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Review

Realising smarter stormwater management: A review of the barriers and a roadmap for real world application

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ABSTRACT

Effective management of stormwater systems is necessary for protection of both the built and natural environments. However, stormwater management is facing multiple, growing challenges, including climate change, ageing infrastructure, population growth, urbanisation, environmental concerns, regulatory and institutional changes and public awareness. While the potential of 'smart', internet-of-things enabled stormwater management systems to address these challenges is increasingly being recognised, with considerable evidence in literature for the benefits of more data-driven approaches, implementation to date remains low. This paper, therefore, provides a comprehensive review of the potential barriers to adoption of smarter stormwater management practices that require addressing, and provides a roadmap for real world application.

Barriers related to all elements of stormwater management, from the asset sensing to the data analytics and online optimisation, are identified. Technical challenges discussed include the availability and reliability of technologies, technological and physical limitations, decision making, uncertainty and security. Technical barriers are rapidly reducing and there is increasing evidence in the academic literature of the efficacy of smart technologies. However, socio-economic barriers remain a significant challenge, and issues such as trust and lack of confidence, resistance to change, expense, and lack of knowledge and guidance are reviewed.

A 'smart stormwater management wheel' that provides a flexible and iterative approach for implementing smart functionality is also presented. Whilst acting as a roadmap, this aims to facilitate a structured methodology for overcoming barriers and benchmarking progress, and may be used to explore trade-offs and relationships between differing levels of implementation for each of the constituent technologies in a smart stormwater system.

1. Introduction

1.1. The need for change

"Stormwater systems" can refer to the physical, digital and organisational infrastructure used to collect, convey, treat and manage rainfall runoff (Butler et al., 2018). Defining the scope of this "system" can include an extensive range of diverse components, particularly where organisational and co-dependent infrastructures are considered. For the scope of this paper we are focused on the physical (i.e. pipes, storage, sensors) and digital (software) components of this system, with limited discussion given to organisational infrastructure where this directly relates to operation of the previously mentioned components. The paper discusses elements such as storage and conveyance in general terms, but both conventional and green solutions could be applied for this function.

Effective management of stormwater systems is necessary for protection of both the built and natural environments. However, stormwater management is facing multiple, growing challenges.

Firstly, existing stormwater systems have been designed based on historical precipitation data; however, there is growing evidence that precipitation patterns are changing with climate change, with many locations subject to more frequent and more intense storm events (Mallakpour and Villarini, 2017). Consequently, stormwater systems are being increasingly subject to events that exceed their design capacities, resulting in a growing frequency and severity of flooding (Whitfield, 2012). Furthermore, these challenges may be compounded in coastal areas, where the functionality of gravity-driven stormwater systems is also being reduced by sea level rise (Sadler et al., 2020) and increased

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tidal locking.

Secondly, additional pressures are being imposed by population growth, rapid urbanisation and land use change (Browne et al., 2021). Urbanisation, for example, typically increases impermeable areas, which in turn increases runoff. More generally, the expansion of urban areas alters natural processes, influencing infiltration and evapotranspiration and complicating understanding of their dynamics (McGrane, 2016). It can also have quality implications, with catchment-scale factors such as the design of urban land also influencing the effects of stormwater on eutrophication in downstream waterbodies (Taylor et al., 2004).

An increase in contaminants in stormwater runoff poses further challenges (Kerkez et al., 2016; Naughton et al., 2021), and there is recognition in particular of the impact of development on nitrogen and phosphorus loadings (e.g. Environment Agency, 2019; Natural England, 2022). There is also a growing understanding of the significance of emerging contaminants such as microplastics, pharmaceuticals, agri-chemicals, metals and persistent organic pollutants (Webber et al., 2021). These can be problematic since the first runoff entering passively-controlled detention basins when dry, for example, has a very short residence time, which can result in negative consequences due to its high pollutant load (Gaborit et al., 2013).

There is also growing public awareness and demand for addressing associated issues such as combined sewer overflows (CSOs). Further pressures are imposed by evolving regulations (e.g. new runoff control requirements for National Pollutant Discharge Elimination System permits in the US (USEPA, 2023)), and governmental plans are starting to target stormwater challenges (e.g. the 'Storm Overflows Discharge Reduction Plan' policy paper produced by DEFRA (2022) sets new targets for UK water companies).

The need to preserve downstream ecosystems is a further driver for change, since stormwater is recognised as a major source of quality degradation in receiving water bodies (Jefferson et al., 2017) and pollutants in the runoff can threaten the health of downstream ecosystems (evidenced by, for example, harmful algal blooms) (Mullapudi et al., 2017). This in turn can result in a loss of habitats (Muschalla et al., 2014), unsafe drinking water sources, impaired fisheries and damage to recreational sites (Kerkez et al., 2016). It is also recognised that structures designed with excess capacity may convey water too quickly and increase runoff volumes, stream erosion and floodplain encroachment (Kerkez et al., 2016), and that there is potential for overdesigned conveyance systems to actually cause rather than prevent damage to downstream property and ecosystems, thus necessitating further remediation (Mullapudi et al., 2018).

Ageing infrastructure and limitations of current design and operational practices provide further impetus for change. Mullapudi et al. (2017), for example, highlighted that ageing infrastructure is struggling to keep pace with the dynamic and changing climate, and Naughton et al. (2021) that it may not have sufficient adaptive capacity to adequately address the new demands placed on it. Furthermore, while increased stormwater runoff is commonly addressed by expanding or upsizing grey infrastructure (Kerkez et al., 2016; Rosenberg et al., 2010), traditional, hard-engineered solutions to increase the capacity of stormwater systems provide a sub-optimal, static solution to a dynamic and evolving problem, and are thus unfavourable (Rimer et al., 2019; Shishegar et al., 2019). Detention ponds with static control, for example, are designed for large storms and provide almost no retention for low return period events due to the large outlet pipe diameter. Passive systems also contain structures that are over-designed for many situations since they cannot adapt to an event, and may incur higher capital expenditure than necessary (Xu et al., 2021). Large-scale infrastructure construction may also be undesirable or impractical, or the costs prohibitive.

Lastly, further challenge is posed by a lack of real-time knowledge of system status and antecedent conditions and the need to develop models for real-time, adaptive control, with Eggimann et al. (2017) having described flood risk management as "a process of decision making under uncertainty". Modelling is challenging due to the complexities of the urban hydrologic cycle (Mullapudi et al., 2017), and increased data provision is required to improve model calibration and validation. A lack of remotely accessible data or system monitoring also necessitates regular visits for routine inspection and reactive maintenance, and may result in avoidably high operational expenditure (Xu et al., 2021). Where monitoring is already in place, this may be undertaken by a range of different agencies and only accessible from disparate sources (if it is accessible at all).

1.2. The role of smarter stormwater management

New and innovative approaches that enable stormwater to be managed dynamically are needed to address the aforementioned challenges, and the potential of 'smart', internet-of-things (IoT) enabled stormwater management systems is being increasingly recognised (e.g. Bartos et al., 2018; Xu et al., 2021). Such transformative systems augment rather than replace existing green and grey infrastructure, through utilising sensors and information technology to provide embedded connectivity and intelligence (Kerkez et al., 2016). They offer widespread provision of remotely accessible, real-time data, and provide opportunities for enhanced and automated control. Further information on the definition and functionality of 'smart stormwater management' is available in Webber et al. (2022), and its key components are outlined in Section 2.1.

There is considerable evidence in literature for the significant potential benefits of more data-driven urban water management approaches such as real-time control (RTC) (Eggimann et al., 2017). It is also widely acknowledged that adaptive measures must be implemented in existing systems (Bilodeau et al., 2018), and IoT technologies will allow stormwater infrastructure to become highly adaptive in the face of changing conditions (Kerkez et al., 2016). More specifically, integration of sensors, actuators, weather forecasts and model-based forecasts enables stormwater runoff to be pro-actively and adaptively managed (Naughton et al., 2021) – where infrastructure has previously acted passively and independently, smart systems can provide the capability to control releases with precision from distributed storage components (Ewing and Demir, 2021).

Although it is impossible to guarantee that a system will perform as designed and it will at times be pushed beyond its design, real-time sensing and control can help enable adaptation to these uncertainties (Mullapudi et al., 2017). Knowledge of hydrologic states and rainfall predictions provided in real-time can, for example, be used to determine how to modulate outflow rates from stormwater management infrastructure (Shishegar et al., 2019), and whereas conventional stormwater systems with passive control are designed based on historical data and with capacities to match design events, active real-time monitoring and control enables a flood hazard to be anticipated and the system adapted to create storage for each event (Xu et al., 2021). This may minimise the need for new construction, and thus provide a lower carbon solution. Smart stormwater systems can also be used to maximise pollutant removal and enable water-shed scale benefits to be achieved (Mullapudi et al., 2017).

As low-cost sensors, microcontrollers and wireless-communication technologies are becoming increasingly accessible, there is now growing scope to retrofit existing stormwater systems with the IoT technologies to provide versatile, inexpensive and fully automated stormwater control interventions (Rimer et al., 2019). Whilst the cost of radar sensors was formerly prohibitively expensive, for example, Southern Water has recently completed installation of 22,000 to monitor flows across their sewer network to enable enhanced and proactive management (Southern Water, 2023). IoT-based systems can also be easily scaled and may be retrofitted with little configuration (Singh and Ahmed, 2021), and thus equipping existing stormwater systems with low-cost sensors and controllers offers an unprecedented opportunity to improve urban water flow and quality (Kerkez et al., 2016).

1.3. Implementation to date

Use of IoT technologies globally is increasing rapidly across many sectors, including particularly power and communication (Webber et al., 2022), and major investment is being made in data transmission technologies and networks (Eggimann et al., 2017).

In the water sector specifically, IoT technologies have been implemented for many purposes. Information and communication technologies have been widely used historically in centralised facilities such as water and wastewater treatment plants, and now also cover critical locations such as combined sewer overflows (CSOs) in urban drainage systems and inlets to district metered areas in water distribution networks (Oberascher et al., 2022). Further applications include water quality monitoring and leak detection in water distribution systems, optimisation of water usage for irrigation based on environmental data (Radhakrishnan and Wu, 2018), and management of water supply (Yasin et al., 2021). RTC has also been studied extensively in water and wastewater treatment (Kerkez et al., 2016), and used for decades to control combined sewer system flows (Naughton et al., 2021).

However, implementation in stormwater systems is still in its infancy, with the sector having been slow to adopt IoT technologies (Kerkez et al., 2016). Eggimann et al. (2017) suggest that most utilities are still data-scarce with respect to urban water management applications, and integrated, system-wide management is still only applied occasionally (Oberascher et al., 2022).

There are signs of progress – sensor networks are increasingly being deployed to monitor flooding (Ewing and Demir, 2021), for example, and sensors are starting to be used to study the performance of individual stormwater facilities (e.g. Barraud et al., 2002; Barthelemy et al., 2020; Kerkez et al., 2016) and there is movement towards greater monitoring of sewer systems (Anglian Water, 2021; Southern Water, 2023). Whilst sensors and monitoring alone do not provide smart functionality, they are a critical component and illustrate progression towards smarter stormwater management.

There is also a growing body of research that supports the use of smart stormwater systems with remote monitoring and RTC (e.g. Bilodeau et al., 2018; Mullapudi et al., 2017; Persaud et al., 2019), and multiple current projects in the UK under the ‘Flood and Coastal Resilience Innovation Programme’ are aiming to improve evidence on the costs and benefits of smart technologies (Environment Agency, 2022). However, despite the clear potential of such systems to improve stormwater management, IoT technologies have yet to achieve widespread adoption (Naughton et al., 2021; Webber et al., 2022) and there is significant scope for further rollout.

1.4. Aims of the paper

Given the current low uptake of IoT technologies in stormwater systems, this paper aims to identify the potential barriers to adoption of smarter stormwater management practices, including potential challenges and risks, and to provide a roadmap for real world application.

To achieve this aim, barriers are explored systematically, with issues relating to each of the different technologies and capabilities that contribute to the ‘smart’ functionalities of stormwater management systems identified, as well as any broader challenges. This utilises the framework of Webber et al. (2022) to provide the foundation for a logical, structured analysis of the barriers and risks associated with every element of smart stormwater management.

Following analysis of the potential barriers, a ‘smart stormwater management wheel’ which provides the basis of a roadmap for transition to smarter stormwater management in real world applications is introduced. This enables identification of opportunities for barriers to be overcome, and facilitates a step-by-step, iterative approach.

It is hoped that, by identifying potential barriers to the implementation of smarter stormwater management systems and providing a roadmap that may be used to overcome them, they can be more easily addressed in the future, and the potential benefits that these systems offer can be more widely realised.

2. Barriers to implementation

2.1. Framework for analysis

Barriers are analysed in relation to elements of the smart stormwater framework presented by Webber et al. (2022) (shown in Fig. 1). This framework identifies the different technologies required to provide increasing levels of smart functionality, and highlights the control and operational capabilities provided by each incremental increase in technology provision. Briefly: Existence of just the stormwater assets allows only passive operation; addition of asset sensing enables active operation; if the sensor data is collected, offline optimisation can be applied; communication and management of the data can enable online control at either an asset or network level; and provision of data analytics and external data integration allows online optimisation.

2.2. Barriers

Barriers to the implementation of smarter stormwater management systems can be categorised as technical or socio-economic (Webber et al., 2022; Xu et al., 2021). Furthermore, different technologies and operational strategies involved in smart stormwater management will pose different challenges. This section, therefore, addresses technical barriers first, and maps these onto the technology or control and operational capability in Fig. 1 that they relate to in order to aid identification of steps by which they may be overcome and the order in which they may need to be tackled. Socio-economic barriers are not (necessarily) specific to any of the technologies involved, and are thus addressed separately.

2.2.1. Technical

A summary of potential technical barriers to the implementation of smarter stormwater management (and associated challenges and risks) is provided in Table 1, with further discussion on each category following. For each barrier, the directly associated framework element or elements are identified. A barrier to one technology will also pose an indirect barrier to implementation of every subsequent technology that is dependent on this element (e.g. a barrier to data communication will be an indirect barrier to data management and data analytics and integration); however, for clarity, these dependencies are not included in Table 1. Where relevant, direct relationships between a barrier, the technology it impacts and the immediate capability that is impacted are included in the identification of relevant framework elements (e.g. a barrier to asset sensing may also pose a barrier to active operation). The ‘asset’ and ‘passive operation’ elements of the framework are not considered, since these represent the baseline technology and operation of stormwater system (i.e. prior to implementation of smart functionalities), and thus do not present barriers to the transition to smarter management.

2.2.1.1. Availability and reliability of technologies. Many of the technologies required for smart stormwater systems, including sensors, actuators and communication technologies, are available and reliable, and already ubiquitous across other sectors such as energy, transport and communication (Webber et al., 2022). This includes, for example, sensors that can be used for measurement of stormwater quantity (including levels and flow rates). There remain, however, a number of potential challenges associated with the availability and reliability of technologies.

Firstly, whilst many of the underlying technologies exist and are

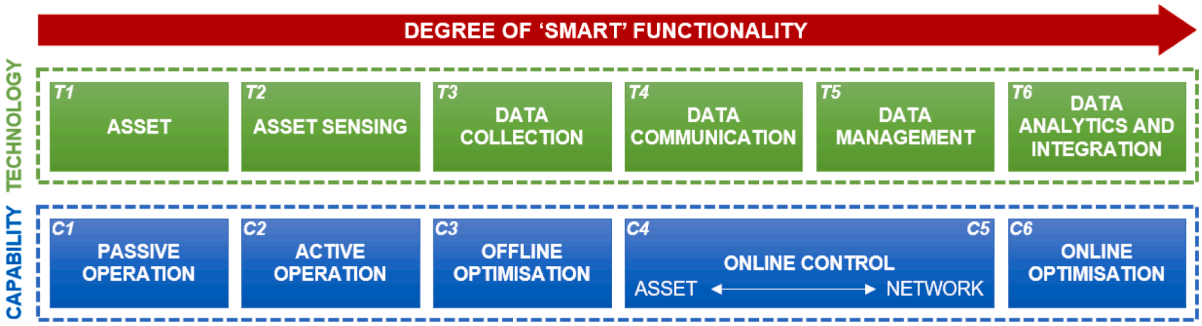

Fig. 1. Smart stormwater management framework (Webber et al., 2022).

Table 1

Summary of technical barriers, challenges and risks associated with the implementation of smarter stormwater management, with identification of the corresponding framework elements (refer to Fig. 1 for interpretation of the element codes).

Barrier, challenge or risk	Relevant framework elements *									
	T2	T3	T4	T5	T6	C2	C3	C4	C5	C6
Availability and reliability of technologies:										
1. Sensor technologies	x					x				
2. Data collection and communication technologies		x	x				x	x		
3. Data management provision				x					x	
4. Models for decision making and control					x	x	x	x	x	x
5. Absence of end-to-end solutions	x	x	x	x	x	x	x	x	x	x
Technological and physical limitations:										
1. Dependencies and legacy infrastructure limitations	x				x	x	x	x	x	x
2. Ease of deployment and maintenance	x	x	x	x	x	x	x	x	x	x
3. Power requirements and power supply	x		x							
4. Communication range and geographical constraints			x							
5. Computational demands and capabilities					x		x	x	x	x
Decision making:										
1. Selecting what and how much data to collect	x	x				x	x			
2. Development and performance of control algorithms						x	x	x	x	x
3. Performance evaluation methods						x	x	x	x	x
4. Lack of standardisation	x	x	x	x	x	x	x	x	x	x
Uncertainty:										
1. Uncertainty and noise in sensor measurements	x					x	x	x	x	x
2. Uncertainty in external data sources					x					x
3. Data validation and data cleaning requirements				x	x	x	x	x	x	x
4. Performance uncertainty and knowledge gaps						x	x	x	x	x
5. Unintended negative consequences						x	x	x	x	x
Security:										
1 Cyber security			x	x	x					

[*] T2: Asset sensing, T3: Data collection, T4: Data communication, T5: Data management, T6: Data analytics and external data integration, C2: Active operation, C3: Offline optimisation, C4: Online control (asset level), C5: Online control (system level), C6: Online optimisation.

available, they have not necessarily been applied previously or tested in the stormwater domain, and still need to be implemented at scale for their practical effectiveness to be proven (Webber et al., 2022).

Secondly, there remain gaps in the sensor market, particularly for water quality applications, where technologies are not at the same maturity level as for water quantity due to challenges associated with real-time measurement of chemical and biological contaminants (Campisano et al., 2013). In particular, there remains a need for affordable and reliable in-situ sensors for metals, nutrients and emerging contaminants if the impacts of control on pollutant removal are to be fully understood (Kerkez et al., 2016).

With respect to data collection and communication, technologies that are robust against interference and highly secure are required (Olatinwo and Jouber, 2019). There are several options available; however, obtaining sufficient reliability may pose a challenge in some cases. Low power wide area network (LPWAN) technologies such as SigFox and LoRa, for example, operate in unlicensed bands and are subject to data packet losses and, therefore, data gaps due to interference (Oberascher et al., 2022). However, such technologies may still represent the preferred solution due to lower deployment costs, and thus the issue of reliability must be addressed.

The availability and reliability of models for real-time control can pose further challenge (Xu et al., 2021). Whilst stormwater models exist, these have not typically been developed to interface with real-time data, with catchment data instead used predominantly for parameterisation (Mullapudi et al., 2017). Further challenge will be posed by the need for models to work and remain reliable with varying spatial and temporal levels of real-time data. However, although real-time models will be required for implementation of control systems, it has been suggested that stormwater control models may not need to be as complex as those used currently for simulation (Mullapudi et al., 2017).

Lastly, the availability of end-to-end solutions remains limited, with few providers able to demonstrate a fully coordinated or network scale implementation of a synergistic smart solution which offers an 'all included' service to utilities or consumers. Although the market for end-to-end solutions is developing and companies are developing offers towards this, the lack of 'all included' installation and services means customers are typically required to upskill in order to support organisational change towards smart solutions, which is a hinderance to adoption in the water sector.

2.2.1.2. Technological and physical limitations. Legacy infrastructure may pose a barrier to implementation of smarter stormwater management, since existing capacity will constrain flexibility to alter control of the system (Eggimann et al., 2017). Reliance on proprietary technologies is also widespread, and may be a further hinderance to the adoption of smart water systems (Bartos et al., 2018) due to challenges such as a lack of interoperability and flexibility.

Power requirements and available options for power supply can be a barrier to the use of some technologies. At the sensor node, for example, the communication module is usually the dominant power consumer, but well established options such as conventional cellular networks are not optimised for low power applications (Olatinwo and Jouber, 2019). Whilst LPWAN communication technologies aim to address this challenge, they are still not recommended for use in applications requiring high temporal resolution since this increases power demand (Oberascher et al., 2022). It is also necessary to consider potential trade-offs between power requirements and communication range.

Ease of deployment and maintenance is an essential attribute for efficient smart water management systems (Singh and Ahmed, 2021); however, a trade-off between installation and maintenance requirements and the reliability of data transmission may be necessary in the selection of communication technologies (Oberascher et al., 2022) – systems with higher energy demand, for example, may enable more reliable and/or frequent data transmission, but need either a wired power supply or solar panels to be installed, or additional maintenance visits for battery replacement.

Further potential barriers specific to telemetry technologies include communication range and geographical constraints, with the choice of appropriate solutions strongly dependent on the spatial requirements (Oberascher et al., 2022). Cellular coverage is not universal, for example, and alternatives such as LoRa may require installation of base stations and maintenance of additional infrastructure to provide the range needed. There may also be challenges in relaying signals from underground locations (such as in sewers), although there is ongoing research into potential solutions – for example, trials of a LoRa mesh network at the Swiss Urban Water Observatory (Ebi et al., 2019). Bandwidth size may also be limited for some communication options (Oberascher et al., 2022), thus limiting the number of measurements that can be transmitted at once from a single device.

Lastly, meeting the computational demands of data processing and modelling may pose further challenge. New models will need to update their states using sensor data to reflect real-time conditions and robust to uncertainty, but also execute sufficiently quickly to enable control decisions to be made (Mullapudi et al., 2017). However, whilst improved hardware and techniques are providing advances here (Eggimann et al., 2017), the time taken to optimise complex networks remains a key technological challenge (Webber et al., 2022).

2.2.1.3. Decision making. There is need for decision making at multiple points in the development of smart stormwater management systems. For example, during the planning of asset sensing and data collection implementation, it is necessary to decide where data should be collected, what types and how frequently. Sufficient and appropriate data must be available for the models that are to be used, but more is not necessarily better, especially given the associated costs. Furthermore, the amount of data required may vary between applications, and after a certain resolution is reached the additional benefits gained will taper off; however, determining this optimal resolution may prove challenging since the shape of this trajectory will be specific to the application (Eggimann et al., 2017). Whilst what constitutes an 'optimum resolution' is not currently understood, it is possible to continue progress in decision support through iteratively developing and evaluating applicability and limitations of new data types, sources and models. This is supported by other literature advocating the iterative development and review of data sources such as Barbosa's key principles for stormwater monitoring (2012), which highlight the benefits of installing and evaluating new data collection systems to improve business as usual over time, rather than halting application until an optimal solution is identified. Decision making is also required in the development and selection of models and control algorithms. Developing control rules is feasible for relatively simple systems and single ponds, but as complexity increases, it is increasingly difficult to ensure coordinated and effective system-level control (Bowes et al., 2021). Currently optimisation is typically achieved through local-scale control of small numbers of components (Kandler et al., 2020); however, it is unclear whether such simple rule-based control systems will be robust when applied to distributed stormwater systems, and it is anticipated that the complexity of control algorithms will increase significantly with an increase in catchment size (Mullapudi et al., 2017). Ultimately, there remains a need for future research into catchment-level control of multiple components for stormwater management (Webber et al., 2022).

Selection of appropriate performance evaluation methods (addressing issues such as the choice of evaluation period and performance metrics) may pose further challenge. In a simulation study, for example, real-time control was found to only reduce peak flows under short return period events, whereas for larger design storms it maintained or increased peak flow rates (Schmitt et al., 2020) – this indicates that the extent to which a particular strategy is deemed effective or successful will be sensitive to the approach by which it is evaluated. It has, therefore, been suggested that there is need for a framework to objectively compare the performance of control algorithms implemented in smart stormwater management systems (Rimer et al., 2019). However, although Rimer et al. (2019) did propose such a framework, its has not achieved widespread adoption.

Lastly, a lack of standardisation compounds challenges associated with decision making. Whilst standardisation of data protocols is necessary to enable integration between different providers and systems, smart control systems currently tend to utilise proprietary software and architectures that cannot always easily be migrated into different management frameworks (Webber et al., 2022).

2.2.1.4. Uncertainty. Uncertainty in data which is being used as the basis for decision making (whether through active operation, or model inputs for offline optimisation, online control or online optimisation) poses challenges to stormwater system management. Firstly, uncertainty and noise associated with sensor measurements must be considered, and secondly, uncertainty in data from external sources. Accuracy of meteorological forecasts, which are highly variable across space and time is widely recognised as a particular challenge, especially when considering extended time frames (Kerkez et al., 2016; Eggimann et al., 2017; Shishegar et al., 2019; Bertrand-Krajewski et al., 2021; Webber et al., 2022; Xu et al., 2021). Whilst past studies on real-time control in stormwater management have generally ignored uncertainties in rainfall forecasts (instead running evaluations for historical periods and using actual observations as a perfect forecast) (Xu et al., 2021), it has been shown that performance is typically worse if future rainfall cannot be predicted with certainty (although still better than a system with no real-time control) (Shishegar et al., 2021). Suggestions for addressing uncertainty in forecasts include: adding infrastructure and/or control features to act as a backup in the case of unpredicted events; implementing a robust optimisation approach that considers a variety of scenarios; and using a stochastic approach that considers different outflow probabilities to provide a more reliable solution (Shishegar et al., 2021). However, these all add to the complexity of transitioning to a smarter management system.

To address potential errors and uncertainties in data collected, appropriate validation, cleaning and quality assessments need to be implemented to ensure that a reliable database is maintained (Oberascher et al., 2022).

Further uncertainty may result from models used if poorly constructed, calibrated or implemented. Consequently, uncertainty in performance, and knowledge gaps more widely, should also be considered. Uncertainty related to control algorithms, for example, may impact the benefits of real-time control, and it is important that the impact of input data uncertainties on performance are quantified (Kerkez et al., 2016). There is also currently poor understanding of how multiple real-time control components in a catchment interact (Schmitt et al., 2020) and, although increased rainfall scenarios may be explored, there remains limited knowledge of the impact of future stressors such as climate change and urbanisation on performance. There is also uncertainty regarding the impact of interventions focused on hydrological control and solids removal on other potential performance indicators such as treatment of metals, nutrients and emerging contaminants (Kerkez et al., 2016).

As a result of such uncertainties, there may be unintended negative consequences to contend with. Benefits achieved at a local level, for example, may be eliminated at a catchment level, for example, since implementing local best management practices can produce adverse conditions at a larger scale if global outcomes are not considered (Emerson et al., 2005; Ibrahim, 2020; Mullapudi et al., 2018). Other potential risks include increased downstream erosion due to an increase in the time that flow rate remains above the mobilisation threshold for downstream sediments (Xu et al., 2021).It is important that the inherent uncertainties with new technologies alongside a risk averse industry requiring evidence in practice does not hold back development of pilot studies which can develop this evidence. As such, it is possible to follow engineering design approaches which can provide flexibility to adapt and accommodate new learnings whilst developing evidence in practice. Flexibility can be adapted from existing uncertainty frameworks and design philosophies, such as Antifragility (Babovic et al., 2018), Adaptive pathways (Manocha and Babovic, 2018) and Flexibility in Engineering Design (de Neufille and Scholtes, 2011).

2.2.1.5. Security. Installation of distributed sensors, actuators and real-time control in stormwater systems introduces cyber security risks (Kerkez et al., 2016; Xu et al., 2021). Risks in systems that are reliant on sensors, for example, include information leakage, transmission of malicious sensor patterns or commands, false sensor data injection and denial of service (Sikder et al., 2021).

Particular cyber security challenges for IoT applications include network security, management of data communication, authentication and authorisation, with the following constituting key security requirements: user identification, identity management, secure data communication, secure network, secure storage, secure software execution environment, secure contents and tamper resistance (Burhan et al., 2018).

A recent survey (Naughton et al., 2021) has suggested that these are one of the lowest priority concerns of municipal and consultant engineers; however, failure to manage these risks appropriately may result in new risks to public health and safety, reduce trust in the new systems and pose further barrier to the realisation of potential benefits (Kerkez et al., 2016).

Physical security poses further challenge, and is discussed under socio-economic barriers.

2.2.2. Socio-economic

Despite the existence of numerous technical challenges, much of the technology required for smart stormwater management does already exist, and the ultimate barriers are socio-economic (Webber et al., 2022). This section presents the key socio-economic issues.

2.2.2.1. Trust and lack of confidence. Unfamiliarity and a lack of trust in novel technologies are frequently cited as barriers to the implementation of smarter stormwater management systems (e.g. Frantzeskaki, 2019; Webber et al., 2022; White et al., 2018), and risk aversion by both practitioners and the public is a key cause of resistance to change (Barbosa et al., 2012). This is supported by the results of a survey by Naughton et al. (2021), which revealed that nearly 30% of respondents were not familiar with real time systems, and 50% were not sure that real-time controls were an effective way to manage stormwater; only 38% perceived them to be effective. Performance uncertainty was identified by respondents as a concern.

Although the benefits of smart stormwater systems have been demonstrated in modelling studies (e.g. Lund et al., 2020; Sharior et al., 2019; Shishegar et al., 2021) and at individual assets (e.g. Gilpin and Barrett, 2014; Middleton and Barrett, 2008), there remains a need for catchment scale pilots and demonstrators to provide greater evidence of the aspirational benefits.

There may also be fears around longevity or instability of new technologies. Recent news that the communications provider SigFox has been placed into receivership (Blackman, 2022), for example, illustrates that such concerns may be justified, and that ongoing effort is required beyond deployment to maintain trust of those using the technologies.

Trust and the need to build confidence are also an ongoing theme in the following socio-economic issues discussed. However, it should be noted that public and scientific trust in data driven practices in hydrology have risen in recent years, particularly in data rich environments where approaches such as machine learning are becoming commonplace. For example in rainfall-runoff modelling (Herath et al., 2021), groundwater modelling (Cai et al., 2021) and catchment scale water quality monitoring and modelling (Wang et al., 2019). IoT driven technologies are likely to develop the data rich environment for stormwater systems, where it is likely that the opportunities created by data in other areas of hydrology will develop trust in tools, methods and analysis used in stormwater.

2.2.2.2. Institutional inflexibility and resistance to change. Implementation of a smart, data-driven approach to stormwater management requires a change in practices, including in how networks are operated and decisions are made (Hering et al., 2013); however, such institutional changes can be complex and time-consuming (Eggimann et al., 2017), and thus pose a barrier. Furthermore, there is a general tendency to risk aversion in water management which is not conducive to promoting innovative change (Eggimann et al., 2017; Kiparsky et al., 2016).

Resistance to change has been identified as a major impediment to sustainable urban stormwater management in Australia and the USA (Roy et al., 2008).

2.2.2.3. Expense (capital and operational) and resources. Transition to smarter stormwater management systems will incur both capital and operational costs, including for sensors and actuators, power, data communication, data management and the associated operation and maintenance, and require staff resources.

Smart management systems can actually result in lower life cycle costs – Kerkez et al. (2016), for example, describe two pilot-scale studies in the USA where a real-time control retrofit would have life cycle costs three times lower than the equivalent passive alternative, and Xu et al. (2021) highlighted that implementing monitoring and real-time control can enable a smaller system size and reduced long-term maintenance requirements. However, the trade-off between cost and potential benefits can be difficult to quantify due to challenges associated with forecasting the effects of increased data and monetising advantages such as increased flexibility (Eggimann et al., 2017), and high costs remain a key concern and deterrent to large scale adoption (Naughton et al., 2021; Singh and Ahmed, 2021).

While costs have reduced significantly over recent years (Singh and Ahmed, 2021), and increased access to inexpensive sensors and communication technologies mean that deploying and maintaining large sensor networks is now feasible for many public utilities (Bartos et al., 2018), trust in the whole life costing is crucial, and evidence from demonstrator sites will be a key to providing the confidence needed for wider uptake (Webber et al., 2022).

2.2.2.4. Ownership and business models. Ownership of smart stormwater infrastructure can pose a challenge, since it needs to be deployed across the catchment, including in locations not owned by those responsible for operating it. Mixed ownership amongst a combination of public and private stakeholders may add further complexity, since systems need to be interoperable to provide catchment-level control (Kerkez et al., 2016). Ownership is also important from a cost perspective, i.e. who foots the capital costs and operational bills.

2.2.2.5. Insufficient knowledge and guidance. Implementation of smart stormwater systems will require non-traditional skillsets encompassing electrical engineering and computer science (Kerkez et al., 2016), and unfamiliarity with the technologies required and a lack of guidance on how to build them is currently hindering their adoption (Bartos et al., 2018; Naughton et al., 2021). Development of the control systems also typically requires expert knowledge of the urban drainage system (Schmitt et al., 2020). However, an increasing number of solutions are being proposed, such as the web-based guide for ‘Open Storm’ that intends to empower newcomers to develop and deploy their own smart systems based on the Open Storm hardware stack and cloud services platform (Bartos et al., 2018), as well as online resources from companies such as OptiRTC (OptiRTC, 2023) and Sensors for Water Interest Group (SWIG, 2023).

Increasing familiarity with smart stormwater systems could also help to address the challenge of trust and a lack of confidence in the technologies, and allay perceived concerns related to costs and operation and maintenance requirements.

2.2.2.6. Regulation, standards and a lack of incentives. Trust issues are compounded by uncertainty over regulation, with regulation related to smart stormwater management piecemeal at best (Webber et al., 2022). This is particularly challenging as stormwater management is regulatory-driven, with a need for compliance to be maintained, and if there are no regulatory incentives then adoption of smart technologies is highly unlikely (Naughton et al., 2021). As such, lack of a legislative mandate is a major impediment to sustainable urban stormwater management (Roy et al., 2008). Beyond regulation, there is also a lack of financial incentives, and there is need to investigate business models that address different permutations of centralised, decentralised, public and private ownership, control and incentive relationships to drive investment (Webber et al., 2022; Xu et al., 2021).

Clear standards are crucial also where system components are distributed across the catchment and include novel assets which may not be operated by the water utility providing overall management (Hoang and Fenner, 2016).

2.2.2.7. Privacy and ethical concerns. Although not all data collected in smart stormwater systems is sensitive, privacy is still a key societal issue in data-driven urban water management, with dependence on ‘intelligent’ systems increasing potential vulnerability to cyber-crime (Eggimann et al., 2017). Furthermore, ethical issues must be sufficiently considered whenever artificial intelligence is implemented for control purposes (Oberascher et al., 2022) – for instance, the ethics of redirecting flood water to an alternative, ‘preferable’, location (if flooding cannot be avoided) may pose a barrier to use of such algorithms. The limitations and shortfalls of studies upon which control strategies are designed may yield further ethical and moral concerns, since evaluations are often based on simplified abstractions of real networks and thus do not capture social and economic variations across the catchment, nor the societal implications of different distributions of flooding across region (Ewing and Demir, 2021).

2.2.2.8. Physical security. Ensuring physical security of assets installed in the catchment, including sensors, communication equipment and control devices will be a consideration particularly in areas with public access. In locations where vandalism is known to be of concern, this may pose a barrier to the installation and long-term operation of smart systems, with damage to equipment an ongoing risk. It is important to understand how assets may continue to operate whilst in a degraded condition, and whether the consequences of partial damage could lead to erroneous readings, necessitating an ongoing diagnostic or fail-safe mechanism to prevent unregistered faults propagating into decision making.

2.2.2.9. Need for community engagement. Public involvement may be required for installation and maintenance operations. However, as the positive effects on the environment are not generally known by the public, it may be necessary to increase awareness of the functionalities of digitised systems and the future challenges that they aim to address (Oberascher et al., 2022).

Advances in low cost, fast and efficient technologies can promote socio-technical acceptance amongst communities, especially where citizen science can engage community data within systems. For example, opportunistic data from devices such as surveillance cameras, have been proposed as ways to measure rainfall intensity when combined with computer vision techniques (Allamano et al., 2015; Jiang et al., 2019); thus opening an avenue to engage community data and aid acceptance of new technologies.

3. A roadmap for real world application

At present, implementation of smart stormwater systems is in its infancy and, as outlined above, there are many potential barriers to be overcome before they achieve widespread adoption. The framework provided by Webber et al. (2022) (Fig. 1) delivers a means of classifying systems and tracking progress, providing a clear link between the technologies implemented and the degree of smart functionality that the system is capable of providing. However, transition to smarter stormwater management is not (necessarily) a linear process, and there may be multiple iterations of development during which different barriers are addressed and capabilities enhanced. Therefore, a new roadmap for real world application which incorporates the framework of Webber et al. (2022) and facilitates a flexible, iterative approach with opportunity to learn and adapt is proposed in this section.

3.1. Smart stormwater management wheel

The ‘smart stormwater management wheel’, illustrated in Fig. 2a, aims to provide a roadmap which can be used to aid the transition to smarter stormwater management in the real world. The concept is derived from the principles in ‘agile’ project management, key features of which include incremental change and rapid feedback (Fernandez and Fernandez, 2008).

The wheel supports an iterative, circular approach for implementing smart functionality, allowing systems to be built up gradually with additional or enhanced technologies and capabilities added on each iteration as lessons are learned and barriers overcome. Crucially, the roadmap and iterative process it facilitates illustrates that it is not necessary to know everything or have the solution to all barriers before progress can start to be made in the transition to smarter stormwater management.

The components of the wheel match those of Webber et al. (2022)’s framework, with the addition of ‘learning and adaptation’ to create a circular process and highlight the opportunity for incremental development. The inner circle contains the technologies (T1-T6) required for smart stormwater management, and the outer circle the control and operational capabilities provided by each technology (C1-C6).

A key concept offered by the roadmap is that there is a spectrum of

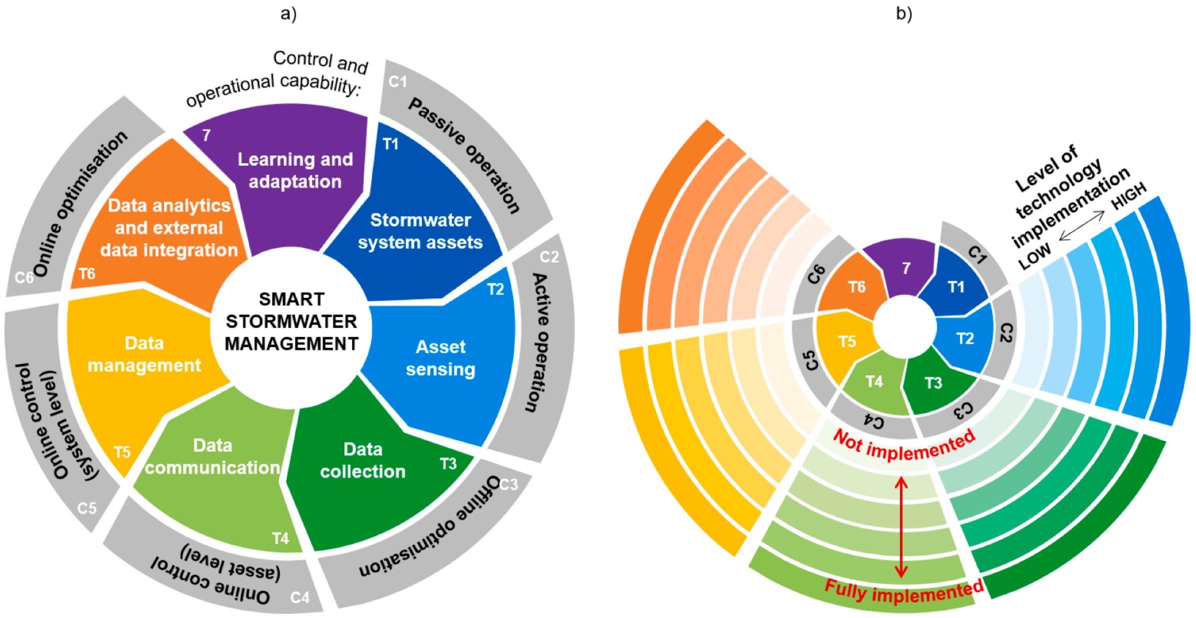

Fig. 2. Smart stormwater management wheel, showing a) progression of technologies and control and operational capabilities; and b) potential levels of implementation.

potential implementation levels for each technology (illustrated in Fig. 2b), and technologies may be implemented to a varying degree on each iteration: A complete circuit of the wheel may be made with zero or only partial implemental of some components (for example, only sensors and manual data collection may be installed on the first iteration), and this can then enable better informed expansion of technologies and capabilities implemented in future iterations.

Potential levels of implementation for each technology range from low (not present) to high; however, to retain maximum flexibility and applicability, specific definitions and criteria for each level are not given in the roadmap, since these will be context specific and should be tailored to the system to which the roadmap is being applied. The number of implementation levels for each technology is also flexible. To ensure that the wheel is appropriately customised, it is suggested that system-specific levels of implementation for each technology are defined in collaboration with industry and stakeholders for every application. This also provides the opportunity for complementary approaches already used by project partners, such as Technology Readiness Levels (TRL), to be applied in support of this; with this flexibility to align with existing organisational resources supporting familiarity and buy-in across a range of potential partners.

3.2. Application

3.2.1. Notes on practical application of a flexible framework

This framework is intended as a flexible and high level tool, suitable for adapting to a range of circumstances to enable a holistic view of how transition to smart stormwater can be iteratively applied.

A key first step for practical implementation is in identifying the components of the user's system (T1 – 6) and then defining the "levels" of these (i.e. what elements of the system could be made smarter), from "not implemented" to "fully implemented". This process should be undertaken through stakeholder engagement to identify the range of possible implementation levels and mapping these to corresponding technologies.

For example, regarding asset sensing: No implementation would be no sensing. Level 1 implementation would equal basic or a small number of sensors on components. Full implementation would equal an aspirational full coverage of the asset with a sensor capable of measuring both water quantity and quality.

This mapping process requires careful and methodical engagement at the commencement of a project, and may take considerable time in the case of large or complicated systems. However, this approach provides a standardised and systematic way of comprehensively mapping a transition to a smart stormwater system, which remains is flexible to the scope, type and scale of systems.

3.2.2. Scale and context

There is flexibility in how the wheel can be applied, with it retaining applicability for development of smart stormwater management systems at a range of different scales and in different contexts. It may be applied, for example, to aid the transition of how an individual system component is managed, or any combination of distributed assets, right up to a full, integrated catchment scale. It could also be used by different utilities and risk management authorities with ownership and/or control of any stormwater management assets in a catchment.

3.2.3. Overcoming barriers to increase smart functionality

The smart stormwater management wheel provides a step-by-step approach to overcoming the barriers to smart functionality, allowing them to be addressed incrementally with each iteration.

As discussed previously, each technology can be implemented to a differing level (or not at all) on each iteration. This enables progress to be made in small, manageable steps, without needing to address all the barriers related to each technology immediately or in turn. Where there is not yet sufficient knowledge, technologies can be implemented with the understanding that they may be subject to limitations and shortfalls, thus enabling learning and adaptations to be made. This early implementation of technologies even when there may be awareness of potential challenges, can provide the knowledge needed to address key barriers robustly, thereby increasing the potential of long-term success.

Major socio-economic barriers that may be overcome with this iterative approach, for example, include a lack of trust and confidence, institutional inflexibility and resistance to change. By enabling the transition to occur as a process of small steps, the framework may help to overcome these by illustrating that there is no need for there to be a sudden switch to a new, 'smart' management approach in which there is insufficient confidence and acceptance – instead, evidence of success (or a lack of negative impacts) can be provided regularly with each incremental development, and there are frequent opportunities for feedback and collaboration during a two-way learning process to increase trust.

With respect to technical barriers and challenges, the roadmap again offers regular opportunity to learn and adapt. Sensors of a variety of types and/or from a range of providers may be installed in the first iteration, for example, enabling their reliability to be evaluated in-situ before upscaling their deployment. Similarly, different communication technologies (cellular, LoRa etc.) might be trialled on a small scale to gain a better understanding of their real-world performance with respect to issues such as communication range and power consumption before deciding on a preferred solution. The roadmap is also well placed to address technical challenges such as uncertainty in data sources and data validation requirements, since the extent of the problem can be evaluated following initial data collection and/or analysis of operational performance when using this data, and mitigation measures and adaptations then implemented and tested as required. Other barriers could be addressed similarly with the iterative approach to smart stormwater system development and focus on learning and adaptation proposed in the roadmap.

3.2.4. Benchmarking and progress mapping

Having a set of clearly defined levels of implementation for each technology, ranging from zero to full implementation and with specific definitions and criteria defined in collaboration with stakeholders, provides an opportunity to map the current status of a system (whether at a component or catchment level) and provide a detailed framework for benchmarking progress in the transition to smarter stormwater management. This builds upon and extends the function of the framework presented by Webber et al. (2022) (Fig. 1), which also provides benchmarking capabilities, by enabling the current implementation status of each technology to be captured in greater resolution. This an important extension, since it may not be feasible or desirable to implement a technology to its ultimate required capacity in a single stage, and differing levels of implementation of one component of the framework may have implications on what can be achieved with the subsequent components – for example, although data collection is a pre-requisite for data communication, if only rudimentary (e.g. manual) data collection is in place then the options available for data communication will be restricted (e.g. no real-time communications). In such an example, it would be useful to be able to capture that both data collection and communication are present, and that the control and operational capabilities they provide could be implemented to a limited degree, but also that there remains scope for further development in these areas.

In addition to identifying the level to which each technology (T2–T6) has been implemented, the control and operational features (C1–C6) applied should also be highlighted, since the capability provided by the technologies present will not necessarily match the installed functionality – for example, sensors may have been installed and data from these collected and transmitted (T2–T4), which theoretically enables asset-level online control (C4), but no changes from the default passive operation (C1) of the system yet implemented.

The current status and progress of the transition to smart stormwater management can also mapped visually onto the wheel. A conceptual example is given in Fig. 3, although note that the technology implementation levels have not been defined and those suggested are illustrative only. In this example, the level of implementation for each technology and the control and operational type are highlighted in a separate diagram for each iteration of the development (Fig. 3a to Fig. 3e), as shown in the key. Briefly, this shows:

a) A ‘dumb’ system with no smart technologies and only passive operation
b) Installation of a limited number of sensors, with data collected manually but not yet used to inform operation or control.
c) Installation of telemetry to provide near real-time transmission of data from the sensors, and data used for offline optimisation.
d) Upgrade and expansion of the sensor installation, based on learning from those installed in the first iteration.
e) The final smart management system, following several iterations, with a high level of implementation in all technology categories and use of online optimisation.

In reality, the actual levels representing this conceptual transition may differ from those illustrated, depending on the system-specific definitions provided by the stakeholders. Note also that it is not

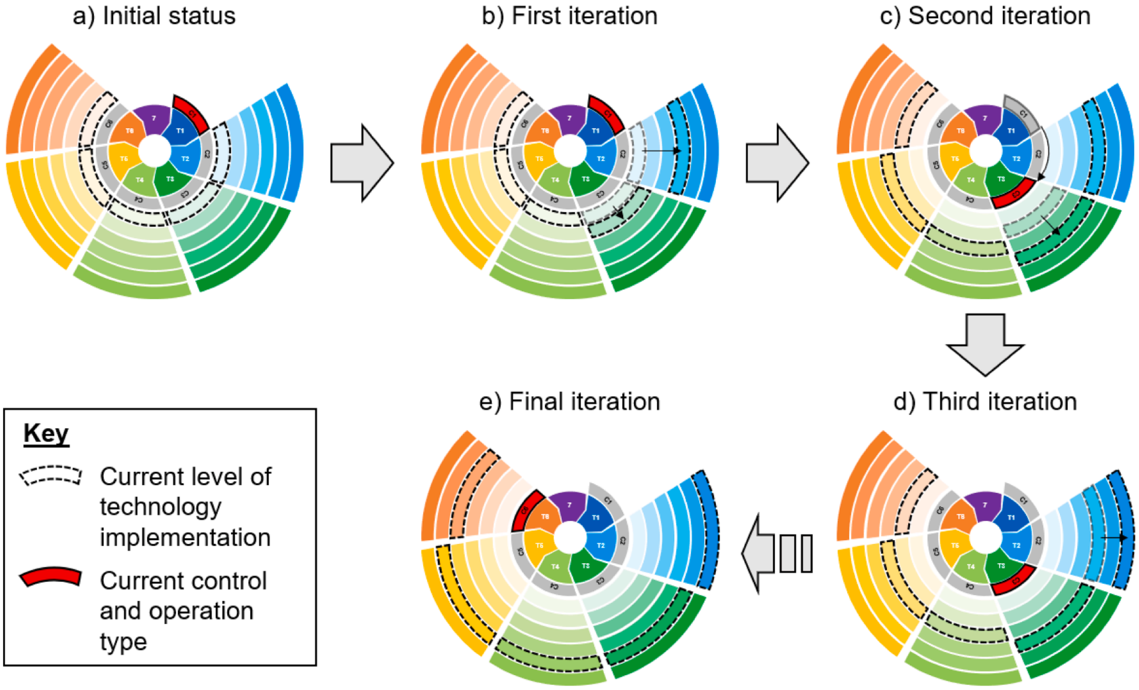

Fig. 3. Conceptual illustration of an iterative transition to smarter management of a stormwater system, with corresponding technology levels mapped at each iteration; See Fig. 2 for interpretation of the smart stormwater management wheel elements.

necessary to provide the maximum possible functionality for every technology in order to deliver a smart system (as shown in Fig. 3e), and that there remains scope for further learning and improvement.

3.2.5. Exploration of trade-offs and relationships between implementation levels

Lastly, following benchmarking of a system's status (as in Section 3.2.4), the wheel may be used to explore trade-offs and relationships between the level of implementation for different technologies. In particular, it would be interesting to learn whether it is possible to provide the same level of performance with respect to operation and control with a variety of different combinations of technologies – for example, can the same level of performance be achieved using cheap and relatively inaccurate or unreliable sensors in conjunction with advanced artificial intelligence as when using expensive, high quality sensors that provide greater accuracy and reliability? Such questions may be addressed by comparison of different technology implementations in systems providing similar smart functionality and performance.

4. Conclusions

Whilst both the need for improved stormwater management and the potential of smart, IoT-based solutions are evident, there remain a significant number of barriers and challenges to overcome before change becomes widespread. Barriers have been identified in relation to all elements of smarter stormwater management, from the asset sensing to the data analytics and online optimisation, with technical challenges including the availability and reliability of technologies, technological and physical limitations, decision making, uncertainty and security.

Technical barriers are rapidly reducing, with many of the required technologies already available and ubiquitous across other sectors, and their potential benefits for stormwater management increasingly demonstrated in the academic literature. However, socio-economic issues such as trust and lack of confidence, resistance to change, expense and lack of knowledge and guidance remain key challenges.

Evidence from the review undertaken also points to a clear knowledge gap relating to design codes and implementation standards. In the UK and globally, energy is now required to develop appropriate standards in sewer and stormwater design manuals that will help permit the impending shift to smarter stormwater delivery. Opportunities to integrate the technologies of the fourth industrial revolution within the toolkit of design consultants should be pursued to unlock their benefits in the years' ahead.

To aid the transition to smarter stormwater management, this paper has provided a) a structured and comprehensive review of specific barriers that require addressing, including identification of which requisite technologies and/or capabilities they impact; and b) a 'smart stormwater management wheel' aimed at developing a systematic yet flexible approach for implementing smart functionality and benchmarking progress.

The wheel presented offers multiple avenues for future research, including case study application to explore how specific barriers identified in this paper can be addressed using such an iterative approach, and to demonstrate the development and use of system-specific levels for benchmarking and progress mapping. There is also scope to further develop use of the wheel for exploration of trade-offs and relationships in future research.

Declaration of Competing Interest

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

Peter Melville-Shreeve and Chris Sweetapple report financial support was provided by United Kingdom Department for Environment Food and Rural Affairs. Peter Melville-Shreeve reports a relationship with United Kingdom Department for Environment Food and Rural Affairs that includes: funding grants. Peter Melville-Shreeve reports a relationship with Ofwat that includes: funding grants. Prior to 2020, co-author Peter Melville-Shreeve was director of a real-time control system provider (Over the Air Analytics Ltd).

Data availability

No data was used for the research described in the article.

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