Automation and real-time control of urban wastewater systems: a review of the move towards sustainability

Biniam B. Ashagre, Guangtao Fu and David Butler

ABSTRACT

Automation and real-time control have long been used in urban wastewater systems. However, there is a critical need to review how real-time control contributes to sustainable water management. This review provides a systematic review of the role of real-time control towards creating a sustainable wastewater system. This review identifies the social, economic and environmental pillars of sustainability that can be achieved using automation and control systems, considering individual systems and different scales of integration. Results obtained from a systematic literature review show that previous research on automation and control related to sustainability in the water sector focuses on addressing economic issues (mainly operational cost reduction) and improving the quality of the water environment, while the social pillar of sustainability is not addressed to a significant degree. Integrated control is identified as a promising approach to address the three pillars of sustainability. Future research on automaton and real-time control in the water and wastewater system needs to explicitly demonstrate the contribution of control strategies towards the attributes of sustainability. To this end, regulatory bodies should focus on creating an overarching sustainability framework with indicators of sustainability clearly defined. Further, addressing three pillars of sustainability requires an integrated approach at a catchment scale where upstream and downstream processes are considered.

Key words | automation, integration, real-time control, sustainability, urban wastewater system, water system

Biniam B. Ashagre (corresponding author)
School of Engineering and the Built Environment,
Anglia Ruskin University,
Bishop Hall Lane, Chelmsford CM1 1SQ,
UK
E-mail: *biniam.ashagre@aru.ac.uk*

Guangtao Fu
David Butler
Centre for Water Systems, College of Engineering, Mathematics and Physical Sciences,
University of Exeter,
Exeter EX4 4QF,
UK

HIGHLIGHTS

- This study provides critical analysis of the use of automation and real-time control in urban wastewater systems.
- Currently there is no clear path linking the benefits of automation to wastewater system stainability.
- Future study needs to explicitly demonstrate contributions of control strategies towards sustainability attributes.

INTRODUCTION

The concept of sustainability has been around since the 1990s and is used in different disciplines and contexts. Although there is no general consensus on its definition (Muga & Mihelcic 2008), it is generally accepted that sustainability consists of three pillars: maintenance of economic well-being, protection and improvement of the environment, and improvement of social well-being both in the short and long terms (Butler *et al.* 2014). However, when it comes to measuring sustainability, it becomes more complicated, mainly in the definition of the scope of each pillar. For example, protection of the environment is limited to the protection of the water quality in a context,

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but it extends further to ecosystems in another context. In the context of urban wastewater treatment, Sweetapple et al. (2015) pointed out that reducing operational energy use does not necessarily mean a sustainable approach without considering greenhouse gas (GHG) emissions such as nitrous oxide and methane. Although there is still work to be done in selecting sustainability indicators, there is a consensus that improved water and wastewater management is key in securing a sustainable development (Water 2010).

Automation and real-time control of water and wastewater systems can play a significant role in the journey towards sustainability. However, it is not uncommon to come across publications on automation and real-time control that highlight their benefits from the point of meeting water quality legislation standards and reduction of costs through the reduction of operational energy and chemical use. For example, Meng et al. (2016) showed how such approaches reduce energy use and thus impact on the water environment. Similarly, Olsson (2007) identified several benefits of such approaches in the water and wastewater sector, including reduction of energy use and improved biogas production in the wastewater sector (Liu et al. 2004). The benefits of automation and control of water systems were also demonstrated by Misiunas et al. (2005) and Lee et al. (2015). However, there is a lack of a clear picture of how real-time control helps achieve sustainability and what indicators are generally considered in water and wastewater systems. This review aims to identify the latest advances in the literature in linking control strategy objectives with sustainability indicators.

Many studies on automation and real-time control of the water system, however, did not feed themselves to the big objective of achieving sustainability and did not clearly demonstrate the contribution of their benefits towards sustainability. The lack of such an overarching objective can lead to segregated solutions which cannot be easily brought together to create a sustainable future. Sweetapple et al. (2015) and Mannina et al. (2019) are good examples in identifying and highlighting the risk of lacking such objectives. Sweetapple et al. (2015) showed the need for a specific analysis in the benefits of automation and real-time control towards sustainability by highlighting contradicting objectives and the need for trade-offs, even within environmental sustainability. Mannina et al. (2019), with a focus on Decision Support Systems (DSS), discussed that lack of a DSS that integrates all the pillars of sustainability can be due to such segregated objectives.

A key element in achieving an overarching goal of sustainability through automation and real-time control in urban water and wastewater management is the system boundary under consideration. Butler & Schütze (2005) and Olsson et al. (2005) evidently showed that the degree of achieving objectives of automation and real-time control is significantly determined by the scope or boundary of the system. For example, in urban wastewater systems, most studies focused on wastewater treatment plant (WWTP) wide process level control, e.g. Li & Zheng (2015) and De Gussem et al. (2014). They are either unit process controls with the objective to optimise the unit process within the WWTP, or they are plant-wide process controls without the integration of other systems such as sewer networks. For example, plant-wide control was done without considering the sewer network (Samuelsson 2005; Sweetapple et al. 2014), and in most cases without considering the capacity of the receiving water (Wu & Luo 2012; Hreiz et al. 2015). Similarly, automation and real-time control of sewer networks were widely tested without considering the WWTP (Cembrano et al. 2004; Lacour & Schütze 2011). However, a more holistic approach was used to integrate the sewer network, WWTP, and the receiving water (Butler & Schütze 2005; Fu et al. 2008; Muschalla 2008; Benedetti et al. 2013; Saagi et al. 2016; Ashagre 2018).

In the UK, Sustainable Drainage Systems (SuDS) have been investigated in the last several decades, and frameworks and guidelines have been developed for the selection of sustainable options using sustainability indicators. Such approaches encourage a holistic view of the management of the urban water and wastewater systems, but the work on an automation and real-time control of existing systems is still ongoing. This review provides a critical review of the contributions of automation and real-time control strategies to the attributes of sustainability. It analyses previous studies with different scopes, systems and integration of systems in the application of control strategies. This review attempts to give a clearer picture of where the focus of previous studies on automation and real-time control of the urban water and wastewater system was and where the shift in the trend is, and perhaps where the focus should be in the future. The previous review papers, including Yuan *et al.* (2019), Mannina *et al.* (2018), García *et al.* (2015) and Schütze *et al.* (2004), provided a detailed review on the state-of-the-art of system control and its application in urban water and wastewater systems. However, these reviews were not necessarily seen through the lenses of sustainability.

To avoid complications in the review of studies on the automation and control of water and wastewater systems, this study limits the scope of economic sustainability to any short-term or long-term financial benefit to the public or to the industry. Regarding the social aspect of sustainability, the review does not go into the details of social indicators, rather it critically analyses studies that considered the benefits of society from any suggested real-time control strategy. Protection and improvement of the environment can be classified into three major areas: water availability, water quality and ecosystem, and reduction of GHG emissions. All these indicators focus on the water environment except GHG emissions. These divisions are also reflected in regulations as well. For example, in the UK and most European countries, climate-related regulations such as the Climate Change Act for Scotland (CC-Scotland-Act 2009) sets an overall target of 42% reduction in CO_2 emission by 2020 and 80% reduction in GHG emissions by 2050 against the 1990 baseline which applies to the water and wastewater industry. The other regulation can be categorised as waster-environment regulations. Among others, the EU WFD (2000/60/E) is the most influential water legislation produced by the European Commission that focuses on the water environment (Ashagre 2018). Hence, this review looks at environment sustainability from two angles: protection of the water environment and reduction of GHG emissions.

This paper is structured as below: section 'Overview of automation and real-time control' presents the fundamental concepts of control systems and discusses different types of control approaches and the variation in objectives. In the section 'The role of automation and control in water and wastewater systems', the classes of sustainability indicators are introduced so that the systematic literature search on the role of automation and real-time control of urban water and wastewater systems towards sustainability can be analysed and discussed systematically. Section 'Discussion' provides discussion based on the findings of the systematic literature review presented in the 'The role of automation and control in water and wastewater systems' section.

OVERVIEW OF AUTOMATION AND REAL-TIME CONTROL

Control strategies and control systems

A control strategy describes the framework of the control system, i.e. how the identified process units in a system are controlled using measured information (Schütze *et al.* (2002a). We will use the term 'control system' in this review and it worth clarifying its specific definition. Distefano *et al.* (1997) defined 'system' as an arrangement or set of elements connected to form or act as an entirety, which is also adopted in this article. Control systems can be defined as the arrangement or connection of components (e.g. sensors, controllers, actuators and communication networks) in such a way that they regulate, direct or command themselves or another system to achieve certain objectives.

For example, considering a dart player and her/his control process of the dart, the player can throw the dart without any pre-calculation and hit anywhere on the board. Alternatively, the player can judge the distance between him/her and the dart board and adjust the angle and the speed of throwing to hit the target point, showing a certain computation and arrangement to achieve the target. In the latter case, the input is the signal (location of the dart board and the dart itself) sent by the player's eyes to his brain (eyes can be considered as *sensors*). The signal from the eyes goes to the brain where the control action is decided (*controller*), and the signal goes to the arm (the muscles on the arms are the *actuators*) to throw the dart to the intended location on the dart board.

In the above example, the control system is one-directional and there is no feedback to close the cycle since no control action can be taken based on the direction of the dart once it left the player's hand. Such control systems are referred to as open-loop or feedforward control systems. In feedforward control systems, the control action is based on expected output but is independent of actual output, i.e. no feedback loop (Åström & Murray 2010; Figure 1).

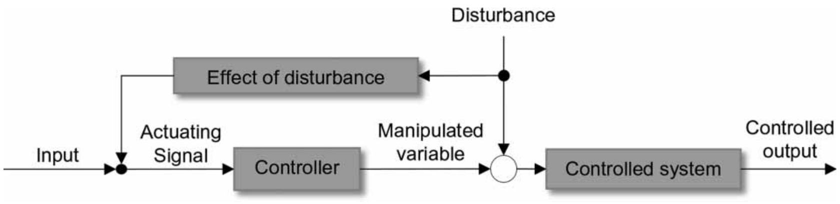

Figure 1 | Feedforward control system.

In a closed-loop system, commonly referred to as feedback control, the control action is dependent on the actual output, i.e. check output post-activity and adjust offsets accordingly (Figure 2). Take a closed-loop example of a girl picking up a cup, her arm and hand positions (outputs in this case) are continuously sensed by her eyes and position of arm continuously adjusted (output) using arm muscles (actuators). The continuous checking of inputs and/or outputs to adjust control variables concurrently is commonly termed as real-time control, active control or dynamic control. In water/wastewater systems, processes are usually dynamic, and therefore, the term control is associated with dynamically or actively regulating, adjusting or directing the system.

Feedforward control systems use early warnings by identifying potential disturbances and prevent any diversion from a targeted output. In wastewater systems, this necessarily requires monitoring and understanding pattern of flow and nutrient load coming into the WWTPs (Santín *et al.* 2015) or forecasting of rainfall to forecast sewer and river flow and quality (Yan *et al.* 2013; Jing *et al.* 2015). Hence, control systems can be set up with a fixed set-point without feedback or with an advanced feedback loop including a forecast system. The former is cheaper and easier to set up, while the latter can be more complex and expensive but can help in improving system performance and reliability (Lukasse 1999; Olsson & Newell 1999; Olsson *et al.* 2005; Dirckx *et al.* 2011; Olsson 2012).

The need for control

The driving force for the need for control is the existence of disturbances and the need to handle them. However, the intended objective and expected outcome can be different. In most common cases, processes within a system are controlled for the following three reasons: reduce variability, increase efficiency and ensure safety (Schilling *et al.* 1996; Lindberg 1997; Olsson & Newell 1999; Svrcek *et al.* 2014; Li & Zheng 2015). Safety refers to the safety of the environment, staff on site or the asset. Through efficiency, one can achieve increased use of energy but might increase emissions of GHGs at a process level. Regarding safety, improving river water quality can increase environmental safety in their control design but may completely ignore the impact of their control design on GHG emissions. Hence, the need for system control requires a specific objective and some of the common situations that control systems were developed in the past are listed below:

- The need to reduce the impact of disturbances within the system such as variations of inflows in WWTP, and pressure management in water distribution networks.
- Systems to cope with the increased load, for example, high demand in water distribution systems or high nutrient load to WWTPs due to increased urbanisation or industrialisation.

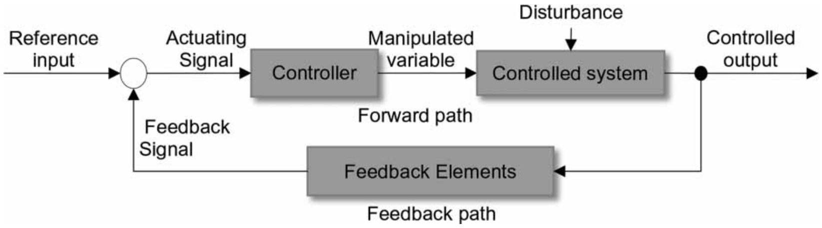

Figure 2 | Closed-loop control (feedback control system).

- The need to increase system capacity using resource use efficiency; for example, the need for WWTPs capacity due to increased load or tighter regulation.
- Protection of the environment which may include the reduction of GHG emissions from WWTP or maintain desired effluent quality to protect the water environment.
- Protect assets from acute failure and reduce deterioration which are the key characteristics of a sustainable and resilient system.
- Reliable service with a consistent and high quality of output, for example, ensuring consistent effluent quality.
- Reduction of capital investment and operational cost.
- Increasing system efficiency through the reduction of operational energy consumption.
- Monitoring and diagnosing.

Performance goals and objectives

The main goals of system automation and control include maximising efficiency, purely economic benefit, improving the water environment, and so on. Olsson & Newell (1999) referred to them as community/societal goals which should not be confused with the social element of sustainability. Societal goals are met by specific goals at a system level or a process scale (Figure 3) usually referred to as process goals (Olsson & Newell 1999; Schütze *et al.* 2004). Process goals, for example in wastewater, can be meeting effluent quality requirements, reduce dry weather spills to receiving water bodies, system optimisation to reduce cost and minimise control actions (Schütze *et al.* 2002b; Ocampo-Martinez 2010). Olsson & Newell (1999) manifested that the process goal can be even more specific, referred to as operational objectives, and designed so that a specific treatment plant can meet the plant or process goals. A water utility can have the same plant or process goal for several WWTPs, but this goal might be achieved through different operational objectives based on site conditions and schemes.

Real-time control and integrated real-time control

In addition to the type of control system, the structure of control systems plays a key role both in ensuring an overall system reliability and achieving wider or multiple objectives. For example, real-time control is a type of control where continuous checking of inputs and/or outputs are performed to adjust control variables concurrently and commonly used on a unit process or single system basis (Schütze *et al.* 2004). However, integrated real-time control (or active control) refers to the application of real-time control to two or more systems where the information from one system is used to control another system or to achieve the objective defined in another system. Hence, integrated real-time control approach can have single or multiple objectives with a capacity in delivering a wider goal (societal goals) than the real-time control approach objectives (plant-wide or process-based goals).

The scope of an integrated approach is variable, and the boundaries are not always clear. Integrated urban water and wastewater system management is a catchment scale approach that covers both wastewater systems, water supply systems, water resources (receiving water bodies) or the wider river basin processes. 'Urban area' in this study is equivalent to 'agglomeration' as defined in CEC (1991); it is an area where the population is sufficiently concentrated so that urban wastewater can be collected through a sewer network and conveyed to the WWTP. The appropriately treated wastewater from the WWTP is discharged to the

Figure 3 | Interlinks between different goals and objectives that drive control designs of water and wastewater systems (based on Olsson & Newell (1999)).

receiving water. Integrated urban wastewater system (UWWS) refers to the integration of at least the three systems: the sewer network, the wastewater treatment and the receiving water (Schütze *et al.* 2002a), as shown in Figure 4.

Integrated control of UWWS presents opportunities both in design and operation of the system with different objectives (Vanrolleghem *et al.* 2005; Benedetti *et al.* 2013). However, the objectives can be different and the resulting degree of complexity as well.

THE ROLE OF AUTOMATION AND CONTROL IN WATER AND WASTEWATER SYSTEMS

This section will look into the role of automation and control in the water and wastewater system from the perspective of sustainability. System configuration and control structures, especially system boundaries and level of integration, can play a key role in the development of more sustainable systems. The following sections look into this aspect in more detail.

Classes of sustainability

The relationships between the environmental, economic and social aspects of sustainability are shown in Figure 5. The indicators for each aspect are discussed below. Environmental sustainability in urban water/wastewater systems can be measured using energy consumption, GHG emissions, degradation of water and soil resources (loss of nutrients and waste production), and overflow volume and frequencies (Muga & Mihelcic 2008; Fagan *et al.* 2010).

From the point of installing or selection of control systems, economical sustainability implies comparing the costs and economic benefits of implementation of the options (Balkema *et al.* 2002). However, several studies considered the reduction of operational cost as a sustainability indicator without cost-benefit analysis (Bongards *et al.* 2005; Brdys *et al.* 2008). Casal-Campos *et al.* (2015) presented the regret-based approach where the cost of doing nothing or economic loss in adopting option A instead of option B is used to assess the economic feasibility of sustainable options from the point of system robustness and reliability. Although this review is not focusing on the method of costing or economic feasibility, it is important to acknowledge that economic sustainability has been calculated in different ways based on the context of the study.

Systems can be said that they assure societal sustainability if they consider the interests and benefits of the public. In selecting appropriate technologies and control strategies, Muga & Mihelcic (2008) gave detailed lists of the social indicators of sustainability. This includes local area aesthetic values, social acceptance, compliance with institutional requirements (which is a loose terminology that can vary significantly in different contexts) and economic benefit to the

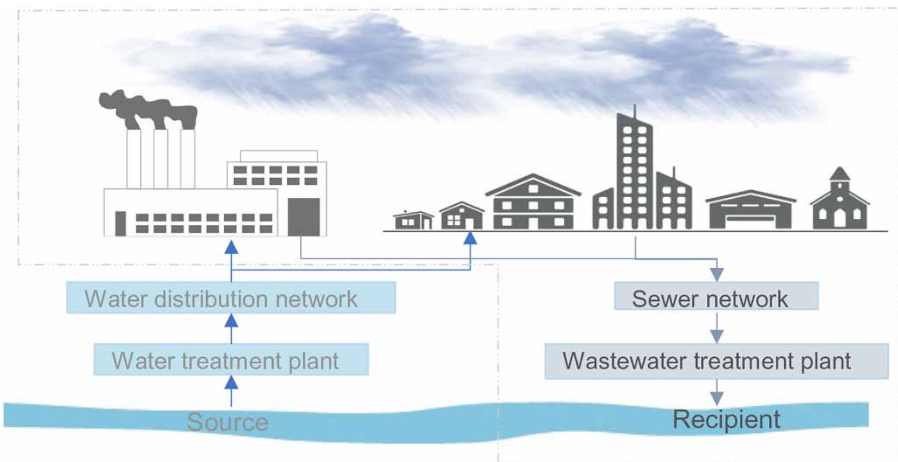

Figure 4 | Interlinks among the main components of a typical urban water and wastewater system. The dotted line showing the boundary of an urban wastewater system.

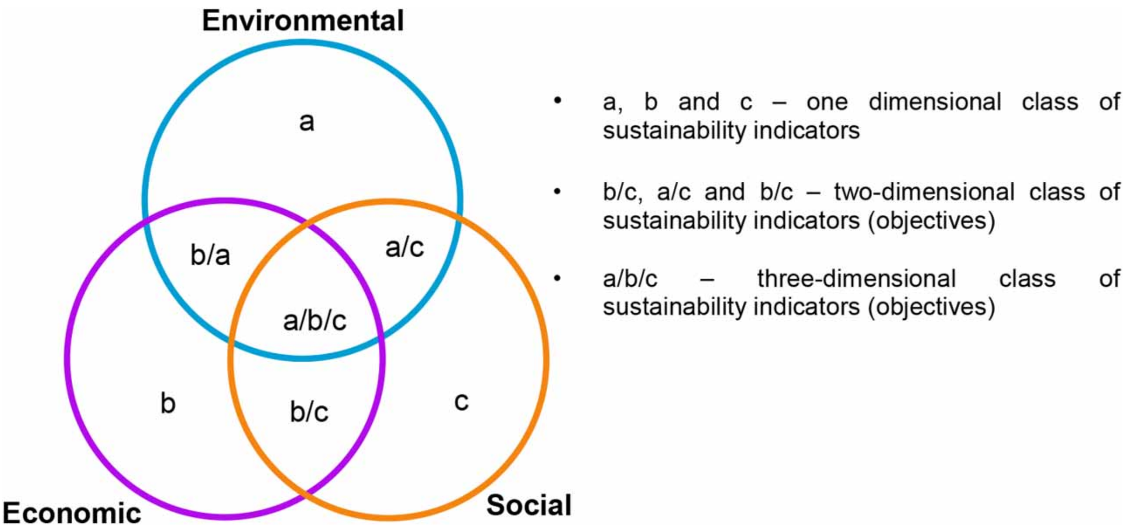

Figure 5 | Classes of sustainability indicators.

local community. In the study of McClymont *et al.* (2020) that focuses on sustainable drainage systems, societal benefits of systems or management options are measured based on contributions towards social well-being, which include mental well-being, aesthetics and improved social interactions.

It was considered important to sub-classify environmental sustainability from the point of mitigation of climate change, specifically reduction in GHG emissions and the water environment. Both sub-classes have several indicators by themselves but due to the fundamental objective difference and since these objectives are driven by different (in some cases, contradictory) legislations (which is the case in most European countries), it is important to look at them separately (Water 2011; Sweetapple *et al.* 2015; Ashagre 2018).

Systematic review of the literature on automation and real-time control from the perspective of sustainability

Without going into further details on how these indicators of sustainability are calculated, a systematic literature review is done to identify the role and trends in the use of automation and real-time control of water/wastewater systems. The large interdisciplinary abstract and citation database Scopus from Elsevier was chosen due to its strengths in science and technology and higher number of journals since 1996 (Bakkalbasi *et al.* 2006). In the database search, the following word combinations were used in Article Title, Abstract and Keywords, to identify publications in this area.

- Artificial intelligence OR AI OR,
- automation and control OR,
- real-time control OR,
- optimisation AND (including optimization),
- wastewater OR,
- reclaimed water OR,
- recycled water OR,
- UWWS OR,
- WWTP OR,
- sewer network AND,
- sustainability OR sustainable.

The above search returned 166 publications. There is a clear increase in articles published in this area of research especially since 2009 (Figure 6). Although the trend in increase is observed, there are some years with a significantly higher number of publications such as the years 2011, 2013 and 2014. The spike in 2011 is mainly due to publications from the World Environmental and Water Resources Congress 2011, which focuses its topics towards sustainability. Unlike the 2011 spike, the increase in the

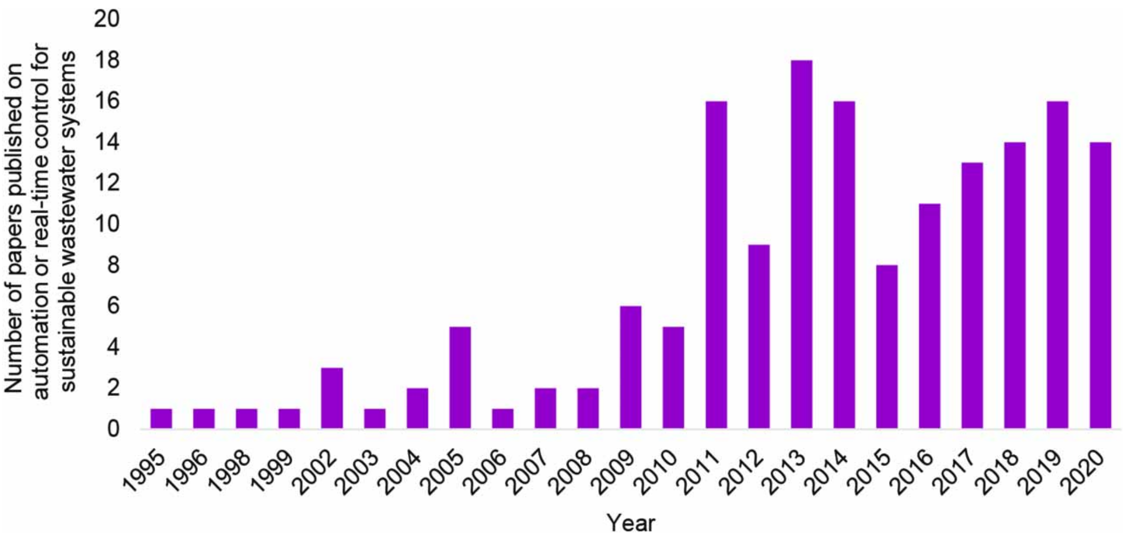

Figure 6 | Literature search counts based on the year of publication.

number of publications in the year 2013 and 2014 is not driven by one specific conference. Instead, there is a general increase in publication both in journal and conference papers.

The search was narrowed further by selecting only peer-reviewed journal articles and book chapters, resulting in 102 publications. Out of these, 57 publications are out of scope for several reasons, including:

1. The focus is more on management rather than automation or real-time control (Hollingum 1998; Baron *et al.* 2016; Gruiz *et al.* 2017; Wolfe & Richard 2017; Maurya *et al.* 2018; Zhao *et al.* 2019; Ullah *et al.* 2020).
2. Comparison of new technologies or method of management (Shoji *et al.* 2008; Bottero *et al.* 2011; Molinos-Senante *et al.* 2012; Bartrolí *et al.* 2013; Woods *et al.* 2013; Ahmadi *et al.* 2017; Bertanza *et al.* 2018; Wen *et al.* 2020).
3. Main focus is on agricultural practices (Ekasingh & Ngamsomsuke 2009; Benami *et al.* 2013; Jeong *et al.* 2014).
4. Water scarcity management without considering automation or real-time control (Thomas *et al.* 2011; Shadman 2013; Singh *et al.* 2015; Yang *et al.* 2015).
5. Focuses on alternative sources of energy without a clear focus on system automation or real-time control (Yuan *et al.* 2013; Gu *et al.* 2018; Niknejad *et al.* 2018).

The role of system boundaries and level of integration on sustainability

Focusing only on those publications which are within the scope of this review (control strategies from the point of view of sustainability, see section 'Systematic review of the literature on automation and real-time control from the perspective of sustainability'), 45 publications are identified. The scope of the studies identified varies from automation and control of a unit process within a system to a different scale of integration. The integration scale varies a great deal with only two studies using an integrated approach to consider sewer network and water networks in a holistic way (Table 1). Most of the studies on automation and real-time control identified in this search focus on integrating WWTP and receiving rivers. However, there is an increasing trend in integrated approach studies that aim to bring WWTP, sewer network and receiving rivers together, although objectives or indicators of sustainability vary widely (Table 1).

No publications were found considering only sewer network and WWTP without considering the receiving river. This is mainly because river water quality is stringently regulated, wastewater systems should be operated directly to meet the regulatory compliances rather than effluent-based criteria (Meng *et al.* 2016, 2017). All the publications found

Table 1 | Publication distributions over different aspects of sustainability

Class of sustainability (Figure 5)	/Scope	Integrated approach	Sewer and water network	Sewer network – river	WTP	WWT	WWTP	WWTP – river
a	Water-Environment	Beck (2005), Suner Roqueta *et al.* (2005), Erbe & Schütze (2005), Bai *et al.* (2019)	Srinivas & Singh (2018)	–	–	–	–	–
	Water-Environment – GHG-Environment	–	–	–	–	–	Garrido-Baserba *et al.* (2014)	–
	GHG-Environment	–		–	–	–	–	–
b	Economy	–	–	–	Chung & Lansey (2008)	–	Frombo *et al.* (2009), Conrad *et al.* (2010)	–
c	Social	–	–	–	–	–	–	–
b/a	Economy – Water-Environment – GHG-Environment	–	–	–	–	–	–	Flores-Alsina *et al.* (2011)
	Economy – Water-Environment	Pintér *et al.* (1995), Butler & Schütze (2005), Brdys *et al.* (2008)	–	Ellis & Marsalek (1996), Campisano *et al.* (2013), Sousa *et al.* (2014), Bartos *et al.* (2018), Rose *et al.* (2020)	–	Zhang *et al.* (2013)	Puchongkawarin *et al.* (2015), Verdaguer *et al.* (2016), Chen *et al.* (2018), Webb *et al.* (2018), Su *et al.* (2019), Bhagat *et al.* (2020)	Bongards *et al.* (2005), Van Hulle *et al.* (2006), Guo *et al.* (2009), Thornton *et al.* (2010), Lee *et al.* (2013), Gruiz & Fenyvesi (2017), Gaida *et al.* (2017), Man *et al.* (2019), Pang *et al.* (2019)
	Economy – GHG-Environment	–	–	–	–	–	–	–
b/c	Economy – Social	–	–	–	Galelli *et al.* (2014)	–	–	–
a/c	Environment – Social	–	–	–	–	–	–	–
a/b/c	Economy – Water-Environment – GHG-Environment – Social	Herva & Roca (2013), Chamberlain *et al.* (2013), Chhipi-Shrestha *et al.* (2017), Mannina *et al.* (2019)	–	–	–	–	–	–
	Economy – Water-Environment – Social	Zoltay *et al.* (2010), Du Plessis (2014), Pinto *et al.* (2014), Hadjimichael *et al.* (2016)	Valentin *et al.* (2016), Boulos (2017)	–	–	–	–	–

in this search focusing on sewer networks and river, without exception, all focuses on cost-saving and improving the quality of the water environment mainly through the reduction of combined sewer overflows. Only two publications identified to bridge the sewer network management and water distribution network or water supply management using real-time control.

Perhaps due to the nature of the system, there is a lack of publications that used real-time control in water treatment plants and established a clear path towards sustainability. However, more studies were identified with a focus only at WWTP, showing a link to the sustainability indicators. Most of them address the cost-saving (economy) aspect of sustainability and protection of the water environment through the attempt in achieving the fixed effluent quality standards set in regulations. Most of the studies considering the automation of WWTP are limited to the use of unit process control and limit their objectives in the stabilising of effluent concentration without considering the assimilative capacity of the river except the studies by Meng *et al.* (2020), Ashagre (2018) and Meng *et al.* (2017). Although some of these studies do not consider the state of the receiving river, real-time control plays a role in protecting the environment through achieving effluent pollutant concentration as stated in regulatory pollutant limits. As a result, almost all the studies with this scope are limited to economic and water-environment sustainability indicators.

In this review, the catchment scale real-time and automation system should at least consider the three elements: WWTP, the sewer network and the receiving water body (Butler & Schütze 2005; Erbe & Schütze 2005; Brdys *et al.* 2008; Bai *et al.* 2019). However, some studies consider water distribution, water resources systems to automate and control the water and wastewater sector (Beck 2005; Zoltay *et al.* 2010; Pinto *et al.* 2014). 33% of the literature is found to address sustainability using an integrated approach. However, due to the scope of studies and system boundaries, the sustainability indicators considered through an integrated approach vary significantly, from considering only the environment towards the most aggregated or three-dimensional sustainability indicators. For example, without considering sustainability, the integrated control approach presented in Meirlaen *et al.* (2002) and Vanrolleghem *et al.* (2005) has been adopted and applied by many researchers. However, it is common that multiple objectives are considered while using integrated real-time control approaches (Butler & Schütze 2005; Fu *et al.* 2008).

Those studies with a societal objective such as sustainability or meeting regulatory standards as presented by Olsson *et al.* (2005) showed the ability to meet at least two of the sustainability classes. The same is observed for control strategies designed at a system level. However, publications that use control strategies at one system level (for example, WWTP without the integration of the receiving water bodies) are limited to meeting a maximum of two sustainability classes, mainly economy and environment.

There are not many studies out there only focusing on just the economy aspect of sustainability using real-time control since the water industry is closely related to the environment. Those identified focus on one system only, either WWT or WWTP, see Table 1 class b. Their focus was the optimisation of a system to reduce operational energy without giving clear emphasis on the environment. Similarly, there is only one study identified looking both at the economy and social aspects of sustainability. Galelli *et al.* (2014) applied the concept of real-time control in the optimisation of urban water reservoirs from the point of system efficiency and water resource management.

Most of the researches provided a clear consideration of economy and protection of the water environment (Figure 7). Fifty-three percent of the research in automation and real-time control addresses the economy and water-environment aspects of sustainability; 38% of them focusing on automation of the WWTP considering the receiving river.

The search showed that only 2% of the publications in automation and real-time control strategy focuses on economy, water environment and reduction of GHG emissions with a clear link to sustainability. Studies such as Sweetapple *et al.* (2014) focus on these objectives mainly GHG emissions, but there was no attempt to demonstrate the contributions of the results towards sustainability although a solid discussion is presented mainly on the environmental sustainability later in Sweetapple *et al.* (2015). The only scope found to address both environmental (both water and GHG emission) and social is through an integrated approach. Some studies such as Valentin *et al.* (2016) and Boulos (2017) showed that three-dimensional sustainability indicators (without the consideration of GHG

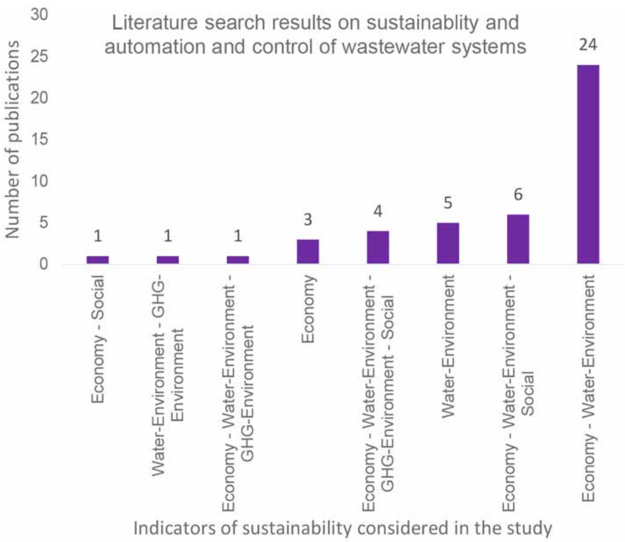

Figure 7 | Relevant literature search results (journal articles and book chapters) demonstrated automation and control to the attributes of sustainability.

emissions) can be achieved through integrating only the sewer networks and water supply systems.

A few studies did not appear in this literature search but clearly showed the benefits of automation and real-time control in the water/wastewater systems. For example, Campos *et al.* (2016), Sweetapple *et al.* (2014) and Caniani *et al.* (2015) looked at the reduction of GHG; Dirckx *et al.* (2011), Meng *et al.* (2017), Zhang *et al.* (2008) and De Gussem *et al.* (2014) showed an optimal reduction of GHG and cost through energy saving; and Fu *et al.* (2008), Meng *et al.* (2020), Meng *et al.* (2017), Reußner *et al.* (2009), Muschalla (2008), Butler & Schütze (2005) and Schütze *et al.* (2002b) focused on an integrated real-time control of water/wastewater systems. They did not appear in this literature search mainly due to their benefit towards sustainability was not specifically demonstrated. This indicates:

1. the need for publications in this topic to map their benefits against the classes and indicators of sustainability; and
2. the limitation of the method used in this study.

DISCUSSION

Future demand for integrated real-time control of the water systems is expected to increase due to stricter regulations, the need for higher efficiency to mitigate climate change, reduction of operational cost, equalisation of peak flow and pollutant load to effectively use spare capacity (Schütze *et al.* 2002a; Astaraie-Imani *et al.* 2012). Water utilities have started to incorporate WWTP models in decision-making, process control and optimisation (UKWIR 2013). The potential of advanced control systems to save energy, chemical usage and greenhouse gas emissions will be increasingly materialised in practice.

However, regulations such as the EU Water Framework Directive (WFD) require a holistic approach to improve the status of water bodies which is a major driver to look at wastewater systems as an integrated system and broaden objectives beyond meeting effluent quality standards (Rauch *et al.* 1998; Fu *et al.* 2008). The scale of integration and the objectives that are assessed so far in the literature vary significantly. On the one hand, Langeveld *et al.* (2002) clearly showed the necessity of an integrated approach to assess sewer systems and WWTPs as an integral unit but not emphasise the need of integrating the receiving water. On the other hand, Benedetti *et al.* (2007) focused on integrating only the WWTP and the receiving river. Erbe & Schütze (2005) presented an integrated approach that allows a holistic pollution-based control of the drainage system as a function of state variables in the WWTP and the receiving water but focusing mainly on managing the drainage network. In contrast, Meirlaen *et al.* (2002) integrated the three subsystems (urban drainage network, WWTP and receiving water) and used the river's ammonia concentration to influence the total flow to the WWTP without influencing processes within the WWTP.

Integrated approaches commonly focus on a single UWWS and often ignore the water treatment system and other WWTPs within a hydrologic catchment. These approaches focus on managing the UWWS regardless of what is going on in the upstream or downstream of the catchment. If the objective is to achieve a 'good' water-environment quality, reducing GHG emissions, creating an efficient system with reduced energy use and cost, and with the societal benefit it is key to widen the scope of management from a single UWWS scale to a hydrologic catchment scale, where activities upstream and downstream urban conglomerates can be put into consideration.

For urban wastewater systems at a catchment scale as shown in Figure 8, it is possible to develop integrated

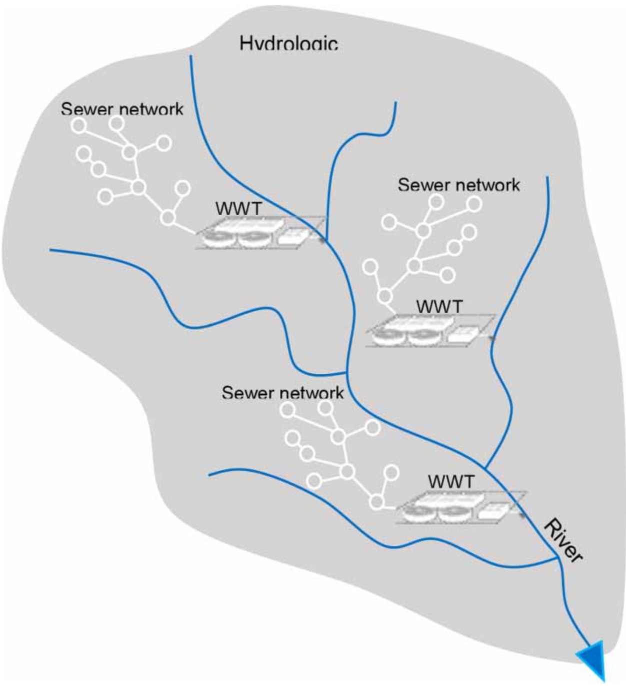

Figure 8 | Scope of catchment scale management of UWWSs.

pollution management considering both diffuse and point sources and achieve a three-dimensional sustainable pathway. For example, Dickinson (2018) suggested when the ammonia concentration in the river upstream of the WWTP is already above the ammonia limit for the river, the catchment scale approach should be used for the river to achieve a 'good' status. Further, river quality-based control approaches and policies should be developed to utilise the capacity of receiving rivers and water resources (Meng *et al.* 2017, 2020).

CONCLUSIONS

This review provided a critical analysis of the use of automation and real-time control in water and wastewater systems, with a focus on achieving economic and environmental sustainability. The presented literature showed that automation and real-time control approaches play a key role in the sustainable management of water and wastewater systems. However, there is no clear path and direction in linking the benefits of these approaches to sustainability indicators. The review showed that there is a need for a structured approach to link these benefits to sustainability indicators in order to support decision-making processes. The review also identified that the research in the area of reduction of GHG emissions is still limited and more work is required not only to quantify this benefit but also their contribution towards each class of sustainability indicators. Most studies considered the efficiency of energy use and had their emphasis on the reduction of operational cost and meeting regulatory requirements but seemed to overlook the advantage of their approach in the reduction of GHG emissions. In addition, adopting an integrated approach in managing wastewater systems is crucial in order to achieve a three-dimensional sustainability pathway. Further, a deeper exploration in the use of an integrated approach with an objective of achieving three-dimensional sustainability is required to reinforce this path. Future work on automaton and real-time control in the water and wastewater needs to explicitly demonstrate the contribution of their control strategies towards the attributes of sustainability. In most of the work reviewed the control objective was driven by regulatory standards, indicating the crucial role of regulations. Hence, regulatory bodies should focus on creating an overarching sustainability framework with indicators of sustainability clearly defined.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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