OPINION

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Building resilient urban water systems: emerging opportunities for solving long-lasting challenges

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ABSTRACT

In this perspective paper, we analyse the challenges and opportunities of hydrology in the urban context and propose solutions for innovation and sustainability by leveraging advancements across technology, society, and governance for resilient cities. Technological breakthroughs, such as smart sensors and artificial intelligence, can enhance the efficiency and resilience of real-time water monitoring and predictions. Public awareness and community engagement can foster behavioural change and empower residents to actively participate in urban water governance through initiatives like rainwater harvesting and participatory planning. Additionally, big data and remote sensing provide cities with the insights needed for adaptive, data-driven decision-making. Together, these developments represent a paradigm shift from reactive problem-solving to proactive, integrated solutions that prioritise equity, environmental health, and urban resilience. Finally, the paper highlights the differences in progress between the Global North and the Global South and proposes research priorities for the future of urban hydrology.

1 Introduction

Urbanization is a major global trend, with 56% of the world's population living in urban areas (United Nations 2019). This tendency is expected to continue, with the urban population more than doubling its current size by 2050, at which point nearly 7 of 10 people will live in cities (United Nations 2019, 2022). Hotspots of intense urban transitions include cities in Asia and Africa, where population growth is influenced by economic opportunities and societal transitions that trigger massive rural–urban migration trends (Behnisch et al. 2022). The growth of cities with population shifts across the rural–urban continuum often exceeds planning capacities and leads to deficiencies in the provision of essential public services, such as inadequate infrastructure, traffic congestion, water supply shortages, pollution, and housing shortages, as well as challenges in water resource management (United Nations 2022).

Cities are, therefore, on the frontlines of climate change, particularly considering emerging pollutants, landscape alteration, water supply and demand challenges (Dadashpoor et al. 2019, Oswald et al. 2023). Urban development has been fuelling an ever increasing demand for freshwater resources (He et al. 2021). Urbanization has already altered water balances on the Earth's surface by increasing the rates of imperviousness of urban areas and modifying groundwater recharge, regional water flows, urban surface runoff, urban drainage, and baseflow (Oswald et al. 2023). Urban water pollution is also worth noting because of the lack of adequate sanitation infrastructure. Cities might have to deal with excessive urban runoff, which translates into pluvial flooding due to high-intensity rainfall events, inadequate drainage systems and urban infrastructure, and limited natural space and vegetation. However, potable water scarcity is also a significant risk, as high demand frequently surpasses availability, further amplified by the increased frequency and

duration of heat waves and drought events (Yang *et al.* 2015). Further, urban wetlands are also threatened by reduced vegetation in favour of construction, resulting in ecohydrological disturbances that affect the local water cycle and the transfer of nutrients (Hanford *et al.* 2020, Oswald *et al.* 2023).

The challenges of water in urban contexts are numerous, in terms of not only quantity but also quality. Urban areas may face rapid population growth and an increasing volume of waste (Lu *et al.* 2024), which is poorly managed in many regions (UNHABITAT 2010). Solid wastes are leached by rainwater and infiltrate into shallow aquifers, affecting groundwater quality. Urban water overflows could take pollutants to the streets and therefore present a threat to aquatic health and ecosystems.

Consequently, urbanization presents a fundamental impact on the water cycle and sustainable development, necessitating the need to advance urban hydrological knowledge more than ever. The Hydrology Engaging Local People IN one Global world (HELPING) Decade of the International Association for Hydrological Sciences (IAHS), defined as the "scientific decade (2023–2032) for solutions" (Arheimer *et al.* 2024), is intended to be a vehicle for translating science into action by gathering and engaging hydrologists to address issues around specific topics of potentially local to global relevance. Within this framework, an international group was established to develop a shared vision for advancing hydrological research in urban areas worldwide. The IAHS Urban Water group aims to improve urban water resource management and enhance strategies for mitigating associated risks. This opinion paper is therefore proposed in order to contribute to sharing a vision of Integrated Urban Water Management (IUWM).

The emergence of urban hydrology as a distinct scientific discipline highlights its growing significance in promoting the sustainability of human societies (Qi *et al.* 2020, Dada *et al.* 2021, Mabrouk *et al.* 2023). Initially, the study of urban hydrology started with a strong engineering focus, particularly on storm hydrograph modelling. With the onset of modern urbanization in the early 1900s, a primary challenge was the development of numerical models for urban runoff simulation to predict peak discharge (Gregory and Arnold 1932, Horner 1933). Over the century, progress was made in the understanding of the response of surface flows to rainfall events. Efforts in urban hydrology were then directed towards advancing urban drainage and sewage system concepts, and the urban catchment concept was introduced (McPherson 1979). This was the first pivotal shift, recognizing urban areas as complex hydrological systems shaped by intricate interactions between natural and anthropogenic processes. These systems are marked by high spatiotemporal variability and intricacy across scales. Consequently, urban planners began to prioritize the environmental and sustainability implications of modifications to natural drainage systems, ensuring that their actions aligned with broader ecological and societal goals (Elga *et al.* 2015). Meanwhile, with the increasing frequency of flood events (Devi *et al.* 2019, Oswald *et al.* 2023), research projects have now advanced stormwater drainage design and management modelling to remove runoff from urbanized areas, thereby preventing floods and minimizing their negative impacts (Gironás *et al.* 2010, Zhang *et al.* 2020). Historically, the focus of urban hydrology revolved around drainage and runoff, but the

paradigm has since broadened to encompass water quality (Singh *et al.* 2022) and interactions with urban climates (Jongen *et al.* 2024, Lipson *et al.* 2024). In addition, some researchers have adopted a more integrated perspective than the conventional "urban catchment," referring instead to the critical zone (Welty *et al.* 2007, 2023). Defined as the "heterogeneous, near-surface environment, where complex interactions involving rock, soil, water, air, and living organisms regulate natural habitats and determine the availability of life-sustaining resources" (NRC 2001), the critical zone underscores the interconnectedness of bedrock, groundwater, soil, vegetation, and atmosphere (NRC 2001). This concept has paved the way for the advancement of ecohydrological science, which is now shaping current urban hydrology research (Wagner and Breil 2013, Stevenson *et al.* 2022, Warter *et al.* 2024).

Thinking on previous success stories, this paper discusses the current and future challenges of hydrology in an urban context, targeting urban water managers, hydrologists and urban planners. Since the world is urbanizing at an unprecedented rate and climate change is gaining momentum, there is a pressing need to explore how hydrologists, urban planners and residents can help develop sustainable urban environments.

2 Advancing understanding of the urban water cycle

Urbanization is motivated by strong social and economic reasons; however, it is well recognized as a process by which a natural landscape is converted into one that is complex, sealed, and impervious. It may also be described as the transformation of unoccupied or sparsely occupied land into densely occupied cities. Moreover, it has become increasingly critical to comprehend the changes in the urban hydrological cycle (Fig. 1). The urban water cycle, the dynamic interplay of water through natural and human-engineered systems in urban environments, remains a cornerstone of sustainable urban development. Compared to natural landscapes, urban and periurban environments are marked by complex interactions of built infrastructure, rapid land use changes, and human activities that significantly disrupt and alter the hydrological cycle and influence the river basin water balances (Jampani *et al.* 2020, Balha *et al.* 2023). Impervious surfaces, such as roads and buildings, and decreased vegetation cover prevent water infiltration into the soil and groundwater, which leads to altered patterns of runoff, stormwater generation, and evaporation that do not occur in natural ecosystems (O'Driscoll *et al.* 2010, Bhaskar *et al.* 2016, Tam and Nga 2018, Yadav *et al.* 2024). Rainfall and other precipitation traditionally taken up by the natural water cycle now become stormwater and urban runoff, collecting on roofs, roads, footpaths and other sealed surfaces and resulting in flooding and pollution of watercourses. Meanwhile, the urban water cycle also features unique components such as leaks from pipes and sewer systems (Fig. 1) during transport, additional input from urban irrigation, and moisture emissions from anthropogenic activities (Wang *et al.* 2019, Wang 2020, Huang *et al.* 2021). The altered patterns in urban hydrological cycles drive the mechanisms that control heat waves, droughts, and floods in urban agglomerations (Patra 2016, Auerswald *et al.* 2024). The likelihood of flash floods has risen globally, driven by
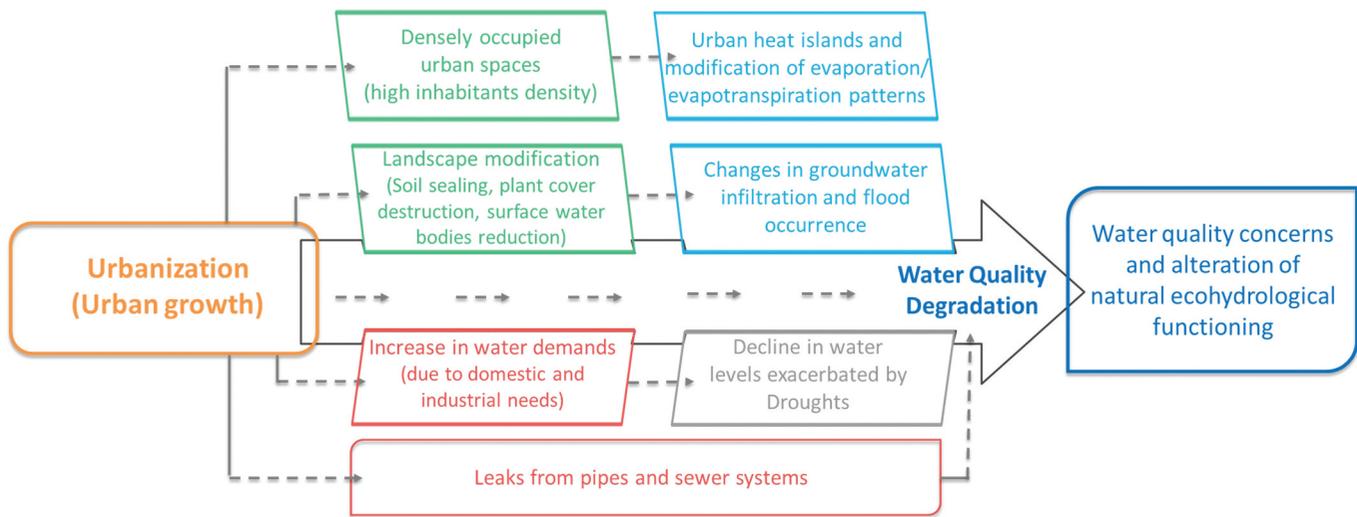
Figure 1. Urbanization dynamic and consequences for water resources.

intense rainfall events and rapid runoff exceeding urban drainage systems' capacity (Devi *et al.* 2019). Likewise, the increasing density of urban populations and their consumption patterns elevate water demands, often resulting in unsustainable water extraction from surrounding urban and periurban areas. Such practices make regional water systems more vulnerable to climate extremes, including drought conditions (Yang *et al.* 2013). Urban heat waves accelerate the hydrological cycle, creating warmer and drier conditions that escalate plant water demand and hinder groundwater recharge (van Hateren *et al.* 2023, Cheval *et al.* 2024). Overall, understanding these complex hydrological processes and their interactions with social–human activities across a wide range of spatial and temporal scales (Yang *et al.* 2021) is critical for developing effective strategies aimed at mitigating the impacts of extreme climate events.

Particular attention must be paid to tipping points, defined as the value of the critical threshold at which the future state of a hydrological system is irreversibly altered (Blöschl *et al.* 2019, Yang *et al.* 2022). Extreme weather events combined with urban growth have already surpassed tipping points beyond which adaptation could mitigate these effects (Ahmed *et al.* 2018). Another example is groundwater abstraction, which can potentially jeopardize urban groundwater-dependent ecosystems (Barron *et al.* 2014). Given the potentially catastrophic consequences of hydrological tipping points, improving our understanding of urban processes and predictive capacity is critical for future urban hydrological research.

Advances in technology, growing economic resources, extensive data availability, transitions in societal priorities, and enhanced international cooperation are reshaping how cities address these changes and build resilience (Hülsmann and Jampani 2021, Büyüközkan *et al.* 2022). Here we want to highlight the new concept of "water-sensitive cities," focusing on the physical flows of water and the innovative systems, tools, and governance mechanisms that enhance urban water sustainability and resilience (Wong *et al.* 2020). This concept leverages modern developments holistically, turning long-

standing problems into opportunities for sustainable development. The concept of water-sensitive cities embraces a forward-looking approach that integrates natural processes with engineered solutions while prioritizing equity and environmental health. This vision transcends traditional problem-solving frameworks by combining innovative technologies, sustainable financing, and community engagement. It invites cities to rethink water management as a transformative opportunity to enhance resilience, foster inclusivity, and achieve long-term urban sustainability. This is one area where we see opportunity and that we wish to highlight in our commentary.

3 Long-lasting challenges and solutions

3.1 Water shortages

Population growth, rapid urbanization, and socioeconomic development are projected to increase industrial and domestic water demand in urban areas by 50–80% over the next three decades (Krueger *et al.* 2019). At the same time, climate change is expected to alter the spatial distribution and timing of water availability (Greve *et al.* 2018) and exacerbate extreme events that can damage water supply infrastructure (Yang *et al.* 2013). As a result, urban water scarcity is likely to become significantly more severe in the future, posing serious challenges to achieving the United Nations Sustainable Development Goals (SDGs), particularly SDG 11: Sustainable Cities and Communities, and SDG 6: Clean Water and Sanitation (Larsen *et al.* 2016). The greatest challenges will be observed in the Global South, where the largest urban populations facing water scarcity are in India (222 million) and China (159 million) (He *et al.* 2021). Meanwhile, several megacities, such as Los Angeles and Istanbul, face perennial and seasonal water scarcity, respectively (He *et al.* 2021). With rising global temperatures, declining or more variable regional precipitation and growing urban populations under various future scenarios, the number of large cities projected to face water scarcity is expected to increase by 55.5% by 2050 (He *et al.* 2021).

Various technical solutions have been developed, and some have already been implemented to address water scarcity, including seawater desalination, groundwater exploitation, and interbasin transfer (Nazemi and Madani 2017). However, these technologies can be expensive in terms of cost and sustainability. Here we recommend that cities must rely on surface and groundwater if possible and intensify the fight against water leaks. Also, nature-based solutions, such as rainwater harvesting and artificial groundwater recharge, can contribute to mitigating water shortages (Ferrario et al. 2024). Implementing comprehensive water conservation practices will further alleviate pressure on urban water supplies and ensure sustainability. In addition, better water management is possible through private–public partnerships.

3.2 Flood hazards and impacts

The risk of flooding in urban areas is exacerbated by the urban environment and management of drainage and also by increasingly extreme rainfall events from climate change but potentially also from urban enhancement of convection. The impact is direct upon SDG 11 (Sustainable Cities and Communities), SDG 1 (No Poverty) and SDG 2 (Zero Hunger). Yet there have been many studies on urban floods analysing the phenomena of flooding, outlining risks, modelling, and carrying out optimal predictions (e.g. Agonafir et al. 2023). However, we emphasize that a deeper understanding of urban flash floods should be a priority. A flash flood is defined as a flood event resulting from high-intensity precipitation over a short duration, usually less than 6 h (Mohtar et al. 2020). Localized convective storms in small catchments can cause a rapid rise in water levels, often with little or no warning. Additionally, urban districts located along the coast need more attention (Wannewitz et al. 2024). In particular, Woodruff et al. (2013) demonstrated that, due to sea level rise, flood levels in coastal urban districts previously associated with a 100 year storm are now occurring with return periods of just 3–20 years. Thus, in certain urban areas, flooding occurs more frequently due to the rising heights of the surrounding water bodies.

Residential buildings, and especially occupied buildings in the floodplain, require the greatest attention because they are the closest related part of people's daily lives (Tu et al. 2023). It is important to take steps to reduce the vulnerability of residential buildings to flooding, such as designing and constructing flood-resistant buildings, installing efficient drainage systems, and implementing flood protection measures. Traditional stormwater management systems, which rely on underground pipes to quickly move water away from urban areas, may not be sufficient to handle stormwater's increasing volume and intensity. Nature-based solutions, such as green roofs, permeable pavements, rain gardens, and constructed wetlands, must spread in both the Global North and the Global South as sustainable alternatives for stormwater management (Oral et al. 2021, Warter et al. 2024). These solutions help reduce runoff, enhance groundwater recharge, and improve resilience to floods while providing other benefits like improved air quality and urban aesthetics.

Finally, addressing all the abovementioned challenges requires a combination of innovative technological and societal solutions, infrastructure investments, and integrated water management strategies not only in the city itself but also at a basin scale. This holistic vision with few tradeoffs allows progress on one issue and therefore helps the other. For instance, reducing flooding is likely to improve water quality and can increase recharge to help with water scarcity. Meanwhile, a detailed understanding of whether, where, and how cities are growing within or into flood- or drought-prone areas is an urgent prerequisite for assessing future risk trajectories, risk-informed planning, and adaptation decisions (Reimuth et al. 2023).

3.3 Water pollution and quality management

The ongoing metamorphosis of urban landscapes worldwide has significantly affected the natural environment, including water quality (Hibbs and Sharp 2012, Banerjee and Sikdar 2022). Understanding both the mechanisms and anthropogenic impacts contributing to water quality deterioration in urban environments is crucial for preserving urban ecosystems and public health (Lapworth et al. 2017, Nlend et al. 2018, Chathuranika et al. 2023, Djieugoue et al. 2024). Land use changes, untreated wastewater, solid waste dumping, climate change, population growth, and expanded industrial activities are the main factors influencing water quality (Jampani et al. 2018, Mokarram et al. 2020, Dong et al. 2023, Chen et al. 2024). Such anthropogenic stress is set to intensify as urban areas continue to proliferate at an unprecedented rate, calling for vigilance and action at both global and local levels (Marx et al. 2023). They also constitute a serious limitation for the achievement of SDG 6 (Clean Water and Sanitation) and particularly target 6.3.1 (improve water quality) (IAH 2017).

Global population growth has led to an increased detection of substances in water bodies that were previously unrecognized or inadequately monitored (Vörösmarty et al. 2010). These emerging contaminants, which include various chemicals, pharmaceutical compounds, and microbes, have become more apparent due to changes in consumption patterns (Lapworth et al. 2012). However, it is important to note that there is still a disparity between the main factors of urban water degradation in developed and developing countries. While point-source contaminants are more regulated in the Global North, the discharge of untreated wastewater underground, on the soil, and into rivers remains a common practice in the South (Olmstead and Zheng 2019, Vaidya et al. 2024). In such countries, where about half of the population lacks access to sanitation facilities (UNICEF/WHO 2023), it has been found that about 90% of urban sewage is released directly into the environment without any prior treatment (Zorn et al. 2020). In contrast, water pollution in Europe and North America arises mainly from sewer leakages (Miller and Hutchins 2017), leading primarily to high loads of microbial pathogens, nitrogen, heavy metals and suspended solids (Abdellatif et al. 2014). Point sources of contamination remain rare in such countries because infrastructure and regulatory oversight are generally more advanced compared to countries from the Global South. In these countries, nitrate contamination remains a major concern for urban water quality. This issue is mainly related to onsite pollution sources, such as septic tanks, cesspools, and latrines, which reflect the inadequate sanitation systems in these regions (Nlend et al. 2018, Chen et al. 2024). High nitrate (NO_3) concentrations are

generally associated with increasing concentrations of chloride (mostly from excreta), sulphate and borate (from detergents), organic carbon (which can lead to enhanced mobilization of Fe and/or Mn) and strong occurrence of faecal pathogens (Lapworth *et al.* 2017, Dong *et al.* 2023). Conversely, a lack of hygiene and sanitation can also lead to denitrification, often followed by increased heavy metals such as iron, zinc, and copper (Dovonou *et al.* 2015). Diffuse pollution is more widespread in the Global North, including various sources such as residential runoff and commercial/industrial runoff (Ellis and Mitchell 2006).

Beyond the aspects of point source and diffuse pollution, urban water quality issues have evolved. While the historical focus of urban water quality has been on suspended solids, organic matter, heavy metals, and nutrients, interest has recently turned to pathogens and emerging contaminants (Fig. 2) such as industrial byproducts, pharmaceuticals, anti-microbial-resistant bacteria and genes, and microplastics. These anthropogenic contaminants are being increasingly identified through advanced analytical tools (Richardson and Ternes 2018). Moreover, urban groundwater is often impacted, making urban aquifers more vulnerable to anthropogenic pollution.

Another emerging water quality issue is the combined effect of climate change and urbanization. While climate change exacerbates the frequency and severity of floods due to increasing rainfall in some regions, urbanization further complicates this issue by increasing impervious surfaces, intensifying runoff, and raising water volumes. This compounding effect contributes to the mobilization and accumulation of various anthropogenic contaminants in freshwater systems (Miller and Hutchins 2017) and can only be limited by adequate stormwater management infrastructures. In contrast, urbanization increases water demand, and excessive abstraction combined with drought can lead to numerous water quality complications (e.g. increased river temperatures, and changes in dissolved oxygen) (Zhi *et al.* 2023). Some studies have shown that drought starts with a water quantity problem, but the result might be a water quality problem (Mosley 2015, McGrane 2016). However, the impacts of climate change on water quality remain less predictable and poorly understood. Extreme events, seasonal changes, and altered recharge patterns are expected to influence contaminant transport and water quality significantly. Nevertheless, it is unclear how these changes will be reflected in the fate and transport of many water pollutants. This represents a critical modelling gap in our understanding of the effects of urbanization on water quality.

A pragmatic solution relies mainly on addressing the lack of adequate hygiene and water conditions in urban centres. A global compact and a transfer of experience in sanitation practices from the Global North to the Global South are needed for sanitation in cities. However, community-based approaches can serve as a low-threshold strategy to start by helping local neighbourhoods to generate income and build sustainable livelihoods. This could involve designating water, sanitation, and hygiene (WASH) practice leaders within urban communities, with a focus on gender inclusivity. Organizing seminars and training sessions on water conservation and reducing water wastage would further enhance these efforts. An effective WASH strategy not only helps reduce water pollution but also mitigates the prevalence of waterborne diseases. Additionally, the community-based approach should
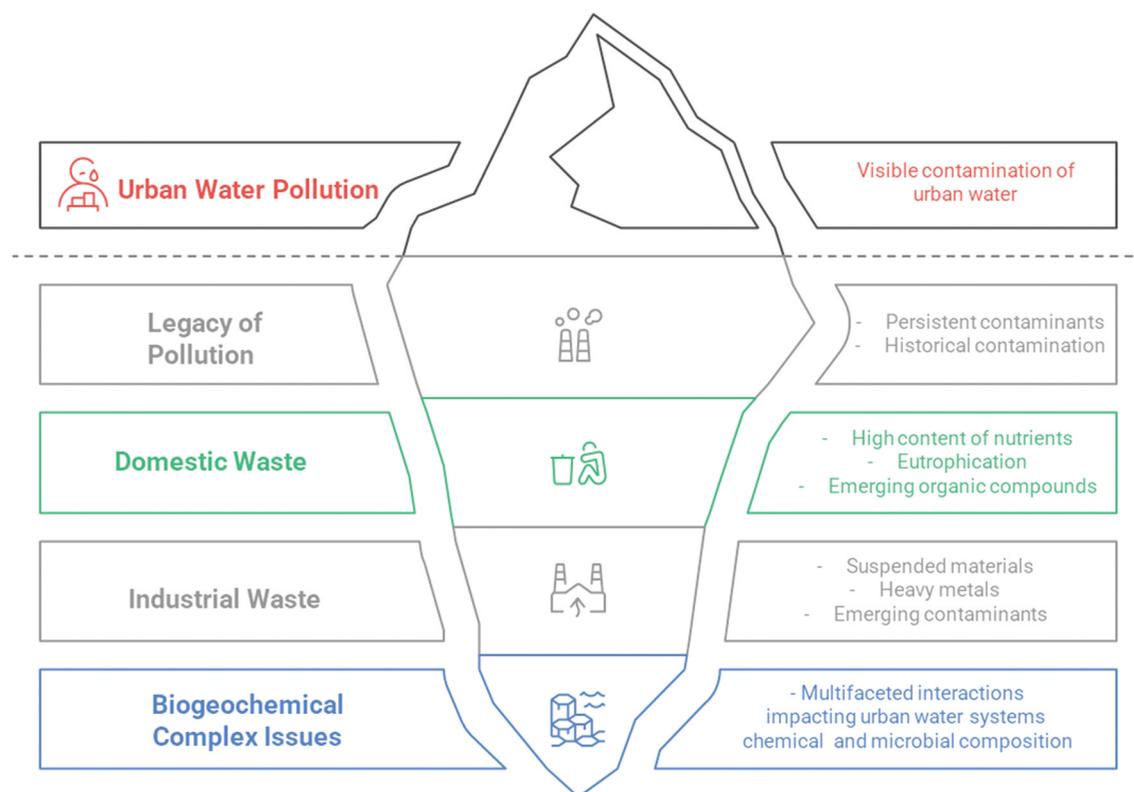

Figure 2. Conceptual view of urban water pollution with the main sources of contaminants and the main water quality concerns.

include the establishment of a robust solid waste management system, featuring timely door-to-door waste collection, composting, and recycling initiatives in collaboration with local authorities.

4 Opportunities for urban hydrology and for building resilient urban water systems

4.1 More and new data types from technological advances

The sustainable management of water-sensitive cities needs a deep understanding of processes supported by data collection and monitoring. For example, reliable information on the drivers, patterns, and dynamics of flood risk is crucial for identifying, prioritising, and planning risk reduction and adaptation measures (Nguyen et al. 2021). A significant challenge for hydrological monitoring in urban systems worldwide is the issue of vandalism of water monitoring devices and access restriction in urban areas, which often limits installations of major and cost-intensive equipment. Despite these obstacles, advances in sensor technologies (e.g. divers for groundwater monitoring, commercial microwave links from cellular communication networks for rainfall measurements and street-monitoring closed circuit television for runoff estimation) – now more affordable and reliable – enable high-resolution water quality measurements, often deployable when devices are properly concealed and protected.

Water-stable isotopes provide valuable insights into the sources, pathways, and ages of water (e.g. Kuhlemann et al. 2021, Marx et al. 2021, Nlend et al. 2021, Szeles et al. 2024). These isotopes can be measured through simple grab sampling (if autosamplers are not available or feasible), which provides "fingerprints" of water sources and pathways (Tetzlaff et al. 2015). Water isotope analysis in the laboratory using laser spectrometry allows for cost-effective analysis and high turnover. When isotopes are integrated into so-called isotope-aided models, new insights into mechanisms of water cycling and total storage dynamics in urban systems are possible, such as heterogeneous vertical and lateral flow of soil moisture, fluctuations in groundwater recharge, preferential uptake of soil water held under different tensions and depths by plants for transpiration, and storage connectivity (Wu et al. 2016, Ring et al. 2024). Water-stable isotopes are peculiarly useful in determining or quantifying the different sources of pollution, especially nitrogen contamination (Buškulić et al. 2025). Indeed, deciphering the origins of nitrates in waterways can be difficult. Conventional chemistry can tell how much nitrogen pollution is in a river, but not where this pollution comes from. Analysing the isotopes of nitrate can give this kind of information.

The field of urban hydrology is also taking advantage of the improvements to remote sensing technologies (e.g. spectral and spatial resolutions of satellite sensors). From the first land use classification (Anderson et al. 1976), thanks to aerial photo interpretation, remotely sensed spectral, spatial, and temporal characteristics are now used in the direct assessment of water pollution (Adjovu et al. 2023). While quantitative analysis of water requires statistical relationships between spectral response and in situ data (Huang et al. 2022), remote sensing has several applications in flood management. It aids runoff calculations by providing input, such as impervious surface data, and offering validation datasets, such as flood extents. The same techniques can approximately be deployed to evaluate water scarcity. In general, time series imagery from sensors like Landsat and SPOT proves invaluable for monitoring urban dynamics, calibrating land use change models, and estimating the potential impacts of urban growth on the hydrological dynamics of watersheds. When combined with geostatistics, remote sensing has the potential to greatly improve urban water resource monitoring and management capacity (Liu et al. 2023). It is worthwhile to use drones as a low-cost technology that can be used by almost anyone, including local government, thereby aiding decision making. A key challenge for future research lies in integrating spatial metrics into automatic calibration algorithms, enabling the development of more objective and reliable models.

In addition, the current constellation of remarkable lab facilities (including living labs, which consider citizens for elaborating new services in research and innovation; Alamanos et al. 2022), equipped with state-of-the-art monitoring systems, are able to deliver datasets from which valuable new understanding can be gained on urban flow and transport (contaminants, sediments) processes, as well as urban flood risk (e.g. the interplay between floodwater and pedestrians). Lab tests also play a key role in validating novel solutions before they go to the market (e.g. innovative porous material for urban pavement). Overall, lab research in urban water acts as an essential complement to modelling.

4.2 Modelling frameworks and artificial intelligence

Modelling remains an important and widespread tool in urban hydrology. Major applications have been developed for city flood and storm event modelling in data-rich contexts (Zwirglmaier et al. 2024). However, recent years have seen a new focus on modelling ecohydrological processes to understand the partitioning of incoming precipitation into blue (e.g. runoff generation and groundwater recharge) and green (e.g. evaporation and transpiration) water fluxes in cities (Gillefalk et al. 2021). In addition, efforts have been made to improve the representation of artificial water inputs, especially urban irrigation, and their potential impacts on urban hydrometeorological conditions and the carbon cycle (Wang et al. 2019, Li et al. 2024). Applications also exist in water quality in terms of prediction and classification of pollution sources. Even if model applications usually require an advanced set of skills, their results can be visualized in user-friendly formats to facilitate communication of the model findings back to citizens and governance stakeholders (Reinert et al. 2023). This approach creates opportunities for collaborative future scenario development and shared decision making.

The high efficiency of machine learning (ML) in processing large datasets and automation in capturing complex non-linear relationships has substantial potential for forecasting and prediction, particularly if coupled with process-based modelling approaches, resulting in increased applications in recent years (Bergen et al. 2019). However, despite this potential for urban hydrological investigations, ML suffers from limited

interpretability (black box), limited validation options and difficulties discerning underlying causal relationships. The optimal areas of application are data-rich sites with good process understanding (Tague and Frew 2021). Importantly, as AI/ML is trained on existing data and therefore often limited to past events, it must be used cautiously for future predictions.

Relevant research has shown an upward trend facilitated by these new transversal tools over the past decades. Looking ahead, we expect that advancements in machine learning, remote sensing, and geographic analysis systems will enable more accurate, intelligent, and fast monitoring to improve the management and sustainability of urban water resources and a holistic understanding of the urban water cycle. This will definitely be useful in data-scarce regions and beneficial for decision making.

4.3 Citizens' active involvement and awareness

Another promising avenue for advancing urban hydrology is the engagement and integration of citizen science to obtain more spatially extensive insights into the water cycle in cities. Citizen science has major potential – particularly at larger city scales – and has been used effectively to expand and increase observational data (Seibert et al. 2019, Nardi et al. 2022). By involving vulnerable communities and diverse stakeholders within a platform, innovative and place-based adaptation and mitigation measures for sustainable and climate-resilient land and water management can be developed and optimized in modelling experiments. Data crowdsourcing has emerged as a transformative approach, pushing frontiers for collecting and applying big data in water science (Scheller et al. 2024). Through effective citizen engagement, crowdsourcing can provide water utilities with cost-effective, near-real time water quality and quantity data collected at high temporal and spatial resolution with minimal costs (Niu et al. 2021). However, ensuring proper quality control of crowdsourced data remains crucial. Beyond data quality, continuity of records presents another challenge for citizen science projects. This can mostly be addressed by ensuring the continuous and reliable involvement of young citizens who will have longer term commitments to these projects. In addition, municipalities should take advantage of crowdsourcing to gain better control and understanding of water systems and related risks, using this data to inform decision making and enhance resilience against urban water challenges. A citizen approach can also be beneficial to investigate the willingness to pay for the implementation of nature-based solutions in the urban environment (Cristiano et al. 2023) through online surveys and face-to-face interviews. Having an idea of how much the community is willing to invest enables policymakers and urban planners to check the financial feasibility of city projects (Netusil et al. 2022).

Although citizen approaches are a modern way to deal with water quality, scarcity, and floods in cities, citizen science is still not well developed in sub-Saharan African cities, while the potential is obvious. Elias et al. (2023) explained that this is mainly related to institutional bureaucracies in such countries.

Citizen science approaches in some countries from the Global South are hindered by limited access to the internet and technology and limited finances that are generally received from external partners. This inhibits continuity and sustainable long-term monitoring since the projects often stop when the external funding cycles end. However, with access to the internet via the cell network and the tangible increase in ownership of phones and smartphones, we expect a significant source of data collection but also more engagement with citizens in this part of the world.

4.4 New ecological concepts

In recent decades, new solutions have been proposed in the literature to reduce urban runoff generation and mitigate pluvial flood risk (Rosenzweig et al. 2018) rather than the more traditional approaches, which usually involve large pipes to drain stormwater as quickly as possible. However, there is not yet any consistent terminology for these solutions. Currently, multiple conceptually overlapping expressions have been used (e.g. sponge city, sustainable urban drainage systems, green infrastructures, low-impact development, or best management practices) (Fletcher et al. 2013).

Studies have shown that green infrastructure – rather than blue infrastructure – plays a more effective role in mitigating flood risks in most urban areas, while grey infrastructure tends to aggravate flood risks (Wang et al. 2024). One key solution is the restoration and conservation of wetlands (Fig. 3), which serve as natural filters, absorbing pollutants and regulating water flows (Sonkamble et al. 2019, Pricope and Shivers 2022). Wetlands can also provide critical habitats for biodiversity while reducing the impacts of urban flooding (Ferreira et al. 2023, van Rees et al. 2023). Further, permeable pavements, acting as green infrastructure that mimics nature, increase the permeability of surfaces through the use of porous asphalt or permeable concrete and reduce surface runoff, thereby preventing localized flooding and decreasing the burden on urban drainage systems (Huang et al. 2020, Wang et al. 2021). Similarly, rain gardens (Fig. 3) absorb excess water and allow it to percolate into the ground, reducing stormwater runoff and improving water quality by filtering out pollutants through shallow, planted depressions designed to capture and filter runoff from roofs, streets, and sidewalks (Mabrouk et al. 2023). Rain gardens typically have native vegetation, enhancing biodiversity while supporting urban wildlife.

Focusing more on the building scale, green roofs and green facades also mimic nature by integrating vegetation into building envelopes, contributing to stormwater management by capturing rainfall and allowing it to be absorbed by plants and soil (Castellar et al. 2021). Both green roofs and green facades ensure multiple benefits for sustainable urban development (Cristiano et al. 2021), such as positively impacting the urban heat island effect, improving air quality and enhancing biodiversity (Ferrario et al. 2024). These nature-based solutions offer multiple benefits for the sustainable development of the urban environment by managing stormwater in urban environments, as they not only mitigate the risks associated with excessive runoff and flooding but also contribute to creating greener, more
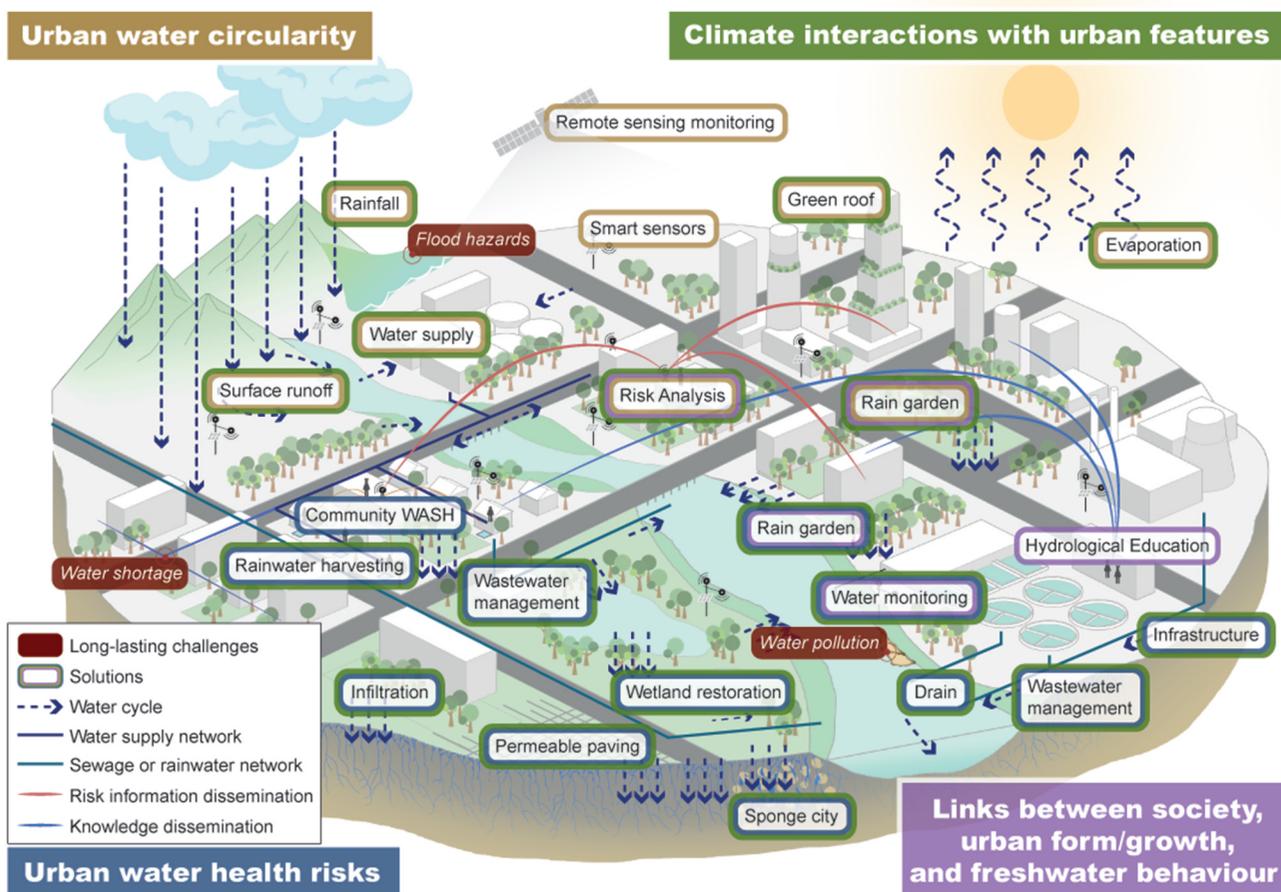
Figure 3. Conceptual diagram examining the challenges and opportunities for developing a resilient, water-sensitive city.

resilient cities that harmonize with natural processes. Although nature-based solutions provide multiple benefits for the sustainable development of the urban environment, the stormwater mitigation impacts of a single nature-based solution are often quite limited. It is therefore important to utilize an integrated approach (Dada *et al.* 2021), which should include multiple nature-based solutions to achieve a significant reduction of stormwater generation. Moreover, models that can simulate nature-based solutions can help identify potential solutions at scale.

The "sponge city" concept integrates multiple nature-based solutions to address urban water management challenges, particularly stormwater control, flood mitigation, and water resource sustainability. Originating in China as a response to rapid urbanization and associated flooding issues, the concept emphasizes using blue-green infrastructure – such as wetlands, rain gardens, and permeable pavements – to absorb, retain, and reuse rainwater. This approach contrasts with traditional grey infrastructure (e.g. concrete drainage systems) by enhancing urban water resilience through ecological means. The sponge city framework focuses on multiscale integration, combining source control measures at micro levels (e.g. bio-retention and green roofs) with larger watershed-level interventions. This strategy supports the mitigation of runoff, reduction of peak flow, and improvement of water quality by filtering pollutants naturally through vegetation and soil layers (Zhai *et al.* 2021). Moreover, the initiative supports urban biodiversity, ecological restoration, and climate adaptation by

converting hard surfaces into multifunctional landscapes that enhance both environmental quality and urban aesthetics. Despite its benefits, the sponge city approach faces challenges, including uncertainties in hydrological performance under extreme weather conditions, and requires stakeholder coordination across different levels of governance. Successful implementation requires an integrated planning framework that considers diverse socio-economic and environmental factors to optimize the spatial arrangement of nature-based solutions (Chan *et al.* 2022). Nonetheless, as urban areas worldwide are confronted with similar water challenges, the sponge city model offers a promising paradigm for sustainable urban water management. Although still not very widespread, the concept is beginning to resonate in Europe, for example, where some works are being reported (Pavesi and Pezzagno OECD 2022, 2022). The findings show that, while the sponge city concept is unique and intriguing, it will require careful planning, financing, and stakeholder participation to be implemented successfully. These studies also emphasize the significance of incorporating renewable energy solutions, such as solar panels, to power urban infrastructure responsibly. Unfortunately, this can limit the extension of such ecological approaches in low-income countries, especially those in Africa, due to limitations in finances. However, this can occur through public–private partnerships, transparency in management, and international platforms such as the UN-Habitat's Urban Water Partnerships. Finally, urban planners must prioritize ecohydrological solutions to develop resilient environments to climate

change. Creating a focus on enhancing urban biodiversity and improving residents' quality of life is essential to creating healthier and more sustainable cities (Hill *et al.* 2017, Uchida *et al.* 2021). In doing so, urban areas can foster a synergistic relationship between natural systems and human development, ensuring that the needs of communities and ecosystems are met. Overall, taking a comprehensive approach to urban hydrology and water management will enable cities to not only thrive during the uncertain times of climate change but also safeguard their regional water resources, ultimately avoiding the risk of 'water shortages. Figure 3 well summarizes the challenges and solutions to build a sustainable city.

5 Conclusions and recommendations

The above sections outline the state of science with respect to urbanization research and remaining gaps. We propose the following recommendations to close these gaps and accelerate research on this topic.

5.1 Where do we stand regarding urban water management?

This paper advocates that the world's towns and cities urgently need an integrated urban water management (IUWM) approach focusing on the interconnections between water, infrastructures, and land use while ensuring a reliable supply through diversified water sources. By empowering citizens, an IUWM plan aims to decentralize and strengthen the freshwater monitoring systems from local to national scales. An IUWM approach aligns urban development with watershed management, aiming to ensure both the quality and quantity of water resources while preserving related ecosystems. Urban water management, however, must extend beyond hydrological sciences to incorporate environmental, economic, social, technical, and political dimensions. Nevertheless, as proposed in this paper, implementing resilient urban water systems requires a perfect linkage between technological advancements (remote sensing, modelling/machine learning, crowdsourcing) and effective decision making tools (citizen engagement and model outputs). Addressing these needs poses significant challenges (especially in low-income countries) but is essential for achieving sustainable urban water management. To overcome these challenges, we propose to build partnerships between the public and private sectors to facilitate the implementation of IUWM across all levels. It is imperative to shift from fragmented problem-solving approaches that address aspects of the urban water cycle in isolation to an integrated, stakeholder-supported approach.

5.2 What are the research priorities for urban hydrologists?

Researchers and city stakeholders must expand both the quantity and diversity of urban data collected, particularly in the Global South. Information on informal settlements and constructions is often sparse or even non-existent. In addition to improving data availability, efforts should focus on enhancing the coverage, quality, resolution, and reliability of data while also standardizing reporting practices. These datasets need to be used and gathered around four research priority themes regarding the future of urban hydrology:

(i) Links between society, urban form/growth, and freshwater behaviour

Rapid urbanization is closely intertwined with water management challenges. Therefore, governing the future growth of cities is crucial for global sustainability through efficient land use and effective water management strategies. As noted in Sections 4.1 and 4.2, by leveraging physics-based and data-driven (artificial intelligence) modelling tools, urban hydrologists should develop models that integrate urban growth scenarios for water levels and nutrient loads. Understanding the interactions between water and society across different civilizations is a significant gap that urban hydrologists must address in the coming decade. However, these challenges cannot be solved by hydrology alone, and interdisciplinary collaboration will be key to finding comprehensive solutions.

(ii) Climate interactions with urban features

The complexity of climate processes increases significantly in cities. Urban environments alter the distribution and quantity of clouds and precipitation through changes in surface roughness, thermodynamic processes, and aerosol emissions, thus leading to water contamination and an increase in flooding events and/or dry periods. Taking into account this climate interface, urban hydrology has to move forward in the next few decades by integrating atmospheric aspects in critical zone sciences. To better manage urban flooding, as well presented in Section 3.3, it becomes essential to fully understand the mechanisms behind convective events and their interactions with urban climates. Meanwhile, urban land surface models should also integrate more complete representations of hydrological processes, including the potential interactions with groundwater. An investigation into how urban morphology, building materials, and human activities influence urban energy and water budgets and eventually contribute to water pollution is also needed.

(iii) Urban water circularity

Urban circularity means implementing the concept of a circular economy (CE) at the city level and moving away from the unsustainable linear paradigm of "take–make–dispose." Achieving urban water circularity requires rethinking urban living practices and their interfaces with water resources, rethinking ecosystem services (e.g. the role of urban wetlands), developing approaches for artificial groundwater recharge and redesigning hydraulic engineering, services, or even entire infrastructure systems.

(iv) Urban water health risks

The threat behind the long-lasting challenge of urban water pollution is the amplification of human and ecological risks. The insufficient infrastructure to treat wastewater is one major factor in the cities of the Global South that often creates "sewage-driven" urban water streams. Urban dwellers actively interact with surrounding polluted water bodies, which is causing human health risks. We need to know to what extent urban pollution, including chemical and microbial pollution, is directly linked to waterborne diseases or indirectly related to long-term diseases. In addition, climate change is creating

seasonal patterns of some diseases, including water- and vector-borne diseases, and urban areas are also often under high health risk zones after a flood event.

Overall, building resilient urban water systems requires holistic approaches with multi-stakeholder engagement to tackle the ever-increasing challenges in cities. To this end, researchers from IAHS's new HELPING Decade will prioritize urban hydrology research that addresses the need for innovative and multidisciplinary approaches, and we encourage global researchers from diverse urban-related fields to focus on developing new methods and directions to advance the understanding of complex urban systems.

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References

Abdellatif, M., Atherton, W., and Alkhaddar, R., 2014. Assessing combined sewer overflows with long lead time for better surface water management. *Environmental Technology (United Kingdom)*, 35 (5), 568–580. doi:10.1080/09593330.2013.837938.

Adjovu, G.E., *et al.*, 2023. Overview of the application of remote sensing in effective monitoring of water quality parameters. *Remote Sensing*, 15 (7), 1938. doi:10.3390/rs15071938.

Agonafir, C., *et al.*, 2023. A review of recent advances in urban flood research. *Water Security*, 19, 100141. doi:10.1016/j.wasec.2023.100141

Ahmed, F., *et al.*, 2018. Tipping points in adaptation to urban flooding under climate change and urban growth: the case of the Dhaka megacity. *Land Use Policy*, 79, 496–506. doi:10.1016/j.landusepol.2018.05.051

Alamanos, A., *et al.*, 2022. Water for tomorrow: a living lab on the creation of the science-policy-stakeholder interface. *Water (Switzerland)*, 14 (18), 2879. doi:10.3390/w14182879.

Anderson, J.R., *et al.*, 1976. *Land Use and Land Cover Classification System for Use With Remote Sensor Data*. USA: US Geol Surv, Prof Pap Professional Paper. doi:10.3133/pp964.

Arheimer, B., *et al.*, 2024. The IAHS science for solutions decade, with Hydrology Engaging Local People IN one Global world (HELPING).

Hydrological Sciences Journal, 69 (11), 1417–1435. doi:10.1080/02626667.2024.2355202.

Auerswald, K., *et al.*, 2024. HESS Opinion : floods and droughts - Land use, soil management, and landscape hydrology are more significant drivers than increasing temperatures. *EGUsphere*, June 13, doi:10.5194/egusphere-2024-1702.

Balha, A., *et al.*, 2023. Assessing the Impact of Land-Use Dynamics to Predict the Changes in Hydrological Variables Using Effective Impervious Area (EIA). *Water Resources Management*, 37 (10), 3999–4014. doi:10.1007/s11269-023-03536-7.

Banerjee, S. and Sikdar, P.K., 2022. Hydrochemical fingerprinting and effects of urbanisation on the water quality dynamics of the Quaternary aquifer of south Bengal Basin, India. *Environmental Earth Sciences*, 81 (4), 134. doi:10.1007/s12665-022-10258-3.

Barron, O., *et al.*, 2014. Projected risks to groundwater-dependent terrestrial vegetation caused by changing climate and groundwater abstraction in the Central Perth Basin, Western Australia. *Hydrological Processes*, 28 (22), 5513–5529. doi:10.1002/hyp.10014.

Behnisch, M., Krüger, T., and Jaeger, J.A.G., 2022. Rapid rise in urban sprawl: global hotspots and trends since 1990. (A. Bharat, Ed.). *PLOS Sustainability and Transformation*, 1 (11), e0000034. doi:10.1371/journal.pstr.0000034.

Bergen, K.J., *et al.*, 2019. Machine learning for data-driven discovery in solid Earth geoscience. *Science*, 363 (6433), 1652–1665. doi:10.1126/science.aau0323.

Bhaskar, A.S., *et al.*, 2016. Will it rise or will it fall? Managing the complex effects of urbanization on base flow. *Freshwater Science*, 35 (1), 293–310. doi:10.1086/685084.

Blöschl, G., *et al.*, 2019. Twenty-three unsolved problems in hydrology (UPH)–a community perspective. *Hydrological Sciences Journal*, 64 (10), 1141–1158. doi:10.1080/02626667.2019.1620507.

Buškulić, P., *et al.*, 2025. Tracing nitrate contamination sources and dynamics in an unconfined alluvial aquifer system (Velika Gorica well field, Croatia). *Environmental Science: Processes Impacts*, 27, 154–171. doi:10.1039/D4EM00527A

Büyüközkan, G., Ilıcak, Ö., and Feyzioğlu, O., 2022. A review of urban resilience literature. *Sustainable Cities and Society*, 77, 103579. doi:10.1016/j.scs.2021.103579

Castellar, J.A.C., *et al.*, 2021. Nature-based solutions in the urban context: terminology, classification and scoring for urban challenges and eco-system services. *Science of the Total Environment*, 779, 146237. doi:10.1016/j.scitotenv.2021.146237.

Chan, F.K.S., *et al.*, 2022. Comparison of sustainable flood risk management by four countries - the United Kingdom, the Netherlands, the United States, and Japan - and the implications for Asian coastal megacities. *Natural Hazards and Earth System Sciences*, 22 (8), 2567–2588. doi:10.5194/nhess-22-2567-2022.

Chathuranika, I.M., *et al.*, 2023. Assessing the water quality and status of water resources in urban and rural areas of Bhutan. *Journal of Hazardous Materials Advances*, 12, 100377. doi:10.1016/j.hazadv.2023.100377.

Chen, J., *et al.*, 2024. Multidimensional water level and water quality response to severe drought in Xingyun Lake. *Heliyon*, 10 (11), e32213. doi:10.1016/j.heliyon.2024.e32213.

Cheval, S., *et al.*, 2024. A systematic review of urban heat island and heat waves research (1991–2022). *Climate Risk Management*, 44, 100603. doi:10.1016/j.crm.2024.100603.

Cristiano, E., Deidda, R., and Viola, F., 2021. The role of green roofs in urban Water-Energy-Food-Ecosystem nexus: a review. *Science of the Total Environment*, 756, 143876. doi:10.1016/j.scitotenv.2020.143876

Cristiano, E., Deidda, R., and Viola, F., 2023. Awareness and willingness to pay for green roofs in Mediterranean areas. *Journal of Environmental Management*, 344, 118419. doi:10.1016/j.jenvman.2023.118419

Dada, A., *et al.*, 2021. Water sensitive cities: an integrated approach to enhance urban flood resilience in Parma (Northern Italy). *Climate*, 9 (10), 152. doi:10.3390/cli9100152.

Dadashpoor, H., Azizi, P., and Moghadasi, M., 2019. Land use change, urbanization, and change in landscape pattern in a metropolitan area.

Science of the Total Environment, 655 (2019), 707–719. doi:10.1016/j.scitotenv.2018.11.267.

Devi, N.N., Sridharan, B., and Kuiry, S.N., 2019. Impact of urban sprawl on future flooding in Chennai city, India. *J. Hydrol*, 574, 486–496. doi:10.1016/j.jhydrol.2019.04.041

Djieugoue, B., *et al.*, 2024. Emerging organic compounds in surface and groundwater reflect the urban dynamics in sub-Saharan cities. *Science of the Total Environment*, 956 (2024), 177217. doi:10.1016/j.scitotenv.2024.177217.

Dong, Y., *et al.*, 2023. Wastewater-influenced estuaries are characterized by disproportionately high nitrous oxide emissions but overestimated IPCC emission factor. *Communications Earth & Environment*, 4 (1), 395. doi:10.1038/s43247-023-01051-6.

Dovonou, F., *et al.*, 2015. Pollution des eaux souterraines par les metaux lourds et leur impact sur l'environnement: cas de l'aquifere superficiel du champ de captage intensif de Godomey au sud-Benin.

Elga, S., Jan, B., and Okke, B., 2015. Hydrological modelling of urbanized catchments: a review and future directions. *Journal of Hydrology*, 529 (P1), 62–81. doi:10.1016/j.jhydrol.2015.06.028.

Elias, P., *et al.*, 2023. Mapping the landscape of citizen science in Africa: assessing their potential contributions to SDGs 6 & 11 on access to clean water and sanitation and on sustainable cities. *Citi Sci Theory & Practice*, 8 (1), 1–13. doi:10.5334/cstp.601.

Ellis, J.B. and Mitchell, G., 2006. Urban diffuse pollution: key data information approaches for the water framework directive. *Water Environ J*, 20 (2006), 19–26. doi:10.1111/j.1747-6593.2006.00025.x.

Ferrario, F., *et al.*, 2024. Evaluating Nature-based Solutions as urban resilience and climate adaptation tools: a meta-analysis of their benefits on heatwaves and floods. *Science of the Total Environment*, 950, 175179. doi:10.1016/j.scitotenv.2024.175179

Ferreira, C.S.S., *et al.*, 2023. Wetlands as nature-based solutions for water management in different environments. *Current Opinion in Environmental Sciences & Health*, 33, 100476. doi:10.1016/j.coesh.2023.100476

Fletcher, T.D., *et al.*, 2013. SUDS, LID, BMPs, WSUD and more–The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, 12 (7), 525–542. doi:10.1080/1573062X.2014.916314.

Gillefalk, M., *et al.*, 2021. Quantifying the effects of urban green space on water partitioning and ages using an isotope-based ecohydrological model. *Hydrology and Earth System Sciences*, 25 (6), 3635–3652. doi:10.5194/hess-25-3635-2021.

Gironás, J., *et al.*, 2010. A new applications manual for the Storm Water Management Model (SWMM). *Environmental Modelling & Software*, 25 (6), 813–814. doi:10.1016/j.envsoft.2009.11.009.

Gregory, R.-L. and Arnold, C.-E., 1932. Runoff-rational runoff formulas. *Trans. ASCE*, 96, 10381099.

Greve, P., Gudmundsson, L., and Seneviratne, S.I., 2018. Regional scaling of annual mean precipitation and water availability with global temperature change. *Earth System Dynamics*, 9 (1), 227–240. doi:10.5194/esd-9-227-2018.

Hanford, J.K., Webb, C.E., and Hochuli, D.F., 2020. Management of urban wetlands for conservation can reduce aquatic biodiversity and increase mosquito risk. *J Appl Ecol*, 00, 1–12. doi:10.1111/1365-2664.1357

He, C., *et al.*, 2021. Future global urban water scarcity and potential solutions. *Nat Commun*, 12 (1), 4667. doi:10.1038/s41467-021-25026-3.

Hibbs, B.J. and Sharp, J.M., 2012. Hydrogeological impacts of urbanization. *Environmental and Engineering Geoscience*, 18 (1), 3–24. doi:10.2113/gseegeosci.18.1.3.

Hill, M.J., *et al.*, 2017. Urban ponds as an aquatic biodiversity resource in modified landscapes. *Global Change Biology*, 23 (3), 986–999. doi:10.1111/gcb.13401.

Horner, -W.-W., 1933. Rainfall, runoff, and evaporation in relation to urban areas. *In*: M.M. Leroy, K. Sherman, and R.E. Horton, eds. *Rainfall, Runoff and Evaporation*, :53–56.

Huang, S., *et al.*, 2022. A novel fusion method for generating surface soil moisture data with high accuracy, high spatial resolution, and high spatio-temporal continuity. *Water Resources Research*, 58 (5), e2021WR030827. doi:10.1029/2021WR030827.

Huang, X., *et al.*, 2021. The synergistic effect of urban heat and moisture islands in a compact high-rise city. *Building and Environment*, 205, 108274. doi:10.1016/j.buildenv.2021.108274

Huang, Y., *et al.*, 2020. Nature-based solutions for urban pluvial flood risk management. *Wiley Interdisciplinary Reviews: Water*, 7 (3). doi:10.1002/wat2.1421.

Hülsmann, S. and Jampani, M., 2021. The Nexus Approach as a Tool for Resources Management in Resilient Cities and Multifunctional Land-Use Systems. *In*: S. Hülsmann and M. Jampani, eds. *A Nexus Approach for Sustainable Development*. Cham: Springer, 1–14. doi:10.1007/978-3-030-57530-4_1.

IAH, 2017. *Water security & Groundwater*. Strategic Overview Series. Available from: www.iah.org [Accessed Nov 2024].

Jampani, M., *et al.*, 2018. Spatio-temporal distribution and chemical characterization of groundwater quality of a wastewater irrigated system: a case study. *Science of the Total Environment*, 636, 1089–1098. doi:10.1016/j.scitotenv.2018.04.347

Jampani, M., *et al.*, 2020. Multi-functionality and land use dynamics in a peri-urban environment influenced by wastewater irrigation. *Sustainable Cities and Society*, 62 (2020), 102305. doi:10.1016/j.scs.2020.102305.

Jongen, H.J., *et al.*, 2024. The water balance representation in urban-PLUMBER land surface models. *Journal of Advances in Modeling Earth Systems*, 16 (10), e2024MS004231. doi:10.1029/2024MS004231.

Krueger, E.H. *et al.*, 2019. Resilience dynamics of urban water supply security and potential of tipping points. *Earth's Future*, 7, 1167–1191.

Kuhlemann, L.M., Tetzlaff, D., and Soulsby, C., 2021. Spatio-temporal variations in stable isotopes in peri-urban catchments: a preliminary assessment of potential and challenges in assessing streamflow sources. *Journal of Hydrology*, 600 (2021), 126685. doi:10.1016/j.jhydrol.2021.126685.

Lapworth, D.J., *et al.*, 2012. Emerging organic contaminants in groundwater: a review of sources, fate and occurrence. *Environmental Pollution*, 163 (2012), 287–303. doi:10.1016/j.envpol.2011.12.034.

Lapworth, D.J., *et al.*, 2017. Urban groundwater quality in sub-Saharan Africa: current status and implications for water security and public health. *Hydrol. J*, 25, 1093–1116. doi:10.1007/s10040-016-1516-6

Larsen, T.A., *et al.*, 2016. Emerging solutions to the water challenges of an urbanizing world. *Science*, 352 (6288), 928–933. doi:10.1126/science.aad8641.

Li, P., Wang, Z.H., and Wang, C., 2024. The potential of urban irrigation for counteracting carbon-climate feedback. *Nature Communications*, 15 (1), 2437. doi:10.1038/s41467-024-46826-3.

Lipson, M.J., *et al.*, 2024. Evaluation of 30 urban land surface models in the Urban-PLUMBER project: phase 1 results. *Quarterly Journal of the Royal Meteorological Society*, 150 (758), 126–169. doi:10.1002/qj.4589.

Liu, Z., *et al.*, 2023. Remote sensing and geostatistics in urban water-resource monitoring: a review. *Marine and Freshwater Research*, 74 (10), 747–765. doi:10.1071/MF22167.

Lu, M., *et al.*, 2024. Worldwide scaling of waste generation in urban systems. *Nature Cities*, 1 (2), 126–135. doi:10.1038/s44284-023-00021-5.

Mabrouk, M., *et al.*, 2023. Assessing the effectiveness of nature-based solutions-strengthened urban planning mechanisms in forming flood-resilient cities. *Journal of Environmental Management*, 344, 118260. doi:10.1016/j.jenvman.2023.118260

Marx, C., *et al.*, 2021. Isotope hydrology and water sources in a heavily urbanized stream. *Hydrological Processes*, 35 (10), e14377. doi:10.1002/hyp.14377.

Marx, C., *et al.*, 2023. *Effects of 66 years of water management and hydroclimatic change on the urban hydrology and water quality of the Panke catchment*. Berlin, Germany: Science of the Total Environment. doi:10.1016/j.scitotenv.2023.165764.

McGrane, S.J., 2016. Impacts of Urbanisation on Hydrological and Water Quality Dynamics, and Urban Water Management: a Review. *Hydrological Sciences Journal*, 61 (13), 2295–2311. doi:10.1080/02626667.2015.1128084.

McPherson, M.B., 1979. Urban hydrology. *Reviews of Geophysics*, 17 (6), 1289–1297. doi:10.1029/RG017i006p01289.

Miller, J.D. and Hutchins, M., 2017. The impacts of urbanisation and climate change on urban flooding and urban water quality: a review of the evidence concerning the United Kingdom. *Journal of Hydrology: Regional Studies*, 12 (2017), 345–362. doi:10.1016/j.ejrh.2017.06.006.

Mohtar, W., *et al.*, 2020. Urban flash flood index based on historical rainfall events. *Sustainable Cities and Society*, 56, 102088. doi:10.1016/j.scs.2020.102088

Mokarram, M., Saber, A., and Sheykhi, V., 2020. Effects of heavy metal contamination on river water quality due to release of industrial effluents. *Journal of Cleaner Production*, 277, 123380. doi:10.1016/j.jclepro.2020.123380

Mosley, L.M., 2015. Drought impacts on the water quality of freshwater systems; review and integration. *Earth-Science Reviews*, 140 (2015), 203–214. doi:10.1016/j.earscirev.2014.11.010.

Nardi, F., *et al.*, 2022. Citizens AND HYdrology (CANDHY): conceptualizing a transdisciplinary framework for citizen science addressing hydrological challenges. *Hydrological Sciences Journal*, 67 (16), 2534–2551. doi:10.1080/02626667.2020.1849707.

Nazemi, A. and Madani, K., 2017. Urban water security: emerging discussion and remaining challenges. *Sustainable Cities and Society*. doi:10.1016/J.SCS.2017.09.011.

Netusil, N.R., *et al.*, 2022. Valuing the public benefits of green roofs. *Landscape and Urban Planning*, 224, 104426. doi:10.1016/j.landurbplan.2022.104426

Nguyen, M.T., *et al.*, 2021. Understanding and assessing flood risk in Vietnam: current status, persisting gaps, and future directions. *Journal of Flood Risk Management*, 14 (2), e12689. doi:10.1111/jfr3.12689.

Niu, P.H., Feng, Y.F., and Wang, F., 2021. Suitable distribution area for rare and endangered animals in Guangdong-Hong Kong-Macao Greater Bay Area. *Chinese J. Ecol*, 40, 2467–2477.

Nlend, B., *et al.*, 2018. The impact of urban development on aquifers in large coastal cities of West Africa: present status and future challenges. *Land Use Policy*, 75, 352–363. doi:10.1016/j.landusepol.2018.03.007

Nlend, B., *et al.*, 2021. Shallow urban aquifers under hyper-recharge equatorial conditions and strong anthropogenic constrains. Implications in terms of groundwater resources potential and integrated water resources management strategies. *Sci. Total Environ*, 757, 143887. doi:10.1016/j.scitotenv.2020.1438

NRC, 2001. *Basic Research Opportunities in the Earth Sciences*. Washington, DC: National Academies Press.

O'Driscoll, M., *et al.*, 2010. Urbanization Effects on Watershed Hydrology and In-Stream Processes in the Southern United States. *Water*, 2 (3), 605–648. doi:10.3390/w2030605.

OECD, 2023. *Germany's sponge cities to tackle heat and flooding*. Paris: OECD Publishing.

Olmstead, S. and Zheng, J., 2019. *Policy Instruments for Water Pollution Control in Developing Countries*. Washington, DC: World Bank.

Oral, H.V., *et al.*, 2021. Management of Urban Waters with Nature-Based Solutions in Circular Cities—Exemplified through Seven Urban Circularity Challenges. *Water*, 13 (23), 3334. doi:10.3390/w13233334 .

Oswald, C., *et al.*, 2023. Integrating urban water fluxes and moving beyond impervious surface cover: a review. *Journal of Hydrology*. doi:10.1016/j.jhydrol.2023.129188.

Patra, J., 2016. Review of Current and Planned Adaptation Action in India. CARIAA Working Paper no. 10. Ottawa, Canada and UK Aid, London, United Kingdom: International Development Research Centre. Available from: www.idrc.ca/cariaa.

Pavesi, F.C. and Pezzagno, M., 2022. *From Sponge Cities to Sponge Landscapes with Nature-Based Solutions: a Multidimensional Approach to Map Suitable Rural Areas for Flood Mitigation and Landscaping*. Nature-Based Solutions for Flood Mitigation, Springer International Publishing.

Pricope, N.G. and Shivers, G., 2022. Wetland vulnerability metrics as a rapid indicator in identifying nature-based solutions to mitigate coastal flooding. *Hydrology*, 9 (12), 218. doi:10.3390/hydrology9120218.

Qi, Y., *et al.*, 2020. Addressing challenges of urban water management in chinese sponge cities via nature-based solutions. *Water*, 12 (10), 2788. doi:10.3390/w12102788.

Reimuth, A., *et al.*, 2023. Urban growth modeling for the assessment of future climate and disaster risks: approaches, gaps and needs. *Environmental Research Letters*, 19 (1), 013002. doi:10.1088/1748-9326/ad1082.

Reinert, A., *et al.*, 2023. Communication strategies in urban hydrology modeling. *In*: L.K. Wang, C.T. Yang, and M.H.S. Wang, eds. *Advances in Urban Water Management*. Cham: Springer. https://link.springer.com/book/10.1007/978-3-319-22924-9.

Richardson, S.D. and Ternes, T.A., 2018. Water Analysis: emerging Contaminants and Current Issues. *Analytical Chemistry*, 90 (1), 398–428. doi:10.1021/acs.analchem.7b04577.

Ring, A.-M., *et al.*, 2024. Assessing the impact of drought on water cycling in urban trees via in-situ isotopic monitoring of plant xylem water. *Journal of Hydrology*, 633 (2024), 131020. doi:10.1016/j.jhydrol.2024.131020.

Rosenzweig, B.R., *et al.*, 2018. Pluvial flood risk and opportunities for resilience. *Wiley Interdisciplinary Reviews: Water*, 5 (6), e1302. doi:10.1002/wat2.1302.

Scheller, M., van Meerveld, I., and Seibert, J., 2024. How well can people observe the flow state of temporary streams? *Frontiers in Environmental Science*, 12, 1352697. doi:10.3389/fenvs.2024.1352697

Seibert, J., *et al.*, 2019. Virtual staff gauges for crowd-based stream level observations. *Frontiers in Earth Science*, 7, 70. doi:10.3389/feart.2019.00070

Singh, N., *et al.*, 2022. Chapter 9 - Challenges of water contamination in urban areas. *In*: A.L. Srivastav, *et al.*, eds. *Current Directions in Water Scarcity Research*. Vol. 6. Elsevier, 173–202. doi:10.1016/B978-0-323-91838-1.00008-7.

Sonkamble, S., *et al.*, 2019. Hydro-geophysical characterization and performance evaluation of natural wetlands in a semi-arid wastewater irrigated landscape. *Water Research*, 148, 176–187. doi:10.1016/j.watres.2018.10.040

Stevenson, J.L., *et al.*, 2022. Assessing land use influences on isotopic variability and stream water ages in urbanising rural catchments. *Isot. Environ. Health Stud*, 58 (3), 277–300. doi:10.1080/10256016.2022.2070615.

Szeles, B., *et al.*, 2024. Comparison of two isotopic hydrograph separation methods in the Hydrological Open Air Laboratory, Austria. *Hydrological Processes*, 38 (7), e15222. doi:10.1002/hyp.15222.

Tague, C. and Frew, J., 2021. Visualization and ecohydrologic models: opening the box. *Hydrol Processes*, 35 (1), e13991. doi:10.1002/hyp.13991.

Tam, V.T. and Nga, T.T.V., 2018. Assessment of urbanization impact on groundwater resources in Hanoi. *Vietnam. Journal of Environmental Management*, 227, 107–116.

Tetzlaff, D., *et al.*, 2015. Tracer-based assessment of flow paths, storage and runoff generation in northern catchments: a review. *Hydrological Processes*, 29 (16), 3475–3490. doi:10.1002/hyp.10412.

Tu, J., *et al.*, 2023. Assessment of building damage and risk under extreme flood scenarios in Shanghai. *Natural Hazards and Earth System Sciences*, 23 (10), 3247–3260. doi:10.5194/nhess-23-3247-2023.

Uchida, K., *et al.*, 2021. Urban Biodiversity and the Importance of Scale. Trends in. *Ecology and Evolution*, 36 (2), 123–131. doi:10.1016/j.tree.2020.10.011.

UN-HABITAT, 2010. *Solid Waste Management in the World's Cities*. London, UK: Gutenberg Press.

UN-Habitat, 2022. World Cities Report 2022: envisaging the Future of Cities. Available from: https://unhabitat.org/wcr/ .

UNICEF/WHO, 2023. *Progress on household drinking water, sanitation and hygiene 2000–2022: special focus on gender*. New York, USA: UNICEF.

United Nations, 2022. UN Statistical Commission 2022 – progress on implementation of the global urban and rural definitions. Share Your Green Design. Available from: www.shareyourgreendesign.com/events/un-statistical-commission-2022-progress-on-implementation-of-the-global-urban-and-rural-definitions.

United Nations, Department of Economic and Social Affairs, Population Division, 2019. *World Urbanization Prospects: the 2018 Revision (ST/ESA/SER.A/420)*. New York: United Nations.

Vaidya, R., *et al.*, 2024. Assessing wastewater management challenges in developing countries: a case study of India, current status and future scope. *Environ Dev Sustain*, 26 (8), 19369–19396. doi:10.1007/s10668-023-03540-2.

van Hateren, T.C., *et al.*, 2023. Where should hydrology go? An early-career perspective on the next IAHS Scientific Decade: 2023–2032. *Hydrological Sciences Journal*, 68 (4), 529–541. doi:10.1080/02626667.2023.2170754.

van Rees, C.B., *et al.*, 2023. The potential for nature-based solutions to combat the freshwater biodiversity crisis. *PLOS Water*, 2 (6), e0000126. doi:10.1371/journal.pwat.0000126.

Vörösmarty, C., *et al.*, 2010. Global threats to human water security and river biodiversity. *Nature*, 467 (7315), 555–561. doi:10.1038/nature09440.

Wagner, I. and Breil, P., 2013. The role of ecohydrology in creating more resilient cities. *Ecohydrology & Hydrobiology*, 13 (2), 113–134. doi:10.1016/j.ecohyd.2013.06.002.

Wang, C., *et al.*, 2021. Cool pavements for urban heat island mitigation: a synthetic review. *Renewable and Sustainable Energy Reviews*, 146, 111–171. doi:10.1016/j.rser.2021.111171

Wang, C., 2020. Landscape phenology and soil moisture dynamics influenced by irrigation in a desert urban environment. *In*: A. Ghaffarianhoseini, A. Ghaffarianhoseini, and N. Nasmith, eds. *Imaginable Futures: design Thinking, and the Scientific Method*, 670–679.

Wang, C., Wang, Z.H., and Yang, J., 2019. Urban water capacity: irrigation for heat mitigation. *Computers, Environment and Urban Systems*, 78, 101397. doi:10.1016/j.compenvurbsys.2019.101397

Wang, Y., *et al.*, 2024. Attributing effects of classified infrastructure management on mitigating urban flood risks: a case study in Beijing, China. *Sustainable Cities and Society*, 101, 105141. doi:10.1016/j.scs.2023.105141

Wannewitz, M., *et al.*, 2024. Progress and gaps in climate change adaptation in coastal cities across the globe. *Nat Cities*, 1 (9), 610–619. doi:10.1038/s44284-024-00106-9.

Warter, M.M., *et al.*, 2024. Impact of drought hazards on flow regimes in anthropogenically impacted streams: an isotopic perspective on climate stress. *Natural Hazards and Earth System Sciences*, 24 (11), 3907–3924. doi:10.5194/nhess-24-3907-2024.

Welty, C., *et al.*, 2023. Spatial heterogeneity and temporal stability of baseflow stream chemistry in an urban watershed. *Water Resour. Res*, 59 (1). doi:10.1029/2021WR031804.

Welty, C., *et al.*, 2007. Design of an environmental field observatory for quantifying the urban water budget. *In*: V. Novotny and P. Brown, eds. *Cities of the Future towards Integrated Sustainable Water and Landscape*. London, UK: IWA Publishing, 72–88.

Wong, T., Briony, R., and Brown, R., 2020. Transforming cities through water-sensitive principles and practices. *One Earth*, 3 (4), 436–447. doi:10.1016/j.oneear.2020.09.012.

Woodruff, J., Irish, J.L., and Camargo, J., 2013. Coastal Flooding by Tropical Cyclones and Sea-Level Rise. *Nature*, 504 (7478), 44–52. doi:10.1038/nature12855.

Wu, H., *et al.*, 2016. Contrasting water use pattern of introduced and native plants in an alpine desert ecosystem, Northeast Qinghai–Tibet Plateau, China. *Science of the Total Environment*, 542 (Part A), 182–191. doi:10.1016/j.scitotenv.2015.10.121.

Yadav, A., Kansal, M.L., and Singh, A., 2024. Land use and land cover dynamics in the Upper Ganga Riverine Wetland: unravelling ecosystem services over two decades. *Environ Monit Assess*, 196 (6), 590. doi:10.1007/s10661-024-12748-2.

Yang, L., *et al.*, 2015. Climate-related flood risks and urban responses in the Pearl River Delta, China. *Regional Environmental Change*, 15 (2), 379–391. doi:10.1007/s10113-014-0651-7.

Yang, L.E., *et al.*, 2021. Social resilience and its scale effects along the historical Tea-Horse Road. *Environmental Research Letters*, 16 (4), 045001. doi:10.1088/1748-9326/abea35.

Yang, L., Zhang, C., and Ngaruiya, G.W., 2013. Water supply risks and urban responses under a changing climate: a case study of Hong Kong. *Pacific Geographies*, 39, 9–15.

Yang, X., Wang, Z.H., and Wang, C., 2022. Critical transitions in the hydrological system: early-warning signals and network analysis. *Hydrology and Earth System Sciences*, 26 (7), 1845–1856. doi:10.5194/hess-26-1845-2022.

Zhai, J., *et al.*, 2021. Multiscale watershed landscape infrastructure: integrated system design for sponge city development. *Urban Forestry & Urban Greening*, 60, 127060. doi:10.1016/J.UFUG.2021.127060

Zhang, K., *et al.*, 2020. Quantifying the benefits of stormwater harvesting for pollution mitigation. *Water Res*, 171, 115395. doi:10.1016/j.watres.2019.115395

Zhi, W., *et al.*, 2023. Widespread deoxygenation in warming rivers. *Nat. Clim. Chang*, 13 (10), 1105–1113. doi:10.1038/s41558-023-01793-3.

Zorn, C., *et al.*, 2020. Evaluating the Magnitude and Spatial Extent of Disruptions Across Interdependent National Infrastructure Networks. *ASME. ASME J. Risk Uncertainty Part B*, 6 (2), 020904. doi:10.1115/1.4046327.

Zwirglmaier, V., Reimuth, A., and Garschagen, M., 2024. How suitable are current approaches to simulate flood risk under future urbanization trends? *Environmental Research Letters*, 19 (7), 073003. doi:10.1088/1748-9326/ad536f.