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Urban and river flooding: Comparison of flood risk management approaches in the UK and China and an assessment of future knowledge needs

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Abstract

Increased urbanisation, economic growth, and long-term climate variability have made both the UK and China more susceptible to urban and river flooding, putting people and property at increased risk. This paper presents a review of the current flooding challenges that are affecting the UK and China and the actions that each country is undertaking to tackle these problems. Particular emphases in this paper are laid on (1) learning from previous flooding events in the UK and China, and (2) which management methodologies are commonly used to reduce flood risk. The paper concludes with a strategic research plan suggested by the authors, together with proposed ways to overcome identified knowledge gaps in flood management. Recommendations briefly comprise the engagement of all stakeholders to ensure a proactive approach to land use planning, early warning systems, and water-sensitive urban design or redesign through more effective policy, multi-level flood models, and data driven models of water quantity and quality.

Keywords: Urban flooding; River flooding; Water management; Review; Strategic research plans; Sponge cities

1. Introduction

Over the last two decades, China (Hubacek et al., 2009; Chen and Song, 2014) and the UK (Office for National Statistics, 2013) have seen a steep increase in the rate of urbanisation. Following a similar trend, the population in the UK and China is expected to continue rising until at least the end of the twenty-first century (*World Population Prospects: The 2017 Revision* (UNDESA/PD, 2017)).

Due to the increased need for urban development, surface water bodies such as rivers, streams, lakes, ponds, and wetlands have been routinely modified and/or replaced with fixed, or culverted drainage channels, paved areas, and buildings. The impact of such urbanisation on rainfall runoff has been clearly reported in the urban hydrology literature (James, 1965; Hollis, 1975; Booth, 1991; Weng, 2001; Hamdi et al., 2010; Miller et al., 2014; Arnell et al., 2015; Eshtawi et al., 2016; Xu and Zhao, 2016). The increasing area of impermeable surfaces prevents rain from infiltrating into the soil below, causing urban impervious areas to exhibit faster and larger

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hydrological responses than natural pervious areas, even for low rainfall intensity (Dayaratne and Perera, 2008). The increased runoff can create significant flood risk with even moderate rainfall, and the situation is only expected to worsen as a changing climate triggers more extreme rainfall events (Westra et al., 2013; Soetanto et al., 2017). In 2013, in England, 2.7 million properties (of these, around 546000 were in areas where the risk was considered to be significant, with impacts on the health of the communities affected (DEFRA, 2013)) were estimated to be in places at risk of flooding, and this number almost doubled by 2017 (Boyd, 2017; Environment Agency, 2017).

Many intense urban flooding events have been recorded in the UK during recent years, such as the following:

(1) Floods during June and July 2007, mainly in the North East, Yorkshire, East Midlands, and the West Country, which caused the death of 13 people and damaged approximately 48000 homes and 7000 businesses (Pitt Review, 2007).

(2) The Newcastle pluvial flood of June 28, 2012 caused by an intense storm that delivered 26 mm of rain in half an hour, 32 mm of rain in a single hour, and 49 mm of rain in a 2-h period (Environment Agency, 2012). Due to this event, most public transport was closed for many hours, with some roads closed while traffic was impacted in other areas of the city (Pregnolato et al., 2017).

(3) On December 18 through 19, 2013, Northern Ireland and the west of Scotland were affected by a storm that caused major flooding and then, a few days later, (December 23 through 27, 2013), an additional cluster of heavy storms extending across southern England generated urban and river flooding (Thorne, 2014).

(4) In December 2016, Cumbria was affected by extraordinary rainfall events (intense and of short duration) typical of cyclonic areas (e.g., 405 mm of rainfall eclipsed nearby Thirlmere within 48 h in 2016) causing 16000 properties to be flooded in parts of Cumbria (Marsh et al., 2016).

In China, the situation is even more dramatic, considering that 137 million individuals live in areas thought to have a noteworthy risk of flooding. High-intensity flash floods have generated a variety of casualties and economic losses across China (Miao et al., 2016; Jiang et al., 2018). The total number of deaths since 1950 caused by all floods in China is around 280000, while 139 billion CNY have been lost since 1990. Each year around 984 deaths are caused on average by multiple flash flooding events (He et al., 2018). For example, in 2010, due to a flash flood in Zhouqu County, Gansu Province, 1765 people were considered missing or dead. In July 2016, in the central and northern areas of China, the worst floods since 1998 occurred: 32 million people in 26 provinces were affected by severe flooding. Unfortunately, due to the social and economic development that many regions in China are experiencing, the magnitude and frequency of flash floods and their consequent casualties and damages are expected to increase rapidly in all these areas (He et al., 2018; Zheng et al., 2013).

This paper presents a review of the current knowledge of flood management strategies in the UK and China, collected by a comprehensive review of academic and political literature and direct conversation with policy makers. For the first time, it brings together information relevant to flood management strategy in the UK and China in order to provide a resource for other researchers, and presents a summary of key areas for future research. It is intended to inspire future research, and thus does not speculate on the detailed solutions to flood management. The UK (which is currently part of the EU), and China (which is not part of the EU) have been selected to provide insights about the existing policies in a country where multi-national regulation (EU law) is applied at a national level (UK) versus another country (China) that sets its own environmental policy.

2. Identifying the niche: Comparison between expenditure and management in the UK and China

This section describes how management and expenditure are undertaken in both the UK and China.

2.1. Management in the UK

In the UK, flood management is grounded on the principle of risk analysis, quantifying the likelihood of flooding based on an annual exceedance probability (AEP). Risks are quantified according to the likelihood of flooding and the severity of consequences, such as human health impacts, economic activities, and environmental impacts. The Department for Environment Food and Rural Affairs (DEFRA) is the central government department responsible for flood policy, while the Environment Agency (EA) is a non-departmental government body that makes in-depth assessment of flooding and plans the management of flood risk in England at national and regional scales (Miller and Hutchins, 2017). The Northern Ireland Environment Agency (NIEA), Natural Resources Wales, and the Scottish Environment Protection Agency (SEPA) are the equivalent agencies, respectively, in Northern Ireland, Wales, and Scotland. Management of urban flood risk in England is fragmented (Dawson et al., 2008), with responsibility for sources of flooding shared between the EA, Lead Local Flood Authorities (LLFAs), water companies (sewerage operators), internal drainage boards, highways and other local public authorities, and private property owners. Where LLFAs have been well-resourced and led effectively, they have been delivering all of the statutory requirements of the Flood and Water Management Act (FWMA) and often the broader practice of local flood risk management. There are numerous examples of how effective local partnerships, both between different LLFAs and between LLFAs, public authorities, and private organisations, have underpinned the successful implementation of the FWMA. On the other hand, there are still features that act as obstacles to better-quality local flood risk management such as the following (DEFRA, 2017):

(1) Resource constraints: Limitations in the available resources can result in the partial delivery of the statutory responsibilities introduced by the FWMA. Furthermore, limitations in revenue funding result in limited technical

capacity, and consequently many LLFAs have had inadequate access to funding for capital schemes (DEFRA, 2017).

(2) Differing objectives, priorities, and regulatory environments: In different locations, dissimilar objectives, priorities, and regulatory environments have caused multiple challenges to partnerships. For example, data cannot always be shared due to commercial and legal sensitivities, limiting effective collaboration. These differences have also made it challenging to resolve issues regarding the responsibility for the management of assets and the effective response to flooding incidents.

(3) Public engagement and public expectations: Some stakeholders believe that the investigation of flooding incidents is being delayed, due to a reluctance from the public to report such incidents. The public are often more concerned about the impact of flooding on property prices or insurance availability. LLFAs and partner agencies also report challenges in managing public expectations when not all potential solutions can be delivered in a timely manner.

(4) LLFA skills and knowledge: Based on the DEFRA report published in 2017, despite the apparent ongoing improvement in the capability of LLFA staff, concerns remain among some stakeholders about the levels of technical expertise available to LLFAs, with recruitment of specialist staff remaining challenging and some experienced staff being made redundant or retiring, particularly within lower-tier, smaller local authorities.

2.1.1. Pluvial flooding management in the UK

Pluvial flooding occurs when the rate of water falling on an area exceeds the infiltration rate into the ground, and the piped sewer systems cannot cope with a higher amount of flows having reached their maximum capacity, causing overflows from the minor to the major drainage system or vice versa (Wheater, 2006). This phenomenon is often associated with localised, high-intensity, and short-duration rainfall events, which are very difficult to predict. The capacity of each drainage system in the UK is typically calculated by assessing a certain annual exceedance probability for a variety of design rainfall intensity and durations to determine the critical event duration that generates the highest peak flow. The UK FWMA 2010 is the legislation in the UK. The implementation of sustainable drainage systems (SuDS) to control runoff is required by the FWMA for new developments, apart from exceptional circumstances. New developments also need to have a surface water drainage plan that provides capacity for a 1% AEP rainfall event (DEFRA, 2011a, 2011b). The management structure adopted by the FWMA directs the responsibility for flood risk to LLFAs, which are normally Local Authorities (LAs).

Considering that flood frequency estimates are necessary to support the planning and the assessment of flood defenses, in the UK the *Flood Estimation Handbook* (Institute of Hydrology, Wallingford, 1999) provides guidance regarding rainfall to aid in estimates of local flood risk, and to date it reports that extreme, high-intensity, short-duration rainfall is highest in South East England (Faulkner et al., 2000). Extreme rainfall estimation methods rely on an assumption of stationarity that contradicts the trend analysis of some rainfall records (Jones et al., 2013), but recent studies (Milly et al., 2008; Hirsch, 2011; Cheng and AghaKouchak, 2014) have demonstrated the importance of developing and applying non-stationary models and frameworks, which are currently not utilised in the UK methods for quantifying *design flood* rainfall, but are being assessed in order to potentially achieve higher accuracy (Prosdocimi et al., 2015).

2.1.2. Fluvial flooding management in the UK

Acreman et al. (2003) demonstrated that fluvial (overbank) flooding is a natural process that is essential for the proper functioning of river and floodplain ecosystems, but other recent studies (Fletcher et al., 2013; Jacobson, 2011; Walsh et al., 2005) indicate that increasing urbanisation could cause an increase in the frequency and magnitude of river flooding events. As described in the FWMA 2010, naturally inspired solutions, such as SuDS, are more commonly used to manage flooding (DEFRA, 2012) and their ability to handle extreme events is still subject to discussion. Nevertheless, traditional defenses are still a valid option considered by public and private sectors to manage flooding events, with over £900 million spent during 2014−2015, and nearly £200 million on maintenance (Environment Agency, 2014). Flooding events that occurred in 2015 and 2016 have demonstrated the important role of traditional defenses in mitigating flood risk.

2.2. Management in China

President Xi Jinping announced in December 2013 a plan to decrease the impacts of flooding events in China, as a response to repeated serious flooding occurring annually. The main aim was to transform current cities into *sponge cities* by upgrading the existing urban drainage infrastructure and utilising more naturally inspired drainage systems. This, it was thought, would reduce the magnitude and frequency of flooding events. This specific program was inspired by low-impact developments in the US, SuDS in the UK, and water-sensitive urban design in Australia. Despite having started in 2013, this program is still being practically implemented and the first results are expected by 2020. However, many challenges (uncertainties associated with increasing rates of urbanisation and climate change) are still affecting the initial designs (Chan et al., 2018; Li et al., 2018). To tackle these challenges and mitigate the effects of urban flooding, more appropriate solutions must be found.

In China, the Ministry of Water Resources (MWR) takes responsibility for implementing the unified management of water resources in the country. Water administration departments of local government form the Water Resources Bureau, with the responsibility of planning, developing, and managing water resources. The structure for the local water resources management agencies in China includes multiple levels: (1) state level, (2) province level, (3) city level, and (4) county level. In China, the Flood Control Office is the executive branch of flood control and disaster reduction under the supervision of local government. Within the Sponge Cities program launched in 2013 (Lashford et al., 2019), flood risk management in China has been implemented while considering details requested from municipalities, such as topographic characteristics, landscape requirements, and flood control standards already in place. The MWR provides combined resources to the management of flood disasters and the utilisation of water resources, guaranteeing equal attention to flood control and environmental protection.

However, despite the resources provided with the new programs, engineering solutions and strategies adopted for flood risk control and disaster prevention and reduction (e.g., pre-warning plans, timely prediction and early warning, effective organisation of rescue, rapid repair of water damage, and restoration to normal order) need to be improved as in the UK, including by addressing uncertainties associated with climate change, urbanisation, and land use change. For example, the existing urban drainage systems have numerous issues due to deteriorating older drainage systems being prone to failure, causing additional flooding events.

2.2.1. *Pluvial flooding management in China*

Pluvial flooding management in China is under the control of the State Flood Control and Drought Relief Headquarters, which was established on June 3, 1950 after receiving approval from the Central People's Government Administration Council, whose main function is responsibility for organisation of flood control and drought relief activities throughout the country under the leadership of the State Council. In 1997, China promulgated and implemented the so-called *National Defense Law of the People's Republic of China*. Also in that year, the Ministry of Water Resources issued the *Outline of Urban Flood Control Planning*. Before all these actions were undertaken in 1997, the Chinese central government had only provided around 30 million CNY of funds every year to support the construction of national key flood control projects in cities, but after 1998, the investment arranged by the government was increased to 1600 million CNY (OSGHFCDR, 2016). To accelerate the process of constructing urban flood control and disaster mitigation facilities, the Central Committee of the Communist Party of China and the State Council have been promoting water conservation reform, facilitating the development and construction of new and improved urban infrastructure to achieve higher levels of flood protection. In China, urban flood control measures and plans for the reduction of consequences due to flooding disasters are promoted at all levels.

Urban Flood Control Planning Standards (CJJ 50—92) are authorized by the Ministry of Construction and the Ministry of Water Resources of the People's Republic of China. The standards were implemented on July 1, 1993, aiming to standardize and unify the technical requirements of urban flood control planning, design, and the construction of cities in China.

In December 2015, the Central Committee of the Communist Party of China held a conference during work expansions in the city of Beijing. President Xi Jinping said that it was urgent to strengthen the construction of urban flood control measures and expand the capacity of existing drainage systems to enhance the resilience to natural disasters and deal more effectively with emergencies associated with flooding events.

According to data from the Office of the State General Headquarters for Flood Control and Drought Relief, from 2016, more than 47% of cities in China meet the national standards for flood control. Recently, more than 34000 km^2 of urban flood control embankment and 511000 km^2 of urban drainage pipe networks have been built (Zhang et al., 2014). In 2015, the Ministry of Finance, the Ministry of Water Resources, and the Ministry of Housing and Urban-Rural Development jointly launched the pilot work of sponge city construction, with the purpose of building a sponge city with natural water retention, natural infiltration, and natural water purification (Table 1). The concept holds that the city can act like a sponge, with the ability to adapt to environmental change and respond to disasters, through water absorption, storage, seepage, and purification when it rains, and to store

Table 1
General information and goals of pilot sponge city construction (Li et al., 2017).

Pilot city	Some goals of sponge city construction			
	Average annual runoff control (%)	Water quality control for suspended solids (%)	Wastewater recycling (%)	Drainage design standard (year)
Qian'an	80.0		30	2
Baicheng	85.0	60	25	3−5
Zhenjiang	75.0	60	25	2−5
Jiaxing	75.0	40	25	2−5
Chizhou	80.0		30	2−5
Xiamen	75.0			2−5
Pingxiang	80.0			2−3
Jinan	75.0			2−10
Hebi	70.0			2−5
Wuhan	75.0	50		5−10
Changde	80.0	75		2−5
Nanning	75.0	50	20	2−5
Chongqing	80.0	50		3−5
Suining	80.0			2−5
Gui'an	85.0	56		2−5
Xixian	80.0	> 60	30	2−5
Fuzhou	75.0	45	2	3−5
Zhuhai	70.0	50	15	3−5
Ningbo	80.0	60	40	3−10
Yuxi	82.0	50	20	3−5
Dalian	75.0	50	25	> 2
Shenzhen	70.0	60	30	3−5
Shanghai	80.0	80	20	5
Qingyang	90.0	60		2−5
Xining	88.0	60	50	2−5
Sanya	70.0		20	2−5
Qingdao	75.0	65	30	2−5
Guyuan	85.0	40	30	2
Tianjin	80.0	65	60	3−5
Beijing	84.4	42	75	2−10

Note: The first 16 cities are the first group of pilot sponge cities, and the remaining are the second group of pilot sponge cities.

water that can be used when it is needed. The central government provides special funds for the construction of sponge cities and the amount of subsidy is determined according to the size of the city.

The data in Table 1 show that pilot cities have used similar design standards, but have actually focused in a different manner on water quality control and water recycling. This may be related to the fact that there is still a lack of urban planning policies or legal frameworks in place to implement, maintain, and adapt the infrastructure to these specific purposes. To date, strategies for water quality and water recycling are still in the development stage or they have only been implemented in small-scale contexts (Nguyen et al., 2019). Apart from Beijing and Tianjin, all the pilot cities have not yet reached the standards targeted by the Chinese government, which aim at recycling approximately 70% of the stormwater. This figure would be very important for those cities in China recently affected by critical times during droughts, because rainwater could be transformed into a resource that could help during water shortage periods.

Table 2 presents a list of techniques adopted to address the aims of the Sponge Cities program and how they perform in terms of rainwater utilisation, groundwater recharging, peak flow reduction, and total runoff reduction, also highlighting costs for operation and maintenance. The first key message refers to the fact that some techniques incur high costs, especially for operation, but provide average or below-average results (e.g., pervious cement, pervious asphalt, and wet vegetative swale). On a positive note, some low-cost techniques, which offer a feasible solution for other highly densely populated developing countries, can guarantee excellent performance for the criteria previously described (e.g., sunken green space, simple bio-detention, seepage well, rainwater tanks, and dry vegetative swale). The major challenge that the cities are facing relates to the capability of implementing and optimizing these strategies within shorter time frames to cope with rapid urbanisation and climate change. It is therefore essential to continue monitoring and evaluating the effectiveness of these interventions to boost their performance for the objectives selected and identify design ideas that could combine the benefits of multiple options for an enhanced method. Especially considering the Sponge Cities program, China has the opportunity to play a significant leading role in sustainable urban water management in the future.

2.2.2. Fluvial flooding management in China

China, located in southeastern Eurasia, is an area famous around the world for its East Asian monsoon climate. Due to the development of the social economy, the interference of human activities, and the environmental climate changes, the frequency of fluvial flooding is increasing, continuing to cause tangible and intangible damages. Fluvial flooding has always been one of the greatest and most difficult natural disasters in China (Shi, 2010).

The National Climate Center of China states that, since 1990, two-thirds of the area of China, and more than half the total population has been affected by flooding almost every year, leading to huge economic loss (Hong et al., 2018). For example, Hunan, in the Yangtze River Basin, is a key flood-prone province in China, with between one and three floods occurring in cities of Hunan Province on average each year (Song, 2012). Flooding in the southern Yangtze coastal plains

Table 2
Primary technical measures of sponge city construction (Wang et al., 2018).

Technical measure	Function and effectiveness				Cost	
	Rainwater utilisation	Groundwater recharging	Peak-flow reduction	Total runoff reduction	Operation	Maintenance
Pervious pavement	○	●	⊙	●	Low	Low
Pervious cement	○	○	⊙	⊙	High	Mid
Pervious asphalt	○	○	⊙	⊙	High	Mid
Green roof	○	○	⊙	●	High	Mid
Sunken green space	○	●	⊙	●	Low	Low
Simple bio-detention	○	●	⊙	●	Low	Low
Complex bio-detention	○	●	⊙	●	Mid	Low
Permeation pond	○	●	⊙	●	Mid	Mid
Seepage well	○	●	⊙	●	Low	Low
Wet pond	●	○	●	●	High	Mid
Rain garden	●	○	●	●	High	Mid
Storage space	●	○	⊙	●	High	Mid
Rainwater tank	●	○	⊙	●	Low	Low
Regulating pond	○	○	●	○	High	Mid
Regulating pool	○	○	●	○	High	Mid
Transfer vegetative swale	⊙	○	○	⊙	Low	Low
Dry vegetative swale	○	●	○	●	Low	Low
Wet vegetative swale	○	○	○	○	Mid	Low
Infiltration pipe	○	⊙	○	⊙	Mid	Mid
Vegetation buffer zone	○	○	○	○	Low	Low
Initial rainwater discharge	⊙	○	○	○	Low	Mid
Artificial soil infiltration	●	○	○	○	High	Mid

Note: ● indicates above average, ⊙ indicates average, and ○ indicates below average.

is a new threat to the development of agriculture in China. The flood disasters in China have mainly been concentrated in the lower and middle reaches of the Yangtze River in recent years (Shi, 2010). Flood disasters in China are very destructive, highly frequent, unpredictable, and have wide-ranging impacts. Fluvial flood management of the areas at risk is of vital importance for their social and economic development. China has an established history of implementing fluvial flood management strategies beginning with “King Yu combating the flood” (Gu, 2006). The ancients adopted channels, canals, drains, and levees as the measures of fluvial flood management (Luo et al., 2015).

In the past, flood management mainly embodied prevention and utilisation. The Dujiangyan Irrigation System, a large example of irrigation infrastructure, was built in 256 BC by the Kingdom of Qin (during the Warring States Period of China), and is an example of a flood management system that reflects China's enduring efforts to harness water resources. It is located in the Minjiang River, near Chengdu, in Sichuan Province. The Dujiangyan Irrigation System is still in practical use today, and was constructed to manage urban water supply and sediment transport along the river, guaranteeing the reduction of peak flows in case of flooding events (Luo et al., 2015).

Regarding flood control, most of the rivers in China have no more alluvial surroundings. Many historical flood detention areas were transformed due to activities such as agriculture, fishing, and farming expansion, and these areas cannot be used now as natural flood basins (Shi, 2010).

After the major flooding of 1998, the Chinese government declared the current flood management dependence on structural approaches to be inadequate at the task of reducing levels of death and damage from flooding. Thus, fluvial flood management shifted from the exclusive use of structural approaches to using a combination of structural (e.g., dams and reservoirs, dikes, and bypass channels) and non-structural approaches (e.g., changing agricultural land to lakes, and urban land to lakes). In recent years, structural approaches for controlling rivers have been reduced. Non-structural measures mainly include changing land use types, moving people away from vulnerable areas, welfare law, and environmental protection (Luo et al., 2015).

From “King Yu combating the flood” to current monitoring, forecasting, and flood diversion, flood management in China has gone through a long development process and great achievements have been made. In recent years, China has made great efforts to develop water resources, actively introduced advanced technology and software, and made clear progress in water resources management and scheduling. Due to human interventions, some rivers have been modified, making it difficult to restore the original river landscape and, instead of following pure structural engineering or targeted floodplain restoration strategies (Halbe et al., 2018), fluvial flood managers have had to deal with a variety of different circumstances specific to each individual case. In order to realize the rational and efficient sustainable utilisation of regional flood resources and minimize the risk of flooding, the most direct and effective method is to carry out comprehensive regional flood dispatching.

Regional flood comprehensive dispatching should take into account three goals: (1) the prevention of flood events, (2) the sustainable utilisation of flood resources, and (3) the minimization of energy consumption. Flood risk management is carried out using the three aspects of analysis, assessment, and zoning of the risk. The in-depth analysis of the characteristics and evolution trends in fluvial flood risk, the comprehensive use of structural and non-structural flood control measures, and a reasonable combination of risk sharing and risk compensation mechanisms are used to achieve sustainable fluvial flood management (Li, 2013).

Fluvial flooding is not only a disaster, but a resource. Fluvial flood resources can irrigate farmland, generate electricity, and supply energy. The realization of the resource of fluvial flood management and the sustainable utilisation of regional water resources have significant and realistic significance for regional flood prevention, disaster prevention, disaster reduction, and water resources utilisation.

2.3. Hydrological/hydraulic models used in the UK and China

In the UK, the most common watershed/river/urban hydraulic modelling packages used are Flood Modeller Pro, TUFLOW, InfoWorks, MIKE, the storm water management model (SWMM), and JFLOW. Packages based on the shallow water equations are appropriate for supporting decision-making across the full range of Environment Agency flood risk decision-making. Exceptions to this apply in the following circumstances: (1) The area of application is large (1000 km^2) or a probabilistic approach requiring multiple simulations is required. In such instances, the time taken to run simulations may be prohibitively long. (2) Details regarding supercritical to subcritical flow transition are required, such as in areas close to a dam or embankment breach. If this level of detail is required, the numerical scheme used by the software has an influence on capturing the detail of the flow field.

The typical hydro-hydraulic models used in the construction of sponge cities in China include (1) the watershed hydro-hydraulic model; (2) the river hydro-hydraulic model; (3) the urban hydro-hydraulic model; and (4) the unit-scale hydrological model. The macro-watershed-scale hydrological model focuses on the overall security pattern of water ecology and the water environment. Its main parts are the watershed division, regional surface runoff, flood forecasting, non-point source pollution diffusion and migration, and the impact of aquatic ecosystems. Due to the large scale, the watershed simulation is generally based on a hydrological and water quality model, and the hydraulic model is seldom used. The representative free models are AQUATOX, PLOAD, SWAT, SWMM, WinHSPF, HEC-HMS, GSSHA, TR-20, and TR-55. Most of these models have graphical interfaces and can run independently. However, the data input and post-processing modules of the free models are generally weak, and these models cannot be directly connected with geographic information systems and databases, which makes them inconvenient for ordinary users to implement.

From the perspective of sponge cities, rivers are the main sources of water for urban domestic and industrial use, the main channels for rain and pollution discharge and diffusion, and the determinants of urban flood threats. From the point of view of simulation objects, river hydro-hydraulic models mainly simulate the ontological movement of water flow, the change of hydro-chemical water quality, sediment movement, the evolution of river beds and landforms, the sustainable utilisation of river resources, and the health degree of river ecosystems. The hydro-hydraulic models suitable for the river scale in sponge cities include HEC-RAS, TUFLOW, MIKE11, and Autodesk Civil3d (river and flood analysis module). At the macro level, a two-dimensional (2D) surface model and one-dimensional linear river model are usually used to couple the hydrological linkages between basins and rivers in the watershed hydrological model.

There are many kinds of urban surface coverage and their distribution is complex. The calculation of urban hydrology is more difficult than that of watershed hydrology, and it requires higher accuracy. Urban hydrological modelling is usually the coupling of a surface runoff hydrological model and a pipe network hydraulic model. The core contents of the planning and construction of sponge cities are to pay attention to the temporal and spatial changes of urban hydrological systems and focus on the analysis of surface runoff and infiltration, urban flood areas, organic matter and pollutant diffusion, urban rain-flood pipeline system load planning and system design, urban waterlogging threats, and the spatial distribution, type, and scale of low-impact development facilities. Some scientific research institutes in China have also developed hydrological models with independent intellectual property rights, but for various reasons, they have not been widely applied. Urban hydro-hydraulic models and software platforms include SWMM, InfoWorks, MOUSE (MIKE URBAN), and the model for urban stormwater improvement conceptualization (MUSIC), which are suitable for sponge city construction in China and capable of simulating low-impact development facilities.

3. Unified research and management strategy

Over the past decade, policy makers and engineers in the UK, China, and all around the world have used a large variety of 2D inundation prediction models to simulate flood flows on floodplains, aiding in decision-making, planning, design and operation of flood management systems, and flood risk assessment. Such models are ideally calibrated and validated against inundation levels measured via satellite data (Horritt, 2000; Grimaldi et al., 2016; Bates et al., 2012) and river gauge levels (Pappenberger et al., 2005). However, most often, real calibration and validation data are either non-existent or of low quality, despite being deemed essential by new regulations (i.e., water levels, flow exchange, and flood water velocity are all parameters required by the *European Floods Directive 2007/60/EC* for evaluating hazards caused by floods with low, medium, and high probabilities). Resources should be committed by both regional and national correspondent authorities in the UK and in China to the development of methods and technologies to record such data more effectively. Furthermore, in areas where it is not possible to acquire the necessary data, it is important to develop numerical models that can create inundation maps based on data-sparse areas, albeit characterized by higher uncertainty.

Both pluvial and fluvial flooding are related to extreme events that occur infrequently and involve high discharges (Knight, 2013). The volume and frequency combined make it difficult to monitor floods effectively, since they need to be anticipated in order for the necessary equipment and personnel to be prepared in advance.

The research and experience of the UK and China can contribute to projects that can tackle the challenges identified, and the authors have summarized three future strategic research themes for future collaborative international research efforts.

3.1. Flood risk policy and preparedness

The objective of this theme is to further explore flood management practices in the UK and China, particularly once the first data are available from the Sponge Cities program (expected in 2020) and other drainage initiatives in the UK. The purpose is to combine the best design options to create design guidelines and methods for improving preparedness, achieving a higher level of protection and resilience against flooding events by preventing or reducing their effects. This will require stronger collaboration between government, local authorities, industry, academic partners, and local citizens to achieve a common goal and to reduce the fragmentation of flood mitigation efforts and responsibilities. Activities will also need to enhance public awareness of local flood risks and improve the quality of life and local habitat. Outcomes can then be communicated to national/local policy makers to facilitate new guidelines and practices and to enhance innovation and flexibility, especially on the Chinese side. Anticipating urban and river floods before they occur allows managers and leaders to warn people and make them aware of the danger, preparing them in advance and undertaking the necessary precautions requested (for example, utility services can prepare emergency provisions to re-route services if needed or otherwise assure enough provisions to cope with emergencies).

3.2. Multi-level flood modelling and management

Assessing the risk of urban flooding is a complex activity that should not only be distinguished by the development of flood maps. A multi-level approach should be undertaken, facilitating an integrated modelling technique to include hydrology, hydraulics, and morphology. This would provide 2D outputs for the community and local/national authorities to help in implementing mitigation strategies and adaptation measures. This integrated approach should include modelling of groundwater, sediment transport, and pollutant transport in more complex flooding scenarios such as the combination of pluvial and fluvial flooding or the effect of multiple flash floods in the same area. This would enable a higher quality of flood risk assessment as well as environmental impact assessment which already has a higher level of focus in China in comparison to the UK.

The development of multi-level models for flood prediction will facilitate a new holistic framework for flood mitigation and warning, with new technologies and methods operating at multiple scales, such as that of the household, city or the entire catchment. The integration of mitigation efforts across these scales is essential to the optimisation of damage reduction and public protection.

Despite providing the most accurate representation of urban and river flooding, 2D models solving for shallow water require significant computational time to obtain accurate results (Bamford et al., 2008). However, the power of computational modelling is set to grow dramatically, leading modelers to explore what was previously unexamined (Council for Science and Technology, 2018).

3.3. High-performance data-driven modelling techniques for flow and quality

Methods should be developed to collect more accurate data for validating and benchmarking existing numerical flood models developed by engineers and researchers in China and the UK, identifying their strengths and weaknesses. Resources and attention from both governments should be directed to providing (1) higher-quality rainfall data; (2) more detailed ground survey data (existing infrastructure, urban surface characteristics, and topography) since both datasets are commonly used as an input to the numerical models for quantifying urban inundation maps; and (3) more accurate and spatially dense measurement of flow conditions in rivers and hydraulic drainage networks. Furthermore, since the water entering/escaping the sewer system during a flooding event includes pollutants and sediments, new datasets are required to enable numerical models to replicate these phenomena to assess the health risk for citizens and ecosystems.

By developing sensors and telemetry in line with technological advancement, and providing more accurate, dense, and widespread laboratory/field data, models could then be developed to integrate flood prediction and evaluation to improve design as well as flood warning systems. Once a practical and effective flood monitoring and modelling solution is obtained, it should be integrated into existing systems and adopted by the bodies responsible for real-time monitoring and the development of action plans.

4. Summary and recommendations

This paper has (1) demonstrated how increased urbanisation and climate change are having and will continue to have an impact on the magnitude and frequency of pluvial and fluvial flooding events around the world, and (2) summarized the key strategies implemented in the UK and China, while proposing a unified research strategy for the future.

The work presented here demonstrates the challenges to be faced in flood management in order to deliver a desired level of protection and to reduce vulnerability:

(1) Identifying the responsibilities of all stakeholders, including institutions, organisations, and authorities, to achieve a higher level of resilience to climate change and a higher level of water services provision. Principal stakeholders should include government ministries and departments, as well as flood-prone communities (upstream and downstream of the area at risk of flooding) and industry.

(2) Working towards trying to make cities more sustainable and livable. Hence, stakeholders with a strong environmental emphasis should have a critical role. On the other hand, stakeholders not directly involved in the stipulation of new guidelines, such as insurers, should have the capability to play a key role in helping society to adapt (Crichton, 2008), and this depends on how each government regulates them.

(3) Flood risk management in cities is mainly a reactive process. Hence, a more proactive approach that includes the integration of land use planning and flood management is strongly recommended by the authors. All the stakeholders identified should use integrated approaches to activate multiple measures in order to provide more efficient existing drainage networks and focus on the redevelopment in urban areas (such as open swales, green roofs, or ponds) or implement efficient non-structural options targeting building codes, early warning systems, and land-use planning.

(4) Communities need to be involved and communicate their specific interests (e.g., economic development, and protection of the environment), while stakeholders have the role of providing a better understanding of what causes pluvial and fluvial flooding in urban areas, identifying different techniques to be incorporated within the urban planning.

Despite stark differences in climate patterns and rates of urbanisation in the UK and China, positive aspects from both countries should be cross-assimilated to achieve optimal solutions, prioritizing areas at higher risk of flooding and aiming to include environmental hazards and impacts on human health, deaths, and injuries.

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