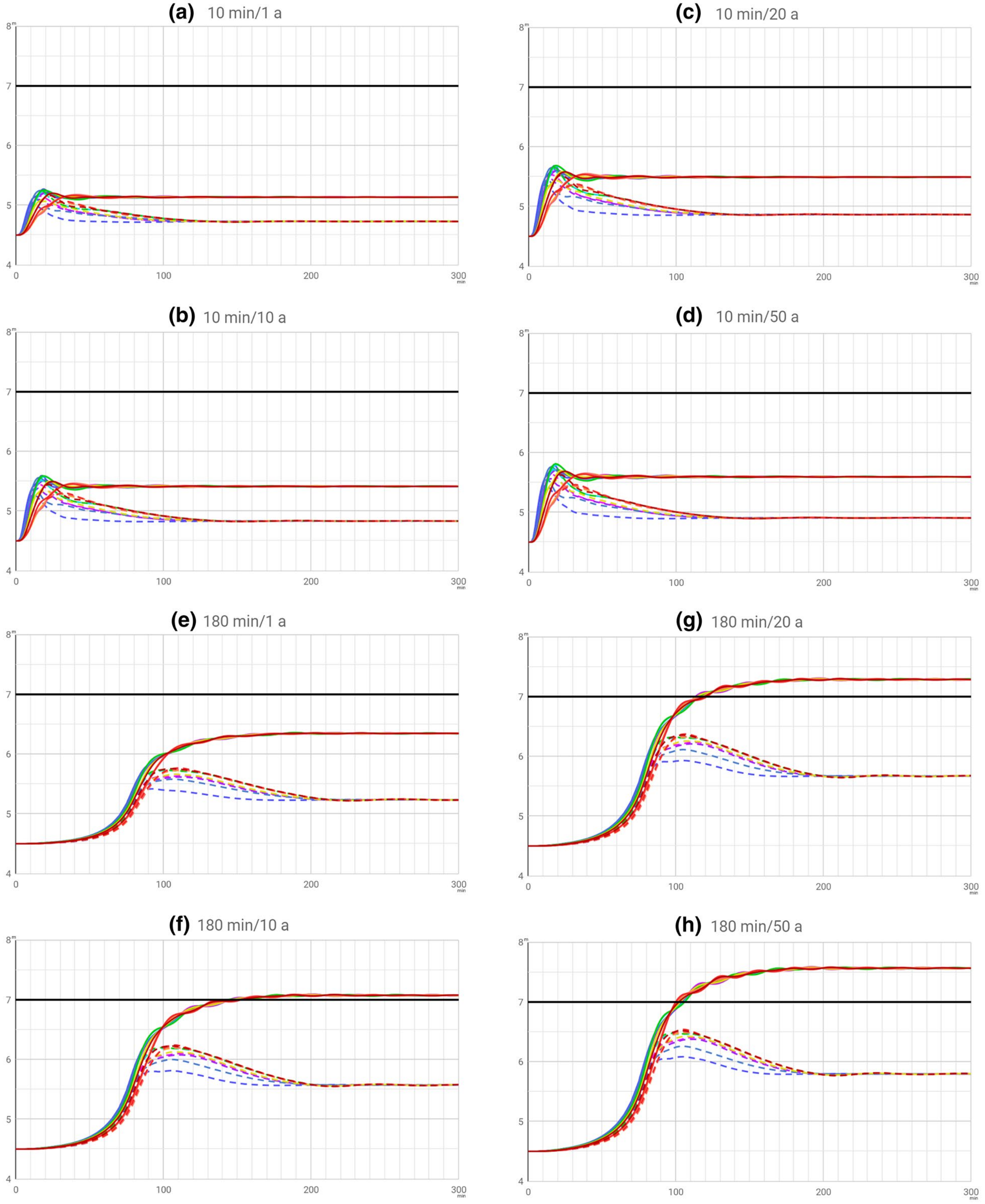


**FIGURE 6** Water levels (m) at the eleven observation points (colour-matched with those points in Figure 1) over time (min) on the inner rivers of the study area under different precipitation scenarios (left: 10 min precipitation at recurrence intervals of 1/10/20/50 years; right: 180-min precipitation at recurrence intervals of 1/10/20/50a (years); solid lines are scenarios before the installation of a constructed wetland; dashed lines are scenarios with the constructed wetland present. The average elevation of the riverbanks is approximately 7 m (bold horizontal line shown here)

contrasting scenarios '***B***efore' (Scenario B) or '***A***fter' (Scenario A) the development of the proposed CW park. Measurements of water levels (in m) over time (minutes) were simulated at 11 points (see Figure 1) at a 1-minute interval (Figure 6).

With the 10-min rainfall, water levels of the inner rivers rose as they collected surface runoff. Water level peaks lagged clearly behind those of precipitation (4 min after onset). In all scenarios water levels were lower than the bank elevation (around 7 m) with common

**TABLE 3** Water level peaks and stabilisation levels under 10 or 180 min rainfall simulations at 1/10/20/50 a recurrence frequencies

| | 1 a | | 10 a | | 20 a | | 50 a | |
|---|---|---|---|---|---|---|---|---|
| | 10 min | 180 min | 10 min | 180 min | 10 min | 180 min | 10 min | 180 min |
| Scenario B (before) | | | | | | | | |
| Max. peak point | *P*03 | *P*01 | *P*03 | *P*01 | *P*06 | *P*01 | *P*06 | *P*01 |
| Max. peak (m) | 5.27 | 6.36 | 5.59 | 7.09 | 5.68 | 7.31 | 5.81 | 7.57 |
| Time to peak (min) | 19 | 216 | 18 | 201 | 19 | 197 | 18 | 192 |
| Stabilisation level (m) | 5.13 | 6.35 | 5.41 | 7.07 | 5.49 | 7.29 | 5.59 | 7.56 |
| Scenario A (after) | | | | | | | | |
| Max. peak point | *P*06 | *P*10 | *P*06 | *P*10 | *P*06 | *P*10 | *P*06 | *P*10 |
| Max. peak (m) | 5.23 | 5.76 | 5.56 | 6.24 | 5.65 | 6.37 | 5.77 | 6.53 |
| Time to peak (min) | 18 | 110 | 18 | 107 | 17 | 107 | 17 | 105 |
| Stabilisation level (m) | 4.72 | 5.24 | 4.83 | 5.57 | 4.86 | 5.67 | 4.91 | 5.79 |

*Note:* Peak point names (*P*01; *P*03; etc.) correspond to designations on Figure 1.

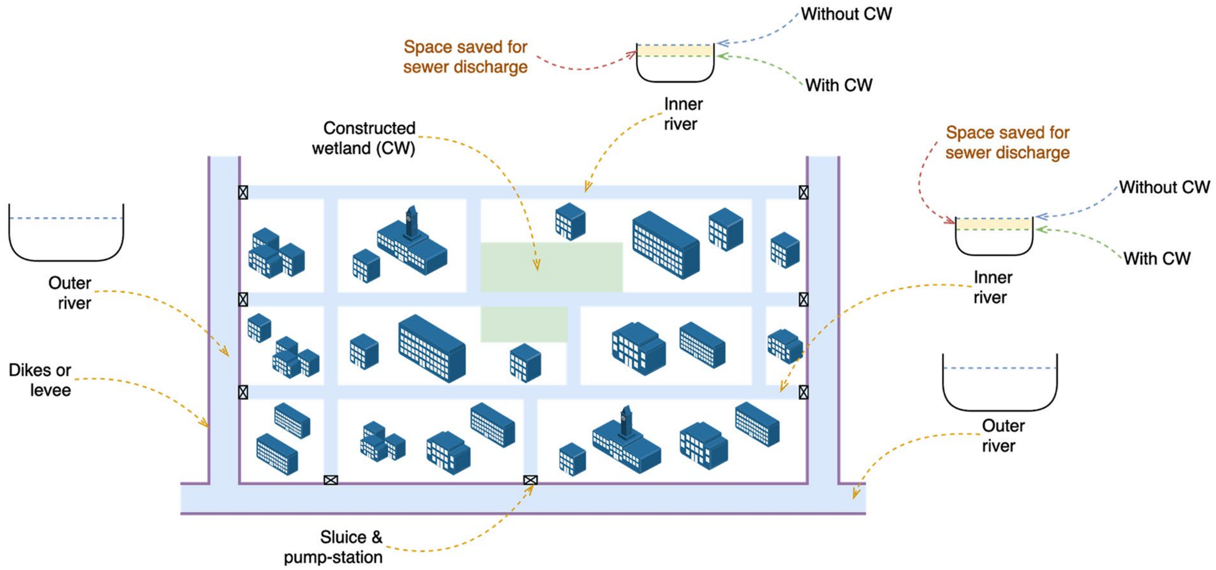


**FIGURE 7** An indicative summary of the effects of a constructed wetland for attenuating urban pluvial flooding (dimensions are disproportionate for purpose of demonstration). In a typical polder, the inner rivers (the rivers running through the polder) are connected to the outer ones (rivers around the polder) through sluices and pumping stations. The introduction of a CW expands the floodplain of the inner rivers, which creates more storage space that helps lowering water levels in the inner rivers (see also Figure 4). The lower levels created in the inner rivers mean more sewer and overland flow discharge can be accepted

reduced levels under all Scenario As. Within each of the eight pairs, water level stabilisation was commonly delayed under Scenario As at around 90 min after precipitation onset. Water levels dropped after reaching a peak under both Scenario Bs and As, but more noticeably under As. The difference grew with recurrence interval (see left panels of Figure 6 and Table 3).

When precipitation duration was increased to 180 min, water levels rose considerably. Water level peaks still lagged behind those of rainfall (72 min after onset). Except for the 1 year recurrence interval, Scenario Bs saw the river banks overtopped, in contrast to Scenario As. Water levels stabilised at peaks as soon as the rainfall stopped under these Scenario Bs. In Scenario As apparent falling limbs occurred after peaks, to stabilise about 20 min later. The difference between stabilisation levels in each pair still grew with recurrence intervals (see right hand panels of Figure 6 and Table 3).

In summary, the modelled CW lowered flood levels considerably in the polder's inner rivers and therefore reducing the risk of out-of-bank flooding of the neighbouring parts of the study area. Firstly, when the surface runoff pushed up river levels, the CW curtailed the rising limb resulting in lower peaks. Secondly, it brought down noticeably the stabilisation levels. When CWs were present falling limbs occurred after peaks, particularly under long duration rainfalls. Both imply valuable space saved in the inner rivers for storing overland flows and sewer discharge (see Figure 7). However, such potential cannot be taken for granted without considering the necessary conditions.

### 3.2.2 | The limitations of the CW for flood attenuation in the study area

The first issue is the unique geomorphology of the study area. Building the CW park expands the floodplains of the inner rivers, which is one of the most effective types of wetlands for flood attenuation (Bullock & Acreman, 2003). The excavation to build the CW creates valuable off-stream storage for the rivers which are connected to it. Since the area is a polder almost separated from the outside, such storage capacity is helpful because the CW is relatively large compared to the size of the polder. However, this characteristic might not occur in other cities where CWs are proposed and are otherwise feasible.

A second limitation is its land requirement. The CW under discussion involves approximately 63.8 ha, approximately one 20th of the polder's area. Given China's soaring land prices since 2009 (Lei, 2018), such a large feature might not be economically sound for other cities where there is a shortage of available land or where scenery is less important than in tourist cities like Yangzhou. Though the CW might occupy land already under significant flood risk, alleviating flood risk might not always be a local priority (Porter & Demeritt, 2012). Moreover, relocating residents and businesses from the area would not be easy or inexpensive in Yangzhou, although exact data on this dimension is not readily available.

This CW plan has additional economic downsides. Besides the initial capital cost of excavation, the CW requires additional resources for operation and maintenance. Ghermandi and Fichtman (2015) estimates that the annual cost for CW operation and maintenance is around 9,060 euros/ha/year (in 2013 prices). This means an annual budget of more than €570,000 (approximately US$ 616 k) for the proposed Yangzhou CW. More costs might be incurred in managing any public health risks brought by the CW, for example through the accumulation of pollutants (Williams et al., 2012) common in such urban areas, and exposure to water related diseases (Anthonj et al., 2018). How to recover such costs or secure grant funding for them are important questions for the project to be sustainable, confirming the concerns found amongst the interviewees.

## 4 | DISCUSSION

Returning to the two key research questions we posed, on CWs' merits and limitations and their likely effects on flood attenuation, both the exploratory interviews we held and the modelling provide valuable insights into the use of CWs in Sponge City piloting, and both condition the comments here.

### 4.1 | Implications for CW use in Sponge City piloting

First, the research has shown that CWs could be very helpful in attenuating urban pluvial flooding, especially for the less extreme events, along with other interventions such as underground storage tunnels. If designed properly to function as floodplains while remaining compatible with other purposes, CWs could provide valuable space for storing excessive water from surface runoff and storm sewer discharge.

But there are caveats. In situations like the polder that was modelled, extensive precipitation feeding the outer rivers means they might already be bankfull and in danger of overtopping their dikes when heavy rainfall affects the polder. Only if such CWs are sufficiently large will their storage capacity mean less need for pumping flood waters into the outer rivers and have the hoped-for effects on Sponge City flood attenuation. But this creates a spatial planning issue: how can large CWs fit into the existing urban fabric? With the currently fragmented responsibilities between water management and urban development administration agencies in China it is therefore useful that the latter are directly responsible for such CW projects and that the former have a rather low-key involvement.

Secondly, CW use in Sponge City piloting should always take into consideration its limitations as emerged from the interviewees. The land requirements could be in conflict with other land use priorities in urban development (e.g., housing). Apart from acquiring the necessary land, the large investment into CW projects needs to be met by either cost recovery or additional public funding in order to be sustainable.

Thirdly, since quantification of user benefits is almost absent in the top-down approach of Sponge City piloting, any CW project has to be heavily reliant on public investment or subsidies, which might not always be available. Therefore letting the 'user pays' principle play a bigger role through market mechanisms could provide alternative funding sources. Careful identification of beneficiaries and the externalities of CW schemes (particularly positive ones) must thereby be revealed and valued (Keohane & Olmstead, 2016) to identify 'winners and losers'. In principle this could allow the implementation of some form of user charge, perhaps at a city-wide level. Such an approach is manifested in a 2019 decision to continue central government subsidies, which also sees the private sector as an additional source of funds. In turn this could promote enduring financial sustainability and garner wider public support.

### 4.2 | The sponge city concept and its political nature

Whilst a favourable future for CWs and Sponge Cities is thus possible, problems are also likely. The disparity of understanding among the professionals interviewed reveals that the Sponge City idea has the nature of a 'Nirvana Concept', which is 'attractive yet woolly consensual' and entails an idealised image of the world (Molle, 2008) which conceals its political nature and institutionalised power differences (Wester & Warner, 2002).

Highlighted by China's top leaders including Xi Jinping himself, the Sponge City concept is political by origin. We judge that it is devised to curtail the scrutiny of emerging urban flooding issues. It was conceived soon after the devastating flooding in 2012 in Beijing, which led to extensive questioning of China's urbanisation amidst public irritation and frustration with the flooding (The Economist, 2015). It disguises its political nature so well in normal discourse that, despite various problems identified within their professions, none of the interviewees questioned the veracity of the Sponge City concept.

Since depoliticising the concept requires neutralising so many antagonistic (or less compatible) goals, it is overloaded by different priorities:

> The Sponge City concept … has been bestowed so much connotation … that it is widely believed among the public (mistakenly) that the adoption of sponge measures is going to solve all the problems of urban flooding. (1)

If serious urban flooding is not seen to be eliminated by Sponge City and CW developments, a downward spiral of CW implementation matched by new public discontent could emerge. The political nature of the Sponge City concept could mean Chinese cities repeating this downward pathway, despite its inherently limited performance. With continued urban growth the cities could become hugely and increasingly vulnerable to extreme rainfalls beyond CWs' limited capacity. Any unsolved urban flood problems will make it politically necessary to continue the implementation of Sponge City projects, or invent new concepts or schemes, at which the Chinese government seems to be rather good. However, as CWs are already developing, more funds and resolution of spatial planning issues are needed to provide the successful flood attenuation that this research has demonstrated to be achievable. Thus it is understandable that the central government decided to extend its subsidies in 2019 for another three years whilst welcoming any private investment that might be forthcoming[2]. The continuation of the experiment is to be applauded but the results must be scrutinised with rigour and supported by all the necessary evidence on the strategy's strengths and limitations.

## 5 | CONCLUSIONS

The Chinese 'Sponge City' initiative has been designed, in part, to mitigate extensive urban pluvial flooding. Research in in the city of Yangzhou included a small number of exploratory semi-structured qualitative interviews with relevant professionals to elucidate key issues concerning the building of Constructed Wetlands (CWs) as part of that initiative. The results showed that the interviewees supported the concept of CWs but were uniformly sceptical about their viability.

A possible CW in the city was also modelled using InfoWorks ICM software, to analyse quantitatively its effects and limitations. Results show that CWs could provide valuable space for storing excessive water from surface runoff and storm sewer discharge, but generally only for the less extreme events. If they are designed appropriately they could function as floodplains while remaining compatible with other purposes such as tourism development.

Such CWs can therefore have promise in attenuating flooding but there are important caveats concerning their implementation that emerged from both the interviewees and the modelling results. These concern their size and capacity, as they need to be large to accommodate likely flood volumes, thereby resulting in doubts about the sufficiency of the appropriate urban space in typical Chinese cities. The results also raise doubts about the economic sustainability of CWs, given their high construction and maintenance costs.

The political dimension of the Sponge City concept, including support from President Xi Jinping, suggests that CWs may be a distraction from more widespread urban flooding, which CWs may well not alleviate because of the capacity and implementation constraints suggested by this research. Nevertheless piloting of the 'Sponge City' approach is continuing and outcomes will need to be more positive than these results show if this is to be a flood mitigation measure that is strategically important both in the chosen site and in similar urban centres elsewhere.

## ACKNOWLEDGEMENTS

The authors of this paper are grateful to Dr. Fan Yang and Dr. Ziwu Fan from the Nanjing Hydraulic Research Institute for their assistance in the modelling of the polder in Yangzhou and to the interviewees for their contribution to the policy analysis.

## DATA AVAILABILITY STATEMENT

Data is available from the authors for all figures except Figure 1 and 6.

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## ENDNOTES

[1] CUREC 1A ethical approval was obtained from the Central University Research Ethics Committee of the University of Oxford (reference: SOGE 1A-19-55).

[2] In July 2019, the central government decided to continue subsidising Sponge City projects with a budget between 400 to 600 million Chinese Yuan (c. 57 to 86 million US$) per city per year for another three years. However, it could be interpreted from the announcement that Sponge City piloting has evidently been somewhat down-played. Available at http://www.gov.cn/xinwen/2019-07/03/content_5405556.htm (in Chinese).

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**How to cite this article:** Zhou T, Penning-Rowsell E. China's 'Sponge Cities': The role of constructed wetlands in alleviating urban pluvial flooding. *Water and Environment Journal*. 2021;35:1133–1146. https://doi.org/10.1111/wej.12705