# The changing drivers and expectations of urban hydrology

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## Abstract

Urbanisation profoundly affects the hydrology of catchments, with impacts on both humans and waterway ecosystems. Impervious surfaces produce stormwater runoff that is typically 5-10 times that from natural surfaces. Stormwater runoff is a primary driver of urban waterway degradation. In this review, we explore the changing drivers and societal expectations impacting the way urban hydrology is managed. We identify new technologies and business models that give stormwater managers and communities options to manage stormwater to deliver multiple benefits, including reducing flood risk, augmenting water supply, protecting ecosystems, and enhancing urban amenity. Increasing density of cities, combined with climate change, will see future flood risk increase. However, cities now have access to a range of stormwater control measures, which can detain, filter, infiltrate, or evapotranspire stormwater. Likewise, the harvesting of stormwater is increasing, given its ability to reduce runoff, thus protecting receiving waters, but also augment the water resources available to cities. User acceptance of stormwater harvesting has been shown to be up to 96%, and the amount of stormwater often exceeds water demand. Low-cost sensing technologies, combined with real-time control capabilities, create new governance models for managing stormwater, delivering a wide range of ecosystem services to communities. Understanding the social and institutional barriers to these new approaches will be critical to creating a future where stormwater is no longer just a nuisance, but a valued resource delivering benefits to society and to waterways.

## Key points

1. Traditional approaches to stormwater management degrade urban streams.
2. Society now expects stormwater to be managed in a more integrated way, balancing flood risk, environmental protection, and opportunities to use stormwater as a resource.
3. Climate change and increasing population density will exacerbate stormwater impacts and increase challenges related to management of stormwater.
4. Greater understanding of stormwater impacts on receiving waters is producing a more nuanced conception of protection/restoration goals and consideration of impacts at multiple scales down to the smallest headwater streams.
5. The mainstreaming of ecosystem service provision as a goal of stormwater management is leading to new decision support tools and design approaches.
6. Improved forecasts, and new sensor and real-time control (RTC) technologies have opened up new ways of managing urban stormwater – both to protect the environment and to reduce the threat of water shortage in cities.

7. New approaches to governance, funding and maintenance, and the involvement of new actors in hybrid centralised-decentralised approaches offer the potential for more sustainable management of urban stormwater, including its use as an important water resource.

## Introduction

Urban hydrology describes the properties, movement and quality of water through the urban landscape. Hydrology in urban areas is characterised by major perturbations to the natural water cycle, brought about by the introduction of impervious surfaces (such as roads, roofs, footpaths) and constructed drainage systems, designed to evacuate water from the urban landscape, to reduce local flood risk (albeit with the common consequence of exacerbating downstream flood risk[1]). This approach increases stormwater runoff during rain events[2], but also changes the flow regime in urban receiving streams when it is not raining, as impervious areas reduce infiltration into soils, thus commonly reducing groundwater levels[3]. Lower groundwater means less contribution to stream flows in dry weather, although this can be offset in some places by other factors such as leaks from water supply networks or from over irrigation[3,4].

Urban hydrology profoundly affects both humans and ecosystems. Flooding can impact life and property, while changes to flow regimes and water quality degrade streams, causing a loss of biodiversity and ecosystem services that streams provide[5]. Changes in water movement through the urban landscape also affect urban vegetation[6], potentially exacerbating the threatening effects of droughts and heatwaves[7]. Flood risks grow as urban density increases, increasing impervious areas and thus volumes of runoff that flow downstream[8].

While mitigating flood risk remains a primary objective of urban management, the societal expectations of urban hydrology management have changed since around 2000, to include other objectives and address new challenges. There is much greater demand from communities that the environmental impacts of urban development – pollution, erosion, loss of habitat and urban amenity – be mitigated along with reducing flood risk[9]. With increasing water scarcity in significant parts of the world, there is also demand in these areas for alternate or supplementary water supplies, and increasing recognition that capturing urban runoff has multiple, important benefits[10,11]. Cities also face challenges relating to increased population density (and thus greater coverage of impervious surfaces) and a changing climate (with trends towards increasing rainfall intensity and incidence of drought in many regions[12]). These threats potentially render stormwater systems unable to meet their current design objectives, let alone to meet the increasing societal expectations of delivering multiple objectives.

The advent of new technologies opens up previously impossible solutions to managing stormwater. The use of low-cost sensors and the Internet of Things create the possibility to create “smart stormwater networks”, which are optimised through real-time control to simultaneously reduce floods, deliver suitable water quality and flow to streams, irrigate the urban landscape, and provide supplementary water supplies[13]. With careful design, there is potential for such technologies to help in addressing the water shortages in many cities around the world, help to provide environmental flows for threatened species living in urban and peri-urban streams, and involve and financially reward the community for their role in managing private “smart stormwater storages”, in the same way as homeowners in many cities around the world are now rewarded for the electricity generated by rooftop solar panels[14,15].

In this Review, we identify the emerging changes in the field of urban hydrology, including the changes to drivers such as population, urban density and climate. We also explore the changing societal expectations of the way urban stormwater is managed, not only as a threat (to the environment and of flooding), but also as a potential resource to alleviate urban water scarcity. Lastly, we identify new opportunities that could transform the way water is managed in cities, including low-cost sensor technologies and the advent of distributed real-time control – allowing stormwater and water supply systems to be optimized with both centralised and decentralised elements – and new business models for stormwater management.

## Urban hydrology background

The need to provide for drainage of human settlements dates back to at least the Minoan Civilisation[16]. Along with water supply and sanitation (removal and management of human waste), urban drainage has been a central preoccupation of humans as they began to coalesce into what we now call “cities” and “towns”.

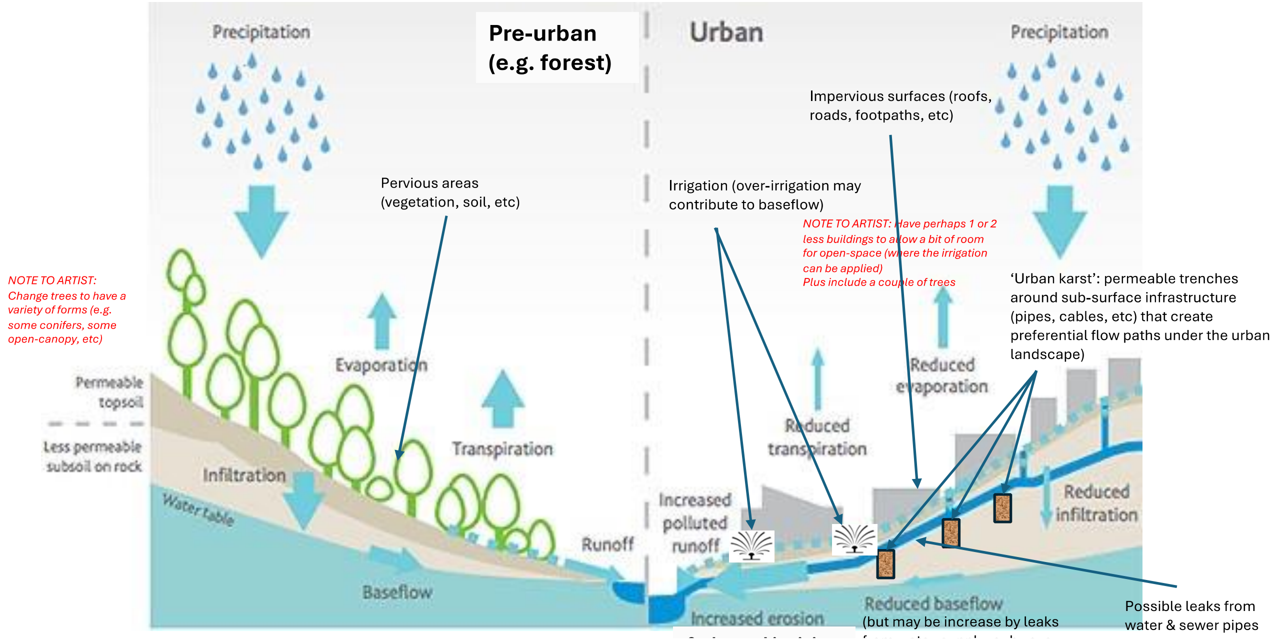
Broadly speaking, drainage in cities and towns around the world is achieved through one of two means: separate sewers (where stormwater and wastewater are carried in separate pipe networks) or combined sewers (where sanitary and stormwater are combined). In systems with separate sewers, stormwater is typically conveyed to receiving streams (typically without prior treatment to improve quality), while wastewater is conveyed to a wastewater treatment plant. In combined systems, the treatment plant is designed to treat both stormwater and wastewater. However, the highly variable nature of stormwater means that the treatment or transport capacity is often exceeded, resulting in untreated water being discharged to urban streams[17].

A fundamental component of hydrology is to understand the fate and pathways of rainfall as it falls on the earth’s surface. Urban hydrology is characterised by the major perturbations to these processes that result from the creation of impervious areas, the construction of urban drainage networks, and the changes to vegetation and soil properties[18]. In urban catchments, the predominant pathway of rainfall is over impervious surfaces (and potentially over compacted soils) and then through constructed pipe networks. This is in stark contrast to natural catchments, where most rainfall infiltrates (typically slowly) into soils, and is subsequently either transpired by vegetation or percolates through to groundwater, and subsequently contributes to baseflows in streams (Figure 1).

The flow paths in urban catchments are theoretically “simple”, being dominated by runoff over impervious surfaces and then flow conveyed along constructed gutters, drains and pipes, rather than the complex pathways of natural areas, where soil, vegetation, topography and bedrock can all interact to change the movement and fate of water. In reality, however, urban flow paths can often be more complex than they appear. Buried infrastructure in cities (such as pipes, conduits, foundations) radically change the movement of water, often resulting in water draining rapidly from urban soils[19]. Water which infiltrates into urban soils can often take preferential paths along infrastructure trenches[20,21].

Urban hydrology is often described as “flashy”, reflecting the large volumes of runoff produced by even small rainfall events, and the speed with which they are conveyed to receiving waters through pipe networks. Indeed, the coefficient of runoff (the amount of rainfall that becomes runoff) from an impervious surface can exceed 90%[22], while in natural catchments made up of forest, the same rainfall might result in less than 10% of rainfall becoming runoff[23]. Conversely, urban streams often experience much lower flows in dry weather, resulting from impervious surfaces preventing infiltration and recharge of groundwater[24]. Effects on baseflow are however complex; over-irrigation, leakage from drinking water pipes and sewers can all add to groundwater stores and thus increase baseflow, and wastewater discharges can dramatically increase baseflow in some urban streams[3,25,26].

Combined, these changes to hydrology result in the degradation of receiving water channels because of increased peak flows during wet weather (causing erosion and loss of habitat diversity), along with a loss of wetted habitat in dry weather due to often-reduced baseflows[27]. The quality of water emanating from urban catchments is typically poor, resulting both from the many sources of potential pollution in cities and towns and from the hydraulically efficient flow paths that act to transport these pollutants downstream[28,29].



NOTE TO ARTIST: Change trees to have a variety of forms (e.g. some conifers, some open-canopy, etc)

NOTE TO ARTIST: Have perhaps 1 or 2 less buildings to allow a bit of room for open-space (where the irrigation can be applied)
Plus include a couple of trees

**Figure 1.** **Urban water balance changes related to urban stormwater.** Changes to flow pathways and water balance as a result of urbanisation, shown by arrows. The size of the arrow represents the relative size of the flux. The urban karst represents the permeable trenches surrounding underground infrastructure (pipes, cables, etc), which act to create a preferential flow path for water which infiltrates into the soil in urban areas. Urbanisation results in a major loss of evaporation, infiltration and transpiration, while increasing runoff directly entering waterways. Impervious surfaces typically produce five to ten times more runoff than do natural surfaces. **[to be re-drawn prior to publication]**.

As the understanding of urban hydrology has become more sophisticated, arguably so too have the philosophies underpinning its management. Just as urban ecology has been described as evolving from an ecology "in the city" to an ecology "of the city" and ultimately towards an ecology "for the city" [30], hydrology has arguably evolved from having a single focus of understanding the movement of water in the city to a focus on water flows in urban ecosystems and "creating the city" that delivers water-related ecosystem services to its inhabitants. While past approaches were characterised by large-scale centralised solutions, with the aim of evacuating water from the urban landscape, emerging approaches increasingly focus on a mix of centralised and more local "at-source" solutions[31]. These aim to reduce flood risk, while protecting receiving waters from pollution and degradation, and enhancing the urban landscape[32]. Such approaches can potentially also result in greater community involvement in solutions to the challenges posed by urban hydrology[33]. In addition, emerging approaches rely on vegetated systems termed blue-green infrastructure, which use vegetation and mimic natural processes in an attempt to improve water quality and flow regimes – including raingardens, green roofs, swales, and retention basins[31,34]. These solutions form part of a larger umbrella of so-called nature-based solutions (NBS) in cities that aim to provide benefits to people and biodiversity[35,36] (see Section *Delivering ecosystem services*).

## Changing drivers

In this section we outline the principal factors affecting the management of urban hydrology. We firstly focus on the increase in population and the density of cities, with consequences for flow regimes and the demand for water. We then consider the impacts of climate change, particularly on flood risk, but also on the security of water supplies, before examining the question of stormwater quality, its treatment, and the emergence of micropollutants of concern.

### *Population and urban density*

The number of people living in cities is rapidly increasing. Some 58% of the world's population now live in cities (up from 30% in 1950) and this is expected to grow to 68% by 2050, with more than half the world's countries having a majority urban population by that time[37]. However, this global urbanization trend varies by continent and region, with Africa and Asia particularly undergoing rapid urban growth. In Africa alone, the urban population is projected to increase by around 57% between 2018 and 2030[37]. Urban population growth is characterized by both expansion and densification. Expansion, the conversion of rural or forested land to new urban land, entails wholesale removal of vegetation, dramatic increases in impervious surfaces, and thus increases in stormwater runoff[38].

In an effort to make cities more sustainable[39], strengthen local economies [40] and prevent habitat and biodiversity loss[41], many cities are increasingly being renewed and densified, involving subdivision of lots, replacement of single-family homes with multi-family and mixed-use buildings, and construction of large apartment complexes and commercial buildings. This has substantial ramifications for urban hydrology, with the proportion of impervious area typically increasing, thus increasing the amount of runoff generated for a given rainfall event[42]. It also results in less space being available for grey and green infrastructure to address changes to hydrology, along with less green space for irrigation[43], making the creation and protection of green spaces during urban renewal even more vital. Existing conventional stormwater drainage systems—designed for less dense urban landscapes—begin to deliver a lower level of service to the community. Stormwater-related flooding becomes more frequent and damaging [44,45].

In cities where a combined sewer carries the flow of stormwater and wastewater, the frequency with which untreated wastewater spills onto the street or into waterways commonly increases with urbanization and thus with increasing population density. For example, in the UK there are more than 20,000 'permitted' combined sewer overflow structures, with the Thames receiving some 50-60 overflows per year alone [46]. This poses a risk to both humans [47] and the environment [48]. Upgrading existing sewer networks in urban areas is very difficult and expensive, and made even more so as the density of development increases, given the difficulties in accessing pipes under existing buildings and urban infrastructure.

While land use change through urban development and redevelopment undeniably poses challenges for the management of urban hydrology, it also creates opportunity for creation of new infrastructure to facilitate better stormwater treatment and flood protection. Such changes, which often result from changes to income distribution, particularly in developing countries[49], also create the opportunity to design urban water management using current knowledge, on a fresh canvas. Doing so, however, often faces challenges. These may include constraints such as integration with existing infrastructure and competition for space, or the increased up-front cost of reserving space, protecting headwater streams, and installing lot-scale and street-scale stormwater control measures. In the absence of an established community to advocate for beneficial solutions, the status quo of traditional urban drainage can often prevail[50].

Given the inevitable increase in population and urban density, research is needed to (i) identify and develop new technologies that will deal with the water balance and water quality impacts of urbanization, but which require the least possible space, (ii) identify ways of encouraging developers and citizens to contribute to more sustainable stormwater management, for example through the implementation of market-based instruments.

### *Climate change*

Documented and projected changes to the earth's climate[12] have major implications for the urban water cycle. Climate change was linked with intensification of short-duration rainfall events globally[51] (Figure 2). Most models predict these effects across the majority of the world's major cities, particularly in North America and Asia[52]. More intense rainfall leads to greater surface runoff generation, both in terms of total quantity and peak flow[53]—especially in urban catchments where catchment soils have reduced storage capacity [54]. Combined with the effects of sea level rise on coastal areas, this will result in substantial increases to flood risk.

The changes in climate will lead to more frequent flooding and overwhelming of the capacity of sewers[55] in urban areas, as well as increases in the frequency[56] or volume[57] of untreated wastewater discharged to the environment via combined sewer overflows. In rapidly developing cities, these climate change-related problems can be aggravated by the accelerated growth of impervious areas, such as reported by Zhou, et al. [58]. There is uncertainty in the expected magnitude of changes in urban hydrological indicators, but the direction towards more frequent problems related to urban stormwater management is now universally recognized. This is leading cities around the world to invest in major upgrades to stormwater infrastructure; the Canadian city of Montreal is but one example, with major investment being made in response to predicted increases in the frequency of flooding and sewer overflows[59].

Flooding is not the only problem that cities will face: annual rainfall is projected to increase in some areas and decrease in others [60], while evapotranspiration is projected to increase across the globe [61]. Changes to both rainfall and evapotranspiration will have interactive effects on the water balance and water availability in cities [62].

Climate change is thus increasing the need to find solutions which maintain and improve the performance of urban drainage systems, but at the same time, it will impact on the ability of these solutions to achieve their goals. For example, the likely longer periods of drought, followed by more intense storm events, will reduce the performance and increase the maintenance costs of nature-based solutions, which use vegetation in an attempt to improve water quality and flow regimes emanating from urban areas[63].

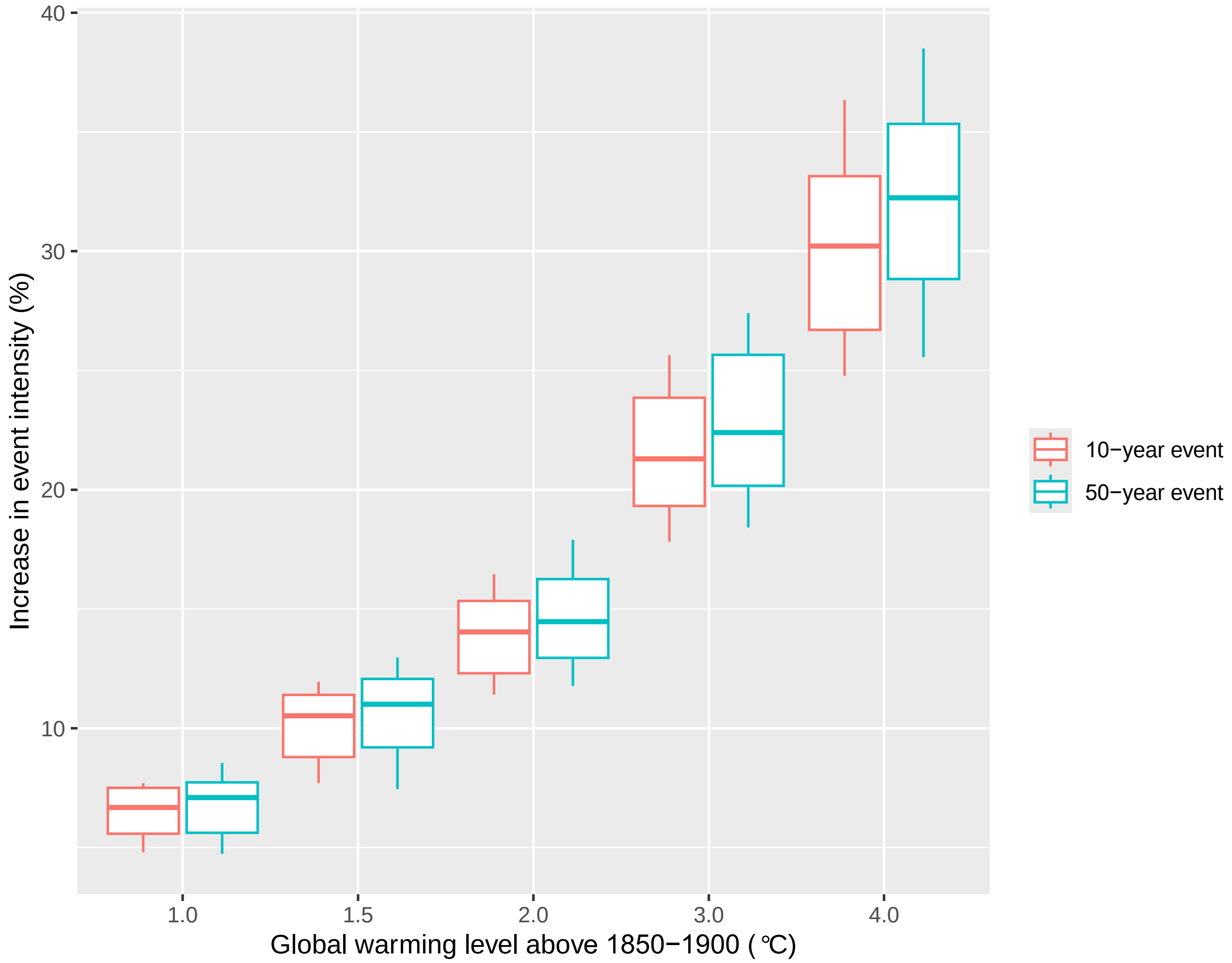


**Figure 2.** **Increasing flood risk with climate change.** Projected increases in rainfall intensities as a function of a changing climate. Figures produced from data from IPCC, 2021[64]. For every half-degree increase in global temperatures, rainfall intensities will experience noticeable increases, which will accelerate for warming above 2.0°C.

The effects of climate change on stormwater are likely to cascade with the effects of increasing urbanization and densification[65], resulting in compounding of risks and subsequent impacts on (for example) the wastewater system and potentially even on water supply systems. Stormwater managers will thus need to undertake analyses of these compound risks in the future, rather than assessments of degradation in performance due to individual factors.

Research efforts are needed to better understand the climate change impacts on the performance of stormwater management systems, relative to their design intent, to inform optimisation of investments in upgrades and transformation of stormwater management assets. Research examining future scenarios will need to inform not only future flood projections, but projections around the moisture availability to green infrastructure (such as street trees installed to receive passive irrigation from stormwater[66]). This is particularly important given the critical role vegetation plays in many stormwater control measures, and the well-documented impacts of a changing climate on the health and phenology of plants[67].

### *Emerging pollutants*

The changes to hydrology through creation of impervious surfaces and the simplification of flow paths result in increased concentrations and loads of pollutants[28,68], the management of which is part of the overall challenge of urban hydrology. Urban areas are a source of many pollutants, resulting from both processes occurring and materials used in urban environments (buildings, roads, cars, etc.). Unsurprisingly, urban stormwater has high concentrations of a wide range of pollutants such as heavy metals, hydrocarbons, sediment and nutrients[28,68]. Stormwater pollutants can be either dissolved (such as nitrate) or particulate (such as phosphorus bound to sediments); in general the dissolved pollutants are the most difficult to remove[69]. In the last two decades, stormwater quality treatment systems have been developed to reduce the concentrations and loads of these pollutants, before they enter receiving waters. Initially, the focus of stormwater quality was primarily on gross pollutants (such as anthropogenic litter), but increasingly treatment systems are designed to deal with the 'invisible' pollutants, including dissolved and small particulate contaminants. 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.

There are a wide range of pollutants of emerging concern, such as pharmaceuticals, microplastics, pesticides, herbicides and fungicides[70], that might not be removed by existing treatment systems. These pollutants are often also referred to as micropollutants, which are found in trace amounts in the environment. They include pharmaceuticals and personal care products, stimulants, trace metals, microplastics, persistent organic pollutants, and trace metals[71]. Monitoring for such pollutants is typically expensive, and further work can help to understand the spatial and temporal dynamics of these pollutants of concern[72]. Given the large number of these emerging pollutants of concern, researchers have attempted to develop 'fingerprinting' methods, where concentrations of various micropollutants within stormwater runoff are compared with measured or known concentrations in various sources, in order to estimate the proportional contributions to the overall pollutant loads from each of these sources[73].

There are many areas where additional research and engineering solutions could improve stormwater management. One area is understanding how commonly-used measures for treating stormwater pollution (such as the constructed wetlands, biofiltration systems, stormwater infiltration described above) perform in removing micropollutants, and in the fate of these pollutants in such measures[72,74]. In particular, it would be helpful to understand which micropollutants will be effectively removed by filtration and sorption, and which ones pass through untreated or leach out over time after initially being retained. Treatment of dissolved micropollutants (such as some hydrocarbons and trace metals) is particularly problematic, since they often pass through filtration media, or are leached out following initial retention[69,75]. Advances since around 2015 in the design of stormwater treatment measures to improve micropollutant removal include use of activated carbon or biochar, along with bioaugmentation to engineer a microbiome in the filter media[76,77]. A better understanding of the accumulation and fate of trapped micropollutants within stormwater treatment facilities may improve stormwater treatment, particularly given the use of such facilities by animals as habitat and legal requirements to eventually remove the trapped materials and store them in an environmentally safe manner[78].

## Changing expectations and perceptions

In this section we explore the changing way in which the management of urban hydrology is considered, reflecting an increasing societal expectation around protection of stream ecosystems and the delivery of ecosystem services to benefit urban communities. We also examine the way in which stormwater is increasingly seen as a water resource, rather than as a nuisance, and discuss the implications this has for stormwater management approaches.

### *Managing urban hydrology to reduce environmental impacts*

Typical approaches to managing urban hydrology result in degraded stream ecosystems (habitat loss, reduced water quality, loss of biodiversity) and therefore in a loss of ecosystem services provided to urban communities. While many factors affect the health of urban streams, hydrology is considered to be a master variable[5]. Hydrology also drives pollution (because it acts to mobilise and transport pollutants in the catchment into the receiving waters) and is the main driver of erosion and channel degradation. Degradation can occur at very low levels of urbanization, with substantial loss of instream species occurring when impervious areas draining to the stream via pipes make up much less than 10% of the catchment[79,80].

Recognising the impacts of traditional urban water management approaches on urban streams, there has been a shift since around 2000 to a more holistic focus. Protection of streams from degradation has become as important as the drainage function for which urban stormwater has traditionally been managed[34]. This more environmentally-focussed approach aims to protect waterways and to maximize the delivery of ecosystem services, both by streams and across the urban landscape more generally. This change in focus has been driven by community expectations[81], for example as urban waterway corridors have become valued for their passive recreation values[82]. The extent to which communities will push for – and be receptive to – improved stormwater management, depends on their attachment to their neighbourhood, including their degree of social connection and a sense of being collectively capable of action[83]. The attachment to local neighbourhood is consistent with the conceptual framework of Haywood, which identifies place, community and nature as creating a sense of attachment, that will regulate pro-environmental behaviour[84]. Arguably, the change is also reflective of a broader increase in environmental awareness and an increasing demand for more sustainable practices around water, energy[85], urban biodiversity[86] and the liveability of cities[87].

The general aims of this more recent, environmentally-motivated approach, can be summarized as being to (i) return a more natural water balance, including the proportion of rainfall which is infiltrated, evapotranspired and which contributes to runoff; thus returning a more natural flow regime, (ii) improve water quality and reduce export of pollutants to downstream receiving waters (such as bays and estuaries), (iii) provide water for human and other needs within cities, and (iv) enhance the urban landscape, providing amenity and ecosystem services to urban communities [34].

Approaches to protecting relatively unimpacted streams from future development may be very different from approaches to restoring highly degraded and constrained urban streams. For example, protection approaches may focus on maintaining near-natural hydrology, using natural or pre-urban reference condition to guide objectives[88,89], or matching pre-urban erosion potential, using hydraulic analysis of modelled streamflows under different stormwater management scenarios[90]. Restoration in lightly impacted streams may take a similar approach[91,92] with interventions that aim to reduce the stressors below degradation threshold levels, acknowledging that if hysteresis responses exist, more extreme measures (stressor reductions far below the original degradation thresholds) may be needed to see ecosystem improvements[93]. In already-degraded urban streams, instead of trying to restore to natural conditions, restoration goals may aim for ecosystem structure and functions that can provide important services and social benefits[94]. For example, highly modified urban waterways and human-constructed water features (for example, canals, stormwater ponds, ornamental ponds) may still provide water storage, nutrient processing, habitat for some flora and fauna, and opportunities for human connection to nature.

Defining management objectives involves considering scale within the landscape. Urban hydrology objectives aimed at protecting or restoring large downstream receiving waters (e.g. targets aimed at reducing loads to a lake, estuary or bay[95]) can encourage large-scale interventions downstream in the catchment, thus inadvertently neglecting the small and important headwater streams higher up in the catchment. Headwater streams (the smallest drainage lines, that act as the first fingers of the natural drainage network, before joining downstream to become streams, then rivers), for example, are often piped and built over[96,97]. These headwater streams are now recognized as providing essential ecosystem functions (such as allochthonous carbon sources, nutrient cycling, groundwater recharge)[98,99] and harbor unique biodiversity[100,101]. Multi-scale approaches that benefit all streams within the drainage network may best protect urban streams[102], rather than only attempting to protect lakes, estuaries or bays downstream. Distributed stormwater management approaches focused on harvesting, infiltrating, filtering and encouraging evapotranspiration of stormwater runoff, throughout watersheds[79,88], provides the best opportunity to restore both headwater systems and the downstream waterways to which they drain[103].

While urbanization is shown to result in homogenization of ecosystems[104], considering urban stream ecosystems as homogenous may hide regional heterogeneity in processes and prevent more targeted and effective management solutions[105]. For example, urbanization of streams in arid environments will have vastly different impacts than those in more humid environments[106]; such specificities are necessary if protection of the natural flow regime is desired[89]. Moreover, freshwater ecosystems are integrally tied to human societies, and in urban areas where large populations interact with streams, a re-envisioning of urban aquatic ecosystems as social-ecological systems may lead to more appropriate solutions to environmental problems. A shift from either utilitarian (streams as drains or sewers) or ecocentric (streams as pristine environments to be protected from human impacts) views of aquatic ecosystems towards understanding cities as functioning (albeit highly modified) ecosystems (sensu Grimm, et al. [107]) may generate new opportunities for creative solutions to urban hydrology problems. This approach may involve, for example, focusing on protecting those ecosystems not yet disturbed by urbanization, while using ecological principles around habitat diversity to design urban waterway ecosystems, which, when combined with appropriate stormwater control measures, permit a stream ecosystem to be sustained in a way that offers some biodiversity and ecosystem services to surrounding communities.

### *Delivering ecosystem services*

Beyond reducing harmful impacts on the environment, there is an increased expectation that urban water management can contribute to delivering 'ecosystem services', helping to ensure that benefits from ecosystems are delivered to people. These expectations can be centred around waterways, such as increased demand for recreational use of water bodies[108], or around the broader waterway corridor or even the broader urban landscape. As management of urban stormwater has moved towards a more water-sensitive framework, the provision of ecosystem services has become a primary objective[109]. It also reflects a broader trend in urban landscape management now covered under the umbrella term “nature-based solutions”, defined as “actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits”[110]. With this definition, strategies relying on green infrastructure such as vegetated stormwater systems are nature-based solutions, helping to connect the agendas of urban water management with more holistic urban planning principles for sustainable cities[34,111].

Examples of ecosystem services provided by vegetated stormwater management systems, in addition to their primary benefit for stormwater management, include: recreation and aesthetic benefits of green open spaces, as well as mitigating urban heat, enhancing carbon sequestration, supporting food production, and enhancing water supply through groundwater recharge or surface water retention (Figure 3). Importantly, the level of services varies broadly across the suite of nature-based solutions[112]. The type of system, ranging from green open spaces to high-tech green roofs[113], influences its benefits – related to stormwater management or 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 demand for green infrastructure vary with residents’ education and income[114]. Ecological factors such as climate and soils influence the potential of green infrastructure – for example, tropical systems need more retention space due to greater rainfall intensity[115]. 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 in the case of combined networks.

The complex and adaptive social, ecologic, and technological subsystems that make up a city highlight the potential tradeoffs and conflicts between different solutions[112]. A street tree may provide important benefits for heat mitigation, but at the expense of water availability, a priority in arid cities. To address this, co-design approaches supported by science can help identify and implement solutions that suit the city, or the neighborhood. Decision-support tools that illuminate these tradeoffs have flourished in recent years[115], some of them with a focus on urban water management[116]. These tools will be critical to achieve the ambitious goals for cities set in international agendas, starting with the Sustainable Development Goal 11 and more recently reiterated in the Global Biodiversity Framework's Target 12 that highlights the contribution of blue and green infrastructure “to inclusive and sustainable urbanization and to the provision of ecosystem functions and services” [117].

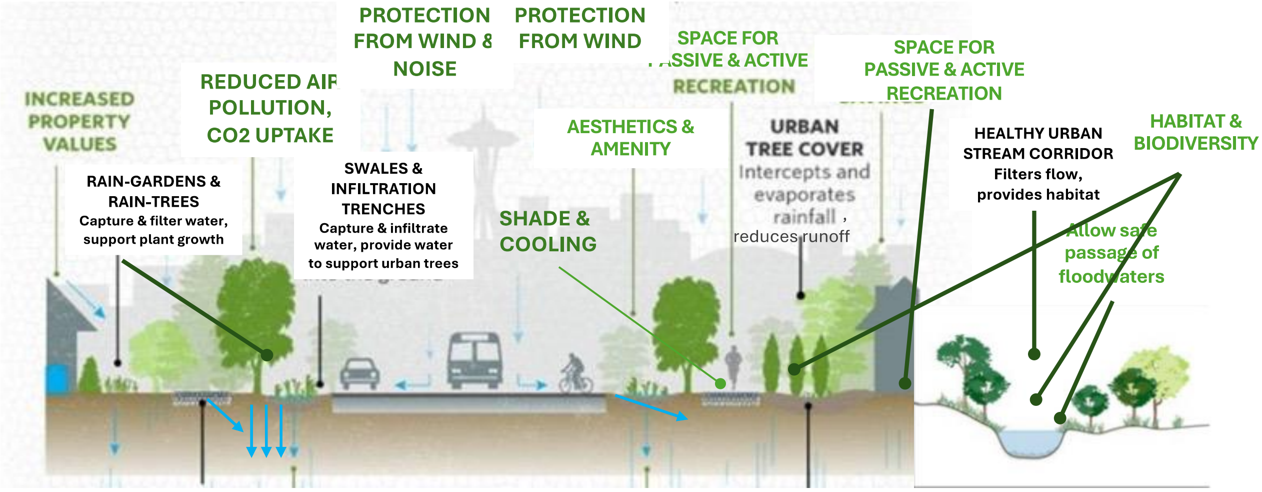


**Figure 3.** **Ecosystem services.** Example of ecosystem services that can be delivered by multi-functional stormwater management approaches. Delivery of such ecosystems is vital for community wellbeing but also critical to building investment cases around stormwater management approaches that better protect the environment. **[To be re-drawn before publication]**

### *Perceptions of stormwater as a resource*

The use of stormwater as a resource has been increasing globally in the last decade[10]. In many parts of the world, stormwater harvesting is common, with examples ranging from household scale systems supplying water for toilet flushing, clothes washing and even drinking[118,119], to precinct scale schemes that provide water for substantial irrigation[120]. The magnitude of the available resource can be quite substantial; for example, many Australian cities generate volumes of stormwater runoff that are similar to the total water supply each year (Figure 4). Uptake of stormwater as an alternative water supply option depends on factors such as public perception and regulation.

User acceptance for rainwater (surface runoff from roofs only) can be as high as 96% for non-potable uses[121], while user acceptance of using stormwater as a supplementary water supply is also quite strong, although more variable[119]. Successful projects such as the Little Stringybark Creek Project in Melbourne, Australia—where hundreds of residential rainwater and stormwater harvesting systems were installed[91]—suggest that public perception can be overcome through education and trust building[122]. In this project, most of the rainwater harvesting systems installed were connected to non-potable demands such as toilet flushing, clothes washing, hot water usage, and garden watering. Similar levels of rainwater harvesting have been achieved in a new residential development called Aquarevo in southeastern Australia[120]. A collaboration between a local water authority and a property developer, this innovative project features new homes with real-time controlled rainwater tank systems installed. The tanks supply hot water to the homes and feature ultraviolet treatment. The treatment train has a fail-safe and potable backup to ensure that the residents are supplied appropriate quality water. These Australian case studies demonstrate the public perception can be addressed using both structural and non-structural measures.

Regulation can influence the uptake of stormwater harvesting. For example in the U.S. State of Colorado, laws limit the use of rainwater for outdoor purposes only (https://kdvr.com/news/local/is-it-legal-to-collect-rainwater-in-colorado/). Rules in other U.S. States can be less restrictive, but compliance with relevant plumbing codes will be required and may, in some areas, be a barrier to adoption. For example, in France, laws restrict the use of rainwater to mainly toilet flushing and cleaning the ground [123]. The lack of regulatory constraints can help in promoting the uptake of rainwater tanks[124].

Part of the attraction of stormwater harvesting is that it can help in alleviating the effects of drought[125,126], but there is also increasing evidence of the role of stormwater harvesting in alleviating both nuisance flooding[127] and riverine flooding[128]. Catchment-scale implementation of tanks can potentially also improve in-stream water quality[129]. Benefits can also extend to human thermal comfort, when stored tank water is used for irrigation in order to deliver microclimate cooling effects[120]. Capturing these sorts of additional benefits of stormwater re-use will be critical to increase up-take and to drive policy change that supports stormwater harvesting as an integrated solution to the supply of water and the delivery of greater environmental and human outcomes in cities.

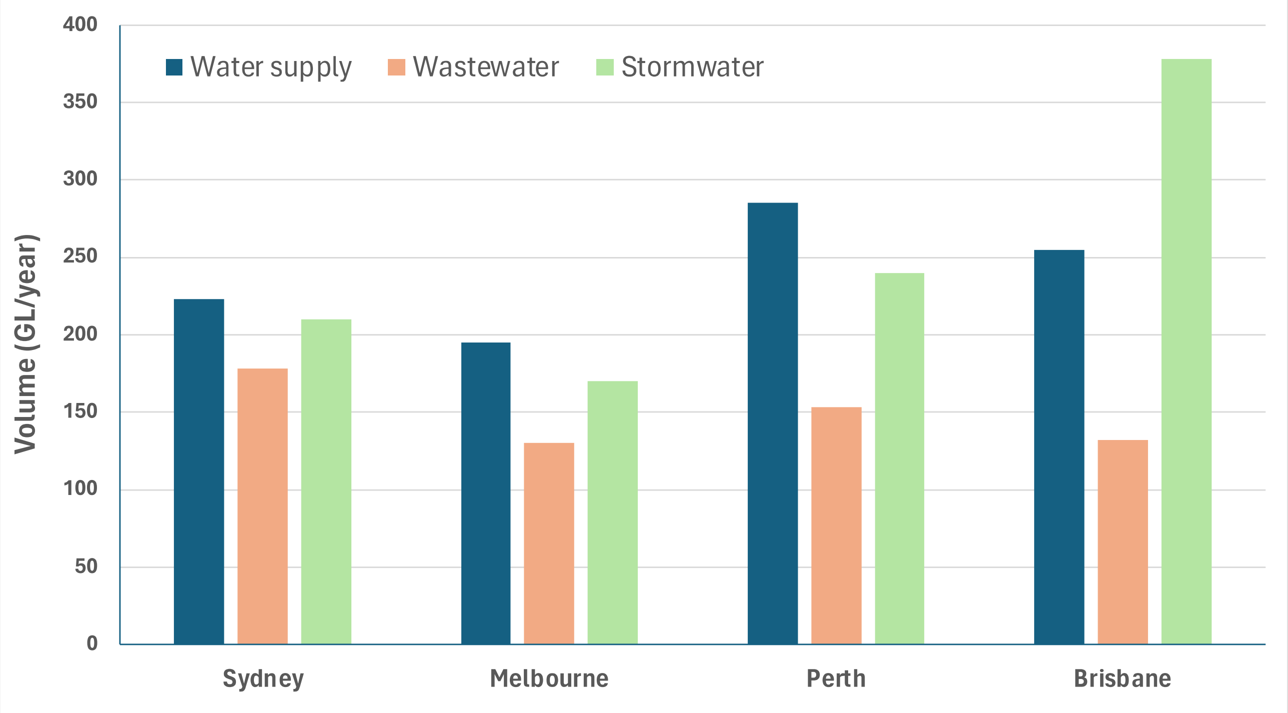


**Figure 4.** **Stormwater as a resource.** Example showing the water balance of major Australian cities, demonstrating the potential of stormwater to augment (or with treatment, replace) existing water supplies[130]. In most cities, the volume of stormwater is similar to, or exceeds, the total water demand. This demonstrates the potential for stormwater harvesting to solve the water shortages often facing cities in many places around the world.

Despite the attractiveness of stormwater harvesting, its implementation needs to be considered in the context of the implications for governance. The widespread use of rainwater tanks at the household scale, acts to transfers the responsibility of managing water supply from government to individuals, with its subsequent benefits and disadvantages[131]. This transfer may accentuate inequality, for example by providing the enhanced security of water supply only to the households able to afford investment in rainwater tank systems[132].

## Changing technologies

In this section we outline the rapid changes that are taking place in the technology used to manage urban stormwater. We commence with a brief discussion of advances over the last couple of decades in the stormwater control measures used to return more natural flow and water quality regimes. We then examine more recent technological advances, including the way stormwater management systems are monitored, with a focus on advances in low-cost monitoring technologies. Lastly, we describe the increasing power of forecasting capabilities to drive real-time control of stormwater systems, transforming them from passively operated infrastructure into systems capable of adapting to variable climatic and environmental conditions.

### *Increased adoption of stormwater control measures*

Technologies used to manage urban runoff have changed in the last two decades, arguably partly because of advances in technology and partly also in response to changed community expectations[133]. Stormwater control measures (SCMs) aim to improve water quality and deliver more natural flow regimes and a more natural water balance. While their use has increased over time, there remain political, institutional and technical barriers[115,134]. In more recent years, SCMs increasingly serve multiple purposes, including reducing flood risk, protecting receiving waters or at least reducing downstream pollutant loads, enhancing local landscape amenity, increasing biodiversity and mitigating the urban heat island effect. As shown in Figure 5, SCMs include a broad range of technologies, such as stormwater ponds and wetlands, swales and filter strips, infiltration trenches and basins, porous pavements, vegetated roofs, rainwater tanks, gross pollutant traps, particular filtration systems and bioretention systems[135,136].

**Figure 5. Examples of stormwater control measures.** Stormwater infiltration pond, Villeurbanne, France (A), stormwater runoff-irrigated street trees, Montreal, Canada (B), Porous pavement, Valence, France (C), Wetland and rain-garden, Singapore (D), Rainwater tank, Melbourne, Australia (E), Streetscape rain-gardens (F & G), Montreal, Canada and Melbourne, Australia, Carpark infiltration swale, Villeurbanne, France (H). Photo credits: Frédéric Cherqui. These examples

show how stormwater control measures are integrated into the urban landscape to provide aesthetic and amenity benefits, along with their primary function of retaining, detaining and treating urban stormwater runoff.

The use of vegetation in SCMs is well recognized for its ability to enhance pollutant removal[137], reduce runoff through evapotranspiration and maintain the porosity of stormwater filtration media, through root-created preferential flow pathways[138]. Recent research now provides very specific insights into the traits of plants that should be used in SCMs such as bioretention systems, to achieve the best water quality treatment performance [139] and to maintain system porosity over time[138]. At the other end of the spectrum, SCMs designed only to treat water quality (without providing other benefits such as flow reduction or improvement of urban amenity) often use no vegetation, with filtration provided by the use of sophisticated and targeted filtration media, such as granulated activated carbon[140]. Specification of filtration media can also be targeted towards the removal of pollutants of particular concern, such as pathogens[141].

Among the functions of SCMs, infiltration is often central, given its role in reducing runoff volume, recharging often-depleted groundwater (and thus supporting stream baseflows, as well as the growth of urban trees). In the last few years, researchers have delivered great insights into the fate of infiltrated water[142], and also its contaminants[72], allowing the risk of contaminating nearby groundwater or baseflows to be quantified and thus avoided. Infiltration systems may take the form of simple trenches or basins, or be ‘hidden’ within the urban landscape, through the creation of porous pavements to replace standard asphalt or concrete.

### ***Low-cost monitoring technologies***

Monitoring is an important component of managing stormwater systems. As an example, continuous monitoring of water level in stormwater treatment wetlands can indicate whether the outlet has become blocked by debris, which could lead to a loss of vegetation[143] and reduce treatment effectiveness[144]. Similarly, stormwater infiltration systems are known to clog over time; and measuring water level drawdown time can be used to schedule appropriate maintenance to remove the deposited silt. Monitoring is also required for regulatory purposes, such as reporting of the frequency and, ideally, quality of sewer network overflows into receiving waters[17].

The spatial and temporal variability of urban hydrology means that monitoring should be undertaken at short timesteps (such as 5 minutes) and at many locations within the system or drainage network. In reality, however, this is usually not possible, due to the high cost. This explains in part why stormwater systems have to date been poorly monitored, leading to inadequate maintenance and frequent system failures[145].

The rapid development and popularity of low-cost sensors in recent years has opened a new avenue for urban hydrology monitoring[146-148]. The development of versatile and cheap electronics with micro-controllers like Arduino and Raspberry Pi has attracted hobbyists and specialized communities[149]. The potential of these solutions to improve accessibility and scope of monitoring and allow collaboration on open-source hardware and software development, have favored the enlargement of these communities[150]. At the same time, growing production of sensors for industry has led to a reduction in prices, greater availability of sensors, and strong technological evolution)[151]. Low-cost systems are especially relevant in urban areas where dense monitoring networks and specialized control systems are required and security of traditional systems can be problematic[152].

The benefits of low-cost systems go beyond their cost savings. In many cases, the problem being solved is not so much the high cost of traditional monitoring, but rather its black-box nature. Low-cost technological development goes hand-in-hand with open-source and open data philosophies, near-real-time data access, low energy consumption, autonomy, modularity, and greater control over the measurement. Other benefits include increased spatial density of measurement points[153,154], bi-directional communication, and the ability to integrate sensors and control systems (for example, triggering water sampling).

Real-time communication is a major development which offers adaptive control (such as remote setpoint change, triggering of actions) and optimizes maintenance (alerts related to lack of data or critical situations such as battery level). Moreover, the availability of sensors produced by industry makes it possible, often after adaptations, to meet the numerous monitoring needs in urban hydrology[155]. For example, cameras can be used to measure water level, flow or turbidity, but also to identify flood damage[156-160]. By extension of the notion of low-cost monitoring, we can also include crowd-sourcing approaches[161,162], such as measuring rainfall using car windscreen wipers[163], private weather stations[164-166] or surveillance cameras[167].

There are numerous limitations of these systems, requiring a research effort from both technology developers and technology users to meet the needs of urban stormwater managers. A major shortcoming is the lack of knowledge crossover between metrology (the science of measurement) and prototyping[168]. Knowledge of programming and electronics is important for prototyping, but without knowledge of metrology or of the behavior of the hydrologic systems being monitored, the measurements produced will either be inaccurate or not provide useful information. At the same time, manufacturers of traditional monitoring equipment can learn from the demand for customization and flexibility. Hybrid systems are now emerging, with some low-cost developers producing more ready-to-use and accurate systems[152], and some traditional manufacturers producing more customizable systems. An evolution towards a spectrum where users can choose their preferred accuracy, reliability and cost, will likely best serve the needs of the urban hydrology community.

### *Forecast capability and real-time control*

Two interacting areas of technological advancement are revolutionising the management of urban hydrology. The first is the development of high spatial resolution rainfall forecasts, available both over longer term (typically up to 7 days) and much shorter term (typically up to 11 hours for 'nearcasting' and up to 1 hour for 'nowcasting'). Such short-term forecasts, which are vital to managing hydrology during intense rain events, have particularly been driven by the development of radar measurement of rainfall [169] and its integration with data from traditional rain-gauges [170]. We note that advances in forecast technologies may not equally benefit all countries, with modelling of tropical systems still facing important challenges[171]. However, social media is also creating new ways of providing flood warning, for example by using mapping apps to identify road blockages during flooding, and allowing real-time sharing of flood behaviour between citizens and emergency management agencies[49].

In parallel, the use of real-time control (RTC) to dynamically operate stormwater networks has increased dramatically. Real-time control systems respond automatically to changing observed or predicted conditions in the network – such as increased flow or a change in water quality [172] – to optimise management of the network. For example, managers may open valves to allow flood waters to flow into a detention basin. While RTC has been used since the 1990s, this early use was primarily for single-objective optimisation (usually mitigation of flood risk or control of combined sewer overflows) of large, centralised infrastructure[13].

The combination of advances in RTC with advances in meteorological forecasting has opened up new applications for real-time control of stormwater systems to meet multiple objectives, such as combined flood mitigation and water quality improvement[173,174]. It has also allowed coordinated control of large numbers of decentralised stormwater control measures, rather than single, large systems[175]. For example, Xu et al [15] employed RTC to operate a network of rainwater tanks, optimising between the multiple objectives of water supply, flood mitigation and supply of baseflow to streams. Shen et al.[176] combined RTC with nature-based solutions, optimising water quality for protection of receiving waters and supply of harvested water for non-potable water supply. With increasingly powerful rainfall forecasts available, model predictive control strategies can operate using longer-term (e.g. 7-day) forecast windows, adjusting as the forecast changes and becomes more certain closer to the rainfall event[177], particularly with radar-based rainfall nowcasts[170]. Such long forecast windows, while much longer than the time of concentration of urban catchments (the time for flow in all parts of the catchment to reach the outlet), allows slow releases from detention storages in the days leading up to storms, so that the storages are ready to capture and detain rainfall.

These advances facilitate some potentially revolutionary approaches to managing urban hydrology. For example, networks of household rainwater tanks could be used to 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[178]. The network of tanks could be further integrated with stormwater control measures throughout the catchment, such as rain gardens within the streetscape, or stormwater treatment wetlands downstream. Such an arrangement can optimise the flow regime through these treatment facilities, ensuring they can perform at their optimum for water quality improvement, while minimising the risk of overflows, which would result in discharge of untreated flows downstream and, in some cases, in increased flooding risks. Likewise, in combined sewer systems, where stormwater and sanitary wastewater are merged, coordinated implementation of nature-based solutions and control of detention tanks has been shown to substantially reduce the incidence of sewer overflows into receiving waters during storms[17]. This introduces the possibility of coordinating networks of real-time controlled detention storages for both wastewater and stormwater (separately), 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.

A major future challenge to the implementation of RTC for urban stormwater networks is in the deployment and maintenance of the large number of sensors[179] needed to provide the necessary data – in real-time – to optimize the network operation. Likewise, while improved operation can be achieved by the use of forecasting and predictive control, doing so requires major computing infrastructure, to ensure system operation can be optimised quickly enough to match the highly variable and stochastic nature of urban hydrology. A promising area of future development is the rapid development of neural-network based machine learning techniques to underpin predictive models of complex drainage systems, avoiding the need to parameterise complex conceptual models. The challenge, however, is obtaining long enough time-series of data to train such models[180].

## Changing governance and business models

In this section we explore the changes in governance, economics and law that may help to achieve a more sustainable management of urban runoff. We firstly examine the frequent misalignment between those who pay for stormwater mitigation measures and those who benefit from them. We then briefly discuss the complex issue of water rights as it pertains to harvesting of stormwater.

### *Alignment of benefit providers and beneficiaries*

A misalignment between the beneficiaries of attempts to improve the management of urban runoff and its impacts, and those who pay for such improvements, has arguably hampered progress. This has led to proposals for more innovative funding models, such as stormwater utility fees [181,182]. While such fees create a more sustainable funding model, the use of credits against these fees arguably shows the most promise, because they can drive behaviour towards reducing stormwater runoff, by sharing in cost-savings with landowners [181].

Some studies have explored the use of offsets, allowing those impacting stormwater runoff (for example through the creation of new impervious areas) to avoid on-site mitigation works, by paying for mitigation works elsewhere [182]. However, offsets have been strongly criticized, given the non-transferability of impact mitigation efforts[183]. For example, if a proposed development will increase runoff in one catchment (A) is offset by works nearby, but in another catchment (B), as is often the case, degradation to the waterway of catchment A will not be reduced. This is fundamentally different to offset arrangements for $CO_2$ reduction efforts, for example, where there is no geographic specificity.

Principal among the research challenges in this area is the development of reliable and easy-to-implement methods for quantifying and valuing the benefits of stormwater mitigation efforts[184]. Indeed, the concept of accounting for and payment for ecosystem services remains at the frontier of current knowledge and research efforts [185]. As challenging as it is, the density and physical constraints of urban landscapes mean that such approaches, where the community participates in efforts to deliver ecosystem services by improvement in the management of urban runoff, holds substantial potential[14].

An additional challenge – yet also an opportunity – is that managing stormwater runoff *at the source* (where the rain falls) offers the best potential for addressing the problems, and these decentralised solutions involve collaboration of many landholders and water or drainage authorities [133]. Perhaps the greatest challenge is in aligning the beneficiaries with investors in nature-based solutions, given the multiple benefits and stakeholders involved [186]. Individual stakeholders are interested in different benefits from the nature-based solutions, depending on who they are and how they interact with the solutions. Building a business model in such cases is complicated by the difficulty in monetizing the many and varied socio-ecological benefits, and by the fact that these benefits are often common or public good in nature, with benefits accruing to multiple stakeholders. For such nature-based solutions, a promising area for advancement is to identify how private investors may capture value from the benefits they create for the wide range of beneficiaries [186]. This may involve a public authority using fiscal instruments (such as charges and taxes) to reimburse private investments in such green infrastructure.

### *Ownership of stormwater as a water resource*

While stormwater runoff undeniably creates a ‘problem’, it also delivers a valuable resource, particularly given the scarcity and relative unreliability of water resources faced by many cities around the world. In recent years, there have been several attempts to develop hybrid supply options for urban water, involving a centralised potable water supply, combined with a decentralised supply of rainwater or stormwater[119,187]. More recently, driven by increasing water shortages, these have included options where stormwater is treated to potable standards and integrated into the full water supply. This has particularly been driven in regions with water scarcity problems, such as the town of Orange in south-eastern Australia[188]. The advent of real-time control technology has also opened up the possibility of business models where individual owners of rainwater tanks within an urban area could be financially rewarded for their contributions not only to water supply, but to reduction in flood risk and to provision of environmental flows to receiving water during times of drought (Figure 6)[13,14].

**Figure 6.** **A smart rainwater grid.** A real-time controlled grid of water storages, informed by sub-daily weather forecasts (A) and a market (B) to encourage releases of water, for example to provide environmental flows to waterways (G), or to reduce flooding. Individual owners of rainwater tanks (either households (E) or businesses (D) can receive financial rewards (B) for contributing to operation of the grid, operated by a central control algorithm and control system (H). The network combines these private storages with large water storages (C) and wetlands (F) operated by water authorities and government agencies. Such a grid represents a potential future for distribute management of stormwater to minimise environmental impacts and maximise the benefits to society.

At the individual allotment scale, such business models can, in many jurisdictions, be pursued without regard to the ownership of the water resource, but 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 will be critical to supporting investment in such larger scale stormwater harvesting schemes[189]. For example, in the US, 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[132].

For stormwater harvesting to be used at a range of scales to effectively reduce excess runoff, while also creating an important supplementary water resource, jurisdictions around the world may 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

Urbanisation substantially changes the pathways and fate of rainfall once it falls on the landscape. Impervious areas prevent infiltration, thus reducing groundwater recharge and contributions to baseflow, and replace it with surface runoff, creating a streamflow regime that is highly flashy. 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. The results of these mechanisms are pollution, erosion, habitat loss and a decline in both biodiversity and ecosystem services. At a time when urban populations are growing larger and denser, and when climate change is leading to higher intensity storms, but also 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 international scientific community, to develop new approaches to governance, to investment, and to enable the deployment of new technologies.

As more is understood about an emerging range of quite toxic and persistent pollutants, research is required to understand their fate in the environment, and to develop effective technologies to achieve their removal from urban runoff. Such research will require both laboratory and field studies and will need to consider the context of the receiving waters.

Economic and social science-based research will be 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. Without this, there will likely remain a market failure, with sustainable solutions remaining as boutique examples rather than becoming everyday practice. Delivering this new model also requires better understanding the social and institutional factors that act as drivers or barriers to change, learning from environmental transitions in other areas such as energy, transport and biodiversity conservation. In particular, understanding the social factors that will drive uptake – by individuals and by institutions – of sustainable stormwater management approaches, will be critical.

Economic research is needed to develop methods to determine the appropriate costing of water as a resource and definition of the ownership over stormwater as a resource, to provide the confidence to invest in practices such as large-scale stormwater harvesting. Economic research will also be needed to identify credible and feasible ways to value ecosystem services, to underpin investment models.

Novel approaches, like those applied in fields such as the energy market, where households contribute to energy production and storage through the use of solar panels and batteries, may offer solutions if successfully tested. While water has very different properties, the potential for networks of real-time controlled rainwater storages to reduce flooding, protect the environment and supplement existing water resources, is compelling. Such innovations open up potential new business models, where the costs of operating and maintaining stormwater control measures, traditionally a major impediment to investment, could be offset by ongoing revenue. Importantly, however, such methods can only be tested through carefully designed experimental interventions to test how such markets would be operated.

Urban hydrology appears to be at a crossroads. Managed in the way it has been over many decades, urban stormwater will continue to degrade urban waterways, reduce the amenity of the urban landscape, and indirectly contribute to the water scarcity that cities increasingly find themselves facing. But with innovative approaches, a very different future is possible – one where stormwater becomes a valued resource and where it both delivers benefits to society and supports healthy urban streams.

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To the best of our knowledge, none of the authors have any competing interests.

## Author contributions

TF, MB, and KR determined the organization and content of the paper, in collaboration with the Editor. TF drafted the Introduction and the Background, MB, KR, PH, FC, SD, AR all contributed to drafting the Changing Drivers, Changing Drivers and Changing Technologies sections. TF, PH, MB and KLR drafted the Summary. All authors contributed to review and editing of the manuscript.