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China's water challenges: present and future–special issue honouring academician Liu Changming

This special issue of the *International Journal of Water Resources Development* is dedicated to honouring the remarkable contributions of Academician Liu Chanming. Over the course of his distinguished career, Academician Liu has profoundly shaped the field of hydrology and water resources and utilization, not only through groundbreaking scholarship, but also by nurturing generations of researchers and fostering a spirit of collaboration and innovation. In bringing together the work of colleagues, former students and collaborators, this issue celebrates both the enduring intellectual legacy and the personal impact of Professor Liu, whose influence continues to resonate across the discipline.

This special issue is based on 12 contributions: Xu et al. (2025) on the Yellow River Basin; Dang and Wang (2025) on legal frameworks to manage urban flash floods; Y. Li et al. (2025) on national water security; Varis and Zhao (2025) on eight water risks; Y. Wang et al. (2025) on water rights reform; Peng (2025) on digital twins; Ren et al. (2025) on terrestrial water storage and economic growth; Xia et al. (2025) on nonlinear hydrological systems; Shen and Fan (2025) on integration of resources, environment and ecology; H. Liu et al. (2025) on public perceptions of scarcity; X. Li et al. (2025) on the Qinling Mountains; and Hartley (2025) on global cities as problematic exemplars in sustainability discourse. Together, these studies tell a story of innovation that redefines how China secures water in the face of scarcity and uncertainty.

The Yellow River, often called the cradle of Chinese civilization, is also a symbol of fragility. By the late twentieth century, over-exploitation left it close to collapse, with frequent flow interruptions and mounting ecological risks. Xu et al. (2025) show how the Yellow River Conservancy Commission responded in 1999 by introducing unified water management, an institutional innovation that has maintained uninterrupted flows for 25 years. Water quotas were tied to ecological safety, 'no levee breaches, no flow interruptions, no excessive pollution, no riverbed elevation', and enforced through provincial accountability. Scarcity was not simply managed: it was recast as a driver of systemic reform. The Yellow River case demonstrates how engineering, markets and ecology have been recombined. Reservoirs such as Xiaolangdi were repurposed as sediment regulators, showing how infrastructure once built for control could be reimagined as ecological instruments. Programmes like Grain-for-Green turned restoration into development strategy, linking livelihoods with ecosystem stability. Scarcity also triggered experimentation with permits, quotas and eventually the China Water Exchange in 2016. Here, innovation is less about individual projects than about transforming governance into a balancing act between people and nature.

Urban flash floods, by contrast, reveal innovation through law. Dang and Wang (2025) compare Zhengzhou in 2021 and Shenzhen in 2023, where both cities endured near-record rainfall but with starkly different outcomes: 380 deaths in Zhengzhou, none in

Shenzhen. The difference lay in legal frameworks. In Zhengzhou, ambiguous regulations delayed decisions such as suspending metro operations; in Shenzhen, rules introduced automatic triggers linking meteorological alerts to closures, especially in schools. Law thus became an enabling safeguard rather than a bottleneck. The authors also highlight how law structures information flows. In Zhengzhou, warnings were vague and inconsistently shared, while in Shenzhen, regulations required standardized, actionable messages distributed across multiple channels within minutes. Coordination was ensured through the 'Four Ones' mechanism: one leader, one leading department, one working group, one unified communication channel. Law here functioned as a bridge, connecting government, citizens and private actors in rapid, coordinated response.

Y. Li et al. (2025) situates these innovations within a national vision of water security as a strategic foundation for food, energy, ecology and political stability. Water challenges are intensified by uneven distribution, urbanization, climate variability and ecological stress. To respond, the principle of human-water harmony is advanced, requiring balance between human and natural needs, between development and ecological capacity, and between risks and mitigation. This philosophy underpins adaptive socio-economic planning, resilient infrastructure that combines engineering with nature-based solutions, and governance mechanisms that align water with land, food, energy and ecology. Innovation here lies in embedding ethics of sustainability and intergenerational equity into governance.

Varis and Zhao (2025) extend this argument by reframing water security as multi-dimensional risk. They identify eight stressors: variability, overuse, groundwater decline, floods, droughts, organic pollution, salinity and eutrophication, and show how these overlap. Using geospatial and statistical methods, the authors map risks into five regional clusters, revealing patterns such as scarcity and vulnerability in the north, and pollution and overuse in the east. Crucially, they argue that vulnerability is socially constructed: megacities face high risks not only from hydrology but from governance pressures and dense populations. Their innovation is diagnostic, offering a typology that allows region-specific policy rather than uniform responses.

Institutional reform is explored in Y. Wang et al. (2025) on a study of the water rights revolution. They argue that China has created a hybrid system: markets exist but are framed and limited by state authority. The reform evolved through three phases: early exploration (2000–2012), policy maturation (2013–2020) and market innovation (2021 to present). Even then, markets remain small, covering just 0.01% of national use. Definitions of water rights remain ambiguous, and quota systems often conflict with trading mechanisms. In comparison to highly marketized systems in Australia or private property regimes in Chile, China's model prioritizes equity and stability. Innovation here lies in institutional design: a hybrid regime that reflects China's political economy, where markets serve as auxiliary instruments rather than replacements for administrative allocation.

Technological innovation is captured in Peng's account of digital twin systems (Peng, 2025). From early 'Digital Yellow River' projects to the national 'Digital Twins of Water Resources System' launched in 2021, China has built real-time virtual models that mirror rivers, reservoirs and irrigation systems. These systems integrate satellite, drone and sensor data with hydrological and AI algorithms, processed through distributed computing. The result is predictive feedback: models simulate scenarios, forecast risks and optimize interventions. Applications are already visible. Flood forecasting accuracy has risen to 85% with 10-day lead times; emergency water transfer in the South-to-North Diversion Project has been reduced from seven days to two; dam safety analysis has been reduced from days to minutes; and irrigation districts have increased yields while saving billions of cubic metres of water. The ambition is a national digital water network, unifying systems into a single platform. Here, innovation is not just technological but institutionalized, embedding predictive intelligence into routine governance.

Ren et al. (2025) add an economic perspective by linking terrestrial water storage (TWS) deficits to growth. Using satellite data and econometric models across nearly 300 cities, they show that TWS deficits depress growth more strongly than precipitation deficits. A one-standard-deviation TWS deficit reduces growth by about one percentage point, with northern and western cities reliant on groundwater, most affected. The relationship is nonlinear: small shocks can be absorbed, but severe deficits trigger sharp declines. Surpluses also pose risks, as high TWS can correlate with slower growth in flood-prone regions. Innovation here is methodological: TWS offers a fuller measure of risk, capturing cumulative stresses such as groundwater depletion, and thus a more accurate predictor of economic vulnerability.

Scientific progress is detailed in Xia et al.'s work on nonlinear hydrological systems (2025). Traditional linear models could not capture rainfall-runoff dynamics under extremes. China's adoption of nonlinear models, such as the time-variant gain model, provided more accurate forecasts by linking soil moisture with runoff generation. These models underpin flash flood early-warning systems in mountainous catchments, where disasters often strike without major infrastructure. The Yangtze River Simulator exemplifies the integration of nonlinear science with digital governance. Drawing on thousands of data sources, it incorporates hydrological, urban and socio-ecological models into one platform, supporting flood and drought forecasting, reservoir coordination, and ecological management. It successfully anticipated the 2020 floods and 2022 droughts, demonstrating how complex science can be converted into operational decision support. Innovation here lies in turning research into infrastructure, embedding scientific complexity into governance.

Shen and Fan's analysis (2025) of integrating water resources, environment and ecology (IWREE) addresses fragmentation. Historically, resource use, pollution control and ecological protection were managed separately, producing inefficiency and degradation. Since 2013, water use has plateaued, allowing a shift in focus from quantity to quality and ecology. IWREE represents this next step, but institutional and legal fragmentation remain obstacles. Ministries divide responsibilities, and water laws are divided across multiple statutes. The authors also recommend moving from reform to mechanism-building: creating cross-sector coordination platforms, involving stakeholders, aligning pricing and rights trading, and embedding IWREE principles into law. Technological tools such as big data and digital twins are also emphasized. Here, innovation lies in governance design: building integrative systems that replace administrative silos.

Public perceptions add a social dimension. H. Liu et al. survey (2025) of more than 3000 respondents shows that most underestimate scarcity, with nearly 70% reporting lower levels than reality, even in severely stressed cities such as Beijing. Tap water access and higher income protected people from scarcity, while vulnerable households perceived it more accurately. Perceptions directly shaped behaviour: those who believed scarcity was severe conserved more, while underestimation reduced conservation. This finding reframes governance: technical and institutional measures must be accompanied by perception management. Information campaigns, educational programmes and pricing reforms are needed to close the gap between reality and public awareness. Innovation here is in recognizing the cognitive and behavioural dimensions of water security.

X. Li et al. (2025) examine the Qinling Mountains, a vital watershed dividing the Yellow and Yangtze basins. The region illustrates dual pressures: scarcity and pollution in the northern Guanzhong Basin, and ecological costs from the South-to-North Diversion in the south. Climate change amplifies variability, creating cycles of floods and droughts. Human activities such as urbanization, land-use change and pollution compound the stress. Their proposed strategy is multi-layered: real-time monitoring, adaptive allocation, ecological protection through prevention-control-restoration and cross-regional governance mechanisms. The Qinling case shows that water security is not only technical but systemic, requiring integration of science, policy and ecology. It is a microcosm of China's broader water dilemmas, and a testing ground for adaptive, resilient governance.

Finally, Hartley's work (2025) provides a crucial counterpoint. The author argues that global cities are often treated as exemplars of sustainability despite their resource intensity, inequities and reliance on external hinterlands. The critique highlights how technocratic, standardized approaches, often presented as best practices, risk masking complexity and reinforcing unsustainable models. Hartley adds a reflective dimension to the narrative: China's innovations are significant and diverse, but they are context-specific responses to national pressures of scarcity, climate and development. Recognizing this guards against the temptation to see them as technocratic solutions that can be exported. Instead, they must be understood as adaptive experiments situated within China's unique political economy and ecological realities.

Taken together, these papers reveal the breadth of China's water innovations. At the basin scale, unified management has turned scarcity into a driver of reform (Xu et al., 2025). In cities, legal frameworks have transformed the response to floods (Dang & Wang, 2025). At the national level, water security has been reframed as harmony between humans and nature (Y. Li et al., 2025), and risks have been diagnosed as multidimensional and regionally differentiated (Varis & Zhao, 2025). Institutionally, hybrid water rights regimes have emerged (Y. Wang et al., 2025). Technologically, digital twins have become governance infrastructure (Peng, 2025). Economically, TWS metrics capture vulnerabilities that precipitation alone misses (Ren et al., 2025). Scientifically, nonlinear models have reshaped forecasting and disaster prevention (Xia et al., 2025). Governance frameworks now emphasize integration across sectors (Shen & Fan, 2025). Socially, public perception is recognized as a determinant of conservation (H. Liu et al., 2025). Regionally, the Qinling Mountains exemplify both pressures and adaptive solutions (X. Li et al., 2025).

What unites these innovations is their movement from fragmentation and reactivity towards integration and adaptability. China's water governance has expanded beyond engineering projects to encompass law, markets, science, digital technology, social perceptions and ethics. Innovation here is not defined by a single breakthrough but by the capacity to weave diverse tools and perspectives into a coherent system. Scarcity, floods, droughts and pollution remain pressing, but they have also become catalysts for new institutional and technological forms.

China's story shows that water governance innovation is not only about infrastructure or markets, but about integration of people and nature, state and society, engineering and ecology, science and governance. It is the pursuit of balance under conditions of stress, and the recognition that water security is both a survival imperative and a space for institutional creativity.

Academician Liu Changming has contributed enormously to the in-depth understanding of the above topics. For instance, Northern China grapples with severe water scarcity, making efficient water resource utilization indispensable for the region's sustainable agricultural development (Varis & Zhao, 2025). For decades, Academician Liu Changming has focused his research on crop water consumption, pioneering systematic studies on the mechanisms, observational methods and simulation models of farmland evapotranspiration (H. Wang et al., 2001). Using extensive observational experimental data, C. Liu et al. (2002) verified a significant finding: the water demand of staple food crops, such as wheat and corn, across the North China Plain exceeds regional precipitation. This study also quantified the proportions of soil evaporation and crop transpiration in total farmland evapotranspiration and developed a quantitative model linking the soil evaporation ratio to surface soil moisture and leaf area index. This body of work has laid a robust scientific foundation for improving on-farm water use efficiency and developing agricultural water-saving technologies in northern China. China has long prioritized blue water over green water in the field of water resources research, devoting excessive attention to directly exploitable blue water resources (e.g., river water and groundwater) and overlooking green water resources, which are formed through precipitation infiltration and vegetation transpiration. Academician Liu Changming was among the first to recognize the ecological and agricultural value of green water, demonstrating remarkable foresight in his research on farmland green water utilization. C. Liu et al. (2012) later applied these green water findings from farmlands to natural ecosystems and estimated evapotranspiration changes across China's terrestrial domains (X. Liu et al., 2011; Zhang et al., 2007). His innovative concepts, such as evaporation management, have effectively transformed China's water-saving practices from passive conservation to active regulation. This offers a novel framework for comprehensively utilizing water resources.

The intensive development and utilization of water resources in northern China pose severe threats to the region's ecological and environmental security. Academician Liu Changming was one of the first to observe the depletion of groundwater stemming from the unregulated expansion of irrigated areas in the region. As early as the early 2000s, Liu et al. (2001) documented the formation of large-scale cones of depression in both unconfined and confined aquifers of the North China Plain. This phenomenon has triggered critical water-related environmental issues, including wetland shrinkage, seawater intrusion and deteriorating groundwater quality (Xia et al., 2007). These issues directly endanger regional ecological balance, human livelihoods and economic growth (Ren et al., 2025). To address this crisis, C. Liu and Zheng (2002) conducted a rigorous analysis of potential water transfer routes for the South-to-North Water Diversion Project, which was proposed at the time. Guided by the principles of integrated water resources planning and management, their research made scenario-based projections of the water balance in the project's water-receiving and water-source areas. The research conclusively showed that, without implementation of the project, water scarcity would remain a fundamental barrier to sustainable development in northern China. These evidence-based findings promoted the development of public policies aimed at strengthening groundwater management and improving water use efficiency. They also served as pivotal scientific support for the decision to plan the water transfer project. By the end of 2024, the first phase of the Middle Route of the South-to-North Water Diversion Project had delivered over 76.7 km^3 of water to northern China, significantly increasing the water-carrying capacity of the North China Plain. Thanks to the combined effects of the water transfer project, water-saving policies and ecological restoration efforts, the problem of groundwater over-exploitation in northern China has been effectively alleviated.

China is a country prone to water-related disasters, and floods pose a grave threat to infrastructure safety. However, the scarcity of hydrological observation data, particularly in western China, remains a pressing challenge. To address this issue, Academician Liu Changming developed an innovative model to estimate flood peak discharge in small river basins. Based on measured data from multiple small experimental watersheds across China and a comprehensive analysis of geographical factors, including topography, climate and vegetation, this model is not reliant on long-term observational data like traditional hydrological models are (C. Liu & Wang, 1980). It optimizes parameters according to the geographical and climatic characteristics of different regions in China and can be used to estimate rainstorms and flood peaks in ungauged small river basins. Since its development, the model has been widely applied to the design of flood control systems for railway projects in northwestern China and to the planning and construction of water conservancy projects in other regions. It has notably enhanced infrastructure flood safety. Building on this work, C. Liu et al. (2008) further developed the Hydro-Informatic Modelling System (HIMS). Together, these hydrological theories, models and derivative tools comprise a comprehensive technical support system for China's water disaster prevention and control initiatives (Xia et al., 2025).

Climate change and human activities are profoundly reshaping the terrestrial water cycle, placing new pressures on water security. As early as the advent of global change research, Academician Liu Changming keenly identified this trend. Through long-term observations and data analysis, C. Liu and Zheng (2004) discovered a significant downward trend in the natural, surface and groundwater runoff of the Yellow River Basin, which directly undermines the basin's water supply capacity. C. Liu and Xia (2004) foresightedly identified natural changes and human activities as the primary drivers of change in the hydrological processes and water resource decline. Together, they emphasized that this changing environment has exacerbated water resource crises in northern China, and were among the first to advocate for a deeper understanding of how the water cycle responds to a changing environment and the development of adaptive measures to safeguard water security amid global change. Their scientific insights have helped establish an integrated, multidimensional theoretical framework for China's water security research, encompassing water quantity, quality, disasters and ecology (C. Liu & Liu, 2009; Shen & Fan, 2025), under the influence of climate change and human activities (Y. Li et al., 2025). This framework has become the scientific cornerstone of achieving China's water security (C. Liu et al., 2010). Beyond his research, Academician Liu Changming has inspired generations of young water scientists to advance frontier research in global change hydrology (Tang, 2020; Tang & Chen, 2025) and water resources management (Dang &

Wang, 2025; Y. Wang et al., 2025), and promoted the long-term development of China's water security science, technology and education (H. Liu et al., 2025; Peng, 2025).

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