Water Research 218 (2022) 118409

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Review

Moving to a future of smart stormwater management: A review and framework for terminology, research, and future perspectives

James L Webber [a,*], Tim Fletcher [b], Raziyeh Farmani [a], David Butler [a], Peter Melville-Shreeve [a]

[a] Centre for Water Systems, University of Exeter, UK
[b] Waterway Ecosystem Research Group, University of Melbourne, Australia

ARTICLE INFO

Keywords:
Active control
Internet of things (IoT)
Real time control (RTC)
Smart systems
Smart water management
Stormwater

ABSTRACT

Stormwater hazards are a significant threat across the globe. These are continuing to increase in line with urbanisation and climate change, leading to a recognition that the historic paradigm of passive management using centralised infrastructure is insufficient to manage future hazards to our society, environment, and economy. The cross-sector Internet of Things revolution has inspired a new generation of smart stormwater management systems which offer an effective, cost beneficial and adaptive solution to enhance network capacities and reduce hazards. However, despite growing prominence within research, this technology remains under-utilised, in a large part due to fragmented and inconsistent alignment and terminology, obscuring the strategic co-ordination of research. We respond to this through systematically reviewing the terminology, practice and trajectory for smart stormwater management and developing a framework which can be applied to both coordinate and understand the existing research landscape, as well as identifying key research gaps for future development. We find that literature almost universally agrees that smart technology is, or will be, beneficial to stormwater management and that technology has reached partial maturity in terms of quantity management, although this has not yet transferred to water quality. However, research is dominated by proof-of-concept modelling studies, with limited practical application beyond real time control of large assets, individual pilot studies and monitoring. We recommend that future research explores and evidences the substantial benefits likely through expanding current implementation towards a coordinated, decentralised, and optimised catchment-scale approach.

1. Introduction

Stormwater hazards, created through intense rainfall overwhelming drainage systems, generate enormous impacts to our societies, environments and economies at a global scale (IPCC, 2014; DEFRA, 2018). Historically these hazards have been managed through extensive deployment of passive infrastructure across cities and catchments (Butler et al., 2018). This has been predominantly achieved through implementing subterranean grey infrastructure, with a contemporary drive towards increasing application of green infrastructure to extend the scope of stormwater management across catchment surfaces and buildings (Wong and Brown, 2009; Cettner, 2012; Fletcher et al., 2015; Scholz, 2015). However, current predictions highlight that the scale of stormwater hazards is increasing at a rate far higher than previously anticipated (Wing et al., 2018; Swain et al., 2020). Consequently, there is a growing realisation that managing stormwater using passive networks of the twentieth century is insufficient to meet the needs of the future; and instead, more cost effective, adaptable and sustainable use of existing networks can be achieved through deploying 'smart' technology (Bartos et al., 2018; Yuan et al., 2019; Xu et al., 2021).

The concept of smart stormwater and smart cities has emerged from the cross-sector Internet of Things (IoT) revolution (Atzori et al., 2010; Oberascher et al., 2022), where cost-effective and multi-functional sensing, communication, actuation and optimisation devices installed to monitor, control and optimise operation have become ubiquitous across various network infrastructures, notably including power and communication systems (Weiser et al., 1999; Edmondson et al., 2018). Translating cross-sector advances in IoT to achieve smart stormwater management has the potential to enable cost effective management of day-to-day operations alongside adaptability to reconfigure operation and enhance resilience to manage extreme events (Mullapudi et al., 2017, 2018; Xu et al., 2021), whilst also retaining opportunities for

* Corresponding author.
E-mail address: j.webber2@exeter.ac.uk (J.L. Webber).

https://doi.org/10.1016/j.watres.2022.118409
Received 15 December 2021; Received in revised form 16 March 2022; Accepted 3 April 2022
Available online 9 April 2022

re-assessment and upgrade of future operation procedures (Dirckx et al., 2011; Altobelli et al., 2020).

However, despite a growing prominence within research, the adoption of emerging smart technology remains constrained by several key challenges, of pertinence being a fragmented, inconsistent and confusing terminology (Gourbesville, 2016). As with other potentially transformative step changes in water management, for example resilience (Davoudi et al., 2012) and nature based solutions (Schanze, 2017), there is a real risk that application of the term ‘smart’ can be constrained as a buzzword, with the vernacular applied in a non-specific manner to describe a range of tangential applications. This is exacerbated by ubiquitous application and claims regarding ‘what smart is’; creating ambiguity and uncertainty with regards to mapping the overarching progress of where smart stormwater research is now, and what the next research steps should be, on to a consistent knowledge framework.

In this review we aim to address these gaps through:

1 Reviewing smart technology research in the field of stormwater management.
2 Providing a resource to align terminology.
3 Mapping research onto a consistent knowledge framework to facilitate clear identification of the progress to date.
4 Identifying the research gaps and barriers to propose further studies for the systematic and meaningful development of smart stormwater management.

2. Clarifying the terminology

The use of ‘smart’ technology as a term is ubiquitous across everyday discourse, science, governance and practice, although arguably far more so in fields such as energy, telecommunications, heating, cooling and ventilation (HVAC) than in stormwater, hydrology and hydraulics. While the use of ‘smart technology’ as a general descriptor has the advantage of attracting interest from decision-makers, policy-makers and even the public (Fletcher et al., 2015), there is a risk that such general terms will lead to confusion about what is actually meant when describing scientific progress and needs. Clear dissemination of knowledge requires consistent application of terminology, such that the audience understands the nature, scope and intent of proposed approaches. In this review, we use a range of terms to describe similar but subtly different applications of smart technology, in an attempt to link our discussion to the sources of literature from which it is drawn.

To avoid confusion, we attempt to define the terms we use in the following section. We argue that in an evolving field such as this, there is a need for authors to clearly define the terms they are using. Doing so will not only help to ensure clarity of communication within the stormwater discipline, but help to open up the discussion to other related disciplines, such as system optimisation and control, green infrastructure, urban planning and even urban ecology.

Smart technology: Smart technology’ encapsulates technologies able to: sense; monitor (collect data); communicate; manage; analyse; integrate; control; or optimise devices in a systematic manner. This includes both standalone devices with integrated ‘smart’ features and technologies which can be retrofitted to enhance the capabilities of other devices, assets or networks. This definition covers a wide range of technologies, encapsulating varying degrees of ‘smartness’ and leading to the fragmented and inconsistent application of ‘smart’ technologies within current research; as such we will develop a framework within this paper to facilitate this range of technologies and capabilities to be benchmarked and compared.

Real time control (RTC): In terms of stormwater management, the term ‘smart’ is a progression from an established research field in real time control (RTC) (James, 1984; Kändler et al., 2020b; Sadler et al., 2020; Xu et al., 2021). Campisano et al. (2013) provide a succinct summary of components and terminology in RTC systems, including actuators, controllers, sensors, and telemetry.

Passive / active control: Passive control systems typically rely on hydraulic conditions to alter the discharge rate from a given asset. They include orifices, vortex flow controls and weirs. Passive systems might include some degree of ‘smartness’ if they are monitored (e.g. via telemetry reporting the water level). An active control system can permit some form of intervention at an asset typically involving a device such as an actuator. The actuator may be driven by local or global control systems. Active control does not include assets which can control flow velocities using mechanical principles such as vortex flow controls.

Internet of Things (IoT): The Internet of Things describes the interconnection of devices (both physical and virtual) to the Internet and to other connected devices (IBM, 2016). In the context of smart stormwater, this encapsulates all elements of smart technology including hardware and software.

3. State of the art

3.1. Global literature review

We used the terminology identified in our evaluation of what smart stormwater systems are to explore the maturity of existing stormwater literature using a systematic literature review set into three stages.

Our initial stage included conducting a global search of literature, based on the SCOPUS indexed research database. We searched for all literature which included the keywords “smart”, “smarter”, “active control”, “real time control” (and hyphenated variations thereof) or “RTC”, AND “stormwater” or “storm water” within the title, abstract or keywords. This search returned 319 documents (as of 7th May 2021).

We then applied filters to refine our selection to publication in journals as an article or review, which resulted in 154 documents, and removed any non-English documents (due to our inability to accurately assess their content). In total this process retained 145 documents.

Our final process was a manual review of all remaining abstracts to ensure that the title, abstract and key words accurately reflected smart stormwater technology. We found that the word “smart” proved a popular basis for acronyms and as an adjective describing decision making based on non-IoT linked advances, and after discounting these non-relevant documents we were left with a collection of 94 documents.

Fig. 1 shows the cumulative publication of smart stormwater articles, according to our search procedure. The earliest recorded article is from 1984 and from there a slow steady rate of publication is apparent through to the late 1990’s, with publication accelerating through 2000-2015 and again during the past five years. This trend aligns with the growth of articles citing ‘smart technology’ across all disciplines in the SCOPUS database; highlighting the increasing potential of ‘smart’ systems and their increasing utilisation across disciplines (Fig. 2), which accelerates during the past decade and has more than doubled in the

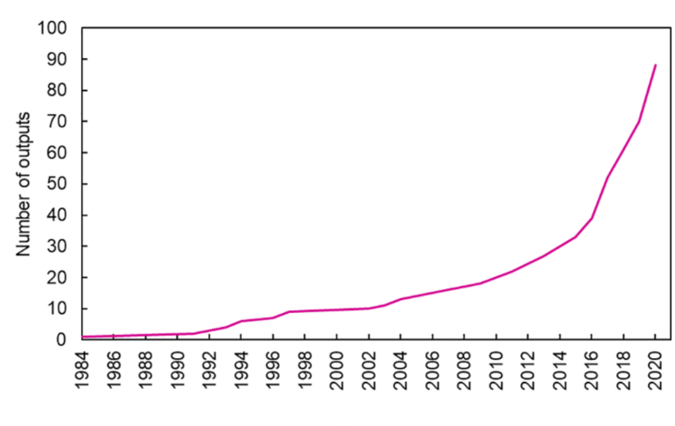

Fig. 1. Cumulative smart stormwater articles published (1984 - 2020), based on our search procedure.

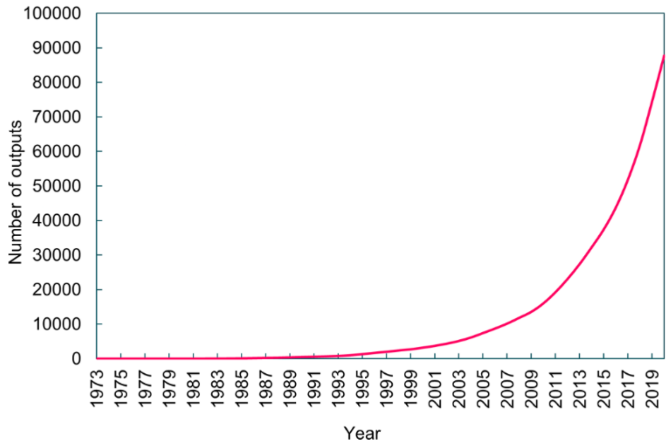

Fig. 2. Cumulative entries containing the words "smart technology" in the entire Scopus research outputs database (1973-2020).

past five years. We note that our search terms and procedure will not capture the full range of smart stormwater systems within the global discourse; however, the SCOPUS database represents a significant proportion of sources, with over 75 million records and 23 500 journals from 5 000 publishers (SCOPUS, 2019). As such this provides a strong indication of publication history to draw general conclusions, whilst acknowledging some articles may not have been captured within the search. We also note that we have been unable to compare the trajectory of outputs including these terms with the overall number of publications in the SCOPUS database year-on-year; therefore, although we identify the increasing use of terms, we cannot determine how this increasing prominence relates to the overall increase in papers over the period.

In our analysis of titles from our literature search we have identified a trajectory of smart stormwater systems with key themes emerging over the past four decades of research. This section outlines these key themes and publications. Our intention of identifying and evaluating these themes is two-fold. Firstly, to draw together a comprehensive narrative describing research to date with regards to smart stormwater, identifying the state of the art and the state of the possible. And secondly, using our review to map the future trajectory and research needs to achieve the benefits of smart stormwater for communities and the environment through evaluating research across a consistent theoretical framework in subsequent sections of our paper.

3.2. Centralised real time control of large infrastructure

Many early adopters of smart technology applied the term RTC technology to describe controlling assets through actuation in response to sensors, with application predominantly driven by cost benefit factors at large infrastructure projects, such as sewer trunk mains and reservoirs (James, 1984; Campisano et al., 2013).

The earliest discussion of smart stormwater found using our search terms was in 1984, where Bill James evaluated the use of RTC as an emerging technology to support urban runoff forecasting and reservoir operation (James, 1984). Although this is an example of an early transfer of the RTC approach to stormwater, through discussion within the paper it is apparent that James did not coin this term and that the concept of RTC already existed within engineering discourse; therefore, it is very likely that the concepts of RTC had been discussed significantly prior to this.

Early conversation also commonly took place alongside an evaluation of applying emerging hydraulic modelling software to develop RTC schemes for storm sewer systems; clearly highlighting that, at the time, the essential factor in success was the limitations in accuracy and processing capabilities for running hydraulic modelling (Cardle, 1991). However, despite these technical limitations, basic implementation on large infrastructure was considered possible from the early 1990's (Schilling, 1994) and deployment of RTC in sewers continued, with case studies developing through literature from the early 1990's onwards (Kwan et al., 1993; McCann, 1993).

RTC gradually entered the mainstream scientific consensus regarding best practice for effectively utilising available space in urban drainage systems, although was still considered state of the art (Ellis and Marsalek, 1996; Urban storm drainage, 1996; Weyand, 2002). In the mid 1990's RTC principles and tools began to enter mainstream products and practice, with commercial software such as 'Hydroworks PM' being developed and sold to planners and utility providers (Hayes, 1994). Examples of implementation from this era are almost exclusively in the control of large infrastructure features, including sewer mains and wastewater treatment, reflecting limitations in monitoring data, computation, communication and cost.

This application to large scale infrastructure remains today, with RTC frequently described as a solution to issues of network capacity, such as combined sewer overflow (CSO) spills (Campisano et al., 2016). It is worth noting one authors comments regarding this: "*combined sewer overflows which discharge untreated sewage under storm conditions are* ***an old headache*** *for the water industry*" (Wyman, 1994); a sobering thought given ongoing unprecedented issues and calls to respond to the same challenges almost three decades later (The Rivers Trust, 2019; UKWIR, 2019).

3.3. Integration towards a network scale

In the early 2000's, advances in measurement technology enabled wider monitoring of the stormwater system, with multiple sensors throughout networks feeding control data from physical assets, including sewers, treatment plants and receiving waters (Schütze et al., 2004). However, as with previous application, the costs, uncertainties and limitations in sensor distribution meant that active control remained limited to large strategic assets operated by utility companies.

The commercial introduction of Geographic Information Systems in the 1990's presented an opportunity for a wider consideration, interpretation and management of geospatial data, supporting concepts such as 'catchment and network management' becoming more visual and actionable (Skop and Loaiciga, 1998). Throughout the 2000's the scope, scale and complexity of what was considered to be the 'stormwater network' began to increase, with studies introducing new concepts such as water sensitive urban design (Wong and Eadie, 2000) and technologies such as sensor networks (Fenner, 2000; Ruggaber et al., 2007) and data-driven analysis of runoff using rainfall radars (Vieux and Vieux, 2005). Of pertinence to RTC was the developing implementation of sensors, with studies demonstrating sophisticated control using widespread decentralised sensing across sewer infrastructure (Ruggaber et al., 2007). It is around this time that 'smart' began to enter and proliferate through the stormwater vernacular (Fig. 1), much in line with the popularity of this term across scientific literature (Fig. 2).

Despite the growing prominence of RTC within urban water literature, the technology has not yet developed from individual projects to mass application. Common issues for the lack of implementation were reported including high costs of implementation and uncertainty over operational success (Schütze et al., 2008). Working groups, such as the German DWA (DWA, 2005), began to prepare RTC guidelines for sewer systems and reviews indicated the cost-effectiveness of installing RTC to manage network capacity, whilst also retaining adaptive capacity for later re-assessment and upgrade of control measures (Dirckx et al., 2011; Altobelli et al., 2020); However, despite advances, implementation remained targeted at the operation of large single infrastructures, rather than distributed IoT applications.

3.4. Optimisation of smart systems

In parallel with the advancement of network scale monitoring, development of optimal real time control strategies was also underway, for example using genetic algorithms (Rauch and Harremoës, 1999; Cembrano et al., 2004; Rathnayake and Faisal Anwar, 2019; Eulogi et al., 2021; Wang et al., 2021), neural networks (Darsono and Labadie, 2007; Zhang et al., 2018; Mullapudi et al., 2020; Saliba et al., 2020) and fuzzy logic control (Li, 2020).

Research in this area has developed, with recent reviews by Shishegar et al. (2018) indicating significant progress across aspects of optimising RTC to achieve effective performance across networks. However, catchment-scale RTC which encapsulates the full range of assets across a network remains a significant challenge to address. And, even in the modern era, many optimisation algorithms are not applied to networks in real time due to computational costs (Rathnayake and Faisal Anwar, 2019). In particular, increasing data and complexity of interconnected systems has yet to take into account feedback loops between multi-sector smart system capabilities and operators of such systems at a synergistic city scale (Jose et al., 2015; Fenner, 2017; Meng et al., 2017).

The majority of optimisation approaches tend towards water quantity (flooding, CSO and network capacity management) as opposed to water quality functions (Campisano et al., 2013). This is predominantly because the components needed to monitor quantity have reached a mature stage, with sensing, actuation and telecommunication technology all reliably available, versus water quality technology, in particular sensors, which are still not at a sufficient reliability or scale of application for real time feedback. This is often due to the time-lag between water quality samples being taken and then analysed in a lab, versus the near instantaneous nature of water level monitoring. In recent years proxies, such as colour, turbidity and dissolved oxygen concentration have been applied to advance this field, often feeding forward RTC to control downstream treatment options (Hoppe et al., 2011; Lacour and Schütze, 2011). Recent research has also investigated asset scale RTC of green infrastructure to enhance water quality in laboratory environments (Shen et al., 2020), which could be upscaled in future iterations of projects.

Significant sensor networks have begun to be deployed to support the data required for this, with examples including large scale demonstrators, such as that in Lille (Abbas et al., 2017), where a demonstrator representing a town of 25 000 people installed flow and turbidity sensors on wastewater with links to 'smart city' functionality of sewage, potable water, energy and heat sensors distributed across buildings, networks and campus infrastructure. However, this action remains focused on monitoring, data gathering and offline optimisation, as opposed to active and responsive real time optimisation and control.

3.5. The role of short-term forecasting in smart stormwater

The most significant progress integrating catchment-scale data within smart stormwater has been through integration of weather data and short term forecasting, or 'nowcasting' within RTC of networks (Xu et al., 2020). At its simplest level this involves prediction of future network states using rainfall, for example to deploy early flood warnings; a practice which has existed for a long time (Plate, 2002). Yet development of more powerful computational modelling, at a price point which enables distribution, alongside high-resolution input data, i.e. weather radar, has now led to integration of rainfall radar in managing large sewer systems (IWRA and K Water, 2018; Tabuchi et al., 2020).

This has been developed through two main approaches: data gathered from internal sewer network monitoring systems; and nowcasting based on external conditions.

The most straight forward approach is to implement a local active control loop. This is achieved through continuous monitoring the internal state of assets or networks, linked with automated control to optimise performance one component at a time (Kändler et al., 2020b; Lund et al., 2020). At an asset scale this may include monitoring water levels in tanks or basins (Melville-Shreeve et al., 2016; Parolari et al., 2018), or at a network scale this could include monitoring of upstream conditions to regulate flow valves downstream. An example of this is distributed smart manholes to create an in line storage system without need for centralised RTC (Kändler et al., 2020b) through distributed measurements acting independently (Maiolo et al., 2020). The distinction of this relative to other internal state measurement controls is the scale at which the synergistic effect of many distributed interventions acting independently can coalesce, and the possibility of collecting operational data for offline optimisation.

However, a more powerful tool for urban drainage is the possibility of applying external data, for example rainfall forecasts, as a predictor for near-future system performance at a co-ordinated network scale. Initial deployment of weather data has been focused on prediction, rather than actuated control of network features (Thorndahl and Rasmussen, 2013), although some models developed auto-calibration feedback loops using observed measurements within drainage catchments. However, modelling studies have now developed proof of concept implementing nowcasting approaches towards actuation and control, with rainfall radar being used to control outlets on detention ponds (Gaborit et al., 2013, 2016) and multiple actuators on urban drainage systems (Löwe et al., 2016).

Recent reviews have evidenced strong potential of nowcasting, with some limited pilot studies being implemented commercially. Best practice generally uses 24-hour forecast windows; however recent research highlights that extending this window of prediction up to a 7-day forecast delivers enhanced flood mitigation and water regulation benefits (Xu et al., 2021), prompting a need for reliable services to connect weather data and smart control. The application of weather predictions alongside RTC can be support stormwater management objectives at building, plot or site level and evidence has been identified from a range of industry trials across a number of countries (Melville-Shreeve et al., 2016; IWRA and K Water, 2018).

3.6. Decentralised smart stormwater systems

The majority of literature describing implementation of smart systems for stormwater management has focused on embedding RTC in large infrastructure systems. In many ways this echoes a historic paradigm focused on engineering similar centralised, often referred to as 'grey', systems to address water supply, treatment and sewerage functions (Butler et al., 2018). Over time this has slowly developed from a large asset focus, towards maximising network capacity through mobilisation of several to many large assets across the traditional definitions of a sewer network, ie pipes, CSO's and tanks (Kändler et al., 2020a, 2020b; Maiolo et al., 2020). In this context, RTC has been widely demonstrated to achieve cost effective application for increasing network capacities (Wang et al., 2021), whilst retaining options for future adaption through retrofit, or iteration and upgrade of control rules (Dirckx et al., 2011; Altobelli et al., 2020).

However, through contemporary advances such as the principles of water sensitive urban design (Wong and Eadie, 2000; Wong, 2006; Wong and Brown, 2009) and novel stormwater interventions (Fletcher et al., 2015; Schanze, 2017; O'Donnell et al., 2020; Oral et al., 2020), we now understand that the boundaries of what has historically been considered the 'stormwater system' are far wider than just a sewer network. Recognition that decentralised, distributed and co-ordinated application of smart technologies to manage stormwater at this catchment scale have the potential to realise significant future benefits for resilient and sustainable systems (Butler et al., 2014, 2017; Troutman et al., 2020).

In 2016, Kerkez et al. published a review introducing the Open Storm consortium (Open Storm, 2021), working on the potential for advances in low cost sensors and actuators to progress historic static stormwater systems towards dynamically controlled systems, benefitting from optimal adaptive control of a mix of centralised grey and distributed green infrastructure; translating the IoT narrative towards the stormwater community (Atzori et al., 2010). This work recognised the limitations of previous RTC technology in urban drainage; restricted to application of large infrastructure and realised the potential of reduced cost and increased adaptive capacity when systems were deployed at a catchment scale (Riaño-Briceño et al., 2016). The review identified critical knowledge gaps, including: incomplete application of systems thinking; a lack of certainty over new technologies; adoption of standards and governance models; and, cyber security. Supporting follow up publications developing this knowledge into frameworks have now been completed (Mullapudi et al., 2017; Bartos et al., 2018).

The benefits of 'smart green infrastructure' at a catchment-scale are supported throughout literature, with municipalities seeing their potential to reduce stormwater hazards, but unsure over performance and costs in the long term (Meng et al., 2017). This reluctance is often amplified by a lack of certainty over green infrastructure performance in general (Brown and Farrelly, 2009; Scholz, 2015; O'Donnell et al., 2017; Thorne et al., 2018; White et al., 2018). However, a growing body of evidence is emerging to challenge this stigma and set out distributed smart green infrastructure as an alternative and promising solution. Prominent solutions include attenuation basins and rainwater harvesting tanks (Xu et al., 2021).

Attenuation basins are storage facilities which capture stormwater during intense events and hold it for later controlled release (Woods Ballard et al., 2015). Attenuation basins are consistently popular to implement infrastructure due to the possibility for a single intervention to be sized to hold significant quantities of stormwater, and the ease of installing a single attenuation intervention to control outlets. Basins can be implemented as an individual asset, simplifying the need for complicated catchment-scale coordination (Gaborit et al., 2016; Sharior et al., 2019; Shishegar et al., 2019), or implemented as part of a synergistic system of multiple interventions (Di Matteo et al., 2019; Schmitt et al., 2020). Recent studies investigating application have found that optimisation of RTC rules across catchments has significant benefits (Shishegar et al., 2021), which can be further accelerated with IoT technology enabling effective and near-instantaneous communication between centralised control and distributed infrastructure.

Rainwater harvesting tanks operate in a similar way to attenuation basins, but are typically smaller, so could benefit from distributed deployment across a catchment, taking advantage of coordinated regulation, communication and security. Rainwater harvesting involves rainwater capture from a surface (typically a roof) followed by storage in tanks for later re-use as a form of non-potable water supply, or attenuation through a pipe or infiltration outlet (Melville-Shreeve et al., 2014, 2016; Gee and Hunt, 2016). Systems are classified as passive (no smart control) or active control (systems dynamically manage storage volumes) (Melville-Shreeve et al., 2016; Parolari et al., 2018). Literature identifies the potential for these systems to achieve multiple benefits in both stormwater attenuation to protect downstream networks and rainwater re-use to supplement existing water supplies (Campisano et al., 2017; Xu et al., 2018); the dual benefit of which makes these systems an effective target for smart control to optimise asset benefits (Rohrer and Armitage, 2017).

Most effective application of both rainwater harvesting and attenuation basins is deemed to be through development of networks of coordinated systems at a catchment scale (Kerkez et al., 2016). The majority of current coordination is achieved through offline optimisation of each asset's independent performance, either through the status of the asset itself (Mullapudi et al., 2018), upstream conditions (Kändler et al., 2020a, 2020b; Lund et al., 2020; Sadler et al., 2020) or forecasting (Thorndahl and Rasmussen, 2013; Tao et al., 2020). Research has identified that distributed smart controls system control have substantial benefits, even when compared to individual tanks matching the volume of distributed measures (Di Matteo et al., 2019; Shishegar et al., 2019).

Decentralised control is increasingly perceived as a robust solution, due to limited requirement for communication (Schütze et al., 2004; Xu et al., 2021) and substantial evidence indicating that assets perform to a better standard, capturing water in higher magnitude events than passive operation alone (Bilodeau et al., 2018; Wong and Kerkez, 2018), sometimes referred to as "sweating the assets" (Yuan et al., 2019). Most studies to date have focused on this asset scale (Xu et al., 2021); however this misses the benefits of smart coordination across networks (Troutman et al., 2020), leaving a research need for further studies addressing how benefits can be maximised.

3.7. Best practice and real-world examples from literature

Although the majority of research refers to modelling studies, as opposed to practical implementation, there are several notable examples of network scale smart stormwater systems in practice, including the Louisville and Jefferson County Metropolitan Sewer District (Louisville MSD) in Kentucky (Tao et al., 2020) and the MAGES system in Paris (Tabuchi et al., 2020).

The Louisville MSD was established in 2006 and integrates sewer-monitoring data, weather forecasting, and network scale optimisation to maximise network capacity and treatment inflows. The scheme has resulted in a saving of over \$200 million in capital costs through maximising network efficiency and reducing the need for stormwater storage facilities, as well as reducing operational and environmental costs through reducing sewer overflows by over 2-million gallons per year (Tao et al., 2020).

The MAGES system in Paris applies real time monitoring from 2000 sensors combined with a linked model with 23 000 calculation points. This information is updated every 5-minutes to provide a near real time representation of current network conditions. The system also integrates monitoring with rainfall forecasts to predict future network conditions for up to 24-hours in dry conditions and 6-hours where rain is forecast. Predictions are then carried forward for calculation and implementation of optimal solutions for current and future conditions (Tabuchi et al., 2020).

Application of future smart stormwater application is likely to rapidly develop, with multiple water and municipal organisations starting to purchase and install large networks of battery operated water level and flow monitors across networks, for example Southern Water (UK) recently purchasing 30 000 network sensors, in part to manage capacity and blockage issues across the combined sewer system (Southern Water, 2021). Other water companies are undertaking similar work to install monitors, highlighting the need for researchers to develop ways to record, evaluate and realise the value from these sensors.

4. How smart is smart? A conceptual framework for benchmarking progress

It is apparent that smart stormwater is a rapidly growing topic within literature, with many examples of current cutting-edge research demonstrating the advantages of adopting smart approaches. However, terminology and perceptions of what a "smart" system entails are fragmented, with many tangential or incomplete applications labelled as smart stormwater systems. To alleviate this, we have developed a classification framework to map, align and track progress in this field and ensure remaining challenges in research and application are effectively addressed in a systematic and strategic manner. We present this framework in Fig. 3, below.

4.1. Framework overview

Our framework maps smart stormwater through from a passive asset, which cannot be defined as smart, towards increasing levels of smart functionality through incremental fundamental developments in "technology" and "capability" (Fig. 3). Technology represents the underlying scientific knowledge, machinery or equipment required for a particular

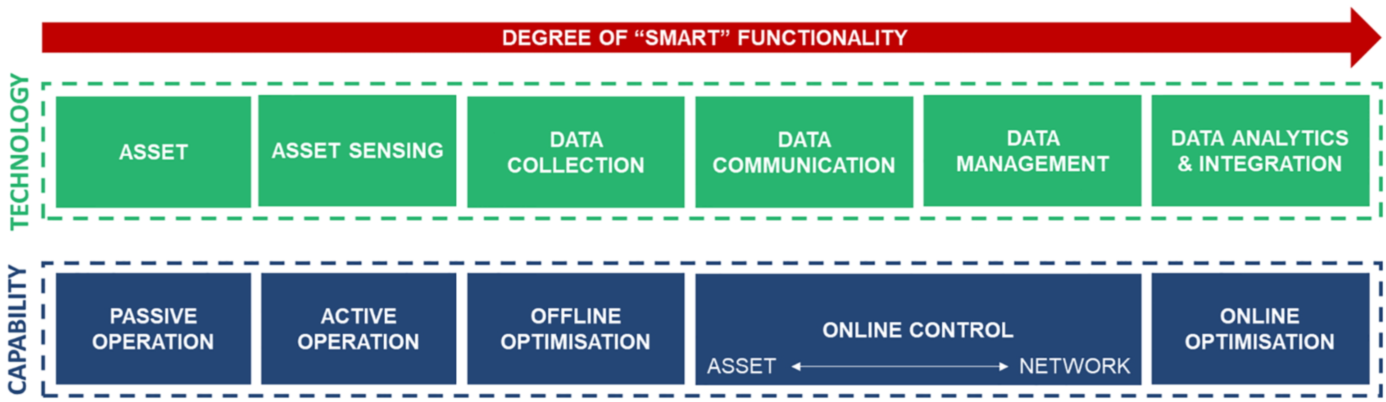

Fig. 3. Smart stormwater framework

task; whereas 'capability' represents the power or ability that a particular technology affords. The relationship between technology and capability is delimited by each technology realising the capability aligned directly below it in the figure.

For example, each technology aligns with a capability and progression of these towards the right (degree of functionality) iteratively builds the smart functionality of a system. For example: Just installing an asset enables passive operation; Installing sensing on that asset enables it to operate actively in response to its condition; Data collection technology enables that data to be used for offline optimisation; Whereas data communication then enables online control of assets (up to networks if appropriate data management is in place); Finally, data analytics and integration enables online multi-objective optimisation of a network.

Through this framework we aim to differentiate the 'degree of smartness' for a particular technology and capability (Fig. 3); with the simplest passive operation on the left of the diagram, progressing through to connected, coordinated and responsive smart stormwater systems on the right. The increments towards smart stormwater have been informed by themes drawn from our literature review, and through expanding comparable frameworks, such as the Smart Water Networks Forum 'SWAN layers' (SWAN, 2021), towards stormwater specificity.

We discuss the significance of each increment within the framework and map existing research to this in the section below.

4.2. Passive operation of assets

Passive operation is achieved through day-to-day operation of the physical elements representing the stormwater network, for example SuDS devices, tanks, sewers, overspills and other green infrastructure (Butler et al., 2018). Once installed, passive operation is achieved through data-less operation of the system. This approach is indicative of pre-twentieth century technology, where assets are designed, installed and left to function, with any further analysis or maintenance being undertaken manually, sporadically and more often than not, on a reactive basis. This represents the vast majority of existing stormwater networks at a global scale (Barbosa et al., 2012). We note that there is nothing intrinsically wrong with these reliable legacy systems, and in many cases these systems are able to effectively and efficiently manage stormwater networks with little intervention, as well as providing opportunities for passively achieving multiple benefits when integrated within interventions such as green infrastructure or passive rainwater harvesting (Fletcher et al., 2015; Mijic et al., 2016; Fenner, 2017). However, this approach cannot be deemed 'smart', and growing awareness of issues with legacy systems (Marlow et al., 2013; Butler et al., 2017; The Rivers Trust, 2019) has developed a consensus that more effective utilisation of networks using smart technologies is desirable (Dirckx et al., 2011; Yuan et al., 2019; Altobelli et al., 2020).

4.3. Asset sensing and active operation

The first and most basic manifestation of a smart stormwater system is the capability for assets to automatically actuate in response to local sensors monitoring their own or nearby network conditions. This type of solution is a common and widely implemented strategy, and is reported as a form of RTC within literature associated with responsive asset operation. This style of control is particularly synonymous with measures designed to enhance inline stormwater storage assets (Gaborit et al., 2013; Löwe et al., 2016; Bilodeau et al., 2018; Shishegar et al., 2019) or valves on combined networks (Ruggaber et al., 2007). Most advanced application occurs through deployment across networks (Kändler et al., 2020b; Schmitt et al., 2020). The ease of sensors determining water level means that the majority of implementations are focused on water quantity, and implementations which do address water quality issues are typically limited to controlling runoff quantity from high risk sites, as opposed to measuring contamination levels (Campisano et al., 2013). However proxy measures, such as modelled or indirectly measured suspended solids (for example via absorption spectra) have become more commonplace in recent years (Gaborit et al., 2016; Zhang et al., 2018; Bachmann-Machnik et al., 2021), with other studies developing promising applications of responsive quality based monitoring as part of green infrastructure (Shen et al., 2020).

4.4. Data collection and offline optimisation

The next level of capability when implementing smart systems arises from data collection. This differentiates from sensing through capturing and storing data from previous operations, as opposed to purely adjusting performance based on a sensor's current status. The main advantage of capturing data over time is in analysing this to develop insight into system operation, providing the potential for offline optimisation of adjusting operational rule sets.

With manual data collection in place, for example temperature/vibration sensors on pump assets, or water level probes in storm tanks, it is possible to understand the performance of an asset through subsequent offline appraisal. Such assessments are familiar with asset and network managers, who might routinely undertake regular performance audits. In this context, with basic asset data collection in place, operators can potentially target maintenance to those stormwater assets with anomalous water levels (e.g. those that might have a higher chance of siltation or blockage than other assets) or manually and iteratively investigate the effects of applying different rule sets to control basic responsive operation at an asset (Melville-Shreeve et al., 2014) or network scale (Bachmann-Machnik et al., 2021; Eulogi et al., 2021; Wang et al., 2021).

A further advantage with data collection is the ability to validate and test the hydraulic modelling synonymous with the design and operation of stormwater networks (Pender and Neelz, 2010; Dottori et al., 2013).

4.5. Data communication, management and online control

A range of wireless communication technologies are now enabling real time and multi-directional communication between sensors, actuators and centralised control systems, enabling data capture in real time (as opposed to only collecting retrospective data as discussed above) and subsequent remote control.

Historically data communication has been achieved through cellular networks and satellites (Das and Jain, 2017; Nguyen and Phung, 2017; Sobel et al., 2017). However success of these measures has been curtailed by issues of cost, battery limitations due to the significant power required for transmission (Olatinwo and Joubert, 2019) and the a lack of radio penetration to connect underground sensors with above ground networks (Lalle et al., 2019). This has historically limited communication to below ground infrastructure assets, contributing to the previously discussed dominance of centralised monitoring at larger assets in the early adoption of smart systems.

However, the ubiquity of smart sensors across sectors now means a range of low cost, energy efficient alternatives are commonplace (Lalle et al., 2021) leading to the potential for widespread deployment at scale. Deployment of two-way communication systems has enabled real time decentralised control of assets, and when twinned with data management systems this ability can be upscaled to monitor entire networks. This capability is frequently assumed in modelling studies emphasising the potential for smart systems. Many municipalities and utilities are beginning to develop distributed sensor networks to realise this capability (IWRA and K Water, 2018); however, although a handful of examples exist (Tabuchi et al., 2020; Tao et al., 2020), most of these networks are focused on monitoring and have not achieved network scale active control outside of individual assets (Ibrahim, 2020).

An opportunity to bridge from an asset-scale towards network-scale management and control lies in data assimilation (Hansen et al., 2014; Hutton et al., 2014; Palmitessa et al., 2021). Data assimilation is the process of dynamically estimating the status across different locations in a network through combining modelled and observed data (Lund et al., 2019). This is a pertinent capability in terms of complementing gaps in hardware sensing, with many current examples of network monitors relatively sparse. Advanced implementation of real world and modelled data can be developed towards 'digital twins'. Digital twins integrate embedded sensing, data assimilation and modelling to develop a digital representation of a system in real time (Bartos and Kerkez, 2021). Within stormwater management, a digital twin is likely to include sewer flow sensors coupled to an integrated hydrodynamic model of the stormwater network. Basic application of this process may be used for real time monitoring of the stormwater system, with 'smarter' application of this developing towards control and actuation.

4.6. Data analytics and online optimisation

Stormwater data analytics and optimisation is a topic of broad and well-developed research, often synthesised under the banner of 'hydroinformatics' (Ellis and Marsalek, 1996). However, with regards to our smart stormwater framework it is apparent that analytics, optimisation and learning need to take place in a manner which can actively optimise system operation in real time (Shishegar et al., 2018). Although certain studies have demonstrated this level of optimisation on small systems, we note that consistent application up to a coordinated catchment scale perspective has not been achieved. This is typically due to the limitation of processing time for hydraulic modelling, which can be in the order of hours, for decisions required in the order of minutes (Rathnayake and Faisal Anwar, 2019). However, we note that new models and increases in computational efficiency are improving the outlook in this regard. Some limited application of real time optimisation of complex stormwater systems is beginning (Tabuchi et al., 2020); however, developing optimisation to the network scale and real time perspective required for coordinated decentralised infrastructure remains a limitation of current approaches (Schütze et al., 2004; Xu et al., 2021).

4.7. Data integration and multi-functional online optimisation

The most advanced degree of smartness in stormwater management is the ability for smart networks to make optimal decisions regarding data from inside the network, aligned with data from external sources. The most common utilisation of this approach is through current integration with rainfall radar and forecasting (Gaborit et al., 2013, 2016; Thorndahl and Rasmussen, 2013; Löwe et al., 2016), This develops the capability to optimise decisions based for current and future condition of the network, as demonstrated in practice in the Paris MAGES system (Tabuchi et al., 2020).

This is further advanced through integrating data to expand optimal performance from a focus on hydraulics towards other external additionalities and interactions across subsystems. This is most pertinent when considering the potential multiple benefits and cross-sector interactions of novel green infrastructures, which can be managed to achieve significant benefits to stormwater alongside environmental and societal functions (Mijic et al., 2016; Frantzeskaki, 2019; O'Donnell et al., 2020; Zhang et al., 2020). Development of smart management across multiple subsystems brings stormwater management towards the smart cities agenda (Abbas et al., 2017; Meng et al., 2017).

4.8. Cyber security

Cyber security is beyond the scope of this review, but remains of absolute importance as infrastructure advances from passive operation towards connected and controllable smart stormwater systems which may be vulnerable to malicious or accidental digital threats (Kerkez et al., 2016). We strongly recommend that advances towards smart stormwater take cyber security into account at every stage of implementation and data management. To emphasise this risk we highlight several recent cyber attacks on infrastructure: The 2021 Colonial Pipeline ransomware attack, which led to cascading and unaccounted damages across the United States (BBC, 2021); the 2017 'NotPetya' attack which was estimated to cause $850 million in damages, including $300 million each to the companies Maersk and TNT (BBC, 2017); and the 2017 'WannaCry' attack, which was estimated to cost $8 billion globally, including shutting down the systems of 80 UK NHS trusts, resulting in the cancellation of 20 000 health appointments (Reuters, 2017; The Guardian, 2017). Water systems have also been targeted, with particularly dangerous results when cyber criminals have gained access to control infrastructure. An early example of this is the Maroochy Water System attack in 2000, where a disgruntled ex-employee gained control of a water system and discharged over one million litres of sewage into a river and a hotel (Miller and Rowe, 2012). However, even where physical controls are safeguarded, cyber attacks on digital infrastructure, such as data management systems, can also lead to significant damage; Lloyds of London estimate that a large to extreme coordinated hacking of cloud systems could result in economic losses of $53 billion, with actual losses as high as $121 billion (Reuters, 2017).

5. What are the barriers and challenges to advance best practice?

We have identified several significant barriers and challenges which should be addressed for future research to realise effective smart stormwater management.

5.1. Technological challenges

5.1.1. Specialised technologies

From a technological perspective, many of the components including sensors, actuators and communication technologies are available and reliable when deployed under appropriate management and maintenance regimes (Campisano et al., 2013). In fact, many comparable technologies are already ubiquitous across other sectors, predominantly energy, transport and communication, as part of the IoT revolution (Atzori et al., 2010; IBM, 2016; Das and Jain, 2017; Edmondson et al., 2018). In this regard, we argue that the underlying components of actuation, communication, security are already available, but have not necessarily been combined or translated to provide utility and transferability to the stormwater domain.

Specialist technologies which are specific to the stormwater or water domain are typically less available. This includes sensors and actuators, which record or control components not directly transferable from other sectors. Specialist sensors and actuators are available for stormwater quantity control, however water quality applications are not at the same maturity level due to challenges in real time data for chemical and biological contaminants (Campisano et al., 2013). Furthermore, although sensing and actuation technology exists, this still needs to be implemented and tested at scale to demonstrate practical effectiveness.

5.1.2. Computation time and multi-functionality

A further key technological challenge is the current disconnect between the timescale of optimising complex networks versus the timescale of required action at which network management decisions need to be made in practice. Modelled strategies which show significant promise (ie Shishegar et al., 2021) require advances in distribution and application of sensor technology (Atzori et al., 2010) as well as modelling and optimisation which can be undertaken at the same timescale as decisions need to be made (Xu et al., 2021). Current optimisation and control is achieved through control of small numbers of local scale components (Kändler et al., 2020b) or with simple pre-defined rules, however future research is required to achieve catchment or network wide control of multiple components. Optimisation and control also requires confidence in data streams, particularly when networks are controlled relative to predicted rather than current conditions. A key factor with data is accuracy of forecast data, particularly when extending timeframes (Xu et al., 2020).

While computing power increases consistently over time, thus theoretically reducing computation time required to solve optimisation problems, the move towards increasingly multi-functional stormwater management will dramatically increase computational time through requiring simultaneous modelling and solving trade-offs between multiple objectives. There are significant advances in developing objective functions for stormwater that simultaneously consider water quality treatment, flood mitigation, water supply and delivery of more natural streamflow regimes (Shishegar et al., 2019; Shen et al., 2020; Xu et al., 2020). Similarly, there is an increasing trend towards hybrid centralised-decentralised systems in both water supply and stormwater (Liang et al., 2019), which are ideal for smart stormwater technology, for example jointly optimising the flood mitigation performance of large stormwater retention basins with distributed (e.g. household scale) systems that also act as supplementary water supply. Such an approach dramatically increases the number of control elements in the optimisation, with subsequent impacts on computational requirements. While increased computational power provides one solution to these challenges, there are also promising advances in uses of longer forecast windows (Xu et al. 2020), allowing system operations requiring longer modelling timeframes to be undertaken well in advance of critical events.

5.2. Socio-economic challenges

5.2.1. Trust

Much of the technology underlying smart stormwater systems exists, but remains under-utilised in practice. This highlights that many of the ultimate barriers to implementation remain socio-economic.

A frequently cited barrier to smart stormwater is the lack of trust in novel technologies, particularly when viewed in the context of a risk averse water industry (Kerkez et al., 2016; White et al., 2018; Frantzeskaki, 2019). Modelling studies routinely demonstrate the benefits of smart, distributed systems; however future application requires development of demonstrator sites from current ad-hoc site-scale pilots towards catchment scale implementation (Ibrahim, 2020).

Trust in whole life costing of systems is also crucial, with many municipalities willing to invest more in smart technology if lower overtime costs can be achieved (Meng and Hsu, 2019). Developing demonstrator sites which can evidence technology costs and reliability are a key step in enhancing trust and up-scaling implementation will also drive positive feedback loops to enhance economies of scale. Securing implementation with municipalities and utilities also requires investigation of appropriate business models to drive investment (Xu et al., 2021). Investigating business models will benefit from multi-disciplinary research to explore the many permutations of centralised, decentralised, public and private ownership, control and incentive relationships, which have the potential to spark a step change in water industry culture. When describing this step change, we envisage potential parallels with approaches used in the energy (feed in tariffs) and financial (bitcoin processing) markets, where distributed public-private models have proved mutually beneficial and replicable at scale.

Issues with trust are also compounded by uncertainty over regulation and ownership of assets. Regulation regarding smart stormwater is piecemeal at best, but consequences for poor water quantity or quality outcomes can be severe, evidenced through the recent £126 million fine charged to Southern Water (UK) for CSO spills. Smart water systems are likely to alleviate these pressures; however clarity over operation and standards is required to ensure utilities are confident deploying them; this is particularly crucial where smart systems are network wide and include novel assets, such as rainwater harvesting, which may be operated by individuals or companies not within the water utility itself (Hoang and Fenner, 2015).

5.2.2. Business-cases and business models

The advent of smart stormwater technologies opens up new ways of managing stormwater. For example, flood mitigation can now be provided not only by large infrastructure operators, but also by householders, with rainwater and stormwater harvesting systems that operate collaboratively with larger, downstream storages, to mitigate peak flows or shift flow peaks. Similarly, smart stormwater systems have the potential to be operated to improve urban amenity, by increasing landscape moisture during critical heat events. Such services have a market value to consumers, creating new business opportunities. However, for investments in these opportunities to be successful, there needs to be an efficient market that allows providers to receive financial benefits for their investments (Mell, 2018). This will require development of new business models, which in turn may require regulatory changes to open up currently monopolistic service provision arrangements to a wider range of players. Doing so, however, also opens up new opportunities for current water service providers, such as in the installation, operation and maintenance of decentralised stormwater and water supply infrastructure, such as the AquaRevo example in Australia, where South East Water joined with a private company to create an urban development offering smart stormwater, water supply, wastewater and energy provision, including ongoing system maintenance and support (Livesley et al., 2021).

5.2.3. Standards and standardisation

Similarly, standardisation of protocols - for data, communication and interoperability - is required to ensure integration across multiple companies and systems (Edmondson et al., 2018; Tabuchi et al., 2020). Current smart control systems tend to be based on proprietary software architectures and may not be easily migrated into existing management frameworks. This is made worse by the rapidly evolving nature of the

IoT, with new sensor, communications and data storage technologies developing. Despite the obvious attractions of such advances, these can also act as significant barriers to entry for water agencies and service providers, whose scale of deployment requires confidence in the long-term operation, maintenance and interoperability of installed systems. There is thus a need for national and international standards and consistent adoption, alignment and adherence to these, to provide the industry with the required long-term confidence, and thus to provide more certain market access for future technological advances.

6. Conclusions

Literature almost universally agrees that smart technology is, or will be, beneficial to stormwater management; however, studies present disconnected and diverse smart applications which often only partially capture the true potential of this emerging technology. Effective future research relies on an aligned, strategic and consistent direction when evaluating smart stormwater. To this end we have evaluated best practice and developed a framework to benchmark progress and highlight next steps.

Despite high availability of components for implementation of smart stormwater approaches across connected sectors, the current state of smart stormwater is dominated by proof-of-concept modelling studies, with limited real-world application beyond RTC of large assets, individual pilots, and monitoring; and with most applications made to water quantity and not quality challenges.

Future research should advance the ‘degree of smartness’, and corresponding benefits, of smart stormwater through investigating how components can be integrated, controlled and optimised across a catchment scale. This can be achieved through developing trust in the technology, economics and benefits of systems using demonstrator projects and cross-sector collaboration; and in particular, through investigating the integration of stormwater within the smart cities agenda, to enhance consideration of novel strategies which realise multiple benefits.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

James Webber reports financial support was provided by Engineering and Physical Sciences Research Council. Peter Melville-Shreeve reports a relationship with Over the air analytics that includes: board membership, employment, and equity or stocks. Peter Melville-Shreeve was Director and employee of Over the air analytics limited, working on real time control solutions for water sector projects (2015-January 2020). Since January 2020 he stepped down as director and is no longer commercially linked to the business.

Acknowledgments

This research was funded by the EPSRC project ‘TWENTY 65: Tailored Water Solutions for Positive Impact’ (EP/N010124/1). The authors also wish to thank and recognise the contributions of Daniel Xu and Matthew Burns at the Waterway Ecosystem Research Group (University of Melbourne).

References

Abbas, O., Abou Rjeily, Y., Sadek, M., Shahrour, I., 2017. A large-scale experimentation of the smart sewage system. Water Environ. J. 31 (4), 515–521. https://doi.org/10.1111/wej.12273. Blackwell Publishing Ltd.

Altobelli, M., Cipolla, S.S., Maglionico, M., 2020. Combined application of real-time control and green technologies to urban drainage systems. Water (Switzerland) 12 (12), 1–15. https://doi.org/10.3390/w12123432. MDPI AG.

Atzori, L., Iera, A., Morabito, G., 2010. The Internet of Things: a survey. Comput. Netw. 54 (15), 2787–2805. https://doi.org/10.1016/j.comnet.2010.05.010. Elsevier.

Bachmann-Machnik, A., Bruning, Y., Bakhshipour, A.E., Krauss, M., Dittmer, U., 2021. Evaluation of combined sewer system operation strategies based on highly resolved online data. Water (Switzerland) 13 (6). https://doi.org/10.3390/w13060751. MDPI AG.

Barbosa, A.E., Fernandes, J.N., David, L.M., 2012. Key issues for sustainable urban stormwater management. Water Res. 46 (20), 6787–6798. https://doi.org/10.1016/j.watres.2012.05.029. Elsevier Ltd.

Bartos, M., Kerkez, B., 2021. Pipedream: an interactive digital twin model for natural and urban drainage systems. Environ. Model. Softw. 144. Available at: https://www.sciencedirect.com/science/article/pii/S1364815221001638 (Accessed: 10 March 2022).

Bartos, M., Wong, B., Kerkez, B., 2018. Open storm: A complete framework for sensing and control of urban watersheds. Environmental Science: Water Research and Technology. Royal Society of Chemistry, pp. 346–358. https://doi.org/10.1039/c7ew00374a.

BBC 2017*NotPetya cyber-attack cost TNT at least $300m - BBC News*. Available at: https://www.bbc.co.uk/news/technology-41336086 (Accessed: 29 June 2021).

BBC 2021*Colonial Pipeline boss confirms $4.4m ransom payment - BBC News*. Available at: https://www.bbc.co.uk/news/business-57178503 (Accessed: 29 June 2021).

Bilodeau, K., Pelletier, G., Duchesne, S., 2018. Real-time control of stormwater detention basins as an adaptation measure in mid-size cities. Urban Water J. 15 (9), 858–867. https://doi.org/10.1080/1573062X.2019.1574844. Taylor and Francis Ltd.

Brown, R.R., Farrelly, M.aA., 2009. Delivering sustainable urban water management: a review of the hurdles we face. Water Sci. Technol. 59 (5), 839. https://doi.org/10.2166/wst.2009.028.

Butler, D., Farmani, R., Fu, G., Ward, S., Diao, K., Astaraie-Imani, M., 2014. A New Approach to Urban Water Management: Safe and Sure. Procedia Eng. 89, 347–354. https://doi.org/10.1016/j.proeng.2014.11.198.

Butler, D., Ward, S., Sweetapple, C., Astaraie-Imani, M., Diao, K., Farmani, R., Fu, G., 2017. Reliable, resilient and sustainable water management: the Safe & SuRe approach. Glob. Challenges 1 (1), 63–77. https://doi.org/10.1002/gch2.1010.

Butler, D., Digman, C., Makropoulos, C., Davies, J., 2018. Urban drainage, Fourth edi. CRC Press, London.

Campisano, A., Cabot Ple, J., Muschalla, D., Pleau, M., Vanrolleghem, P.A., 2013. Potential and limitations of modern equipment for real time control of urban wastewater systems. Urban Water J. 10 (5), 300–311. https://doi.org/10.1080/1573062X.2013.763996.

Campisano, A., Butler, D., Ward, S., Burns, M.J., Friedler, E., DeBusk, K., Fisher-Jeffes, L. N., Ghisi, E., Rahman, A., Furumai, H., Han, M., 2017. Urban rainwater harvesting systems: Research, implementation and future perspectives. Water Res. 115, 195–209. https://doi.org/10.1016/J.WATRES.2017.02.056. Pergamon.

Campisano, A., Creaco, E., Modica, C., 2016. Application of Real-Time Control Techniques to Reduce Water Volume Discharges from Quality-Oriented CSO Devices. J. Environ. Eng. 142 (1), 04015049 https://doi.org/10.1061/(asce)ee.1943-7870.0001013. American Society of Civil Engineers (ASCE).

Cardle, J.A., 1991. Evaluation Of Stormsewer Control Algorithms Using A Transient Mixed Flow Model. JAWRA J. Am. Water Resour. Assoc. 27 (5), 819–830. https://doi.org/10.1111/j.1752-1688.1991.tb01480.x.

Cembrano, G., Quevedo, J., Salamero, M., Puig, V., Figueras, J., Martí, J., 2004. Optimal control of urban drainage systems. A case study. Control Eng. Pract. 12 (1), 1–9. https://doi.org/10.1016/S0967-0661(02)00280-0.

Cettner, A., 2012. Overcoming inertia to sustainable stormwater management practice. Luleå University of Technology.

Darsono, S., Labadie, J.W., 2007. Neural-optimal control algorithm for real-time regulation of in-line storage in combined sewer systems. Environ. Modell. Softw. 22 (9), 1349–1361. https://doi.org/10.1016/j.envsoft.2006.09.005.

Das, B., Jain, P.C., 2017. Real-time water quality monitoring system using Internet of Things. In: 2017 International Conference on Computer, Communications and Electronics, COMPTELIX 2017. Institute of Electrical and Electronics Engineers Inc., pp. 78–82. https://doi.org/10.1109/COMPTELIX.2017.8003942

Davoudi, S., Shaw, K., Haider, L.J., Quinlan, A.E., Peterson, G.D., Wilkinson, C., Fünfgeld, H., McEvoy, D., Porter, L., Davoudi, S., 2012. Resilience: A Bridging Concept or a Dead End? "Reframing" Resilience: Challenges for Planning Theory and Practice Interacting Traps: Resilience Assessment of a Pasture Management System in Northern Afghanistan Urban Resilience: What Does it Mean in Planni. Plann. Theory Pract. 13 (2), 299–333. https://doi.org/10.1080/14649357.2012.677124.

DEFRA 2018*Surface Water Management: An Action Plan*. Available at: www.nationalarchives.gov.uk/doc/open-government-licence/version/3/oremailPSI@nationalarchives.gsi.gov.ukwww.gov.uk/defra (Accessed: 11 September 2018).

Dirckx, G., Schutze, M., Kroll, S., Thoeye, C., De Gueldre, G., Van De Steene, B., 2011. Urban Water Journal Cost-efficiency of RTC for CSO impact mitigation Cost-efficiency of RTC for CSO impact mitigation. Taylor Francis 8 (6), 367–377. https://doi.org/10.1080/1573062X.2011.630092.

Dottori, F., Di Baldassarre, G., Todini, E., 2013. Detailed data is welcome, but with a pinch of salt: Accuracy, precision, and uncertainty in flood inundation modeling. Water Resour. Res. 49 (9), 6079–6085. https://doi.org/10.1002/wrcr.20406. Wiley-Blackwell.

DWA 2005*Regelwerk: Handlungsrahmen zur Planung der Abflusssteuerung in Kanalnetzen. M 180, In: Schütze et al 2008*. Available at: https://scholar.google.com/scholar?hl=en&q=+DWA+-+Deutsche+Vereinigung+für+Wasserwirtschaft%2C+Abwasser+und+Abfall+e.+V.%2C+2005.+Handlungsrahmen+zur+Planung+von+Abflusssteuerung+in+Kanalnetzen%3B+Merkblatt+DWA-M180.+ISBN+3-939057-02-9+ (Accessed: 26 May 2021).

Edmondson, V., Cerny, M., Lim, M., Gledson, B., Lockley, S., Woodward, J., 2018. A smart sewer asset information model to enable an "Internet of Things" for

operational wastewater management. Autom. Constr. 91, 193–205. https://doi.org/10.1016/j.autcon.2018.03.003. Elsevier B.V.
Ellis, J.B., Marsalek, J., 1996. Overview of urban drainage: Environmental impacts and concerns, means of mitigation and implementation policies. J. Hydraul. Res. 723–732. https://doi.org/10.1080/00221689609498446. International Association of Hydraulic Engineering Research.
Eulogi, M., Ostojin, S., Skipworth, P., Shucksmith, J.D., Schellart, A., 2021. Hydraulic optimisation of multiple flow control locations for the design of local real time control systems. Urban Water J. 18 (2), 91–100. https://doi.org/10.1080/1573062X.2020.1860238. Taylor and Francis Ltd.
Fenner, R., 2017. Spatial Evaluation of Multiple Benefits to Encourage Multi-Functional Design of Sustainable Drainage in Blue-Green Cities. Water 9 (12), 953. https://doi.org/10.3390/w9120953. Multidisciplinary Digital Publishing Institute.
Fenner, R.A., 2000. Approaches to sewer maintenance: a review. Urban Water 2, 343–356. Available at: www.elsevier.com/locate/urbwat (Accessed: 6 September 2018).
Fletcher, T.D., Shuster, W., Hunt, W.F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.-L., Mikkelsen, P.S., Rivard, G., Uhl, M., Dagenais, D., Viklander, M., 2015. SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. Urban Water J. 12 (7), 525–542. https://doi.org/10.1080/1573062X.2014.916314. Taylor & Francis.
Frantzeskaki, N., 2019. Seven lessons for planning nature-based solutions in cities. Environ. Sci. Policy 93, 101–111. https://doi.org/10.1016/j.envsci.2018.12.033. Elsevier Ltd.
Gaborit, E., Muschalla, D., Vallet, B., Vanrolleghem, P.A., Anctil, F., 2013. Improving the performance of stormwater detention basins by real-time control using rainfall forecasts. Urban Water J. 10 (4), 230–246. https://doi.org/10.1080/1573062X.2012.726229.
Gaborit, E., Anctil, F., Pelletier, G., Vanrolleghem, P.A., 2016. Exploring forecast-based management strategies for stormwater detention ponds. Urban Water J. 13 (8), 841–851. https://doi.org/10.1080/1573062X.2015.1057172. Taylor and Francis Ltd.
Gee, K.D., Hunt, W.F., 2016. Enhancing Stormwater Management Benefits of Rainwater Harvesting via Innovative Technologies. J. Environ. Eng. 142 (8), 04016039 https://doi.org/10.1061/(ASCE)EE.1943-7870.0001108.
Gourbesville, P., 2016. Key Challenges for Smart Water. Procedia Engineering. Elsevier Ltd, pp. 11–18. https://doi.org/10.1016/j.proeng.2016.07.412.
Hansen, L.S., Borup, M., Møller, A., Mikkelsen, P.S., 2014. Flow Forecasting using Deterministic Updating of Water Levels in Distributed Hydrodynamic Urban Drainage Models. Water 6 (8), 2195–2211. https://doi.org/10.3390/W6082195. Multidisciplinary Digital Publishing Institute.
Hayes, N., 1994. Storm raising. Surveyor 181 (5299), 16–17.
Hoang, L., Fenner, R.A., 2015. System interactions of stormwater management using sustainable urban drainage systems and green infrastructure System interactions of stormwater management using sustainable urban drainage systems and green infrastructure. Urban Water J. 13 (7), 739–758. https://doi.org/10.1080/1573062X.2015.1036083.
Hoppe, H., Messmann, S., Giga, A., Gruening, H., 2011. A real-time control strategy for separation of highly polluted storm water based on UV-Vis online measurements - From theory to operation. Water Sci. Technol. 63 (10), 2287–2293. https://doi.org/10.2166/wst.2011.164.
Hutton, C.J., Kapelan, Z., Vamvakeridou-Lyroudia, L., Savić, D., 2014. Real-time Data Assimilation in Urban Rainfall-runoff Models. Procedia Eng. 70, 843–852. https://doi.org/10.1016/J.PROENG.2014.02.092. No longer published by Elsevier.
IBM 2016*What is the IoT?*Available at: https://www.ibm.com/blogs/internet-of-things/what-is-the-iot/.
Ibrahim, Y.A., 2020. Real-Time Control Algorithm for Enhancing Operation of Network of Stormwater Management Facilities. J. Hydrol. Eng. 25 (2), 04019065 https://doi.org/10.1061/(asce)he.1943-5584.0001881. American Society of Civil Engineers (ASCE).
IPCC 2014*Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*
IWRA & K Water 2018*SMART WATER MANAGEMENT: Case Study Report.* Available at: https://www.iwra.org/wp-content/uploads/2018/11/SWM-report-final-web.pdf.
James, W., 1984. Emerging computer techniques in stormwater and flood management. ASCE, New York.
Jose, R., Wade, R., Jefferies, C., 2015. Smart SUDS: recognising the multiple-benefit potential of sustainable surface water management systems. Water Sci. Technol. 71 (2), 245–251. https://doi.org/10.2166/wst.2014.484.
Kändler, N., Annus, I., Vassiljev, A., Puust, R., 2020a. Peak flow reduction from small catchments using smart inlets. Urban Water J. 17 (7), 577–586. https://doi.org/10.1080/1573062X.2019.1611888. Taylor and Francis Ltd.
Kändler, N., Annus, I., Vassiljev, A., Puust, R., 2020b. Real time controlled sustainable urban drainage systems in dense urban areas. J. Water Supply Res. Technol. AQUA 69 (3), 238–247. https://doi.org/10.2166/aqua.2019.083. IWA Publishing.
Kerkez, B., Gruden, C., Lewis, M., Montestruque, L., Quigley, M., Wong, B., Bedig, A., Kertesz, R., Braun, T., Cadwalader, O., Poresky, A., Pak, C., 2016. Smarter stormwater systems. Environ. Sci. Technol. 50 (14), 7267–7273. https://doi.org/10.1021/acs.est.5b05870. American Chemical Society.
Kwan A., Yue D. & Hodgson J. 1993 'Application of the SWMM4 model for the real time control of a storm trunk sewer'. Lewis.
Lacour, C., Schütze, M., 2011. Real-time control of sewer systems using turbidity measurements. Water Sci. Technol. 63 (11), 2628–2632. https://doi.org/10.2166/wst.2011.159.
Lalle, Y., Fourati, L.C., Fourati, M., Barraca, J.P., 2019. A Comparative Study of LoRaWAN, SigFox, and NB-IoT for Smart Water Grid. In: 2019 Global Information Infrastructure and Networking Symposium, GIIS 2019. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/GIIS48668.2019.9044961.
Lalle, Y., Fourati, M., Fourati, L.C., Barraca, J.P., 2021. Communication technologies for Smart Water Grid applications: overview, opportunities, and research directions. Comput. Netw., 107940 https://doi.org/10.1016/j.comnet.2021.107940. Elsevier B.V.
Li, J.R., 2020. A data-driven improved fuzzy logic control optimization-simulation tool for reducing flooding volume at downstream urban drainage systems. Sci. Total Environ. 732. https://doi.org/10.1016/j.scitotenv.2020.138931. Elsevier B.V.
Liang, R., Di, Ma.tteo M., Maier, H., Water, M.T., 2019. Real-time, smart rainwater storage systems: potential solution to mitigate urban flooding. Water 11 (12), 2428. Available at: https://www.mdpi.com/577940 (Accessed: 2 December 2021).
Livesley, S.J., Marchionni, V., Cheung, P.K., Daly, E., Pataki, D.E., 2021. Water Smart Cities Increase Irrigation to Provide Cool Refuge in a Climate Crisis. Earth's Fut. 9 (1), e2020EF001806 https://doi.org/10.1029/2020EF001806. John Wiley & Sons, Ltd.
Löwe, R., Vezzaro, L., Mikkelsen, P.S., Grum, M., Madsen, H., 2016. Probabilistic runoff volume forecasting in risk-based optimization for RTC of urban drainage systems. Environ. Modell. Softw. 80, 143–158. https://doi.org/10.1016/j.envsoft.2016.02.027. Elsevier Ltd.
Lund, N., Madsen, H., Mazzoleni, M., Solomatine, D., Borup, M., 2019. Assimilating flow and level data into an urban drainage surrogate model for forecasting flows and overflows. J. Environ. Manage. 248, 109052 https://doi.org/10.1016/J.JENVMAN.2019.05.110. Academic Press.
Lund, N.S.V., Borup, M., Madsen, H., Mark, O., Mikkelsen, P.S., 2020. CSO Reduction by Integrated Model Predictive Control of Stormwater Inflows: A Simulated Proof of Concept Using Linear Surrogate Models. Water Resour. Res. 56 (8) https://doi.org/10.1029/2019WR026272. Blackwell Publishing Ltd.
Maiolo, M., Palermo, S.A., Brusco, A.C., Pirouz, B., Turco, M., Vinci, A., Spezzano, G., Piro, P., 2020. On the use of a real-time control approach for urban stormwater management. Water (Switzerland) 12 (10). https://doi.org/10.3390/w12102842. MDPI AG.
Marlow, D.R., Moglia, M., Cook, S., Beale, D.J., 2013. Towards sustainable urban water management: A critical reassessment. Water Res. 47 (20), 7150–7161. https://doi.org/10.1016/j.watres.2013.07.046.
Di Matteo, M., Liang, R., Maier, H.R., Thyer, M.A., Simpson, A.R., Dandy, G.C., Ernst, B., 2019. Controlling rainwater storage as a system: An opportunity to reduce urban flood peaks for rare, long duration storms. Environ. Modell. Softw. 111, 34–41. https://doi.org/10.1016/j.envsoft.2018.09.020. Elsevier Ltd.
McCann, B., 1993. Sewers back into focus. Surveyor 180 (5248), 12–14.
Mell, I., 2018. Financing the future of green infrastructure planning: alternatives and opportunities in the UK. Landsc. Res. Routledge 43 (6), 751–768. https://doi.org/10.1080/01426397.2017.1390079.
Melville-Shreeve, P., Ward, S., Water, D.B., 2016. Rainwater harvesting typologies for UK houses: a multi criteria analysis of system configurations. Water 8 (4), 129. Available at: https://www.mdpi.com/2073-4441/8/4/129/htm (Accessed: 24 July 2018).
Melville-Shreeve, P., Ward, S., Butler, D., 2014. A preliminary sustainability assessment of innovative rainwater harvesting for residential properties in the UK. J. Southeast Univ. (English Ed.) 30 (2), 135–142. Available at: https://ore.exeter.ac.uk/repository/handle/10871/15293 (Accessed: 24 July 2018).
Meng, T., Hsu, D., 2019. Stated preferences for smart green infrastructure in stormwater management. Landsc. Urban Plan. 187, 1–10. https://doi.org/10.1016/j.landurbplan.2019.03.002. Elsevier B.V.
Meng, T., Hsu, D., Wadzuk, B., 2017. Green and Smart: Perspectives of City and Water Agency Officials in Pennsylvania toward Adopting New Infrastructure Technologies for Stormwater Management. J. Sustain. Water Built Environ. 3 (2), 05017001 https://doi.org/10.1061/jswbay.0000824. American Society of Civil Engineers (ASCE).
Mijic, A., Ossa-Moreno, J., Smith, K.M., 2016. Multifunctional benefits of SuDS: techno-economic evaluation of decentralised solutions for urban water management. Geophys. Res. Abstracts EGU General Assembly 18, 2016–9994. Available at: http://meetingorganizer.copernicus.org/EGU2016/EGU2016-9994.pdf (Accessed: 24 August 2017).
Miller, B., Rowe, D.C., 2012. A survey of SCADA and critical infrastructure incidents. In: RIIT'12 - Proceedings of the ACM Research in Information Technology, pp. 51–56. https://doi.org/10.1145/2380790.2380805.
Mullapudi, A., Bartos, M., Wong, B., Kerkez, B., 2018. Shaping streamflow using a real-time stormwater control network. Sensors (Switzerland) 18 (7). https://doi.org/10.3390/s18072259. MDPI AG.
Mullapudi, A., Lewis, M.J., Gruden, C.L., Kerkez, B., 2020. Deep reinforcement learning for the real time control of stormwater systems. Adv. Water Res. 140. https://doi.org/10.1016/j.advwatres.2020.103600. Elsevier Ltd.
Mullapudi, A., Wong, B.P., Kerkez, B., 2017. Emerging investigators series: building a theory for smart stormwater systems. Environ. Sci. 3 (1), 66–77. https://doi.org/10.1039/c6ew00211k. Royal Society of Chemistry.
Nguyen, D., Phung, P.H., 2017. A reliable and efficient wireless sensor network system for water quality monitoring. In: Proceedings - 2017 13th International Conference on Intelligent Environments, IE 2017. Institute of Electrical and Electronics Engineers Inc, pp. 84–91. https://doi.org/10.1109/IE.2017.34.
O'Donnell, E., Thorne, C., Ahilan, S., Arthur, S., Birkinshaw, S., Butler, D., Dawson, D., Everett, G., Fenner, R., Glenis, V., Kapetas, L., Kilsby, C., Krivtsov, V., Lamond, J., Maskrey, S., O'Donnell, G., Potter, K., Vercruysse, K., Vilcan, T., et al., 2020. The blue-green path to urban flood resilience. Blue-Green Syst. 2 (1), 28–45. https://doi.org/10.2166/bgs.2019.199. IWA Publishing.

O'Donnell, E.C., Lamond, J.E., Thorne, C.R., 2017. Recognising barriers to implementation of Blue-Green Infrastructure: a Newcastle case study. Urban Water J. 14 (9), 964–971. https://doi.org/10.1080/1573062X.2017.1279190. Taylor & Francis.
Oberascher, M., Rauch, W., Sitzenfrei, R., 2022. Towards a smart water city: a comprehensive review of applications, data requirements, and communication technologies for integrated management. Sustain. Cities Soc. 76, 103442 https://doi.org/10.1016/J.SCS.2021.103442. Elsevier.
Olatinwo, S.O., Joubert, T.H., 2019. Efficient energy resource utilization in a wireless sensor system for monitoring water quality. Eurasip J. Wirel. Commun. Networking 2019 (1). https://doi.org/10.1186/s13638-018-1316-x. Springer International Publishing.
Open Storm 2021*Open Storm: OPEN-SOURCE SENSORS, HARDWARE, AND ALGORITHMS FOR THE MEASUREMENT AND CONTROL OF WATER SYSTEMS*. Available at: http://open-storm.org/.
Oral, H.V., Carvalho, P., Gajewska, M., Ursino, N., Masi, F., Hullebusch, E.D., van, Kazak, J.K., Exposito, A., Cipolletta, G., Andersen, T.R., Finger, D.C., Simperler, L., Regelsberger, M., Rous, V., Radinja, M., Buttiglieri, G., Krzeminski, P., Rizzo, A., Dehghanian, K., et al., 2020. A review of nature-based solutions for urban water management in European circular cities: a critical assessment based on case studies and literature. Blue-Green Syst. 2 (1), 112–136. https://doi.org/10.2166/bgs.2020.932. IWA Publishing.
Palmitessa, R., Mikkelsen, P.S., Law, A.W.K., Borup, M., 2021. Data assimilation in hydrodynamic models for system-wide soft sensing and sensor validation for urban drainage tunnels. J. Hydroinf. 23 (3), 438–452. https://doi.org/10.2166/HYDRO.2020.074. IWA Publishing.
Parolari, A.J., Pelrine, S., Bartlett, M.S, 2018. Stochastic water balance dynamics of passive and controlled stormwater basins. Adv. Water Res. 122, 328–339. https://doi.org/10.1016/j.advwatres.2018.10.016. Elsevier Ltd.
Pender, G., Neelz, S., 2010. Benchmarking of 2D hydraulic modelling packages. Bristol.
Plate, E.J., 2002. Flood risk and flood management. J. Hydrol. 267 (1–2), 2–11. https://doi.org/10.1016/S0022-1694(02)00135-X.
Rathnayake, U., Faisal Anwar, A.H.M., 2019. Dynamic control of urban sewer systems to reduce combined sewer overflows and their adverse impacts. J. Hydrol. 579. https://doi.org/10.1016/j.jhydrol.2019.124150. Elsevier B.V.
Rauch, W., Harremoës, P., 1999. Genetic algorithms in real time control applied to minimize transient pollution from urban wastewater systems. Water Res. 33 (5), 1265–1277. https://doi.org/10.1016/S0043-1354(98)00304-2. Elsevier Sci Ltd.
Reuters 2017*Global cyber attack could spur $53 billion in losses - Lloyd's of London | Reuters*. Available at: https://www.reuters.com/article/uk-cyber-lloyds-report-idUKKBN1A20AH (Accessed: 29 June 2021).
Riaño-Briceño, G., Barreiro-Gomez, J., Ramirez-Jaime, A., Quijano, N., Ocampo-Martinez, C., 2016. MatSWMM - An open-source toolbox for designing real-time control of urban drainage systems. Environ. Modell. Softw. 83, 143–154. https://doi.org/10.1016/j.envsoft.2016.05.009. Elsevier Ltd.
Rohrer, A.R., Armitage, N.P., 2017. Improving the viability of stormwater harvesting through rudimentary real time control. Water (Switzerland) 9 (6). https://doi.org/10.3390/w9060371. MDPI AG.
Ruggaber, T.P., Talley, J.W., Montestruque, L.A., 2007. Using embedded sensor networks to monitor, control, and reduce CSO events: a pilot study. Environ. Eng. Sci. 172–182. https://doi.org/10.1089/ees.2006.0041.
Sadler, J.M., Goodall, J.L., Behl, M., Bowes, B.D., Morsy, M.M., 2020. Exploring real-time control of stormwater systems for mitigating flood risk due to sea level rise. J. Hydrol. 583. https://doi.org/10.1016/j.jhydrol.2020.124571. Elsevier B.V.
Saliba, S.M., Bowes, B.D., Adams, S., Beling, P.A., Goodall, J.L., 2020. Deep reinforcement learning with uncertain data for real-time stormwater system control and flood mitigation. Water (Switzerland) 12 (11), 1–19. https://doi.org/10.3390/w12113222. MDPI AG.
Schanze, J., 2017. Nature-based solutions in flood risk management - Buzzword or innovation? J. Flood Risk Manage. 10 (3), 281–282. https://doi.org/10.1111/jfr3.12318. Wiley/Blackwell (10.1111).
Schilling, W., 1994. Smart sewer systems: improved perfomence by real time control. Eur. J. Water Pollut. Control 4 (5), 24–31.
Schmitt, Z.K., Hodges, C.C., Dymond, R.L., 2020. Simulation and assessment of long-term stormwater basin performance under real-time control retrofits. Urban Water J. 17 (5), 467–480. https://doi.org/10.1080/1573062X.2020.1764062. Taylor and Francis Ltd.
Scholz, M., 2015. Sustainable Drainage Systems. Water 7 (12), 2272–2274. https://doi.org/10.3390/w7052272.
Schütze, M., Campisano, A., Colas, H., Schilling, W., Vanrolleghem, P.A., 2004. Real time control of urban wastewater systems - Where do we stand today? J. Hydrol. 299 (3–4), 335–348. https://doi.org/10.1016/j.jhydrol.2004.08.010. Elsevier B.V.
Schütze, M., Erbe, V., Haas, U., Scheer, M., Weyand, M., 2008. Sewer system real-time control supported by the M180 guideline document. Urban Water J. 5 (1), 69–78. https://doi.org/10.1080/15730620701754376. Taylor & Francis.
SCOPUS 2019*SCOPUS database fact sheet*. Available at: https://www.elsevier.com/__data/assets/pdf_file/0017/114533/Scopus_GlobalResearch_Factsheet2019_FINAL_WEB.pdf.
Sharior, S., McDonald, W., Parolari, A.J., 2019. Improved reliability of stormwater detention basin performance through water quality data-informed real-time control. J. Hydrol. 573, 422–431. https://doi.org/10.1016/j.jhydrol.2019.03.012. Elsevier B.V.
Shen, P., Deletic, A., Bratieres, K., McCarthy, D.T., 2020. Real time control of biofilters delivers stormwater suitable for harvesting and reuse. Water Res. 169, 115257 https://doi.org/10.1016/j.watres.2019.115257. Elsevier Ltd.
Shishegar, S., Duchesne, S., Pelletier, G., Ghorbani, R., 2021. A smart predictive framework for system-level stormwater management optimization. J. Environ. Manage. 278. https://doi.org/10.1016/j.jenvman.2020.111505. Academic Press.
Shishegar, S., Duchesne, S., Pelletier, G., 2018. Optimization methods applied to stormwater management problems: a review. Urban Water J. 276–286. https://doi.org/10.1080/1573062X.2018.1439976. Taylor and Francis Ltd.
Shishegar, S., Duchesne, S., Pelletier, G., 2019. An integrated optimization and rule-based approach for predictive real time control of urban stormwater management systems. J. Hydrol. 577. https://doi.org/10.1016/j.jhydrol.2019.124000. Elsevier B. V.
Skop E. & Loaiciga H.A. 1998*Investigating Catchment Hydrology and Low Flow Characteristics using GIS, Hydrology Research*. Available at: https://iwaponline.com/hr/article-pdf/29/2/105/4521/105.pdf (Accessed: 20 April 2020).
Sobel, R.S., Kiaghadi, A., Rifai, H.S., 2017. Using Satellite Imagery to Quantify Water Quality Impacts and Recovery from Hurricane Harvey. AGUFM 2017 pp. NH33E-01. Available at: https://ui.adsabs.harvard.edu/abs/2017AGUFMNH33E..01S/abstract (Accessed: 11 June 2021).
Southern Water 2021*Innovative sewer technology to tackle blockages*. Available at: https://www.southernwater.co.uk/our-performance/innovative-sewer-technology-to-tackle-blockages (Accessed: 2 December 2021).
Swain, D.L., Wing, O.E.J., Bates, P.D., Done, J.M., Johnson, K., Cameron, D.R., 2020. Increased flood exposure due to climate change and population growth in the United States. Earth's Fut. 8 (11) https://doi.org/10.1029/2020ef001778. American Geophysical Union (AGU).
SWAN 2021*A Layered View of Smart Water Networks*. Available at: https://www.swan-forum.com/swan-tools/a-layered-view/.
Tabuchi, J.P., Blanchet, B., Rocher, V., 2020. Integrated Smart Water Management of the sanitation system of the Greater Paris region. Water Int. 45 (6), 574–603. https://doi.org/10.1080/02508060.2020.1830584. Routledge.
Tao, D.Q., Pleau, M., Akridge, A., Fradet, O., Grondin, F., Laughlin, S., Miller, W., Shoemaker, L., 2020. Analytics and optimization reduce sewage overflows to protect community waterways in Kentucky. Interfaces 50 (1), 7–20. https://doi.org/10.1287/inte.2019.1022. INFORMS Inst.for Operations Res.and the Management Sciences.
The Guardian 2017*WannaCry, Petya, NotPetya: how ransomware hit the big time in 2017 | Malware | The Guardian*. Available at: https://www.theguardian.com/technology/2017/dec/30/wannacry-petya-notpetya-ransomware (Accessed: 29 June 2021).
The Rivers Trust 2019*Is my river fit to play in?, The Rivers Trust*. Available at: https://experience.arcgis.com/experience/e834e261b53740eba2fe6736e37bbc7b?org=theriverstrust.
Thorndahl, S., Rasmussen, M.R., 2013. Short-term forecasting of urban storm water runoff in real-time using extrapolated radar rainfall data. J. Hydroinf. 15 (3), 897–912. https://doi.org/10.2166/hydro.2013.161. IWA Publishing.
Thorne, C.R., Lawson, E.C., Ozawa, C., Hamlin, S.L., Smith, L.A, 2018. Overcoming uncertainty and barriers to adoption of Blue-Green Infrastructure for urban flood risk management. J. Flood Risk Manage. 11 (11), 960–S972. https://doi.org/10.1111/jfr3.12218. Wiley/Blackwell (10.1111).
Troutman, S.C., Love, N.G., Kerkez, B., 2020. Balancing water quality and flows in combined sewer systems using real-time control. Environ. Sci. 6 (5), 1357–1369. https://doi.org/10.1039/c9ew00882a. Royal Society of Chemistry.
UKWIR 2019*Big questions facing the water industry*. Available at: https://ukwir.org/eng/big-questions-facing-uk-water-industry.
Urban storm drainage, 1996. Selected proceedings of the 7th IAHR/IAWQ international conference on urban storm drainage. Water Science and Technology. Hannover, Germany. Available at: https://www.scopus.com/record/display.uri?eid=2-s2.0-0031403107&origin=resultslist (Accessed: 17 May 2021).
Vieux, B.E., Vieux, J.E., 2005. Statistical evaluation of a radar rainfall system for sewer system management. Atmos. Res. 77 (1–4 SPEC. ISS), 322–336. https://doi.org/10.1016/j.atmosres.2004.10.032. Elsevier BV.
Wang, X., Tian, W., Liao, Z., 2021. Offline Optimization of Sluice Control Rules in the Urban Water System for Flooding Mitigation. Water Resour. Manage. 35 (3), 949–962. https://doi.org/10.1007/s11269-020-02760-9. Springer Science and Business Media B.V.
Weiser M., Gold R. & Brown J.S. 1999*The origins of ubiquitous computing research at PARC in the late 1980s, ieeexplore.ieee.org*. Available at: http://www.ubiq.com/ (Accessed: 25 June 2021).
Weyand, M., 2002. Real-time control in combined sewer systems in Germany - Some case studies. Urban Water 4 (4), 347–354. https://doi.org/10.1016/S1462-0758(02)00031-6.
White, I., Connelly, A., Garvin, S., Lawson, N., O'Hare, P., 2018. Flood resilience technology in Europe: identifying barriers and co-producing best practice. J. Flood Risk Manage. 11, S468–S478. https://doi.org/10.1111/jfr3.12239. Wiley/Blackwell (10.1111).
Wing, O.E.J., Bates, P.D., Smith, A.M., Sampson, C.C., Johnson, K.A., Fargione, J., Morefield, P., 2018. Estimates of present and future flood risk in the conterminous United States. Environ. Res. Lett. 13 (3), 034023 https://doi.org/10.1088/1748-9326/aaac65. IOP Publishing.
Wong, B.P., Kerkez, B., 2018. Real-Time Control of Urban Headwater Catchments Through Linear Feedback: Performance, Analysis, and Site Selection. Water Resour. Res. 54 (10), 7309–7330. https://doi.org/10.1029/2018WR022657. Blackwell Publishing Ltd.
Wong, T.H., Eadie, M.L., 2000. Water sensitive urban design: A paradigm shift in urban design. In: 10th World Water Congress: Water, the Worlds Most Important Resource. International Water Resources Association, p. 1281. Available at: https://search.informit.com.au/documentSummary;dn=519426635188728;res=IELENG (Accessed: 3 August 2018).

Wong, T.H.F., 2006. Water sensitive urban design - the journey thus far. Aust. J. Water Resour. 10 (3), 213–222. https://doi.org/10.1080/13241583.2006.11465296.
Wong, T.H.F., Brown, R.R., 2009. The water sensitive city: Principles for practice. Water Sci. Technol. 60 (3), 673–682. https://doi.org/10.2166/wst.2009.436.
Woods Ballard, B., Wilson, S., Udale-Clarke, H., Illman, S., Scott, T., Ashley, R., Kellagher, R., 2015. The SuDS manual (C753). CIRIA, London, UK.
Wyman, V., 1994. Controlling storm water in real time. Surveyor 181 (5288), 16–17.
Xu, W., Fletcher, T., Duncan, H., Bergmann, D., Breman, J., Burns, M., 2018. Improving the Multi-Objective Performance of Rainwater Harvesting Systems Using Real-Time Control Technology. Water 10 (2), 147. https://doi.org/10.3390/w10020147.
Xu, W.D., Fletcher, T.D., Burns, M.J., Cherqui, F., 2020. Real Time Control of Rainwater Harvesting Systems: The Benefits of Increasing Rainfall Forecast Window. Water Resour. Res. 56 (9) https://doi.org/10.1029/2020WR027856. Blackwell Publishing Ltd.
Xu, W.D., Burns, M.J., Cherqui, F., Fletcher, T.D., 2021. Enhancing stormwater control measures using real-time control technology: a review. Urban Water J. 101–114. https://doi.org/10.1080/1573062X.2020.1857797. Taylor and Francis Ltd.
Yuan, Z., Olsson, G., Cardell-Oliver, R., van Schagen, K., Marchi, A., Deletic, A., Urich, C., Rauch, W., Liu, Y., Jiang, G., 2019. Sweating the assets – The role of instrumentation, control and automation in urban water systems. Water Res. 381–402. https://doi.org/10.1016/j.watres.2019.02.034. Elsevier Ltd.
Zhang, K., Deletic, A., Dotto, C.B.S., Allen, R., Bach, P.M., 2020. Modelling a “business case” for blue-green infrastructure: lessons from the Water Sensitive Cities Toolkit. Blue-Green Syst. 2 (1), 383–403. https://doi.org/10.2166/bgs.2020.018. IWA Publishing.
Zhang, P., Cai, Y., Wang, J., 2018. A simulation-based real-time control system for reducing urban runoff pollution through a stormwater storage tank. J. Clean. Prod. 183, 641–652. https://doi.org/10.1016/j.jclepro.2018.02.130. Elsevier Ltd.