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PERSPECTIVES

Challenges and countermeasures of urban water systems against climate change: a perspective from China

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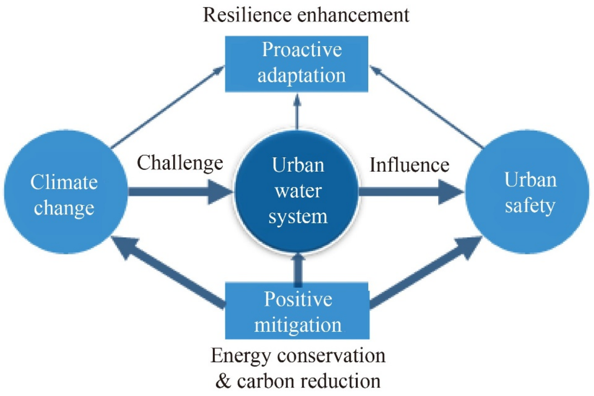
HIGHLIGHTS

- Urban water systems are challenged by climate change.
- Proactive adaptation and positive mitigation were proposed as the coping strategies.
- Proactive adaptation is to enhance the resilience of urban water systems.
- Positive mitigation is to strengthen the energy conservation and carbon reduction.

GRAPHIC ABSTRACT



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ABSTRACT

Urban water systems are facing various challenges against climate change, impacting cities' security and their sustainable development. Specifically, there are three major challenges: submersion risk of coastal cities as glaciers melt and sea level rises, more and severe urban flooding caused by extreme weather like intensified storm surge and heavy precipitation, and regional water resource patterns challenged by alteration of spatial distribution of precipitation. Regarding this, two strategies including proactive adaptation and positive mitigation were proposed in this article to realize the reconstruction and optimization of urban water systems, to enhance their resilience, and eventually increase their adaptability and coping ability to climate change. The proactive adaptation strategy consists of 1) construction of sponge cities to accommodate the increased regular rainfall and to balance the alterations of spatial redistribution of precipitation; 2) reconstruction of excess stormwater discharge and detention system to increase capability for extreme precipitation events based on flood risk assessment under future climate change; 3) deployment of forward-looking, ecological, and integrated measures to improve coastal protection capability against inundation risks caused by climate change and sea level rise. The positive mitigation strategy is to employ the systematic concept in planning and design and to adopt advanced applicable energy-saving technologies, processes, and management practices, aiming at reduction in flux of urban water systems, reinforcement in energy conservation and carbon reduction in both water supply systems and wastewater treatment systems, and thus a reduction of greenhouse gas emission from urban water systems.

Climate change, a global issue, has been attached great importance by the world community. Within the frameworks of the United Nations, China has taken corresponding actions in effort to peak carbon dioxide emissions before 2030 and to achieve carbon neutrality before 2060, respectively. As an aspect of its influence, the climate change challenges current urban water systems, which further jeopardizes the urban safety and sustainable development. The urban water system is consisted of water sources, and water supply, utilization,

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and drainage systems. It is essential for urban sustainable development because it includes natural and social factors such as natural waters waterfront spaces, and water-related engineering facilities, and their interactions (Fig. 1). Therefore, it is necessary to formulate strategies for the urban water systems, to modify and to reconstruct them, and to enhance the resilience in order to improve their adaptability and coping ability to climate change.

1 Challenges ahead

The essential feature of global climate change is global warming. Climate records showed that the global mean temperature in 2020 was 1.2 ± 0.1 °C above the 1850–1900 baseline (World Meteorological Organization, 2021). The temperature rise rate in China from 1951 to 2020 averaged 0.26 °C per decade, which is higher than the global rate at 0.15 °C per decade (National Climate Center of China Meteorological Administration, 2021). The global warming results in glacier ablation, sea-level rise, increased extreme weather events, and precipitation distribution variation. They all pose serious challenges to the structure, function, and efficiency of the urban water system, which will further influence the urban safety.

1.1 Challenge 1: Submersion risk of coastal cities as glaciers melt and sea level rises

It was estimated that a high tide of 100-year return period in 2050 and 2080 might bring an inundated area of 98,300 and 104,900 km^2 along China's coastlines with a loss of 30.9 trillion Chinese yuan and 68.6 trillion Chinese yuan (price base year 2010), equivalent to 3/4 and 1.7 times of the gross domestic product of year 2010, respectively (Ding et al., 2012; Xu, 2020). Larger inundated area and greater loss would be generated if the trend that coastal cities are developing close to seafront is not timely controlled and suppressed. Beijing-Tianjin-Hebei region, Yangtze River Delta, and Pearl River Delta are the economic engines of the country but also the most vulnerable regions along China's coastlines threatened by the sea level rise (Ding and Du, 2016). Coastal cities all around the world are facing similar situation, e.g., New York, San Francisco, London, Rotterdam, Tokyo, Sydney (Bloomberg, 2013; San Francisco Department of the Environment, 2013; Rotterdam Climate Initiative, 2013; Blakely and Carbonell, 2012; Xu, 2020). As glaciers melt and sea level rises, the urban water supply and drainage systems would bear the brunt. On the one hand, sea level rise will increase the saltwater intrusion distance in the estuary areas, increase the saltwater concentration along the way, and extend the intrusion time. Consequently, the river water quality will fail to meet the salinity standard for drinking water source, and the fresh drinking water sources and water supply security of coastal cities are challenged (Ding et al., 2012). For instance, the sea level in the Yangtze River estuary reached the highest since 1980 in February 2014, resulted in more than 23-day saltwater intrusion, and affected the water supply for ~2

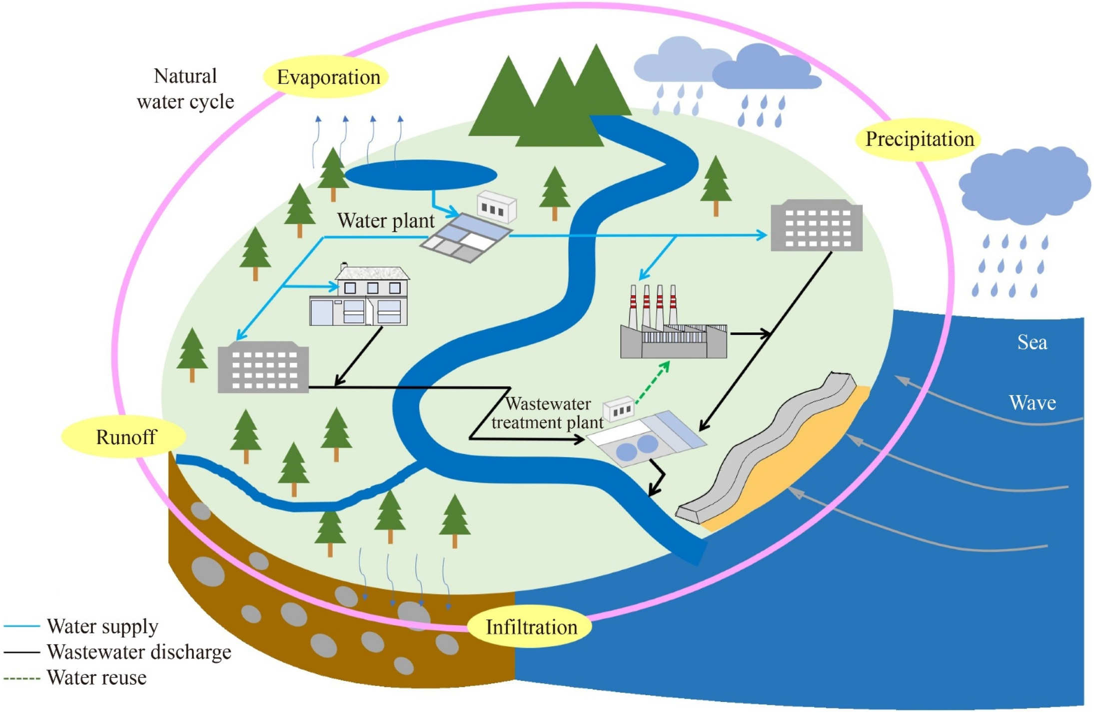

Fig. 1 Diagram of urban water systems.

million residents in Shanghai (Li et al., 2019). In addition, sea level rise will directly compromise coastal protection engineering standards (Yang, 2000), and the superposition of storm surges with higher frequency and intensity will further weaken the capability of coastal city drainage systems. If sea level rises by 50 cm, the design standard of the flood control wall in Shanghai urban area will decrease from 1,000-year return period to 200-year return period, and the drainage capability of the urban area will be cut by 20%, which will seriously threaten the drainage security of Shanghai (Shi et al., 2000).

1.2 Challenge 2: Urban flooding caused by intensified storm surge and heavy precipitation

It was recorded that the annual rain days in China was reducing, while the annual heavy rain days was increasing (Du and Ding, 2021). Extreme precipitation events are showing signs of increasing intensity and frequency (IPCC, 2014; 2022; Ding et al., 2012). As a result, urban flooding has become increasingly serious. Extraordinary storms, for example, those on July 18, 2007 in Jinan, on July 21, 2012 in Beijing, and on July 20, 2021 in Zhengzhou, resulted in heavy casualties and property losses. Besides, Hurricane Katrina in 2005 and Typhoon Fitow in 2013 also severely influenced the urban safety of hit cities. It is predictable that extreme precipitation events and strong storm surges with higher frequency and intensity in the future will bring significant pressure on the existing urban drainage and flooding prevention and control systems, compromise their capability and efficiency, and even trigger their collapse.

1.3 Challenge 3: Regional water resource patterns challenged by alteration of spatial distribution of precipitation

Summer precipitation from 2000 to 2012, compared with that from 1979 to 1999, showed that the rainband moved from the Lower Reaches of the Yangtze River to the Huang-Huai area, and was continuing its migration northward. The precipitation in North-west China also increased significantly in recent years (Ding and Du, 2016). It's worth noting that the alteration of spatial distribution of precipitation induced by the global climate change might influence formation of drought and flood disasters, alter the guarantee rate of urban water source and the frequency of urban flooding, and attack urban water supply and drainage systems. It might further influence the urban industrial structure and layout, urban form and spatial layout, and larger-scale, even national, urbanization strategies.

2 Coping strategies

Scientific research and engineering practices have been conducted globally, applying the idea of source control and gray-green integration to deal with the impacts of climate change on urban water systems (Fletcher et al., 2014). However, locally-adaptive and individual research and practices cannot fulfill the global sustainable development which needs mutual feedback, support and integration between the scientific community and the industrial community. All the issues of urban water systems should be placed under the framework of sustainable development, be viewed, and solved from a systemic and global perspective with the help of concepts and tools like the water-energy-food nexus, etc.

Therefore, dialectical and systematical two-way thinking are required facing the challenges from climate change and the drawbacks of current urban water systems. Principles of "simultaneously adopting source-broadening and resource-saving, centralized treatment and decentralized treatment, gray infrastructures and green infrastructures, rigid measures and flexible measures" should be followed in configuring new management and development mode of urban water systems and in optimizing their spatial layout.

Strategies for both proactive adaptation and positive mitigation are demanded to systematically respond to the negative influence from climate change (Fig. 2).

2.1 To enhance the resilience of urban water systems for proactive adaptation

The urban water system is an integrated system with water cycle as the foundation, water security as the bottom line, water facilities as the carriers, water management as the measures, and water health as the goal. It includes the development, utilization, protection, and management of urban water resource. Modification of urban water system planning and reconstruction of its structure could enhance the resilience of urban water system, improve its anti-risk capability, and strengthen its adaptability to the climate change. Such coping strategy is proactive and direct adaption, and is supposed to include constructions of sponge cities, excess stormwater discharge and detention systems, and coastal protection measures.

Sponge city is a promising measure to accommodate the increased regular rainfall and the altered spatial distribution of precipitation by climate change. Like Europe's Nature-Based Solutions, the United States' Low Impact Development, the UK's Sustainable Drainage Systems, and Australia's Water Sensitive Urban Design, China proposed its concept of sponge cities in 2014. Integrating water supply, drainage, and water environment, decentralized green infrastructures of a sponge city could disperse the impact on the urban drainage system, urban flooding prevention and control system, and water environment from the increased regular rainfall. Besides, the recycling of rainwater can alleviate the shortage of water resources. As it should be, it's necessary to select

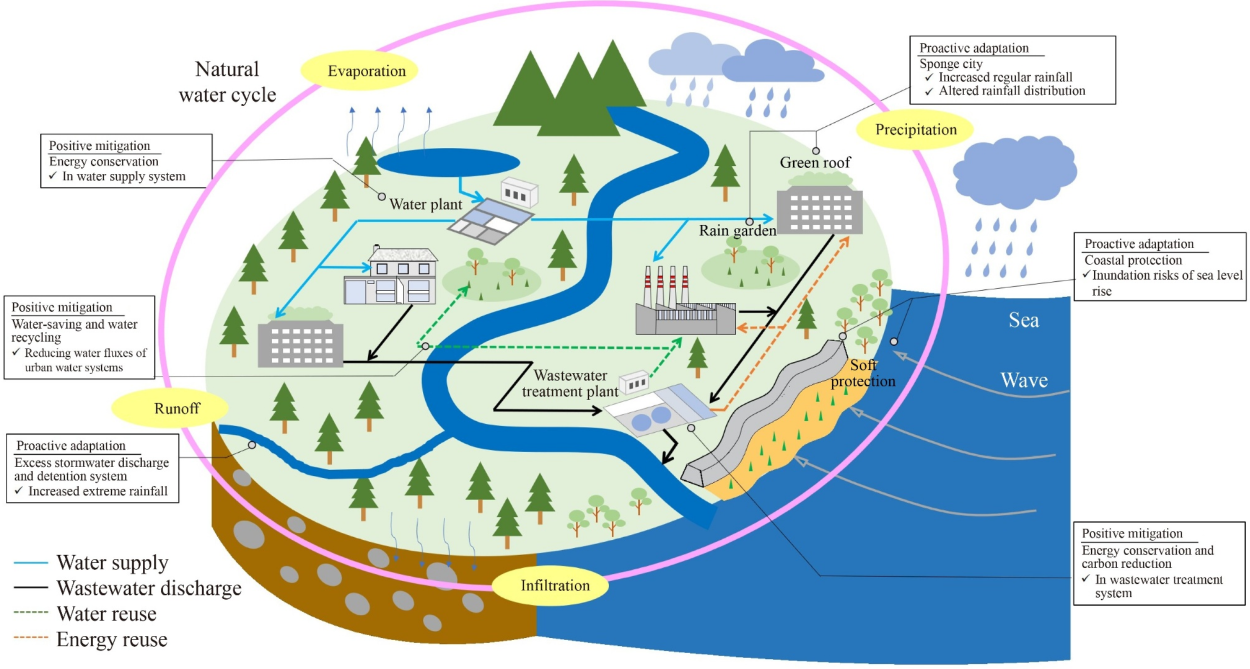

Fig. 2 Countermeasures of urban water systems against climate change.

appropriate technologies differentiating climate and geographical conditions to meet the local demands on regulations of rainfall, water resource, and water environment. In the following 5 years since the concept was proposed, a total of 30 representative pilot cities across the country were selected to construct sponge cities. Technologies such as sunken green areas, rain gardens, green roofs, grass swales, etc., have been selectively integrated in these pilot cities in order to reduce urban flooding, alleviate water scarcity, and to mitigate the urban heat island effect to certain extents. A study showed that sponge city construction saved the costs in investment and in operation and management by 20% and 25%, respectively, compared with the traditional development model (Kong et al., 2020). From 2021 to 2025, 45 more demonstration sponge cities will be constructed to enhance the regional systematicity in the resilience of urban water systems.

Sponge city to the increased regular rainfall is what excess stormwater discharge and detention system to the increased extreme rainfall. The latter should be further modified to combine blue, green, and gray infrastructures to cope with the climate-change-triggered extreme weather events. By projecting the future extreme rainfall intensity, drawing flood risk maps, and assessing flood risks, the spatial layout of critical infrastructures such as water supply, drainage, energy, transportation, communication, etc., could be adjusted and optimized so as to avoid positioning in high-risk areas at source. Integrating such flood risk assessment into the urban planning and the water system design, measures should be conducted to increase both natural and artificial discharge and storage capability, and thus improve the resilience of urban water systems against flood disasters. Feasible measures include optimizing layouts of land use and water system, protecting and/or restoring ecological patterns of natural rivers and lakes, building and modifying river courses and ditches to form a backbone flood pathway network, creating “blue-green spaces” for flood water storage and detention, and rationally planning the scale and spatial distribution of storage tanks. On the other hand, contingency plans should be upgraded to ensure that both hardware and software are in full readiness for emergency response management. A strategy to utilize the blue-green spaces to cope with the future climate change scenario of 15%–40% increment of extreme rainfall intensity was proposed in the urban water system planning of Xiong’an New Area. The storage capacity of 35 km^2 blue-green space of Da Yin Ancient Lake and its surrounding areas would be fully utilized together with wetlands for rainfall detention to ensure the flood safety for millennial significance of Xiong’an New Area (Xu et al., 2021).

Moreover, the coastal protection capability should be improved regarding inundation risks caused by climate change and sea level rise. Climate change and sea level rise should be fully considered in the coastal zone planning, and design standards of coastal protection facilities for storm surge should be upgraded. Additionally, the coastal protection facilities should reserve sufficient extra safety distance and height for dealing with the unexpected impact of climate change. Besides, combination of both “hard” and “soft” measures in the coastal protection system is recommended (Lee, 2014). Ecological buffer zones could be set up in front of the dykes and dams to form “soft protection” by beach nourishment and biological protection. By doing so, the height of protection dams could be reduced, both of the economic cost and eco-cost could be reduced, and the landscape effects improved. Furthermore, with these soft protection measures, the coastal land could be developed for multi-purpose and multi-functions, ground and underground aspects could be developed coherently, and coastal protection could be organically combined with landscape and leisure tourism, so as to maximize the overall benefit of society, economy and environment. The coastal defenses in the Katwijk area, the Netherlands, has been designed to provide additional space for a 200-year return period horizontally and a 100-year return period vertically considering the impact of sea level rise. A hybrid multi-functional system of dike and sandy beach has been established to increase the vitality and resilience of the city without obstructing the view of the waterfront buildings in Katwijk (Du and Ding, 2021). A study showed that a 1-m increment in the protection height of seawalls globally would reduce the inundated area by about 40% and reduce the affected population by about 20%–25% under different RCP/SSP scenarios. Raising seawalls could also save the economic loss from the climate change accordingly. The economic losses were projected to be US$169–482 billion by 2100 without adaptation, while the cost of raising seawalls was US$43–203 billion. (Tamura et al., 2019)

2.2 To strengthen the energy conservation and carbon reduction for positive mitigation

The proactive adaptation is a strategy to effectively improve the resilience of urban water systems, while the positive mitigation is a strategy to fundamentally reduce the pressure on urban water systems by climate change through carbon reduction measures. The latter is positive and indirectly responsive. The huge-scale water supply and discharge system makes the carbon emissions from water systems in China considerable. Though the current carbon emission from water systems accounts for a small proportion of total emissions, it should be noted that the proportion will increase gradually in the long-term along with 1) the reduction of carbon emissions from carbon intensive industries (for instance, steel and cement industries) with economic development and industrial restructuring, 2) the increment of carbon emissions from water systems with development of infrastructures to meet higher living standard. Therefore, energy conservation and carbon reduction in water systems is of great significance, especially that in urban water systems. Regarding this, the following positive mitigation should be proposed.

Firstly, the water fluxes of urban water systems should be reduced by strengthening water-saving and water recycling. Innovative methods should be developed to increase utilization of unconventional water resources such as rainwater and seawater based on the specific local conditions, and to control the leakage of water supply networks, so as to minimize freshwater consumption and wastewater treatment volume. This can fundamentally reduce the energy consumption and carbon emission in the processes of water supply and wastewater treatment. Besides, energy consumption in unconventional water resource production and utilization should be controlled to minimize the overall energy consumption and carbon emission of urban water systems.

Secondly, energy conservation in water supply systems should be enhanced. For instances, applying district metered area (DMA) method according to the local topography and spatial layout could effectively reduce the average pressure of the water supply network. Advanced technologies for pumps, like impeller cutting, variable frequency operation, optimized pumping station system (from planning, design, to management), etc. could reduce the energy consumption in pumping section. Eventually, the energy conservation in water supply systems could be achieved.

Additionally, energy conservation and carbon emission reduction in wastewater treatment system should be strengthened. On the one hand, with advanced and applicable energy-saving technologies and intelligent regulation and control technologies, the aeration efficiency could be increased and the energy consumption by aeration pump reduced. Innovations in treatment processes are promising in carbon reduction besides better pollutant removal efficiencies such as anaerobic ammonia oxidation (Hou et al., 2022), and short-cut denitrification (Luo et al., 2022), and anaerobic membrane bioreactor (Zhang et al., 2022). On the other hand, a systematic concept of planning and design should be adopted to improve the capability of wastewater treatment plants for resources and energy recovery, including phosphorus recovery, methane cogeneration, and wastewater source heat pump system. Investigations have been conducted both in China and abroad aiming at the energy conservation and carbon reduction in urban water systems. For example, the Netherlands NEWs (nutrient, energy, and water factories) (STOWA, 2010) and the China Concept Wastewater Resource Recovery Factory (including resource recovery, energy conversion, and water reclamation) (Qu et al., 2022) are both functionalized with pollution control, water saving, energy conservation and carbon reduction, and resource recycle and reuse. They are of positive significance to the mitigation of negative effects from climate change and the promotion of the virtuous cycle of urban water system.

3 Practical concerns and outlooks

Either proactive adaptation or positive mitigation can be economically cost-saving and environmentally beneficial in combating the climate change. However, the above strategies also have limitations. For example, advanced wastewater treatment, desalination (Caldera et al., 2018), and wastewater reuse require more energy consumption and generate more greenhouse gas emissions. Heavy metals in reclaimed water might cause land degradation, contamination of surface and ground waters, and increased risk of salinization in semi-arid regions (Qadir et al., 2014; Salgot and Folch, 2018). The brine from desalination plants is hard to dispose of (Wilder et al., 2016). It should be noted that these limitations can be offset if the energy is from renewable sources and the treatment process is systematically designed. The pathways to implement the coping strategies need to be carefully designed and the scales shall be reasonably controlled in order to balance the benefits and the side effects.

The implementation of the adaptation and mitigation strategies is also constrained in practice by economic, technological, social, policy, and management issues. The large uncertainties in the projection of future climate change, especially extreme weather events, leads to large uncertainties in the corresponding response measures. The enormous cost in eliminating the negative impacts of climate change, especially the extreme weather events of low probability, calls for a trade-off between costs and benefits. Meanwhile, quantifying the effectiveness of adaptation measures in reducing climate change risk and analyzing the cost-benefit of response strategies are fraught with methodological challenges (IPCC, 2022).

In view of this, the scientific and industrial communities should strengthen their communication and cooperation to address major forward-looking scientific issues and to focus on the actual core problems faced in practice, in order to effectively enhance the resilience of urban water systems and improve their ability to cope with climate change.

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Conflict of Interest The authors declare no competing interests.

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