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Review article

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Concepts and evolution of urban hydrology

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Abstract

Urbanization and climate change are exacerbating the flood risk and ecosystem degradation in urban catchments, with traditional stormwater management systems often overwhelmed. In this Review, we discuss changes in urban hydrology and approaches to stormwater management. Roughly 90% of rainfall on impervious surfaces and drainage infrastructure becomes run-off, enhancing rainfall export away from cities and leading to local water scarcity and downstream flooding and pollution. Projected increases in urban populations (68% in cities by 2050) and rainfall intensity (~12% in the 10-year and 50-year recurrence interval intensity, under 1.5 °C warming) will exacerbate these issues. Transforming stormwater systems is thus urgently needed, to mitigate flood risk and also to address community desires for environmental protection and enhanced water security. Opportunities include rain gardens and other nature-based stormwater control measures (which restore natural flows and offer other ecosystem services), smart sensor monitoring networks and real-time management (which sustain natural flow regimes, mitigate flood risk and protect ecosystem services) and stormwater harvesting (to avoid local water scarcity). Community acceptance of stormwater harvesting is as high as 96% and stormwater is a substantial resource, with volumes often exceeding demand in some parts of the world. Delivering additional transformations globally requires research into strategies to incentivize engagement and investment, and policies to guide governance of decentralized networks.

Sections

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Introduction

Urban hydrology describes the altered state of water properties, quality and flow through urban landscapes. A key feature in urban hydrology is the replacement of naturally porous surfaces, such as forests, grass and soil, with constructed drainage systems and impervious surfaces, including roads and roofs. During rain events, these impervious surfaces enhance overland stormwater run-off and entrainment of pollutants, and transfer water away from urban areas, depleting local groundwater levels and exacerbating downstream flooding[1–3]. The resulting changes in flow regime and water quality degrade stream ecosystems[4], with flooding posing risks to life and property.

Flood risk remains a primary objective of urban management. The focus of traditional urban stormwater systems has primarily been on drainage and sanitation, with rapid evacuation of stormwater through the urban karst – systems of subterranean megapores associated with drainage infrastructure – transferring risk of flash floods and pollution downstream. However, since around 2000 there has been growing community demand to also mitigate the environmental impacts of urban development, including pollution, erosion and loss of habitat and urban amenity[5]. Water scarcity is another issue of concern as, although there is some offset from water system leaks and over-irrigation[3,6], generally traditional management approaches reduce infiltration to groundwater[3] and limit inputs to stream-flow in dry weather. For example, stream baseflows around Delaware in the United States reduced by between 6 and 58% per 10% increase in impervious surface cover[7]. Thus, altered water flows through the urban landscape and water scarcity can impact local vegetation[8] and, potentially, exacerbate urban droughts and heatwaves[9].

Managing the hydrology of cities is challenged further by increasing population densities and, in many regions, climate change-driven increases in rainfall intensity and drought[10], rendering current stormwater systems less effective. In the Guangdong–Hong Kong–Macao Greater Bay Area, for example, flood susceptibility is predicted to increase by between 9 and 14% between 2020 and 2050, depending on the climate change scenario adopted[11]. In addition, traditional stormwater management approaches do not meet objectives to capture urban run-off to provide alternate or supplementary water supplies in cities facing water scarcity[12,13]. With major cities around the world, such as Cape Town in South Africa[14] and cities in California, USA[15], facing water shortages, finding supplementary water supplies is increasingly critical.

Therefore, there is a pressing need to upgrade approaches to urban hydrology management to address concerns regarding flood risk and water scarcity. Advances in technology, such as creating smart stormwater networks using low-cost sensors and the Internet of Things, offer opportunities to optimize real-time management of urban hydrology and reduce floods. Combined with nature-based solutions, these networks could not only deliver suitable environmental flows to streams, irrigate the urban landscape and provide supplementary water supplies[16–18], but also deliver ecosystem services. If well designed, such systems could simultaneously address water scarcity and reduce degradation of waterway ecosystems.

In this Review, we describe the changing drivers of urban hydrology and evolving societal expectations of stormwater management. We discuss the growing demand for urban stormwater management to provide ecosystem services, mitigate degradation of downstream waterways and augment water supply. We explore how combining technological developments, such as smart sensor networks, with nature-based solutions can advance real-time stormwater management to improve flood mitigation and ecosystem service provision. Finally, we consider the potential of innovative transformations and policies to decentralize management practices and incentivize wider community involvement.

Urban hydrology

Prior to evaluating approaches to managing stormwater in urban areas, it is first important to provide context on what urban hydrology is. Urban hydrology refers to the pathways and fate of rainfall over the urban landscape and is strongly controlled by run-off, drainage and preferential flows associated with infrastructure. Characterized by run-off over impervious surfaces[19], reduced soil storage capacity[20] and flow through constructed drainage systems, urban flow paths seem, in theory, less complex than those of natural areas, where soil, vegetation, topography and bedrock interact to influence water pathways[21]. However, urban flow paths are, in reality, complicated by the urban karst, whereby permeable trenches around infrastructure, such as conduits and foundations, allow preferential flows of water under and away from the urban landscape[20,22,23] (Fig. 1).

The large volumes of run-off and preferential subterranean flows produced by even small rainfall events in urban areas lead to flashy hydrology. The coefficient of run-off (the amount of rainfall that becomes run-off) of an impervious surface can exceed 90% (ref. 24), substantially increasing the flood risk in receiving areas of urban landscapes compared with those of natural forested catchments where the coefficient is in the order of 10% (ref. 25). The net effect of this high run-off is reduced local groundwater levels, meaning that urban streams experience very low flow during dry weather[26]. By comparison, most rainfall in natural catchments infiltrates into soils and is subsequently either transpired by vegetation or percolates through to groundwater where it contributes to stream baseflows[25] (Fig. 1).

Drainage is a key component of urban development. Drainage in cities and towns usually consists of one of two distinct approaches: separate sewers, where stormwater and wastewater are carried in separate pipe networks; and combined sewers, where wastewater and stormwater are combined in a single pipe network. In systems with separate sewers, stormwater is conveyed to receiving streams, typically without treatment to improve quality, and wastewater is conveyed to a treatment plant. In combined systems, the treatment plant treats stormwater and wastewater. However, the highly variable nature of stormwater means that the treatment or transport capacity is often exceeded, dramatically increasing baseflow in some urban streams[3,27,28] and resulting in untreated water being discharged into urban streams[29].

The combined effects of flashy hydrology and discharges of untreated stormwater (and potentially wastewater) degrade ecosystems in receiving waterways. Indeed, hydrology is considered to be a dominant factor influencing urban stream health[4]: increased peak flows during wet weather cause erosion and loss of habitat diversity, and reduced baseflows in dry weather cause loss of wetted habitats[30]. In addition, water emanating from urban catchments is typically of poor quality owing to the many potential pollution sources, with run-off and enhanced preferential flows driving efficient mobilization and transport of pollutants downstream[31,32]. However, degradation also occurs at even very low levels of urbanization, not just in dense cities. For instance, substantial loss of in-stream species can occur when impervious areas make up substantially less than 10% of the catchment area draining into a stream[33,34].

Traditional approaches to managing urban hydrology focus singly on reducing the flood risk and contribute to the degradation of stream ecosystems. These past approaches applied large-scale centralized

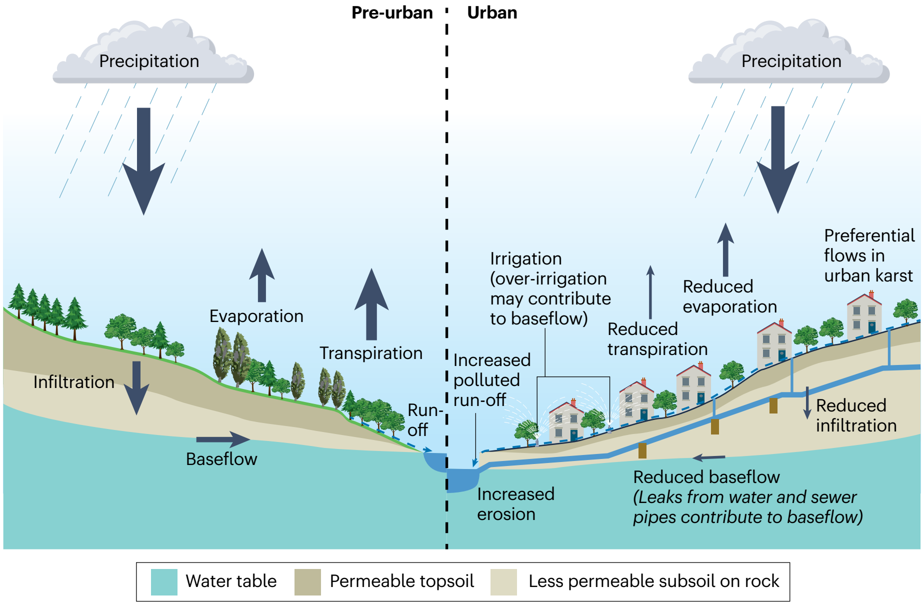

Fig. 1 | Urban stormwater impacts on water flows and balance. Comparison of water flow pathways and water balance between a pre-urban forested catchment and an urbanized catchment. Blue arrows represent water flow pathways and their direction, with arrow size representing the relative magnitude of fluxes; blue dashed arrows represent run-off; blue shading represents groundwater, with the upper boundary representing water table height; solid black lines represent impervious surfaces, including roofs, roads and footpaths; and green solid lines represent pervious surfaces, including vegetation and soil. Urban karst includes preferential flow pathways created by permeable trenches surrounding underground infrastructure, such as pipes and cables. Urbanization substantially reduces evaporation, infiltration and transpiration, with the introduction of impervious surfaces substantially increasing run-off directly entering waterways, typically by five to ten times compared with natural pre-urban surfaces.

solutions to evacuate water from the urban landscape, for instance large pipe networks acted to convey water downstream as quickly as possibly, often with large flood-retarding basins to reduce downstream flood risk. Emerging approaches increasingly focus on a mix of centralized and local, source-based solutions[35] and have evolved to consider water flows through the urban ecosystem and how drainage can be adapted to deliver water-related ecosystem services. Such approaches rely on blue–green infrastructure – including rain gardens, green roofs, swales and retention basins – which uses vegetation and mimics natural processes to improve water quality and flow regimes[35,36]. Through simultaneously reducing flood risk, reducing pollution and degradation, and enhancing the urban landscape[37], these nature-based solutions protect biodiversity and ecosystem services provided to local communities, potentially leading to greater community involvement in urban hydrology management[38].

Evolving concerns

The management of urban hydrology is principally affected by increasing urban populations and densities of cities, climate change and emerging pollutants of concern. These aspects are now discussed.

Population and urban density

The global urban population is growing rapidly. In 1950, 30% of the global population lived in cities, increasing to 58% by 2018 and projected to further increase to 68% by 2050, when more than half of the world's countries will have a majority urban population[39]. Urbanization varies by continent and region. Asia and Africa are experiencing particularly rapid urban growth, with the urban population of Africa projected to increase by around 57% between 2018 and 2030 (ref. 39).

These trends in population growth are accompanied by urban expansion and densification. Expansion of urban areas into previously rural and forested areas replaces vegetated landscapes with impervious urban surfaces[40]. Conversely, densification aims to make cities more sustainable[41], strengthen local economies[42] and prevent habitat and biodiversity loss[43], through replacing single-family homes with multifamily and mixed-use buildings. However, both expansion and densification lead to dramatic increases in impervious surface area within catchments and, often, reduced space for blue–green infrastructure, therefore increasing stormwater run-off for a given rainfall event[40,44,45].

As urbanization progresses, existing conventional stormwater drainage systems become overwhelmed by greater volumes of stormwater and flooding events become more frequent and damaging[46,47]. In cities where stormwater and wastewater are combined in a single sewer system, spills of untreated wastewater onto streets or into waterways become more frequent as urbanization and population density increase[48]. For example, in the United Kingdom there are more than 20,000 permitted combined sewer overflow structures, with the River Thames receiving approximately 50–60 overflows each year[49], posing a risk to humans[50] and the environment[51]. However, upgrading existing sewer networks in urban areas is difficult and expensive owing to difficulties in accessing pipes under existing buildings and urban infrastructure, especially as the density of development increases[48]. Thus, despite the constraints of integration with existing infrastructure and competition for space, implementing improved hydrology management systems and infrastructure during urban development is a priority[52].

Climate change

In addition to urbanization, changes to the Earth's climate have major implications for the urban water cycle[10]. Globally, climate change is driving intensification of short-duration rainfall events. For instance, the intensity of 10-year and 50-year daily heavy rainfall event increases by 5–6% for every degree of global warming relative to 1850–1900, with the effect even more pronounced at 2 °C global warming, reaching 14% (ref. 53) (Fig. 2). These effects are projected for the majority of the world's major cities, particularly in North America and Asia[54]. More intense rainfall means generation of greater surface run-off volume and peak flow[55], which, combined with the effects of sea-level rise in coastal areas, will result in substantial increases in flood risk[56]. However, annual rainfall is projected to decrease in some areas[57], and evapotranspiration

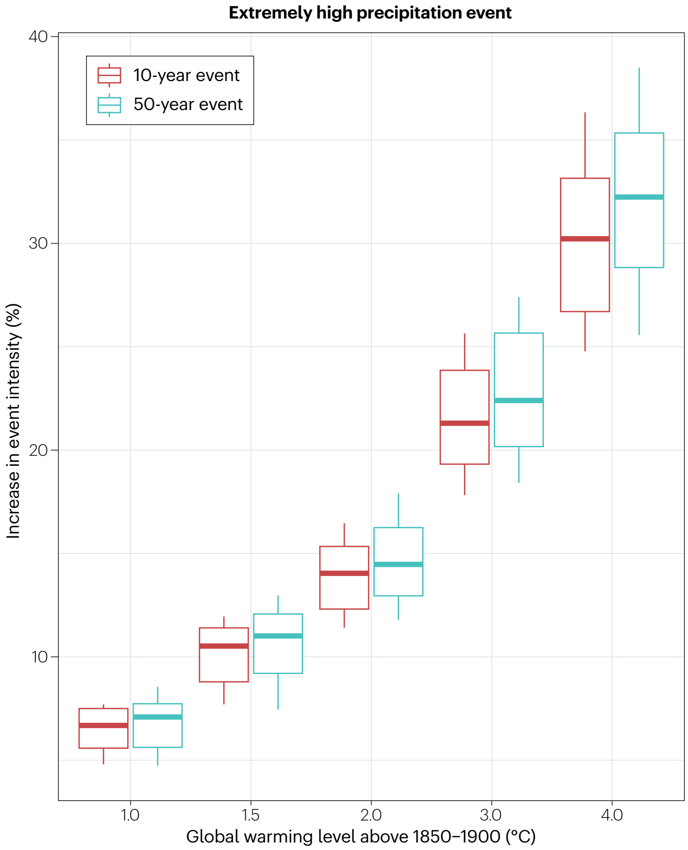

Fig. 2 | Increasing flood risk with climate change. Projected increase in daily rainfall intensity of 10-year (red) and 50-year (blue) events as a function of anthropogenic warming relative to 1850–1900. Boxplots represent the 5th and 95th percentile intensity whereas boxes represent the 17th and 83rd percentiles, and the central horizontal line represents median intensity (ref. 53). At 1.5 °C and 2 °C warming, 10-year rainfall events are expected to increase in intensity by 10.5% and 14%, and 50-year rainfall events by 11% and 14.5%, respectively.

is projected to increase across the globe[58]. Thus, the combined changes in rainfall and evapotranspiration will have interactive effects on water balance and availability in cities in these regions[59], potentially leading to water scarcity.

Although there is some uncertainty in the magnitude of climate-driven changes in urban hydrology, the consensus is that problems related to urban stormwater management will increase in frequency[60]. Urban areas in regions subject to enhanced rainfall intensity will experience more frequent flooding. In addition, the capacity of combined sewers will be exceeded more frequently, with greater volumes of untreated wastewater overflows being discharged to the environment[29,61]. Similarly, projections of longer droughts followed by intense rainfall events will, potentially, reduce the performance of nature-based solutions using vegetation to improve water quality and flow regimes[62]. As a result, cities around the world are investing in major upgrades to their stormwater infrastructure. For example, Montreal, Canada, has invested in the installation of both flood detention infrastructure and green infrastructure (for example, swales and rain gardens) to mitigate projected increases in the frequency of flooding and sewer overflows[48].

The effects of climate change on stormwater are likely to cascade with the effects of increasing urbanization and densification[63] owing to the expansion of impervious surfaces, particularly in rapidly developing cities[64]. Thus, stormwater managers will need to account for these compound risks, rather than individual factors, and improve the performance of drainage systems in both existing and developing urban areas.

Emerging pollutants

Urban hydrology transports pollutants to downstream receiving waters, creating additional, evolving concerns. Urban areas are a source of many pollutants and concentrations are often elevated in urban stormwater, owing to mobilization of pollutants during enhanced flow[31,65]. Stormwater pollutants are either dissolved, such as nitrate, or particulate, such as sediment-bound phosphorus. Removal of high concentrations of a wide range of pollutants, including heavy metals, hydrocarbons, sediment and nutrients[31,65], is an important but challenging aspect of urban hydrology management. Dissolved pollutants, such as some hydrocarbons and trace metals, are the most difficult to remove as they often pass through filtration media and are leached out following initial retention[66,67].

Since the 1990s, treatment systems have been developed to reduce pollutant loads and concentrations of stormwaters, initially focusing on gross pollutants, such as anthropogenic litter, but increasingly targeting dissolved and small particulate contaminants[68]. Such treatment systems include nature-based solutions such as wetlands, bioretention systems and infiltration trenches, as well as grey infrastructure involving settling tanks or granular filtration systems[68].

New challenges to managing stormwater quality are being posed by pollutants of emerging concern. These pollutants, often referred to as micropollutants, are found in trace amounts in the environment and might not be removed by existing treatment systems. They include pharmaceuticals and personal care products, microplastics, pesticides, herbicides, fungicides, stimulants, persistent organic pollutants and trace metals[69,70]. Advances in the design of stormwater treatment measures since around 2015 have improved micropollutant removal by using activated carbon or biochar, and bioaugmentation of microbiomes in filtration media[71]. However, monitoring of micropollutants remains expensive, and their spatial and temporal dynamics are poorly understood[72]. Attempts have been made to develop fingerprinting methods to estimate the proportional contributions of various sources to pollutants in stormwater through comparison of stormwater and source concentrations[73]. These methods work by measuring the concentrations of the pollutants in various sources (such as rainfall, wastewater, run-off) and then constructing a mass balance to estimate the proportion of each source in samples from receiving waters.

With a combination of increasing population density, a shift in the intensity of rainfall events and a suite of emerging pollutants, urban stormwater managers face an increasingly complex task. Their challenge is also increased by evolving expectations from the communities that they serve.

Changing expectations and perceptions

The way in which urban hydrology management is considered is evolving, reflecting changing societal expectations, including reducing environmental impacts, delivering ecosystem services and using stormwater as a resource. These aspects are now discussed.

Reducing environmental impacts

Since around 2000 there has been a shift towards a more holistic focus on urban water management that also aims to protect streams from degradation[36]. This environmentally motivated approach aims to return a more natural water balance and flow regime, improve water quality and reduce export of pollutants to downstream receiving waters, provide water within cities and enhance the urban landscape, providing amenity and ecosystem services to urban communities[36].

Expectations for protecting relatively unimpacted natural streams from future development differ from those of restoring streams already degraded by urban development, in turn influencing ecosystem-based management objectives. For example, approaches to protect relatively pristine streams focus on maintaining near-natural hydrology, either using natural or pre-urban reference[74,75] or pre-urban erosion potential based on hydraulic analysis of modelled stream-flow under different stormwater scenarios[76]. Restoring lightly impacted streams can take a similar approach[77,78] with interventions that aim to reduce the stressors below degradation threshold levels, acknowledging that if hysteresis responses exist, more extreme measures to reduce stressors might be needed to improve ecosystem health[79]. Conversely, in degraded urban streams, restoration goals aim to create ecosystem structure and functions that can provide services and social benefits[80], rather than restoring natural conditions. For example, highly modified urban waterways and human-constructed water features, such as canals, stormwater ponds and ornamental ponds, can still provide some (albeit limited) degree of water storage, nutrient processing, habitat for flora and fauna, and opportunities for human connection to nature[81,82].

Perceptions of hydrological systems in management objectives are also changing, to consider their connectivity at the landscape scale. Multiscale approaches that benefit all streams within the drainage network can best protect urban streams[83], rather than focusing on protecting downstream lakes, estuaries or bays. For instance, protecting or restoring large downstream receiving waters, such as reducing pollutant loads to a lake or estuary[84], can encourage downstream interventions, but inadvertently neglect the small and important headwater streams in the upper catchment. Headwater streams are the smallest drainage lines that make up the beginnings of the natural drainage network in the upper catchment, joining downstream to become rivers. These headwater streams provide essential ecosystem functions, including allochthonous carbon sources, nutrient cycling and groundwater recharge[85,86], and harbour unique biodiversity[87,88], but are often piped and built over[89,90]. The best opportunity to restore both headwater systems and downstream waterways is through distributed stormwater management approaches that focus on harvesting, infiltrating, filtering and encouraging evapotranspiration of stormwater run-off, throughout watersheds[33,74,91].

Considering the context of the landscape and the hydrological setting is also key to delivering effective management objectives. Although urbanization leads to homogenization of ecosystems[92], viewing urban stream ecosystems as homogeneous obscures regional heterogeneity in processes and prevents targeted and effective management solutions[93]. For example, urbanization of streams in arid environments has vastly different impacts to urbanization in humid environments[94]. Accounting for such specificities is an important principle in developing strategies to protect the natural flow regime[75].

Delivering ecosystem services

As urban stormwater management has evolved towards a more water-sensitive approach, provision of ecosystem services has also become an increasingly important objective[95,96]. Ecosystem services can be centred around waterways themselves, or around the broader waterway corridor or even the broader urban landscape (Fig. 3). For example, urban waterway corridors are now valued for their passive recreation and aesthetic values[97,98] and wider services include green open spaces, enhanced water supply and carbon sequestration. Reflecting a broader trend in urban landscape management towards nature-based solutions, these solutions aim to protect, conserve, restore, sustainably use and manage natural and modified ecosystems. In doing so, nature-based solutions also help address social, economic and environmental challenges, and support human well-being, ecosystem resilience and biodiversity benefits[99]. As such, strategies relying on green infrastructure, such as vegetated stormwater systems, are nature-based solutions and connect the agendas of urban water management with planning principles for sustainable cities[36,100].

The level of ecosystem services varies widely across the suite of nature-based solutions[101]. The type of solution, ranging from green open spaces to high-tech green roofs[102], influences its benefits in terms

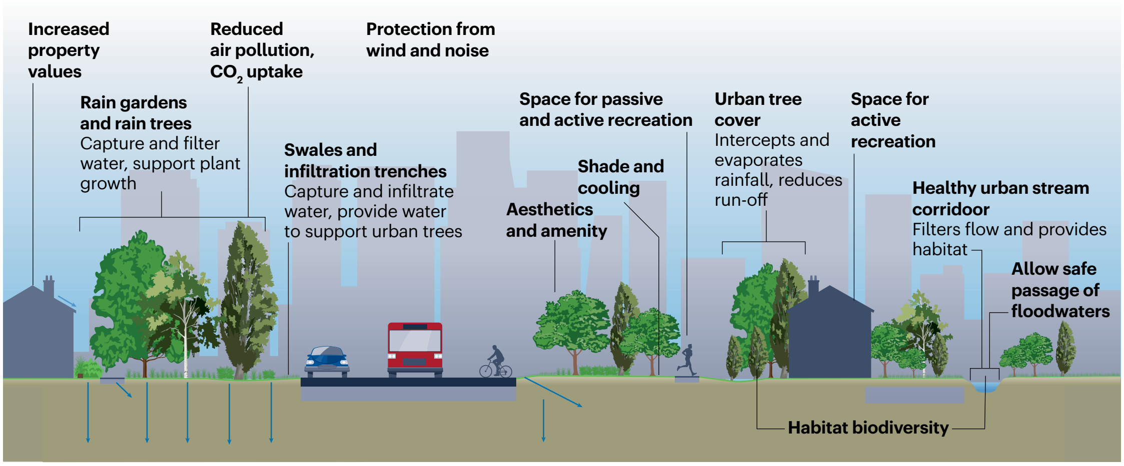

Fig. 3 | Ecosystem services delivered by stormwater management. Different nature-based stormwater control measures and their associated benefits and co-benefits, also termed ecosystem services, that can be delivered by multifunctional stormwater management approaches. Delivery of such ecosystem services is vital for community well-being but also critical to building investment cases around stormwater management approaches that better protect the environment.

of stormwater management and other ecosystem services. In addition, the social, ecological and technological context mediates the level of service for a given type of structure. For example, social benefits and the demand for green infrastructure vary with residents' education and income[103]. Ecological, biogeochemical and climate factors will likely influence the potential of green infrastructure[101]. Technological legacies, such as a combined or separate stormwater drainage network, also influence the potential benefits of vegetated systems, with a greater focus on avoiding peak flows and combined sewer overflows, which may result in damage to vegetation through scour and erosion or through smothering with high loads of organic matter.

The complex and adaptive social, ecological and technological subsystems that make up a city highlight the potential trade-offs and conflicts between different solutions. For instance, a street tree provides important benefits for heat mitigation, but at the expense of water availability, which is a priority in arid cities. Co-design approaches supported by science can help address these issues through identifying solutions that suit the city or neighbourhood. Decision-support tools illuminating these trade-offs have become more common since the early 2000s (ref. 104), some with a focus on urban water management[105].

Stormwater as a resource

The use of stormwater as a resource has been increasing globally[12]. Volumes of water available via stormwater can be substantial; for example, many Australian cities generate volumes of stormwater run-off of similar magnitude to their total potable water supply each year (Fig. 4). Applications of stormwater harvesting can range from household-scale systems supplying water for toilet flushing, clothes washing and even drinking, as has been widely undertaken, for example, in Australia and Italy[106,107], to precinct-scale schemes that provide water for substantial irrigation, as has been used to great effect in both the United States and Australia[108].

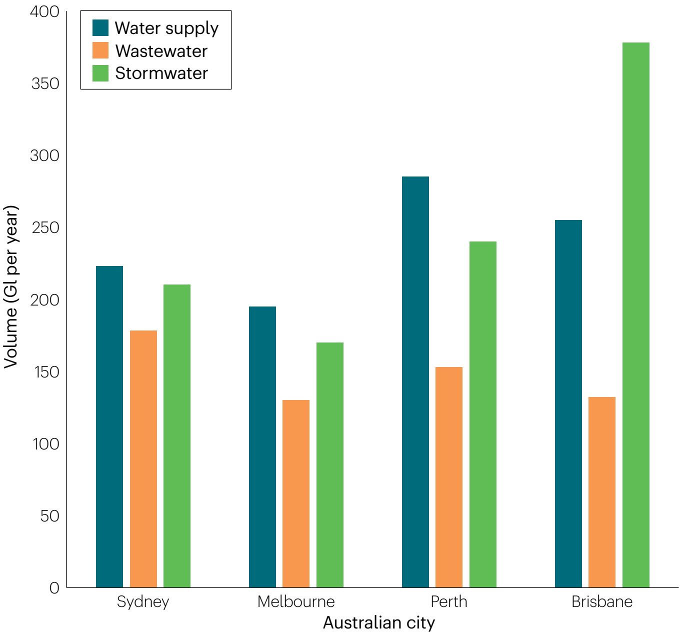

Fig. 4 | Stormwater as a resource. Volume of water supply (blue–green), wastewater (orange) and stormwater (lime green) of four major Australian cities in 2004–2005. In most cities, the volume of stormwater is of similar magnitude or exceeds water demand, demonstrating the potential of stormwater to augment or replace existing water supplies and help address water shortage issues[185].

Uptake of stormwater as an alternative water supply depends on public perception and policy regulation. Acceptance of rainwater harvesting from surface run-off from roofs can be as high as 96% for non-potable uses[109], and acceptance of using stormwater as a supplementary water supply is generally high[107]. The Little Stringybark Creek Project in Melbourne, Australia, is an example of hundreds of residential rainwater and stormwater harvesting systems being successfully installed[77], improving public perception through education and trust-building[110]. In this project, most harvested rainwater was directed to non-potable uses, such as toilet flushing, clothes washing, hot water usage and garden watering. In another example, a residential development called Aquarevo in south-eastern Australia[108] involved a local water authority and a property developer collaborating to build new homes with real-time controlled rainwater tank systems installed. The tanks supply hot water to the homes and feature ultraviolet treatment with a fail-safe and potable back-up to ensure water supply of good quality. These examples illustrate how structural and non-structural measures can improve perceptions of stormwater as a resource.

Regulation can further influence, and in some cases limit, the uptake of stormwater harvesting. For example, in France, laws restrict the use of rainwater to toilet flushing and cleaning the ground[111]. Removing regulatory constraints can help promote the uptake of rainwater tanks and use of stormwater to help supplement water supplies[112].

Stormwater harvesting can also alleviate nuisance flooding[113] and riverine flooding[114], in addition to helping mitigate drought effects[115,116]. Catchment-scale implementation of tanks also potentially improves in-stream water quality[117]. Benefits can extend even further to human thermal comfort through using stored water for irrigation to deliver microclimate cooling effects[108]. Promoting these additional benefits of stormwater use are critical to increasing uptake and adapting policy to deliver stormwater harvesting as an integrated solution to support water supply and greater environmental and human outcomes in cities.

Despite the benefits of stormwater harvesting, its implementation needs to be considered in the context of governance. Widespread use of rainwater tanks at the household scale acts to transfer the responsibility of managing water supply from government to individuals[118]. This transfer might accentuate inequality, for example by providing enhanced security of water supply only to the households able to afford investment in rainwater tank systems[119].

Changing technologies

In addition to evolving social perceptions, rapid changes are taking place in the technology used to manage urban stormwater. Technological advances in managing stormwater control measures, monitoring stormwaters in real time and rainfall forecasting are discussed.

Increase in stormwater control measures

Owing both to technological advances and to changes in community expectations, stormwater control measures are an increasingly common approach to managing urban hydrology[120]. Stormwater control measures aim to improve water quality, deliver more natural flow regimes and restore a more natural water balance, consequently reducing flood risk and reducing downstream pollutant loads and degradation. Stormwater control measures encompass a broad range of technologies, including stormwater ponds and wetlands, swales

Fig. 5 | Stormwater control measures. Stormwater control measures can be integrated into the urban landscape to provide aesthetic and amenity benefits, in addition to retaining, detaining and treating urban stormwater run-off. **a**, Stormwater infiltration pond, Villeurbanne, France. **b**, Stormwater run-off-irrigated street trees, Montreal, Canada. **c**, Porous pavement, Valence, France. **d**, Wetland and rain garden, Singapore. **e**, Rainwater tank, Melbourne, Australia. **f**, Streetscape rain gardens, Montreal, Canada. **g**, Streetscape rain gardens, Melbourne, Australia. **h**, Car-park infiltration swale, Villeurbanne, France. Photograph credit: Frédéric Cherqui.

and filter strips, infiltration trenches and basins, porous pavements, vegetated roofs, rainwater tanks, gross pollutant traps, filtration and bioretention systems[121,122] (Fig. 5). These measures increasingly deliver multiple ecosystem services, for example, through providing local landscape amenity, increasing biodiversity and mitigating the urban heat island effect[123]. However, political, institutional and technical barriers can limit broad implementation of stormwater control measures[104,124]. For instance, a lack of technical expertise within institutions might discourage adoption of new technologies[124], and conflicts with other infrastructure and services could also make widespread adoption complicated[77].

Vegetation is often used in stormwater control measures to help achieve multiple benefits. Vegetation enhances pollutant removal[125], reduces run-off through evapotranspiration and maintains the porosity of stormwater filtration media through root-created preferential flow pathways[126]. Certain plant traits are well suited for use in stormwater control measures, such as the ability to tolerate wetting and drying cycles[127], strong nutrient assimilation rates and a dense, well-developed network of roots[128], and can help achieve the best water quality treatment performance[128] and maintain system porosity[126] in bioretention systems. Conversely, stormwater control measures designed only to treat water quality, without providing other benefits, often use no vegetation and filtration is instead facilitated by manufactured and targeted filtration media, such as granulated activated carbon[129]. In these systems, filtration media specifications can be targeted towards the removal of particular pollutants of concern, such as pathogens[130].

Infiltration is often a central function of stormwater control measures as it reduces the run-off volume and recharges groundwater. Improved understanding of the fate of infiltrated water[131] and contaminant loads[72] has allowed quantification of the contamination risk to nearby groundwater or baseflows. These insights enable contamination to be avoided by careful placement[132] and by use of filter media capable of removing the contaminants of concern[133]. Infiltration systems can take the form of simple trenches or basins, or can be incorporated into the urban landscape through the creation of porous pavements to replace standard asphalt or concrete.

Low-cost monitoring technologies

A further technological advance is monitoring, which is an important component of managing stormwater systems. For example, continuously monitoring water levels in stormwater treatment wetlands can indicate whether an outlet has become blocked by debris, which will lead to a loss of vegetation[134] and reduce the effectiveness of the treatment system[135]. Stormwater infiltration systems also clog over time and monitoring the water-level drawdown time can help schedule appropriate maintenance to remove the deposited silt[136]. In addition, monitoring is required for regulatory purposes, such as reporting the frequency and quality of sewer network overflows into receiving waters[29].

As urban hydrology is highly variable in space and time, it thus requires high-resolution monitoring. Temporal resolution of monitoring should be at short time steps in the order of 5 min and, to ensure adequate spatial resolution, there should be many monitoring sites within the system or drainage network[137]. However, achieving adequate monitoring resolution is usually not possible owing to the high cost of building and maintaining such monitoring networks. Hence, stormwater systems have often been poorly monitored, leading to inadequate maintenance and frequent system failures[138].

The rapid development and popularity of low-cost sensors has substantially advanced urban hydrology monitoring[139,140]. Smart sensor networks offer increased spatial density of measurement points[141,142], bidirectional communication and the ability to integrate sensors and control systems. Versatile and cheap electronics with microcontrollers, such as Arduino and Raspberry Pi, enhance the accessibility and scope of monitoring, and foster collaboration across communities through supporting open-source hardware, software development and open data philosophies[143,144]. Real-time communication offers adaptive control, such as remote set-point change and triggering of actions, and optimizes maintenance of stormwater systems.

The growing production and availability of sensors produced by industry has also led to a reduction in their price, a greater availability of sensors and rapid technological evolution – making smart sensor networks well placed to meet the numerous monitoring needs in urban hydrology[145]. For example, cameras can measure the water level, flow or turbidity, and also identify flood damage[146–150]. Low-cost sensor systems are especially relevant in urban areas, where dense monitoring networks and specialized control systems are required to capture the complex heterogeneity in urban water networks, and where the cyber-security of traditional monitoring and control systems can be problematic[151]. Low-cost networks offer modern security protocols that make unauthorized access into the control network more difficult[151]. The advantages of low-cost systems go beyond their cost-savings; they typically offer near real-time data access, low energy consumption, autonomy, modularity and greater control over the measurement. Crowd-sourcing approaches[152,153], such as measuring rainfall using car windscreen wipers[154], private weather stations[155–157] or surveillance cameras[158], can further support the development of high-resolution real-time monitoring networks.

Forecast capability and real-time control

Advances in high-resolution short-term rainfall forecasting and real-time control (RTC) of stormwater networks are also urban hydrology management. The development of longer-term (typically up to 7 days) and shorter-term (typically up to 11 h for ‘nearcasting’ and up to 1 h for ‘nowcasting’) high spatial resolution rainfall forecasts are vital for managing hydrology during intense rain events. These advances have been driven by the development of radar measurement of rainfall[159] and its integration with data from traditional rain gauges[160]. Social media is also creating opportunities to provide flood warning. For example, mapping apps can identify road blockages during flooding, and flood behaviour can be shared in real time between citizens and emergency services[161].

In parallel, the use of RTC to dynamically operate stormwater networks has increased dramatically. RTC systems automatically respond to changes in observed or predicted conditions across the network – such as changes in flow or water quality[162] – to optimize network management. Although RTC has been used since the 1990s, this early use was primarily for single-objective optimization of large and centralized infrastructure, usually to mitigate flood risk or control combined sewer overflows[16].

Together, these advances allow RTC of stormwater systems to meet multiple objectives, including flood mitigation and water quality improvement[163,164]. Coordinated control of large numbers of decentralized stormwater control measures, rather than single, large systems, has also been made possible[165]. For example, in Melbourne, Australia, modelled RTC operation of a network of rainwater tanks allowed optimization of water supply, flood mitigation and supply of baseflow to streams[18]. Similarly, in another pilot-scale trial in Melbourne, Australia, RTC was combined with nature-based solutions to optimize water quality for protection of receiving waters and supply of harvested water for non-potable water supply[166].

Advances in RTC and forecasting also support improved predictions of stormwater events. With increasingly accurate and high-resolution rainfall forecasts available, predictive model control strategies can operate using longer-term (7-day) forecast windows, updating as the forecast changes and becoming more certain closer to the rainfall event[167], especially with radar-based rainfall nowcasts[160]. Forecast windows that are much longer than the time taken for flow in an urban catchment to be concentrated and reach the outlet allow for slow releases from detention storages in the days leading up to storms, so that the storages are ready to capture and detain rainfall[167]. Similarly, in combined sewer systems, where stormwater and sanitary wastewater are merged, coordinated implementation of nature-based solutions and control of detention tanks can substantially reduce the incidence of sewer overflows during storms[29].

However, a major future challenge to the implementation of RTC for urban stormwater networks is the deployment and maintenance of the large number of sensors[136] needed to provide real-time data to optimize the network operation. Likewise, improved operation through forecasting and predictive control requires major computing infrastructure, to ensure rapid optimization of system operations to match the highly variable and stochastic nature of urban hydrology. Thus, these advances in forecast technologies and RTC might not equally benefit all countries, with modelling of tropical systems in particular still facing important challenges[168].

Governance and business models

Changes in governance, economics and law can help support more sustainable management of urban run-off. These aspects are now discussed.

Aligning benefit providers and beneficiaries

Progress in urban hydrology management has been hampered by a misalignment between beneficiaries of improvements in stormwater management and those who pay for such improvements. As a result, there have been proposals for more innovative funding models, such as stormwater utility fees[169,170]. Such fees create a more sustainable funding model, but the use of credits against these fees shows the most promise, as it can drive behaviour towards reducing stormwater run-off through sharing in cost-savings with landowners[169].

Another approach is offsets. Offsets allow those implementing measures to reduce stormwater run-off to avoid on-site mitigation works by paying for mitigation works elsewhere[170]. However, offsets have been strongly criticized, given the non-transferability of the impact of mitigation efforts[171]. For example, a development in one catchment could be offset by mitigation efforts in a nearby catchment, resulting in the first catchment still experiencing increased run-off and waterway degradation. Thus, stormwater offsets are fundamentally different to CO_2 offset arrangements, for example, where there is no geographic specificity.

Quantifying and valuing the benefits of stormwater mitigation efforts is another approach to incentivize stormwater management measures. Developing reliable and easy-to-implement methods for quantifying and valuing the benefits of stormwater mitigation efforts[172] can support accounting and payment for ecosystem services[173], as is being tested in Melbourne to manage stormwater using privately owned rainwater tanks to deliver improved flow regimes in waterways[17]. Quantifying and delivering ecosystem services through improved stormwater management is challenging, but its potential is greatly enhanced through community engagement and participation[17].

Coordinated and decentralized solutions delivered through collaboration across drainage authorities can help manage stormwater run-off at the source. These decentralized solutions involve collaboration of many landholders and water or drainage authorities[120], thus a challenge is aligning the beneficiaries with investors in nature-based solutions, given the multiple benefits and stakeholders involved[174]. Individual stakeholders are interested in different benefits from the nature-based solutions, depending on who they are and how they interact with the solutions. In addition, building business models for such cases is complicated by the task of monetizing the many and varied socio-ecological benefits, and because these benefits are often common or public good in nature with benefits accruing to multiple stakeholders.

Ownership of stormwater as a water resource

Although stormwater run-off poses a problem, it also delivers a valuable resource. Given the scarcity and relative unreliability of water resources faced by many cities around the world, attempts have been made to develop hybrid supply options for urban water, involving a centralized potable water supply combined with a decentralized supply of rainwater or stormwater[107,175]. Driven by increasing water shortages, further attempts have also included options where stormwater is treated to potable standards and integrated into the full water supply, particularly in water-scarce regions such as the town of Orange, south-eastern Australia[176]. The advent of RTC technology also creates opportunities for business models that financially reward individual owners of rainwater tanks within an urban area for their contributions to water supply, reduction in flood risk and provision of environmental flows during droughts, as is being tested in Melbourne, Australia[16,17] (Fig. 6).

Defining ownership of the water resource is relatively simple at the individual allotment scale, but much more complex at larger scales. Where stormwater from several properties has accumulated, for example in a pipe, issues of ownership become important. Clarity over ownership and rights to such water are critical to supporting investment in large-scale stormwater harvesting schemes[177]. For example, in the United States, harvesting of stormwater has been illegal in many locations because of its potential to impact downstream water entitlements, meaning that enabling household-scale rainwater harvesting has required specific legislative changes, such as by the state of Colorado[119]. For stormwater harvesting to be used at a range of scales to effectively reduce excess run-off, while also creating an important supplementary water resource, jurisdictions around the world might need to implement legal reform to give confidence to investors in stormwater harvesting infrastructure, while also protecting downstream water users and receiving waters from over-extraction.

Summary and future perspectives

Urbanization substantially changes the pathways and fate of rainfall once it falls on the landscape. Impervious areas prevent infiltration, reducing groundwater recharge and contributions to baseflow, and instead enhance surface run-off, creating a highly flashy stream-flow regime. Urban areas generate high loads of pollutants, and the hydraulic efficiency of impervious surfaces and drainage networks result in a marked decline in water quality of receiving waters. Pollution, erosion, habitat loss and a decline in both biodiversity and ecosystem services occur as a result. As urban populations are growing larger and denser, and climate change is leading to higher-intensity storms and more severe droughts and water shortages, there is a societal expectation that urban hydrology be managed in a more holistic way. Doing so can reduce the loss of biodiversity and ecosystem services offered by urban streams, but also deliver a major additional water resource for cities. Achieving this future, however, will require a substantial effort from the

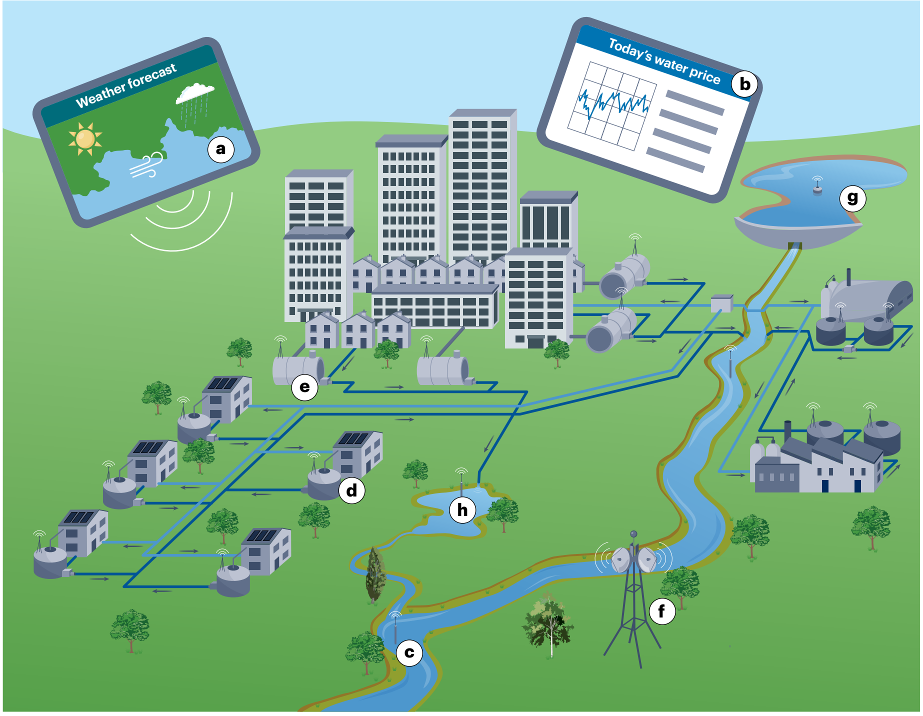

Fig. 6 | A smart rainwater grid. Real-time controlled grid of water storages, informed by sub-daily weather forecasts (**a**) and a water market (**b**) to provide environmental flows to waterways (**c**) or to reduce flooding. Individual households (**d**) or businesses (**e**) receive financial rewards for owning rainwater tanks that contribute to the grid. The grid consists of a central control algorithm and control system (**f**) operated by water authorities and government agencies, combining private and large water storages (**g**) and wetlands (**h**). Smart water grids offer the potential to monitor and manage stormwater and flood risk in real time, in addition to making stormwater available as a resource to supplement drinking water supplies.

international scientific community, to further develop technologies and approaches to governance and investment.

A better understanding of climate change impacts on stormwater management system performance is needed. Representative projections of flooding, water quality, moisture availability to green infrastructure[178] and impacts on urban amenity (such as thermal comfort) can help better inform optimizations of stormwater system upgrades and transformations. Alongside shifting views of aquatic ecosystems towards understanding cities as highly modifying but functioning ecosystems[107], the impacts of climate change on ecosystems and nature-based solutions is also key. For instance, with vegetation being an important component of many stormwater control measures, it is important to account for the well-documented impacts of a changing climate on the health and phenology of plants when designing nature-based stormwater management systems[179]. In addition, protecting waterways ecosystems not yet disturbed by urbanization, climate change impacts on future stream-flow regime and ecosystem health are key considerations in designs of stormwater control measures and management of the waterway.

Improving stormwater treatments to better mitigate the impacts of emerging pollutants relies on a better understanding of their toxicity and fate in the environment. Developing effective technologies and engineering solutions to remove persistent pollutants from urban run-off will require both laboratory and field experiments, including the context of the receiving waters – for instance, greater assessment of how commonly used measures for treating stormwater pollution, such as the constructed wetlands, biofiltration systems and stormwater infiltration, perform in removing micropollutants, and the fate of these pollutants in such measures[72,180]. Understanding which micropollutants are effectively removed by filtration and sorption, and which pass through untreated or subsequently leach out, can give insights into the accumulation and fate of micropollutants retained in stormwater treatment facilities and help eventually remove the trapped materials in an environmentally safe manner[181].

Smart monitoring networks across drainage systems can help enhance performance and facilitate RTC. However, effective and widespread implementation of smart sensor networks requires research effort from both technology developers and technology users to meet the needs of urban stormwater managers. For instance, greater crossover between metrology and prototyping is needed[182], so that new sensor technologies can be developed with a clear understanding of their accuracy (relative to that required) and their useability, as prototyping programming and electronics without knowledge of metrology or hydrologic systems will result in inaccurate or unhelpful measurements. Hybrid systems are now emerging, with some low-cost developers producing more ready to use and accurate systems[151], reflecting an evolution towards a spectrum where users can choose their preferred accuracy, reliability and cost. As these monitoring networks become more widely implemented and long time series are produced, a promising area for development is neural network-based machine learning techniques to underpin predictive models of complex drainage systems, avoiding the need to parameterize complex conceptual models[183].

Nature-based solutions hold opportunities to address stormwater management issues and, simultaneously, provide ecosystem services. For such nature-based solutions, a promising area for advancement is to identify how private investors can capture value from the benefits they create for a range of beneficiaries[174]. Such reward structures might involve a public authority using fiscal instruments, such as charges and taxes, to reimburse private investments in such green infrastructure. However, further economic and social science-based research is needed to identify ways of aligning the beneficiaries of improved stormwater management with the costs of those investments, to offer the best opportunity for incentivizing change and avoid market failure. Delivering such a model also requires better understanding of the social and institutional factors acting as drivers or barriers to change.

Large transformations are required to support the use of stormwater as a resource. Economic research can help build confidence to invest in large-scale stormwater harvesting, through determining the appropriate costing of water as a resource and defining ownership over stormwater as a resource. In addition, learning from environmental transitions in other areas, such as energy, can help build understanding of the social factors that will drive uptake of sustainable stormwater management approaches by individuals and institutions. For instance, approaches applied in the energy market, where households contribute to energy production and storage with solar panels and batteries, could offer similar opportunities through private stormwater tank distribution. Indeed, there is compelling potential for networks of real-time controlled rainwater storages to reduce flooding, protect the environment and supplement existing water resources. Such developments could lead to innovative business models, where ongoing revenue can offset operational and maintenance costs.

The potential of decentralized systems of stormwater management can be further enhanced with improved rainfall forecasting and RTC. For example, networks of household rainwater tanks could deliver distributed supplies of water and flood mitigation services, with homeowners being paid for their contributions to the network's operation, in much the same way as solar panel owners receive a feed-in tariff for their contributions to the electricity network[184]. The network of tanks could be integrated with stormwater control measures throughout the catchment, such as rain gardens within the streetscape or stormwater treatment wetlands downstream. Such systems can optimize the flow regime through treatment facilities, optimizing performance for water quality treatment and also minimizing the risk of overflows. Forecasting and RTC offer the possibility of coordinating networks of real-time controlled detention storages for both wastewater and stormwater, allowing flow rates to maintain within the capacity of the network, even during large storms, so that receiving waters are not impacted by wastewater inputs.

Urban hydrology is at a crossroads. Without transformations in urban stormwater management, stormwater will continue to degrade urban waterways, reduce the amenity of the urban landscape and indirectly contribute to the water scarcity in some regions. However, innovative approaches offer a very different future where stormwater becomes a valued resource and delivers benefits to society and supports healthy urban streams.

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Author contributions

T.D.F., M.J.B., and K.L.R. determined the organization and content of the paper. T.D.F. drafted the introduction and background. T.D.F, M.J.B., K.L.R., P.H., F.C., S.D. and A.H.R. all contributed to drafting the body of the manuscript. T.D.F., P.H., M.J.B. and K.L.R. drafted the summary and future perspectives. All authors contributed to review and editing of the manuscript.

Competing interests

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