Geography and Sustainability 3 (2022) 114–118

Contents lists available at ScienceDirect

Geography and Sustainability

journal homepage: www.elsevier.com/locate/geosus

Sustainable city development challenged by extreme weather in a warming world

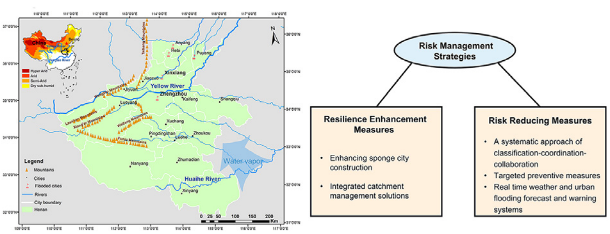
Changjia Li[a,b], Tong Lu[a,b], Bojie Fu[a,b,*], Shuai Wang[a,b], Joseph Holden[c]

[a] State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China
[b] Institute of Land Surface System and Sustainable Development, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China
[c] water@leeds, School of Geography, University of Leeds, Leeds, UK

HIGHLIGHTS

- A record-breaking rainstorm occurred on 20 July 2021 in Zhengzhou, China.
- Both resilience enhancement and risk reducing measures are recommended.
- Extreme weather events challenge progress on sustainable city development.
- Extreme events could accelerate activities to enable cities becoming more resilient.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 22 January 2022
Received in revised form 5 April 2022
Accepted 5 April 2022
Available online 14 April 2022

Keywords:
Extreme weather
Flood
Sponge city
Sustainable urban development

ABSTRACT

The year of 2021 has witnessed many extreme weather events across the world that have shocked and challenged human society, in particular for the populous cities, challenging progress on sustainable city development. In the comment we highlighted the record-breaking rainstorm that is considered to happen only "once-in-a-thousand-years" on 20 July 2021 in Zhengzhou, China; and a series of short and long-term resilience enhancement and risk reducing measures to climate change and natural hazard risks. We found that increasing frequency and intensity of extreme weather events caused by human-induced climate change challenges progress on sustainable city development, but could also accelerate activities to enable cities to become more resilient. This comment is essential to advance towards the sustainable city development goal (SDG 11) in China's mega cities, as well as informing progress for other global cities.

1. Introduction

On 9 August 2021, working group I (WGI) of the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) published *The Physical Science Basis of Climate Change*, which is a major part of the IPCC Sixth Assessment Report (AR6) (IPCC, 2021). The report showed that Extreme weather such as heavy precipitation, droughts and heatwaves caused by human-induced climate change have occurred more frequently worldwide (Zhang et al., 2018). In 2021 there have been many 'unprecedented' events across the world, from the devasting flooding in China, Germany and Belgium, to the extremely high temperatures and droughts in North America, and to the fires in Russia's Far East. These disasters have shocked and challenged human society. Meanwhile, the world is becoming increasingly urbanized (Sun et al., 2020). Since 2007 more than half the world's population (3.5 billion people) has been living in cities, and 5 billion people are predicted to live in urban settlements by 2030 (Seto et al., 2012). Extreme weather events and disasters impose great pressures on human-wellbeing in cities, causing losses of people's lives and property, in particular for the poor and people in vulnerable situations, resulting in negative effects on transportation, environment, and social economy. All these have seriously challenged progress on sustainable development goals (SDGs), and specifically sustainable urban development (SDG 11) with an important target of enabling more cities to mitigate and adapt to climate change and increase resilience to disasters (SDG11.B). This highlights the importance of synthesizing understanding on the appropriate risk management approaches and potential adaptation strategies to cope with continued climate change. The main aim of this commentary is to provide a critical

* Corresponding author: Dr. Bojie Fu, BNU, China
E-mail addresses: fubj@bnu.edu.cn, bfu@rcees.ac.cn (B. Fu).

https://doi.org/10.1016/j.geosus.2022.04.001

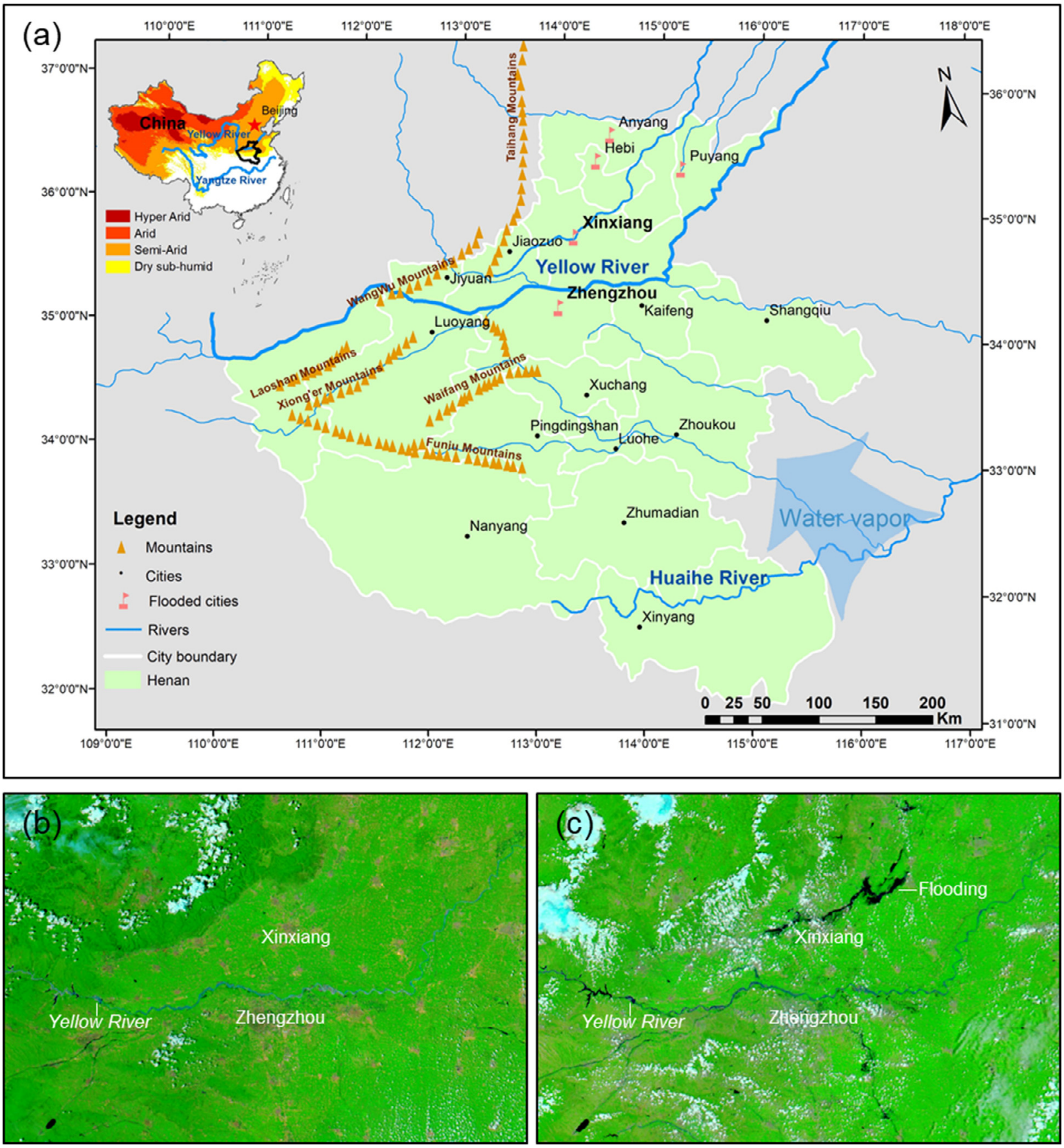


Fig. 1. Map showing the spatial distribution of flooded cities and flood extent for the 20–21 July 2021 rainstorms in Henan along with the surrounding mountains, rivers and main storm path. The flood extent is visible from a comparison of two satellite images on (b) 20 July, 2020 and (c) 26 July, 2021, which are derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite.

overview of how extreme rainstorms and flooding caused by human-induced climate change would affect sustainable city development.

2. A record-breaking rainstorm in China

A recent case is a record-breaking rainstorm and resulting flooding which occurred in the central Chinese province of Henan (Fig. 1). In Zhengzhou, the capital city of Henan province, situated along the Yellow River, the maximum hourly precipitation recorded at the national meteorological observation station (34°43´N, 113°39´E, elevation: 110.4 m) was 201.9 mm which occurred between 16:00 and 17:00 on 20 July 2021, resulting in a new hourly rainfall record among all of the 2,418 national meteorological stations in China, and among the largest one-hour rainfall events collated by the World Meteorological Organization. The rainfall over the 24-hour period from 02:00 20 July to 02:00 21 July 2021 at the same national meteorological observation station in Zhengzhou was 622.7 mm, which is almost equivalent to the city's annual mean precipitation (634.4 mm, during 1990–2019). In Xinxiang, a city approximately 40 km north of the Yellow River, 267.4 mm of rainfall recorded at the national meteorological observation station in Xinxiang (35°19´N, 113°53´E, elevation: 73.2m) fell in two hours on 21 July 2021, exceeding the maximum two-hour rainfall intensity at the Zhengzhou national meteorological observation station (262.5mm). The record-setting rainstorm was regarded as a "once-in-a-thousand-years" occurrence according to the Zhengzhou Weather Bureau, although the basis for this claim in a changing climate is unclear. Zhengzhou and

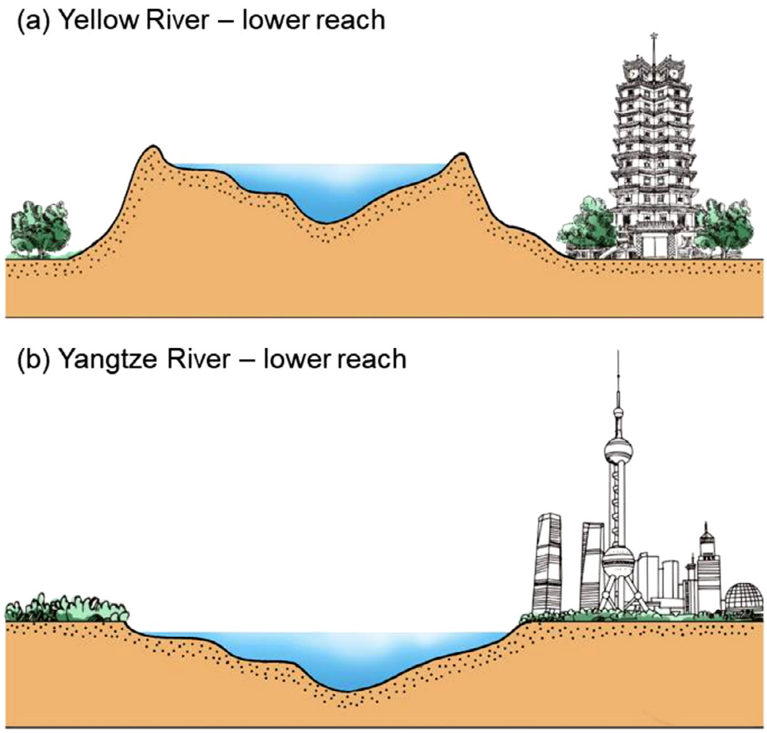


Fig. 2. The differences in the river landforms and cities located in the lower reach of the Yellow River and the Yangtze River. The Yellow River has a flood-prone nature with more than 1,000 floods on record during the past four millennia (Li et al., 2020). These flashy floods carry the world's highest fluvial sediment load (Walling and Fang, 2003) generated from the Loess Plateau (Wang et al., 2016; Fu et al., 2017) downstream, leading to a raised riverbed (Chen et al., 2015) with levees often failing, devastating cities and residents. Historical records show that many dynasties moved their capitals following destruction by a catastrophic flood (Chen et al., 2012). After 350 B.C. the lower reach of the Yellow River was fixed by embankments, and the highly perched channels prevented the river from being fed by many rivers in the North China plains that were tributaries of the Yellow River (Chen et al., 2012). A positive feedback loop exists between the channel bed level and human's efforts to build levee banks (Chen et al., 2012).

Xinxiang are defined as drylands, and specifically semi-arid regions, as determined by the aridity index (AI) (Huang et al., 2017). The semi-arid areas in China are characterized by water scarcity and drought (Huang et al., 2016; Huang et al., 2017), with limited precipitation which is both temporally and spatially highly variable (Huang et al., 2016; Li et al., 2021). However, how did one-year rainfall in the semi-arid Zhengzhou fall in one day? The key reason for the extreme July 2021 rainstorm is that typhoon 'fireworks' and eastern air flow on the south side of the subtropical high-pressure zone transported abundant water vapor to a steady low-pressure zone in the central and western parts of Henan Province; the water vapor was then trapped by the Taihang and Funiu Mountains located in the northwest, forcing large amounts of water-rich air to rise, producing prolonged and extremely high-intensity orographic precipitation. In addition, flood waters in Zhengzhou cannot discharge to the Yellow River (although Zhengzhou is 18 km south of the Yellow River), due to the high level of embankment (see Fig. 2a for full details). Instead, the main flood route is the Huaihe River which is approximately 500 km southeast of Zhengzhou.

The extreme rainfall event put great pressure on the populous cities. The resultant fluvial and pluvial flooding destroyed urban infrastructure and farmland, turned streets into raging rivers, swept away cars and other vehicles, flooded streets and underground stores, parking, traffic tunnels and subways, trapped residents in flood water, led to failure of water and electricity supplies, and threatened people's housing, employment, education and social ties. In particular, Zhengzhou's No.5 subway system was overwhelmed by rapid torrents of floodwaters gushing in, causing commuters to become trapped and 14 passengers drowned. During the rainstorm, flood water rushed into the mile-long Jingguang traffic tunnel, resulting in approximately 200 cars inside becoming stuck and floating in water up to 13 meters. Transport closures or delays not only made life difficult for the 12 million residents in Zhengzhou, but also people living in surrounding regions since Zhengzhou is one of China's key transport hubs. In Xinxiang, the rainstorm swamped many streets under 2 meters of water, trapping elderly residents and children on top of roofs waiting for rescue. By midnight on 2 August, the rainstorm and flooding affected about 14.53 million people in 1,663 villages and towns of 150 counties (cities and districts), killing 302 people and causing a direct economic loss of 114.27 billion CNY. Local government has supported 0.93 million people with emergency transfer to safety areas, and 1.47 million people for emergency resettlement by providing accommodation, water, food and other daily necessities.

3. Possible risk management strategies

There are a series of short and long-term risk management approaches and potential adaptation strategies to climate change and natural hazard risks (Hino et al., 2017), which can be broadly divided into two groups: resilience enhancement measures and risk reducing measures.

3.1. Resilience enhancement measures

We need to enhance the resilience of cities in the long term. First, sponge city construction (and similar initiatives globally) (Abraham, 2017) should be enhanced. *Sponge City* was firstly proposed in 2012, aiming to develop surface water management in Chinese cities to reduce increased urban flood risk, improve surface water quality and conserve water (Chan et al., 2018). In 2014, the *Sponge City Construction Guidance* was published by the State Council of China, providing detailed guidance for the design and construction criteria for urban infrastructure (MOHURD, 2014). *Sponge City* in China is a similar concept to the low-impact development (LID) in the USA, the sustainable urban drainage systems (SUDS) in the UK, or the water sensitive urban design (WSUD) in Australia, while its scope and ambition is much greater (Abraham, 2017). Zhengzhou was identified as candidate *Sponge City* pilot project in 2016, with the short-term (2017–2020) goal of investing 53.48 billion CNY in 23.6% of planned municipal areas to meet the standards of sponge city; and long-term (2021–2030) goal of increasing the proportion to 88.5%, aiming to reduce annual runoff by 75% and annual total suspended sediment by 50%, and improve the utilization rate of rainwater to 5% by 2030. However, the efforts and money devoted to build a sponge city with flood control standards for the planning area as a 'once-in-a-200-year' event, was challenged and overwhelmed by the July 2021 rainstorm in Zhengzhou.

That completely exceeded the maximum regulation capacity of the sponge city measures. This heavy rainstorm reminds us that our efforts need to be much more robust to the changing nature of flood risk in a warming world, and that sustainable development needs to consider extreme events, beyond those observed in our short history of environmental monitoring. However, each coin has two sides. On the other side, the July storm has facilitated speeding up sustainable development by encouraging rebuilding that has more sustainability design. For example, the local government in Zhengzhou has put forward technical guidance on post-disaster reconstruction projects, including specific requirements of site selection, structural forms, foundations, and main building materials to enhance flood prevention. In addition, the sponge city building construction in the main urban area of Zhengzhou is being enhanced and accelerated because of the 20 July rainstorm.

Second, integrated catchment management solutions are needed. The Yellow River is a "mother river" in China, feeding a 4,000-year-old Chinese civilization (Chen et al., 2012). Management of the Yellow River has long been recognized as an important national affair. In September 2019, Xi Jinping (China's President) put forward the ecological protection and high-quality development programme for the Yellow River Basin, since flood risk remains the biggest threat to the basin. The length of the 'overhanging river' in the lower reach of the Yellow River is 800 kilometers. The current river bed is 4 to 6 meters higher than the surrounding ground level, and the river reach in the Xinxiang city region is 20 meters higher than the surrounding ground. The imbalance of water and sediment (low in discharge and high in sediment load) is the root cause of the flooding in the Yellow River. Integrated research into the relationship between water and sediment as well as its regulation and control mechanisms, will help reduce flood risk in the lower reaches of the Yellow River. In addition, integrated catchment management strategies are required to reveal the coupling mechanisms between water and sediment regulation in the upper and middle reaches, and river evolution, delta formation and development in the lower reaches and delta evolution. Planners need to consider how to make entire catchments more resilient to extreme events. It is suggested that nature-based solutions should be implemented across whole catchments, including ecological conservation and restoring functionality (i.e., mountain closure, banning of logging of natural forests) for water storage and slowing downstream flow in the upper reaches; ecological restoration (i.e., afforestation, buffer strips, stabilizing gully erosion, channel erosion control, managing farmland to hold back water and slow the flow of water across the landscape) to slow and store water moving through the landscape, and to reduce soil losses in the middle reaches; and protection of wetlands to enhance their ecological functions such as improving water quality and providing valuable habitat for wildlife, in the lower reaches.

3.2. Risk reducing measures

First, a systematic approach of classification-coordination-collaboration (3C) (Fu et al., 2020) is needed. The sustainable development of cities is a long-term goal, and it is necessary to adopt a systematic approach of 3C to attain SDG 11. It is clear from the 20 July record-setting rainstorm in Henan that coordination and cooperation of all departments is key to tackling natural flood risks. Preparation requires a combination of money, engineering, knowledge and foresight (Reichstein et al., 2021). Scientists should improve surface water flood forecasting models while other partners need to develop enhanced communication and response systems along with longer term investments in precautionary measures and adaptation. The Henan Provincial Meteorological Bureau released orange, yellow and red rainstorm warning signals on 16th, 18th and morning of 20th July, respectively. Although there were several meteorological warnings, it was difficult to predict the instantaneous rainfall specific to a certain location. In particular, the intensity of the record-setting precipitation exceeded the datasets for previous rainstorms in the region held by the scientific community, and exceeded that anticipated by policymakers and civilians. All the flood prevention systems were overwhelmed across Zhengzhou by the hourly 201.9 mm rainfall. For decision-makers it is difficult to appreciate future catastrophes (Reichstein et al., 2021), as a result most parties in society did not respond instantaneously to the warnings to make efficient and effective strategies to cope with such an unprecedented rainstorm and flooding. The No.5 subway tragedy is a painful case illustrating a lack of plans for flood prevention and rescue on the system.

Second, targeted investments in prevention measures are necessary to reduce the flooding risks caused by global warming. However, it is difficult for policymakers and investors to invest large amounts of money in flood prevention and resilience measures as the timing and magnitude of future extreme rainstorm and flooding events are unknown (Reichstein et al., 2021). While there is often no immediate return, in the long-term it is likely to be much more costly to avoid such spending (see go.nature.com/3sx8ren). For example, an investment of 2.6 billion USD in flood protection after a storm surge in 1962 in Hamburg (Germany) is estimated to have avoided losses of more than 20 billion USD. Other examples of successful flood protection include Haihe River basin (China) where investments into flood control reduced losses of flooding in 1996 by 6 billion CNY compared to a similar devastating flood in 1963.

Third, there is a need to improve real time weather and urban flooding forecast and warning systems. It remains a challenge to precisely and rapidly forecast surface water or fluvial flood responses to extreme weather in real time due to poorly understood complexity and the interplay between natural and human constructed landscapes, or lack of empirical data for model calibration and validation. Use of improved interconnected telemetry monitoring systems, probabilistic rainfall forecasting, and high-resolution hydrodynamic modelling is required. It is vital to build real-time forecasting models that can incorporate vulnerability, risk assessment, and multiple real-time data sources to help government to decide where to invest and implement measures and to support real-time responses. Agent-based modelling provides a potentially useful tool for addressing real-time flood emergency management, and long-term flood adaptation planning. It has practical application on decision-making by linking human decisions with flood risks through the human-flood systems. The rapid development of big-data, artificial intelligence and greater computational power are also playing an increasingly important role in real-time flood disaster preparedness, response and recovery (Reichstein et al., 2021).

Another option to reduce risk is managed retreat which refers to the strategic movement of people, abandonment of land or relocation of infrastructure out of vulnerable areas (Hino et al., 2017). It has a long history as a flood management practice in the US (Siders, 2017). However, managed retreat is not a widely adopted strategy to manage natural hazard risk due to social, psychological and economic difficulties. More research is needed to examine how to tackle environmental, social and cultural and issues related to managed retreat to inform potential future applications (i.e., when to retreat, where to relocate).

4. Future perspectives

The frequent occurrence of extreme weather is closely related to global climate change induced by human activities (Donat et al., 2016). China is among the most sensitive and affected regions by global climate change (Wang and Zhou, 2005). The warming rate in China is significantly higher than the global average, and extreme precipitation events have increased from 1961 to 2020 (China Meteorological Administration Climate Change Centre, 2021). Cities are encouraged to optimize their industrial layout such as replacing high-emission enterprises with new clean ones. To further reduce extreme weather and climate events, we need to strengthen the response to climate change and take the road of green and low-carbon development.

The 20 July Zhengzhou rainstorm was a huge challenge for individuals, organizations, groups and policy makers at different levels. Communities will need more knowledge to help them prepare, and officials are challenged to enhance city resilience. Continued global warming and more frequent extreme weather events, combined with rapid urbanization, exerts great pressure on flood prevention, public transport, and the living environment in populous mega cities. Water-related hazards dominate the list of disasters that result in losses of human life and economic costs during 1970–2019 at global level according to a comprehensive analysis by the World Meteorological Organization (2021). Climate models are able to capture general global warming scenarios, but can often underestimate the impact of climate change on extreme weather events (IPCC, 2021). Urban development is closely related to climate change, and floods caused by extreme precipitation events have become an important factor restricting urban economic and social development (Chan et al., 2018). However, it should also be noted that a weather disaster may speed up sustainable development by encouraging rebuilding with advanced sustainability design and raising awareness of the need to do much more to enhance city resilience to cope with extreme weather events.

It remains a challenge to model and quantify flooding risks from high-impact but low-probability events in a changing environment. More attention should be paid to the combined use of big-data, Machine Learning models, Artificial Neural Network approaches, mapping technology, network information technology and computer processing technology, to build real-time forecasting systems and to improve performance and accuracy of predictions. In addition, whole catchment-scale approaches need to be adopted. Rather than focus on individual sponge cities with nature-based approaches we need to look at nature-based solutions across entire landscapes in an integrated way along with understanding feedback within hard engineering approaches and ancient and modern land management changes. Overall it is clear that society needs to strengthen the resilience of the living environment to extreme climate events, to achieve the sustainable city development goal (SDG 11) and associated targets.

Declaration of Competing Interest

The authors declare no competing interests.

Acknowledgments

This research is jointly funded by the National Natural Science Foundation of China Project (Grant No. 41991235), and the Fundamental Research Funds for the Central Universities.

References

Abraham, M., 2017. Encyclopedia of Sustainable Technologies. Elsevier.
Chan, F.K.S., Griffiths, J.A., Higgitt, D., Xu, S., Zhu, F., Tang, Y.-T., Xu, Y., Thorne, C.R., 2018. Sponge City" in China—A breakthrough of planning and flood risk management in the urban context. Land Use Policy 76, 772–778.
Chen, Y., Syvitski, J.P., Gao, S., Overeem, I., Kettner, A.J., 2012. Socio-economic impacts on flooding: A 4000-year history of the Yellow River. China. Ambio 41 (7), 682–698.
Chen, Y., Wang, K., Lin, Y., Shi, W., Song, Y., He, X., 2015. Balancing green and grain trade. Nat. Geosci. 8 (10), 739–741.
China Meteorological Administration Climate Change Centre, 2021. Blue Book on Climate Change in China 2021. Science Press, Beijing (in Chinese).
Donat, M.G., Lowry, A.L., Alexander, L.V., O'Gorman, P.A., Maher, N., 2016. More extreme precipitation in the world's dry and wet regions. Nat. Clim. Change 6 (5), 508–513.
Fu, B., Wang, S., Liu, Y., Liu, J., Liang, W., Miao, C., 2017. Hydrogeomorphic ecosystem responses to natural and anthropogenic changes in the Loess Plateau of China. Annu. Rev. Earth Planet. Sci. 45, 223–243.
Fu, B., Zhang, J., Wang, S., Zhao, W., 2020. Classification–coordination–collaboration: A systems approach for advancing Sustainable Development Goals. Natl. Sci. Rev. 7 (5), 838–840.
Hino, M., Field, C.B., Mach, K.J., 2017. Managed retreat as a response to natural hazard risk. Nat. Clim. Change 7 (5), 364–370.
Huang, J., Li, Y., Fu, C., Chen, F., Fu, Q., Dai, A., Shinoda, M., Ma, Z., Guo, W., Li, Z., 2017. Dryland climate change: Recent progress and challenges. Rev. Geophys. 55 (3), 719–778.
Huang, J., Yu, H., Guan, X., Wang, G., Guo, R., 2016. Accelerated dryland expansion under climate change. Nat. Clim. Change 6 (2), 166–171.
IPCC, 2021. Climate Change 2021: The Physical Science Basis. Cambridge University Press.
Li, C., Fu, B., Wang, S., Stringer, L.C., Wang, Y., Li, Z., Liu, Y., Zhou, W.Environment, 2021. Drivers and impacts of changes in China's drylands. Nat. Rev. Earth Environ. 2 (12), 858–873.
Li, T., Li, J., Zhang, D.D., 2020. Yellow River flooding during the past two millennia from historical documents. Prog. Phys. Geogr. 44 (5), 661–678.
Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD), 2014. The construction guideline of Sponge City in China—Low impact development of storm water system. Ministry of Housing and Urban-Rural Development of the People's Republic of China, Beijing (in Chinese).
Reichstein, M., Riede, F., Frank, D., 2021. More floods, fires and cyclones—Plan for domino effects on sustainability goals. Nature 592 (7854), 347–349.
Seto, K.C., Güneralp, B., Hutyra, L.R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proc. Natl. Acad. Sci. U.S.A. 109 (40), 16083–16088.
Siders, A., 2017. Past US floods give lessons in retreat. Nature 548 (7667), 281.
Sun, L., Chen, J., Li, Q., Huang, D., 2020. Dramatic uneven urbanization of large cities throughout the world in recent decades. Nat. Commun. 11 (1), 1–9.
Walling, D.E., Fang, D., 2003. Recent trends in the suspended sediment loads of the world's rivers. Global Planet. Change 39 (1–2), 111–126.
Wang, S., Fu, B., Piao, S., Lü, Y., Ciais, P., Feng, X., Wang, Y., 2016. Reduced sediment transport in the Yellow River due to anthropogenic changes. Nat. Geosci. 9 (1), 38–41.
Wang, Y., Zhou, L., 2005. Observed trends in extreme precipitation events in China during 1961–2001 and the associated changes in large-scale circulation. Geophys. Res. Lett. 32 (9), L09707.
World Meteorological Organization, 2021. Water-related hazards dominate disasters in the past 50 years [Online]. https://public.wmo.int/en/media/press-release/water-related-hazards-dominate-disasters-past-50-years. (accessed 23 July 2021).
Zhang, W., Villarini, G., Vecchi, G.A., Smith, J.A., 2018. Urbanization exacerbated the rainfall and flooding caused by hurricane Harvey in Houston. Nature 563 (7731), 384–388.