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Towards the integrated management of urban water systems: Conceptualizing integration and its uncertainties

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A B S T R A C T

Climate change and urbanization, as well as growing environmental and economic concerns, highlight the limitations of traditional wastewater practices and thereby challenge the management of urban water systems. Both in theory and in practice, it has been widely acknowledged that the challenges of the twenty-first century require solutions that address problems in a more integrated way.

Although the demand for integration is obvious, implementation has proved challenging because of the complexity and uncertainty involved. In addition, the urban water literature contains a wide diversity of approaches to integration, each contribution having its own understanding of the term, as well as how to deal with the complexity that comes with it.

In this article, we take a first step in supporting both decision-making and decision-makers in urban water systems integration. First, we work towards a more comprehensive perspective on integration in urban water management; one that uses and structures the variety of existing approaches. In so doing, we introduce a typology of urban water systems integration that distinguishes between geographical, physical, informational, and project-based forms. Second, we explore the implications that such integrated solutions bring for decision-makers. They will be faced with additional uncertainty arising (1) at the interfaces of previously unconnected systems and (2) from the social and institutional changes that systems integration requires. Finally, we draft three decision-making challenges that come with integration and provide some possibilities for dealing with them.

1. Introduction

Cities are under increasing pressure from climate change, population growth, and ongoing urbanization. These developments challenge urban systems to change their traditional practices fundamentally and to become more sustainable; i.e., to prevent the production of waste while increasing efficiencies in the use of energy, water, and resources. The urban water system is one of the key systems within the urban environment demanding new solutions to these sustainability challenges. Extreme weather events, the increase in impervious area, degrading environmental quality, the decay of existing infrastructure, and tightening regulations are placing increasing stress on the performance and management of urban water systems (Butler et al., 2016). These trends fundamentally challenge the structure of traditional urban water management (Wong and Brown, 2009).

Traditionally, urban water management has focused on providing safe, reliable, and cost-effective water services. In developed countries, this has resulted in urban water systems with centralized water supply, sewer networks, and large-scale water treatment facilities (Wong and Brown, 2009). In today's world, however, it has been widely acknowledged that the urban water challenges of the twenty-first century require solutions where problems are approached in a more integrated way (see e.g. Pahl-Wostl et al., 2011).

Although the need for such an integrated approach is widely recognized, its implementation is challenging for decision-makers in charge of those urban water systems (e.g. Qiao et al., 2018). The complexity that comes with integration results in many

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uncertainties (Geldof, 1995), related to technical systems as well as to social and institutional factors (Fratini et al., 2012).

In the literature, there is no unequivocal definition of uncertainty. All definitions, however, relate to some extent to the gap between the information available and that required. This information gap may stem from a lack of technological or environmental knowledge, for instance, but it could also result from a lack of consensus on what kind of knowledge is relevant, as well as the values that are at stake (Hisschemöller and Hoppe, 1995). If there is no consensus on values and facts, the associated problems are described as "wicked" (Rittel and Webber, 1973) or "unstructured" (Hisschemöller and Hoppe, 1995). Whereas uncertainty about facts may be reduced by collecting more information, in the case of values more information may actually add to the uncertainty rather than mitigating it (Klijn and Koppenjan, 2004, p. 6).

Both types of uncertainty are relevant to the problem of integration: there is a lack of information stemming not only from technological and economic issues, but also from the erratic behavior of the actors involved (Klijn and Koppenjan, 2004, p. 6). Moreover, integration is a wicked concept: there is no unambiguous view of what it entails, nor of how to deal with the complexity that comes with it. This implies that completely deterministic knowledge regarding the system of integration does not exist. We therefore use the definition formulated by Walker et al. (2003), which states that uncertainty is "any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system."

When it comes to the sources of uncertainty, we see at least three factors contributing to that associated with integration: the interfaces that emerge where previously unconnected systems become interconnected, multi-actor complexity, and the dynamic nature of the environment in which integration takes place.

- First, the interfaces arising between interconnected systems are an important source of uncertainty. Interfaces involve many potential disconnections that are both technical and socio-institutional in nature: urban systems have different technological traditions, different information technology (IT) systems, different planning and decision-making mechanisms, and different institutional structures. Often there is no unambiguous way of connecting systems or bridging these differences.
  Moreover, the interfaces that arise with integration increase complexity, making it more difficult for decision-makers to understand overall system behavior (de Bruijn and Herder, 2009). Interfaces mirror the boundaries of sectors, each of which has its own specialization. While such specialization leads to considerable knowledge about one's own system, there is only limited knowledge of what is happening at the interfaces (Veeneman, 2004). They thus increase the risk of failures (Perrow, 2011), reduce understanding of overall system behavior, and make decision-making less straightforward.

- The second factor contributing to uncertainty is multi-actor complexity. Compared with decision-making on traditional solutions, decision-making on integrated solutions inevitably involves more actors, all of whom have their own responsibilities and interests (de Bruijn and Herder, 2009). And hence also their own perspective on what needs to be integrated, as well as on why and how this should be done (Fratini et al., 2012). The differences between actors' frames of reference and their institutional backgrounds introduce uncertainty as to how other actors interpret particular information, what actions they will take and how the interaction with those actors will develop (Klijn and Koppenjan, 2004, p. 7).
  Moreover, integrated solutions imply that the different parties involved can no longer work in a fully sectoral and sequential manner, but instead have to act and decide together. The lack of a single "language of the field" complicates communication between these multiple parties, and thereby further contributes to uncertainty.

- Lastly, the environment in which decision-making on integration takes place is dynamic, and thereby also introduces uncertainty. The world of today is inevitably different from that of yesterday and tomorrow. The content of the problem shifts over time, actors and their interests may change, institutions are subject to uncertainty, and technological developments continuously open up new possibilities (de Bruijn and Ten Heuvelhof, 2017). As a result, the drivers, opportunities, and technical options for integration are also subject to change, thereby increasing uncertainty and complicating decision-making.

How do these observations relate to the current urban water literature? In the field of urban water management, only to a limited extent have studies addressed uncertainty associated with an integrated approach. Instead, such studies typically focus on the technical component of uncertainty; for instance, regarding the design of engineering solutions (Tedoldi et al., 2016). Additionally, urban water scholars are familiar with viewing uncertainty from a modeling perspective. For example, the uncertainty contained in simulation results (e.g. Tscheikner-Gratl et al., 2019) and/or associated with long-term planning, focusing on uncertainty related to external developments like climate change, urbanization, and policy changes (e.g. Mikovits et al., 2017). This is also referred to as "deep uncertainty" (Tscheikner-Gratl et al., 2019). While all of these interpretations of uncertainty are relevant and certainly also hold for integrated urban water solutions, they do not consider the uncertainty specific to integration; i.e., that arising at the interfaces between previously unconnected systems.

Studies on integrated models (see Schmitt and Huber, 2006) partially address these interface uncertainties; however, these models are not able to incorporate the uncertainties stemming from, for example, the fact that integration involves different sectors, as well as the potential disconnections between such sectors. Furthermore, the barriers to change towards more integrated approaches to urban water management are found to be socio-institutional rather than technical, reflecting issues related to, for instance, coordination, resources, and responsibility (Brown and Farrelly, 2009). Integration therefore requires the consideration of both technological and socio-institutional factors (Kiparsky et al., 2013). These, however, receive only limited attention in the urban water literature. Hence, we argue that, while the urban water literature is familiar with the concept of uncertainty, it lacks a socio-technical perspective on the specific uncertainties that are introduced by an integrated approach. This paper addresses that gap; yet this first requires a better understanding of the concept of integration itself.

The concept of integration has been discussed elaborately in the urban water literature. And a wide diversity of approaches has been proposed. Each of these typically targets a particular flow or subsystem within the urban water cycle. For example, they may focus on storm water (Fletcher et al., 2015), resource recovery from wastewater (Mo and Zhang, 2013), or rehabilitation of water infrastructure (Tscheikner-Gratl et al., 2016). Depending on the system boundaries adopted in these approaches, as well as the challenge(s) on which the particular approach to integration focuses, the term integration is used to denote different things. This paper will bring these different approaches together, thereby working towards a more comprehensive perspective on integration in urban water management. We add to the existing body of literature on this topic by focusing on the integration between different – previously unconnected – urban systems and the uncertainties involved with such integration. In this way, we aim to shed light on the trade-offs and potential conflicts that may emerge at the interfaces between previously unconnected systems.

For this paper, we have used an interpretative review approach (Noblit and Hare, 1988) to identify the use of the concept of integration in different bodies of literature related to urban water management. First, we conducted a broad exploratory search of the literature, using terms such as “integrated,” “collaboration,” and “cross-sectoral” in combination with “waste/urban/storm water management.” This resulted in a predominantly conceptual exploration of integration. The risk of such an approach, however, is that it is *too* conceptual and not connected to real-world experiences. To explore the concept of integration from a more operational perspective, we therefore conducted nine semi-structured interviews with ten Dutch urban water professionals representing local governments (n = 8) and consultants (n = 2). In these interviews, we discussed issues, actors, and strategies related to integrated approaches to urban water management. The findings from the interviews were used to interpret, enrich, and substantiate the conceptual exploration of the urban water literature, resulting in five key approaches to integration. Consequently, we were able to synthesize these approaches to develop a typology of urban water systems integration based on the cross-cutting dimension of the “object of integration.” Finally, we explored the implications that such integrated solutions bring for decision-makers, identifying the uncertainties and challenges specific to urban water systems integration.

Adopting a socio-technical systems perspective, this paper thus (1) develops a typology of urban water systems integration and, consequently, (2) explores the uncertainties and decision-making challenges involved with such systems integration. This conceptualization should be helpful to structure and facilitate further discussion on integration, in science as well as in practice. In this way, we aim to take a first step in supporting decision-making on urban water systems integration.

After we have provided an overview of current urban water literature on integration in Section 2, in Section 3 we go on to develop our typology of urban water systems integration. In Section 4 we discuss the uncertainties involved in systems integration and their implications for decision-making. Section 5 presents our conclusions and recommendations for research to foster further realization of systems integration.

2. The concept of integration in urban water management literature

In response to the multiple sustainability challenges that the urban water sector is facing, a wide diversity of approaches to integration has been developed, each with its own understanding of what needs to be integrated. These approaches range from the fairly concrete, where integration focuses on one component of the urban water cycle, to more abstract concepts where it relates to changing overall urban water practices in order to increase system efficiency.

In this section, we provide an interpretive review (Dixon-Woods et al., 2005) of the concept of integration. Our aim here is to identify the *use* of this concept, and so not to provide a complete overview of the literature on integration. As such, we distinguish five key approaches to integration. These focus on: (1) storm water; (2) resource recovery from wastewater; (3) the rehabilitation of water infrastructure; (4) the urban water cycle; and (5) the optimization of urban wastewater systems. We first discuss each of these approaches to integration, then end with a synthesis in which we address their similarities and differences.

2.1. Integrated storm water management

Where traditional urban drainage solutions had a primary focus on the conveyance of water away from urban areas, in recent decades the focus has shifted towards more holistic approaches (Fletcher et al., 2015). Growing attention to environmental protection and the increasing problems associated with high runoff volumes and peak flows have stimulated the development of more sustainable storm water solutions (Chocat et al., 2007). This has resulted in measures that focus not only on flood mitigation and health protection, but also provide wider benefits in terms of, for instance, ecology, aesthetics, recreation, and the economy (Fletcher et al., 2015). A diverse set of locally developed terms for sustainable storm water management principles and practices has emerged. Fletcher et al. (2015) provide an overview of these (for instance: sustainable urban drainage solutions (SUDS), green infrastructure (GI), and best management practices (BMPs)) and discuss their scope and application. While SUDS are technologies and techniques used to manage storm water and surface water in a manner that is more sustainable than conventional solutions, BMPs describe both non-structural activities and structural measures to prevent pollution caused when processing storm water. Meanwhile, GI is more of a conceptual approach to urban planning, to maximize potential ecosystem services, and so extends beyond storm water (Fletcher et al., 2015).[1] Another concept in integrated storm water management is the Chinese “sponge city,” which aims to create cities with the sponge-like capabilities of natural landscapes to store and absorb rainwater (Jiang et al., 2018).

The projected effects of climate change are also a driver for integrated storm water management. The combination of climate change and urbanization is increasing the risk of flooding, as well as droughts and heat stress (IPCC, 2012). In July 2011, a cloudburst in Copenhagen (150mm/90min) inundated large parts of the city to a depth of 1 m and resulted in damage costing 600–800 million euros (City of Copenhagen, 2012). And it is not just Copenhagen; throughout Europe, cities are struggling with such extreme weather events. Examples include Apeldoorn, the Netherlands (2009), Herwijnen, the Netherlands (2011), Munster, Germany (2014), and Berlin, Germany (2017). Assuming that climate change and urbanization continue in the present manner, drainage problems are expected to worsen further in the future (see e.g. Ashley et al. (2005) and Kleidorfer et al. (2014) for case studies performed in the UK and Austria, respectively). Conventional drainage solutions are not designed to cope with such extreme events, and consequently other solutions for water conveyance and storage have to be found, such as the use of careful spatial planning (e.g. Fratini et al., 2012).

Adaptation to climate change has resulted in more “outside-the-pipe-solutions; ” i.e., non-piped urban drainage solutions that process storm water by means of infiltration, delay, and/or storage. Such systems could be adopted as a full alternative to piped drainage, or as an additional measure to reduce pressure on the conventional infrastructure (Ahiablame and Shakya, 2016). Examples of such integrated urban drainage solutions are bioswales, green roofs, permeable pavements, and retention spaces in parks and squares (Tillie and van der Heijden, 2015). While many

[1] See Fletcher et al. (2015) for a detailed overview and explanation of various storm water management concepts.

contemporary solutions use natural and ecosystem services to simulate natural hydrological processes, thereby providing economic and social as well as environmental benefits – i.e., nature-based solutions (Zölch et al., 2017) – there are also examples of integrated "gray" solutions. The Dutch city of Rotterdam, for instance, has built a multi-functional parking garage that turns into a water storage tank in the event of heavy rainfall (Tillie and van der Heijden, 2015). Another example is cloudburst boulevards: streets that turn into controlled transport corridors during extreme precipitation events (Ziersen et al., 2017).

2.2. Resource recovery from wastewater

As with storm water, the focus on more sustainable and integrated practices has increased for wastewater (e.g. Mo and Zhang, 2013). Its treatment consumes significant amounts of energy, while wastewater also contains valuable resources such as nutrients, energy, and water; i.e., the energy-nutrients-water nexus (Mo and Zhang, 2013). In addition to optimization of current treatment processes by improving their energy efficiency, increased attention is being paid to wastewater as a renewable resource from which water, materials, and energy can be recovered (e.g. Guest et al., 2009).

The valorization of wastewater is possible at both centralized and decentralized treatment plants. In the Netherlands, for example, existing treatment plants have been transformed into "energy and resource factories," which recover energy, cellulose, bioplastics, phosphate, alginate-like exopolymers (bio-ALE), and biomass (van Leeuwen et al., 2018). Examples of more local projects for resource recovery are the production of biogas for cooking at Hammarby Sjöstad in Sweden (Pandis Iveroth et al., 2013) and the Dutch pilot project for decentralized sanitation and reuse in Sneek (STOWA, 2014).

Like chemical energy recovery (McCarty et al., 2011), thermal energy recovery from wastewater is a form of integrated wastewater management. Although it has much greater potential compared with chemical energy recovery, it is still relatively unexploited (Hao et al., 2019).[2]

The recovery of water from wastewater could be a valuable technology to meet the growing water demands in many parts of the world. In the NEWater project in Singapore, for example, reclaimed water serves as an additional source for both indirect potable and direct non-potable use,[3] and is expected to meet more than half of the city state's water demand in the future (Lee and Tan, 2016).

2.3. Integrated rehabilitation management of water infrastructure

Integrated rehabilitation management refers to asset management practices aiming for the synchronization of replacement cycles of different urban infrastructures, like the road, water distribution, and urban drainage networks (Tscheikner-Gratl et al., 2016). In industrialized countries, most households have been connected to urban water infrastructure for the past century. This has resulted in a shift away from constructing new urban drainage systems since the 1980s, towards the rehabilitation and maintenance of existing systems (Oomens, 1992).

Considering typical urban water infrastructure lifetimes of around 50–100 years, much of the current infrastructure is aging and depreciating, and therefore has to be rehabilitated in upcoming decades. In general, however, current replacement rates are far too low. Moreover, existing systems need to be adapted in order to meet changing demands on capacity. To also satisfy the stringent requirements for asset management at the same time, considerable investments are needed. Integrated rehabilitation management – i.e., synchronizing the replacement cycles of different urban infrastructures – has been proposed as a strategy to meet the high demands (Tscheikner-Gratl et al., 2016). In addition to the monetary savings they make, such joint rehabilitation works can reduce inconvenience related to road closures (Carey and Lueke, 2013), as well as discomfort for citizens due to repeated construction works (van Riel et al., 2014).

The overall inconvenience related to construction works could be further reduced by means of multi-utility tunnels, in which cables and ducts, such as drainage, gas, electricity, telecommunications, and street lighting infrastructure, are collocated (Hunt et al., 2014). A tunnel of this kind was constructed in the Zuidas district of Amsterdam, the Netherlands, in 2004 (Municipality of Amsterdam, 2019). In addition to reducing inconvenience, such tunnels save subsurface space. This implies that they could accommodate more infrastructure networks, or leave room for future developments. For example, district heating or a waste-collection system (Municipality of Amsterdam, 2019).

2.4. Integrated urban water management

The concept of integrated urban water management (IUWM) emerged in the 1990s (Geldof, 1995), focusing on the integration of the water supply, storm water, and wastewater components of the urban water cycle (Mitchell, 2006). As such, it is the specifically urban approach to the more general concept of integrated water management (Biswas, 1981), which focuses on the level of catchment areas. Like most of the other integrated approaches to water management, the concept of IUWM was developed in response to the increasingly evident limitations of conventional urban water practices (Harremoës, 1997). Integrated urban water management recognizes the critical role of organizations and institutions in water management (Biswas, 1981), aiming for the coordination of different policy fields such that all parts of the water cycle, both natural and constructed, are managed in an integrated way (Geldof, 1995). It thereby displays some similarities with the concept of water-sensitive urban design (WSUD) (Wong and Brown, 2009), as both focus on processes and institutions as well as addressing the entire urban water cycle.

Integrated urban water management focuses particularly on the complexity of water problems; in other words, such problems are so large, diverse, and interconnected, and therefore involve so many different stakeholders, all of whom have different interests and agendas, that they cannot be dealt with by a single institution. Hence, one of the key principles of IUWM is to involve all relevant stakeholders in planning and decision-making processes, such that the multifunctionality of urban water services can be enabled and system outcomes can be optimized (Mitchell, 2006). In addition, it emphasizes that all requirements for water, both anthropogenic and ecological, should be considered, and that all parts of the water cycle, both natural and constructed, should be recognized as an integrated system, thereby aiming to minimize the impact on the natural environment (Mitchell, 2006). This illustrates that IUWM is not only about viewing the different urban water components as an integrated physical system, but also emphasizes the relevance of considering the broader natural landscape and its socio-institutional structure.

[2] In addition to heat recovery from wastewater, one can recover heat from surface water or drinking water (Elías-Maxil et al., 2014). All three are considered an alternative heating option in a renewable energy transition.

[3] Potable water is water that is suitable for human consumption, while non-potable water is water that is not of drinking quality.

2.5. Integrated optimization of urban wastewater systems: water quality and capacity

Modeling practices have emerged in parallel with integrated management concepts. Hence, since the 1990s, greater attention has been paid to the integrated analysis and modeling of urban wastewater systems; i.e., assessments based on models that not only study the different components of the wastewater system separately, but also take into account the interactions between urban drainage systems, wastewater treatment plants, and receiving water bodies (see Bach et al., 2014). In 1993, the first INTERURBA conference was organized (Lijklema et al., 1993), which is considered a “milestone” in the research and development of integrated urban water models (Bach et al., 2014).

In the European context, most of the integrated modeling studies have been concerned with the optimization of surface water quality, as scientists started recognizing that that is deteriorated by both effluent and urban runoff (Schmitt and Huber, 2006). This has been particularly so since the implementation of the EU Water Framework Directive (WFD) (EC EU, 2000), which sets strict requirements for ecological river quality. By placing its focus on the river basin as a whole, the WFD has advocated a holistic and collaborative approach to the entire urban water system (Bach et al., 2014). In the Australian context, by contrast, integrated modeling has focused not on emissions and water quality, but rather on the reuse of water (Bach et al., 2014). Nowadays, the benefits of integrated modeling are widely recognized and the models themselves are considered a valuable source of information to optimize both the design and the maintenance of urban water systems.

One increasingly common technology for the integrated optimization of urban water systems is real-time control (RTC) (Langeveld et al., 2013), which involves the dynamic operation of wastewater systems through the monitoring of process variables and the direct (or almost direct) usage of this data for control purposes (Schütze et al., 2004). In general, RTC aims to improve the performance of the system by using the existing infrastructure in a more sophisticated way (Schütze et al., 2004). In addition to water quality control (Langeveld et al., 2013), RTC can be used to enlarge the capacity of existing systems; for instance, to meet changing conditions and demands (Beeneken et al., 2013).

Traditionally, RTC was used mainly to optimize the different components of the urban wastewater system independently of each other (Schütze et al., 2004). More recently, though, driven by the WFD and other factors, the focus has shifted towards a more integrated approach to optimization. Such integrated control collects information from different components of the urban water system and enables the optimization of its overall behavior by taking actions at different locations within it (Schütze et al., 2004). Since the objectives of control within one part of the system could be based on indicators from the other subsystems, integration using RTC solutions is based not only on the exchange of information, but also extends to the objectives of systems (Schütze et al., 1999).

2.6. Integration in urban water literature: similarities and differences

The great diversity of literature in this field demonstrates the widespread interest in more sustainable and integrated approaches to urban water management. Table 1 provides an overview of the characteristics of the different approaches and reveals that they all pay close attention to the urban as well as the natural context in which the water system is embedded. In particular, they focus on the creation of synergy with other urban systems, acknowledging that this necessitates the crossing of conventional sectoral boundaries.

At the same time, however, Table 1 also shows that, although these approaches could all be described as integrated, their focus is fundamentally different. They are typically limited to a particular subsystem or thematic area of urban water management, such as integrated storm water management, thereby limiting their focus to the synergy between two (types of) urban infrastructure systems (Table 1). There is thus diversity in understandings of “an integrated approach to urban water management,” as well as in how to best deal with the complexity that it entails.

On the one hand, this diversity is fruitful: all of the integrated approaches are legitimate, and together they provide valuable insights into the different aspects that need to be considered for a truly integrated approach. On the other hand, however, such diversity is confusing and makes decision-making more difficult.

First, the different approaches are typically limited to a particular flow or subsystem in the urban water cycle (Table 1). They therefore do not provide insights into the relationships with other flows or subsystems. To arrive at one integrated solution, however, it is often necessary to combine several integrated approaches. For example, integrated storm water management in response to climate change and urbanization requires the inclusion of urban water infrastructure in spatial design (Fratini et al., 2012). In built-up and densely populated areas, such climate adaptation projects call for a restructuring of public space. This illustrates the need to involve other actors like road authorities and urban planners. Not only to find space and to produce a collaborative design that integrates multiple urban functions, but also, for example, to secure sufficient budget and to align the various project plans. Hence, one cannot focus solely on integrated storm water management (Section 2.1), but also needs to consider the integration of rehabilitation management (Section 2.3). Moreover, the local processing of storm water relates to the possibilities for resource recovery from wastewater (Section 2.2), as well as influencing the receiving water quality; for example, by bringing microplastics (Bollmann et al., 2019) into the environment (see Section 2.4).

Second, the different approaches to integration, just like the different urban water flows, are heavily intertwined. This implies that there are many interfaces that require trade-offs — social and institutional as well as technical. A multitude of parties and institutions are involved, for example, and since they all have different interests, conflict at the interfaces between previously unconnected systems is inevitable. To facilitate the management of such trade-offs, decision-makers need improved insights into the various components of integration that occur in parallel, as well as the socio-technical interfaces that ultimately emerge between the previously unconnected systems.

Third, from a decision-making perspective, integrated urban water management creates an extremely complex situation: decision-makers are faced with a multitude of possibilities for systems integration, and thus with many different interfaces that could emerge. For example, there are diverse solutions able to recover energy from wastewater (Section 2.2), such as thermal energy recovery in building drainage systems, from sewers, and at treatment plants, as well as chemical energy recovery at treatment plants. Each solution involves different parties, technologies, and institutions, and thus gives rise to different interfaces between previously unconnected systems.

To facilitate decision-making, a better understanding is therefore needed of such interfaces, as well as of the implications of their various possible integration configurations. We argue that a more

Table 1
Overview of the literature on integrated approaches to urban water management.

Integrated approach	Urban water component	Systems to be integrated
Integrated storm water management	Storm water	Public and private systems in the urban space, such as urban green, housing, transportation, urban drainage, and surface water systems.
Resource recovery from wastewater	Wastewater	Wastewater treatment plants and resource systems.
Integrated rehabilitation management	Urban drainage infrastructure	Urban infrastructure systems, such as road, water supply, and urban drainage networks.
Integrated urban water management (IUWM)	Urban water cycle	Subsystems of the urban water system; i.e., water supply, storm water, and wastewater systems.
Integrated optimization of urban wastewater systems	Storm water and wastewater	Urban drainage systems, wastewater treatment plants, and receiving water body systems.

comprehensive perspective on integration could provide such insights and thereby play a valuable role in the discussion on integration, both in theory and in practice.

3. Conceptualizing urban water systems integration

To contribute to the urban water literature and to decision-making on integration, this section presents an initial structuring of the different types of urban water systems integration. Adopting a socio-technical systems perspective, we depart from the existing approaches to integration (Section 2). Based on the object of integration, we conceptualize the integrated approaches into four types. By providing insights into the different components of integration that could occur in parallel and how these are connected, such a typology is helpful for structuring and facilitating further discussion on integration. We thereby aim ultimately to shed light on the interfaces emerging between the previously unconnected socio-technical systems, as well as the uncertainties and challenges that such integration inevitably entails.

3.1. A typology of urban water systems integration

Our typology of urban water systems integration is based on the concept of *systems integration*, which is defined as “all attempts that aim at achieving a higher efficiency for two (or more) systems combined, than can be achieved by each system in isolation” (Vernay et al., 2013). As mentioned earlier, in urbanized areas there is a strong need for such integration. Developments like ongoing urbanization, the energy transition, and the push for a circular economy are putting pressure on our cities and often point to a need for more integrated solutions.

Our focus is on urban water systems integration, defined as “the physical, social, and institutional interlinking of (parts of) the urban water system with other urban systems.”[4] To conceptualize the urban water approaches to integration (see Section 2) and work towards a more comprehensive perspective on integration, we thus adopt a socio-technical systems perspective: the interlinking concerns the physical linkage of infrastructures as well as the interlinkage of the various actors involved and of the institutions that direct their perceptions and actions. In addition, we depart from the typical concentration on a particular thematic area, such as integrated storm water management or resource recovery from wastewater (Table 1). Instead, we focus on cross-cutting dimensions of integration — i.e., objects of integration — irrespective of particular thematic areas. As such, we identify five objects of integration: space, resources, infrastructures, data, and planning. This brings us to a typology of urban water systems integration that distinguishes geographical, physical, informational, and project-based systems integration (Table 2).[5]

For each of these types, we briefly describe their objects of integration and their link to the existing approaches to integration (Table 2). By means of an empirical example, we illustrate what the specific integration is about and shed light on the interfaces that arise between the previously unconnected systems.

1) Geographical systems integration arises in solutions in which urban infrastructures are in close proximity to each other and therefore require coordinated spatial organization. This could stem from conflicting spatial interests, both above and below ground, such as those illustrated by efforts towards climate adaptation (see Section 2.1 on the integrated approach to storm water management) and the energy transition. For a city to become fossil-fuel-free, for example, we have to adapt the electricity grid and/or construct heat networks. Both measures require additional space in the subsurface, while in most urban areas this is already occupied by existing cables and pipelines. Additionally, climate adaptation requires extra space; for example, in the form of (additional) storm water sewers, infiltration facilities and groundwater drainage. Moreover, climate adaptation can reduce the impacts of heat and drought through, for example, urban greening. While trees hold water, reduce urban heating, and have many more positive effects, they also require room for their roots, thereby competing one-on-one with pipes and other (underground) infrastructure. Hence, geographical systems integration is not only about making the different solutions fit into the subsurface or the landscape; it also concerns preventing interference between subsurface and above-ground systems, as well as dealing with different interests. This is where the geographical type of systems integration also links to IUWM (see Section 2.4). Note, however, that IUWM aims for an integrated approach to the urban water cycle on a more general level, and thus goes beyond dealing with conflicting spatial interests.
2) Physical systems integration concerns the physical linkage of two or more urban systems and can be based on either resources or infrastructures.
   a) In the case of integration based on resources, the product generated or transported by one infrastructure (output) is required for the functioning of another (input). An aqua-

[4] Note that in their definition of systems integration, Vernay et al. (2013) focused on the *attempt* to integration — i.e., the action itself — while in the case of urban water systems integration, we address the integration itself.

[5] The concept of urban water systems integration is closely related to the concept of infrastructure interdependency (Rinaldi et al., 2004), which addresses the type of relationship between two infrastructures and distinguishes physical, cyber, geographic, and logical interdependencies. While this categorization served as inspiration in identifying the urban water systems integration typology we have developed, our starting point was urban water approaches to integration. As such, the interdependency categorization has been further modified, abridged, specified, and expanded; i.e., cyber to informational, logical, resource-based and infrastructure-based, and project-based integration, respectively.

Table 2
Characteristics of the different urban water systems integration types.

Type of systems integration	Object of integration	Description	Example related to the urban water system
Geographical	Space	Spatial alignment of systems in the same area	Alignment of infrastructures to prevent interference; for example, positioning speed bumps such that, depending on their specific location, they block or not block flow (Rainproof, 2018).
Physical	Resources	Shared use of a resource for multiple functions	Thermal energy recovery from urban water; i.e., wastewater, drinking, surface or groundwater (Elías-Maxil et al., 2014).
	Infrastructures	Shared use of an infrastructure system	Multi-utility tunnels to collocate cables and ducts, such as drainage, gas, electricity, telecommunications, and streetlighting infrastructure (Hunt et al., 2014).
Informational	Data	Use of data from different systems in operating those systems	Optimizing interactions between wastewater and surface systems through impact-based real-time control (RTC) (Langeveld et al., 2013).
Project-based	Planning	Alignment of rehabilitation and construction plans for multiple urban systems	Possible synergies between urban infrastructure systems in rehabilitation planning (Tscheikner-Gratl et al., 2016).

thermal system, in which heat is recovered from surface water, wastewater or drinking water, is one example. The local re-use of water, such as usage of the effluent from helophyte filters to flush toilets, is another, illustrating the physical integration of resources. These examples represent the integrated approach to resource recovery (see Section 2.2).

b) In the case of infrastructure-based integration, one infrastructure uses the other to fulfill its function. For example, a multi-utility tunnel that collocates all cables and ducts, amongst them sewer pipes, in one tube (Hunt et al., 2014).

Another example is GI solutions such as living walls, which grow plants on a vertical surface. While such walls are able to collect and store (and sometimes also treat) storm water, they also have other urban functions, like decreasing the urban heat-island effect and cleaning the air (Riley, 2017).

Such infrastructure-based integration is not directly related to one of the integrated urban water approaches identified earlier (Section 2); however, the examples we have provided here do show some overlap with the integrated approach to asset management (Section 2.3) and with integrated storm water management (Section 2.1).

3) Informational systems integration is based on combining data from different urban systems. It is thereby closely related to the integrated optimization of urban wastewater systems (Section 2.5). One Dutch example is the Kallisto project in the Eindhoven region, which aims to improve the water quality of the River Dommel in a cost-effective way (Langeveld et al., 2013). To this end, De Dommel Water Board and ten local authorities in the Eindhoven region are applying impact-based RTC to optimize interaction between the wastewater chain in Eindhoven and the Dommel's water system (Langeveld et al., 2013).

Another example is the Polder Roof, which provides dynamic water storage (Rainproof, 2018). Through real-time information and remote-control operation, such a roof enables emptying of the system in the event of heavy rainfall and allows for dynamic control of water drainage on, for example, a neighborhood scale.

4) Project-based systems integration focuses on the possible synergies between urban infrastructure systems in rehabilitation and construction planning, and thereby represents the integrated approach to asset management (Section 2.3). By planning replacement and maintenance projects for different infrastructures in such a way that they coincide or take place immediately after each other, inconvenience can be limited and costs may sometimes be saved as well (Carey and Lueke, 2013; Tscheikner-Gratl et al., 2016). One contemporary example is found in the implementation of the energy transition in the Netherlands, where the rehabilitation planning of sewer systems typically serves as a starting point for the planning of district heating systems (e.g. Municipality of Rotterdam, 2019).

Concerning this typology, we would like to make two observations. Firstly, in addition to the four types indicated, systems integration can also come in an overlapping or hybrid form. For example, the informational-physical systems integration in the smart-cities concept of integrated storm water inflow control (Lund et al., 2019), which focuses on the potential synergy between sewers, green infrastructure, and the urban landscape. This particular approach uses real-time control to dynamically link the subsurface drainage system with above-ground GI systems (Lund et al., 2019). By shedding light on potential forms of integration, the conceptualization of urban water systems integration enables the identification of such hybrid or overlapping forms and thereby provides insights into the interfaces that emerge as a result.

Secondly, it will have become clear from the description that each of the four types of integration has both a technical-physical element and a socio-institutional one. While the integration of these elements in socio-technical systems may be evident for the physical type of systems integration, such as in a multi-utility tunnel, it also holds true for, for example, the informational type. For instance, improving the receiving water quality through RTC requires the installation of a physical monitoring network, which means that the actors involved have to agree a monitoring plan. Such a plan includes the monitoring objectives, for instance, but also the quality and time-step of the data, as well as the format and structure used for storing the data (Schmitt and Huber, 2006).

This illustrates that systems integration is a socio-technical challenge, in which actors have a crucial role to play. As well as involving technological innovation, then, the shift to integration also has implications for decision-making (Kiparsky et al., 2013). To foster the realization of systems integration, we should therefore look not just at the concept of urban water systems integration itself, but also address the implications this brings for decision-makers.

4. The implications of urban water systems integration

Decision-makers are key to the successful implementation of integration. In this section, we therefore take a first step in supporting the urban water decision-maker faced with the challenge of integration. Building on the insights gained from the urban water literature on integration and the typology introduced above, we provide insights into the implications inherent to urban water systems integration.

So far, we have learned that:

- urban water systems integration is necessary to address the multiple sustainability challenges;
- systems integration is a socio-technical challenge;
- this challenge typically manifests itself at the interfaces of previously unconnected systems;
- there is a multitude of possibilities for systems integration, and there are thus also many different interfaces that can emerge;
- the urban water literature addresses this need for integration; however, these approaches to integration typically pay limited attention to the socio-technical interfaces that occur in parallel; and,
- another way of addressing urban water systems integration is therefore to focus on the objects of integration – space, resources, infrastructures, data, and planning – that occur at such interfaces.

With respect to decision-making, these observations imply that integration inevitably leads to an accumulation of uncertainty. This raises the question as to how decision-makers can deal with the uncertainty inherent in urban water systems integration. First of all, we therefore need a better understanding of the specific uncertainties introduced by that form of integration.

4.1. Exploring systems integration uncertainty

If we look at the four types of systems integration (Table 2), it first of all becomes clear that uncertainties arise at the various interfaces where previously unconnected systems become interconnected. In the case of geographical systems integration, for instance, urban water decision-makers are faced with uncertainty related to the actions of actors in charge of other urban systems. One can think here of integrated storm water management solutions that require the spatial alignment of the urban water infrastructure and other urban infrastructures. The geographical integration involves accommodating different system functions in a given area. This implies that, in this area, a multitude of actors are involved, each of which takes actions – intended as well as unintended – that could influence the functioning of the urban water system.

Interface uncertainties are thus inherent to urban water systems integration. In addition to uncertainty that follows directly from potential disconnections between previously unconnected systems, there are also the uncertainty that originates *within* the urban water system and that related to *external* developments that may manifest themselves and propagate at the interfaces. Integration thus leads to the accumulation of uncertainty, and decision-making on integrated solutions therefore requires that such interface uncertainties be addressed specifically.

Secondly, it becomes clear that specific uncertainties arise from the actions of the actors involved and of the institutions guiding such actions. Urban water professionals are confronted with a wide diversity of actors with different responsibilities and interests, but also with actors who work from different institutional backgrounds, and thus are likely to consider different rules to be correct and valid (Klijn and Koppenjan, 2004, p. 88). Both the diversity of actors and the diversity of institutions involved with systems integration introduce uncertainty. Informational systems integration, for instance, involves uncertainty related to the sharing of data from different urban systems. The parties involved may have different IT systems and ontologies, and thereby introduce institutional uncertainty[6] for the urban water decision-makers involved. Moreover, such sharing of data highlights the issue of privacy that comes with informational systems integration. Privacy regulations are key to reduce the risk of cybercrime; however, regulations typically develop slowly. They thus involve uncertainty as to whether, when, and how they will be enforced and/or adapted.

Hence, in addition to the well-investigated uncertainties in the urban water literature – i.e., those related to technology and external developments – our typology of urban water systems integration also points to two types of uncertainties that seem in crucial need of further investigation: interface uncertainties related to actors and interface uncertainties related to institutions. This finding is in line with previous research, which has shown that the barriers to change towards integrated approaches to urban water management are primarily socio-institutional and not technical (Brown and Farrelly, 2009).

To take a first step in supporting decision-making on urban water systems integration, we therefore conceptualize the uncertainties that emerge due to systems integration in such a way that they highlight such social and institutional interface uncertainties (Table 3). We combine the socio-technical systems perspective (technical, social, and institutional uncertainty) with the concept of systems integration (internal, interface, and external uncertainty). The highlighted boxes indicate the two types of uncertainty that become more dominant than in traditional solutions, and whose consideration is thus crucial for the successful realization of integration.

While this conceptualization provides insights into the specific uncertainties that are introduced with an integrated approach, the question remains as to what such uncertainties ultimately imply for actual decision-making.

4.2. Decision-making challenges

In this section, we look at the decision-making implications of the uncertainties specific to urban water systems integration. Based on the literature on decision-making in networks, together with the insights already provided in this paper, we have identified the following challenges that urban water professionals face when anticipating the future.

4.2.1. From project to process

A traditional project approach is characterized by its clear goals and fixed, linear planning. This, however, is impossible in a world with an increasing need for integration (De Bruijn et al., 2010, p. 3). As illustrated by the categories of social and institutional interface uncertainties (Table 3), integration is a process involving many actors with different resources, interests, and perceptions. These actors are mutually dependent and there is no hierarchical structure governing them. This raises new questions: what actors should do what, in which way should they do it and when, and how should they deal with actors who have opposing views? The actors involved need to find answers to these questions through a process of interaction (Klijn and Koppenjan, 2004, p. 184). Integrated solutions therefore call for a shift in attention from a project approach to a process approach (de Bruijn and Ten Heuvelhof, 2017, p. 25).

[6] Following the subdivision for institutions applied by Scott (2008), such institutional uncertainty comprises cognitive, regulative, and normative aspects. Cognitive uncertainty relates to shared thoughts and logics that shape institutions' frames of reference, regulative uncertainty to the rules that regulate and constrain behavior, and normative uncertainty to values and norms.

Table 3
Uncertainties associated with urban water systems integration. The focal system comprises all or part of the urban water system, and therefore depends on the perspective one adopts. The gray color highlights the uncertainties we consider most dominant for decision-making on urban water systems integration.

	Internal uncertainties (within the focal system)	**Interface uncertainties (between urban systems)**	**External uncertainties (outside the overall system)**
Technical uncertainties	Uncertainty about the technical functioning of the focal system.	Uncertainty about the technical interactions between the focal system and other systems.	Uncertainty related to the wider context of the overall system (for instance, demography and economics)
Social uncertainties	Uncertainty about actors' decisions for the focal system.	Uncertainty about actors' decisions for related systems (that are beyond the immediate issue).	
Institutional uncertainties	Uncertainty about institutions for the focal system.	Uncertainty about institutions for related systems.	

4.2.2. From an unambiguous view of integration to a negotiated view

Most people will agree with the idea that solutions to meet current challenges should be "integrated." However, we have illustrated extensively that integration is an ambiguous concept. Not only between other urban disciplines, but also within urban water management, actors have different perceptions and interests, and therefore view (the need for) systems integration differently. Hence, there is no one truth when it comes to integration. This results in a dilemma: on the one hand, the actors involved agree that there is a need for urban water systems integration. On the other hand, the same actors disagree about how to define and operationalize urban water systems integration.

Since integration is a wicked problem, there is no alternative but to negotiate – to bring these actors together, to organize a process of interaction between them, and to let them decide collaboratively how integration should be defined and operationalized. In the literature, this is called *negotiated knowledge* (De Bruijn et al., 2010, p. 146). Based on a process of interaction, the different parties involved, with different areas of expertise, have to come collaboratively to a negotiated view on integration.

4.2.3. From taken-for-granted institutions to dealing with institutional mismatches

Rather than working in silos and according to one's own rules and practices, an integrated approach to urban water management requires collaboration across departments and sectors (Dunn et al., 2017). Current institutions, however, fit the current way of organizing and the current systems, but not these more integrated ones (Klijn and Koppenjan, 2004, p. 7). This implies that systems integration always comes with some institutional mismatch between sectors (see Section 4.1 on institutional uncertainty). In addition, as institutions develop only slowly while technology does so continuously, such institutions never fit the state-of-the-art systems (Hajer, 2003). Integration is therefore not always supported by institutions. Decision-makers inevitably have to deal with such institutional mismatches and find their way in the resulting fluidity.

5. Conclusions and outlook

It is evident that urban water systems integration has the potential to increase the efficiency of our urban infrastructure systems, thereby helping societies to become more sustainable. In practice, however, the implementation of such integration has proved challenging due to the high degree of uncertainty involved. To support decision-making, and thereby to realize the potential of integration in urban water management, it is therefore essential to take a comprehensive perspective on integration: this enables the articulation – and thereby supports the anticipation – of interdependencies, trade-offs, and conflicts between different types of integration.

To take a first step in supporting decision-making on urban systems integration, this paper makes three contributions to structure and facilitate the discussion on integration in science, as well as in practice: (1) it brings together the existing urban water literature on integration; (2) it introduces a typology of urban water systems integration; and (3) it provides insights into the implications that urban water systems integration brings for decision-makers.

Although the list of urban water systems integration types – i.e., geographical, physical, informational, and project-based – may not be exclusive and can be further extended, our conceptualization structures, and thereby facilitates, the discussion on integration. We have shown how the typology provides insights into the different components of integration, as well as its overlapping or hybrid forms.

This study has illustrated that the complexity and uncertainty associated with systems integration can be attributed largely to the interfaces between the coupled systems. In addition, the multi-actor complexity associated with integration involves much socio-institutional uncertainty. The shift to integrated urban water solutions therefore calls not only for the technical uncertainties to be addressed, but also the social and institutional uncertainties that manifest themselves at interfaces. Based on the uncertainties and decision-making challenges identified, we have shown that integration needs urban water professionals with both systemic "spectacles" and process management skills; they need to be able to reflect on the position of the water system in relation to other urban systems, as well as understanding the role of other parties and their underlying interests.

As an outlook for the future, we recommend that both the urban water sector and scholars in this field address the decision-making challenges (Section 4.2) that come with integration. With the increasing demand for urban water systems integration, it is vital to support both decision-making and the decision-makers in charge of such integration. Hence, research should not only focus on technological development, or the required institutional changes on a system level, but also support decision-makers in charge of such integration. For example, through serious games — which are not new in the field of urban water management (e.g. van Riel et al., 2017), yet here require a different form of application — that allow decision-makers to develop the process skills essential for integration in a controlled environment. Another possibility is the expansion of decision-support tools to include socio-institutional uncertainty, such as the DAnCE4Water model that aims to link urban and societal dynamics with infrastructure evolution (Rauch et al., 2017).

In addition, we recommend that future research investigates the ambiguity associated with an integrated approach to urban water management in practice: the wide diversity in viewpoints on integrated urban water management in the literature suggests that in practice, too, urban water professionals view (the need for) systems integration differently. Disagreement about the desired goals, intensity or type of integration, for instance, could eventually hinder decision-making and thereby the implementation of more integrated solutions. To foster the ultimate realization of systems integration, future studies should therefore explore the diversity of perspectives on the role of such integration for future urban water systems.

CRediT authorship contribution statement

Eva Nieuwenhuis: Conceptualization, Writing - original draft, Methodology, Visualization, Data curation, Validation. **Eefje Cuppen:** Conceptualization, Writing - review & editing, Supervision. **Jeroen Langeveld:** Funding acquisition, Writing - review & editing, Supervision. **Hans de Bruijn:** Conceptualization, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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