The end of the sectoral approach? Understanding the role of integration in urban water management

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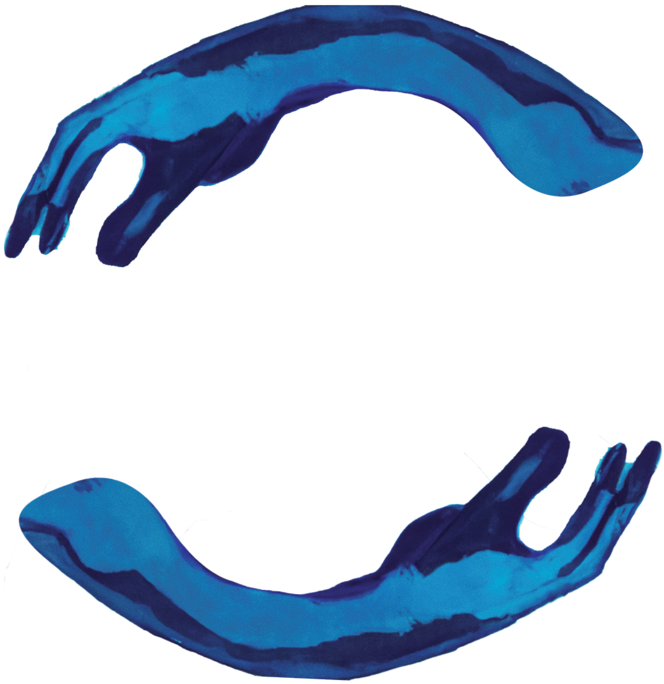

Eva Nieuwenhuis

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Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft
op gezag van de Rector Magnificus prof. dr. ir. T.H.J.J. van der Hagen,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op
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door

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geboren te Leiden, Nederland

Dit proefschrift is goedgekeurd door de promotoren.

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Summary

Urban areas are highly dependent on their urban water systems, which provide essential services such as access to clean drinking water, public health protection, and flood control. Global developments increasingly threaten the provision of these services: changing weather patterns, ongoing urbanization processes, and depleting natural resources lead to environmental and public health issues, and increase the risk of urban flooding.

While traditional urban water systems (i.e., centralized water supply systems, sewer networks, and large-scale wastewater treatment facilities) have significantly contributed to global public health and protected cities from flooding, they are ill-equipped in the face of emerging global developments. For example, traditional systems have a limited ability to cope with extreme climate conditions, have a high net energy consumption, and lead to the deterioration of the environmental quality.

It is becoming increasingly clear that, rather than sectoral solutions, urban water systems need cross-sectoral solutions to address these global developments: they require solutions that connect these systems to other urban infrastructures like roads, parks, and energy infrastructures, and that are planned, designed, and managed in collaboration with other urban actors. These integrated, cross-sectoral solutions should: be more resilient to the consequences of heavy storm events, flooding, and periods of drought; enable the recovery of valuable resources like nutrients, energy, and water; and provide wider social and environmental benefits. In this thesis, such solutions are referred to as Urban Water Systems Integration (UWSI), which the author defines as "the physical, social, and institutional interlinking of (parts of) the urban water system with other urban systems."

While the need for UWSI to prepare urban water systems for the future is widely recognized, its development and implementation has proven challenging. Designing, constructing, and operating integrated solutions is not only technologically complex, but is also a socio-institutional challenge: systems integration requires radical changes to organizations and institutions that are strictly defined by fixed procedures and processes to protect the essential services that urban water systems deliver. Furthermore, rather than being designed, built, and operated solely by water engineers, UWSI necessitates the involvement of other urban actors such as road authorities, urban planners, and citizens. This means that new forms of collaborations and coordination between these actors must be developed. In addition, each of

these actors can have entirely different planning and decision-making mechanisms, as well as different institutional structures, further complicating decision-making on UWSI. Clearly, developing and establishing UWSI is not an easy task. And although it has been widely indicated that the barriers to implementing integration are socio-institutional in nature, most research on integration has used engineering methods, or focused on technology for integration.

This thesis therefore takes an empirical, socio-institutional perspective on UWSI, looking at how integration is developed and organized on the ground. The central aim is to get a better understanding of the socio-institutional processes involved in UWSI, and thereby support the transition to more integrated urban water management practices. Four different studies are conducted, each looking at UWSI from a different perspective. Together, they provide a rich picture of the socio-institutional processes related to UWSI. Based on these four perspectives, the following research question is formulated:

How is integration defined, understood, operationalized, and organized in urban water management?

Each study addresses one part of this research question and thereby applies a different approach and focus (see Table S-1). A visual summary of the four studies and their outcomes is presented in the graphical abstract in Figure S-1.

Table S-1. Overview of the four studies conducted in this thesis.

Study	Chapter	Part of research question addressed	Perspective on UWSI	Looking at UWSI as…	Research Method
1	2	*Defined*	Theoretical	Theoretical concept	Interpretive review
2	3	*Understood*	Practitioner's	Practitioner's perspective	Q methodology
3	4	*Operationalized*	Project	Implemented SUDS	Field study
4	5	*Organized*	Organizational	Innovation	Case study

Note. SUDS = Sustainable Urban Drainage Systems
UWSI = Urban Water Systems Integration

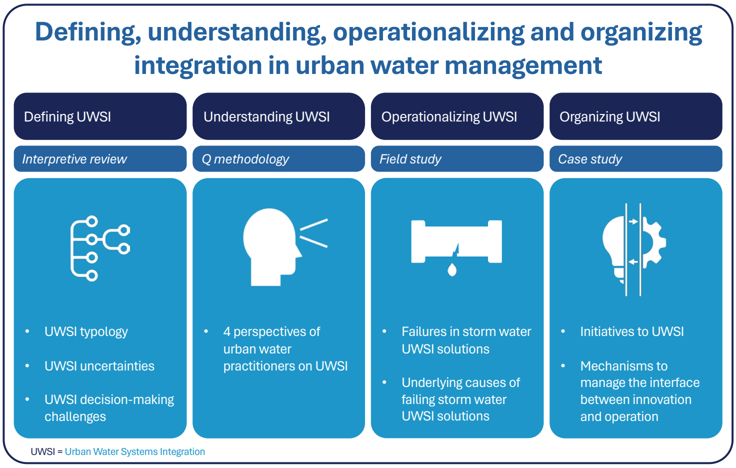

Figure S-1. Visual summary of the four studies conducted in this thesis and their outcomes.

The first part of **Chapter 2** focuses on the *definition* of integration and introduces the concept of UWSI. This concept forms the theoretical basis for the rest of this thesis. Based on an interpretive review of the urban water literature, existing approaches to integration are identified and structured. This review shows that the urban water literature contains a wide diversity of approaches to integration, each having its own understanding of the term, as well as of how to deal with the complexity that comes with it. The approaches typically focus on a particular flow or subsystem in the urban water cycle, such as storm water, (resource recovery from) wastewater, or rehabilitation of water infrastructure.

By introducing the concept of UWSI, the aim is to come to a more comprehensive perspective on integration that does not limit its focus to a particular flow or subsystem, as the existing approaches do. Four types of UWSI are distinguished: geographical, physical, informational, and project-based systems integration.

- Geographical UWSI focuses on the spatial alignment of different urban infrastructure systems and aims to prevent (undesirable) interference between them.
- Physical UWSI involves the physical linkage of two or more urban systems and can be based on either resources or infrastructures. In resource-based integration, the product generated or transported by one system is required for the functioning of another, whereas in infrastructure-based integration, one infrastructure uses the other to fulfill its function.
- Informational UWSI is about combining data from different urban systems.

- Project-based UWSI focuses on the possible synergies between urban infrastructure systems in rehabilitation and construction planning.

The different UWSI types focus on how different systems are connected (i.e., through space, infrastructures, resources, data, or planning, respectively), rather than looking at the integration of a certain part or flow within the urban water system. As such, the UWSI typology can give insight into the different types of integration that occur in parallel, and thereby help articulate and manage interdependencies and trade-offs between these types. The UWSI typology could thus structure the discussion on integration, both in theory and in practice.

The second part of Chapter 2 explores the implications that such integrated solutions have for decision-makers, identifying the uncertainties and challenges that come with the shift to more integrated solutions. The results show that much of the uncertainty associated with UWSI can be attributed to: (1) the *interfaces* between the coupled systems, i.e., where the previously unconnected systems become interconnected, and (2) multi-actor complexity, i.e., the actions of other *actors* and the *institutions* guiding these actions. These findings indicate that the interfaces related to these other actors and institutions require careful attention when working on UWSI solutions.

Chapter 3 looks at UWSI from the perspective of practitioners, focusing on the diversity in *understandings* of UWSI in practice. Using Q methodology, four real-world perspectives of Dutch urban water practitioners on the role of integration for future urban water systems are identified. These reveal that integration is understood in many different ways, but that there is also much common ground between the perspectives. While the perspectives differ as to the opportunities and challenges to focus on, they all recognize that traditional water management practices need to change to prepare for the future.

To explore and define the perspectives, a group of 30 urban water practitioners rank a set of 43 statements about integration in future urban water systems into a normally distributed grid. In addition, post-sorting interviews are conducted to get a better understanding of how participants make their decisions – and thus of their viewpoints. Using factor analysis, the individual perspectives are grouped into four shared ones: In perspective 1 (*Future-proofing through coordination: finding space for urban challenges),* integration is about a collaborative process with other urban actors to coordinate the many urban challenges that need to be addressed simultaneously. In perspective 2 (*Future-proofing through climate adaptation:*

creating livable cities), integration refers to climate adaptation, which is viewed as the key to better social and environmental conditions in cities. In perspective 3 (*Future-proofing through recovery: challenging institutional structures)*, integration is about the recovery of resources and sees an important role for (new) collaborations. Finally, in perspective 4 (*Future-proofing through efficiency: being in control*) integration refers to managing the subsurface space efficiently by having good insights into the system.

The results reveal that the perspectives have different understandings of integration in future urban water systems: they see different drivers for integration, and focus on different spatial scales. Nonetheless, they are not necessarily conflicting, i.e., one perspective does not have to exclude the others. Insight into the similarities and differences between perspectives can be useful to structure the discussion on integration, but also to build effective strategies, for instance regarding what different spatial scales and motivations for integration should be included in those strategies.

Chapter 4 looks at the *operationalization* of UWSI, focusing on experiences with a specific case of UWSI, namely implemented Sustainable Urban Drainage Systems (SUDS). Based on site visits and interviews with water practitioners, technical failures in SUDS and their underlying root causes are identified. The results show that the malfunctioning of SUDS is often related to socio-institutional aspects, such as poor communication between actors (of different disciplines and/or phases), and embedded practices that do not support integrated solutions. This illustrates the need to pay attention to integration not only in the early stages of the development process (i.e., the policy and design phase), but also in the later stages of the development process (i.e., the construction and operation/maintenance phases).

To define the kind of failures, three types of SUDS are distinguished: infiltration, conveyance, and storage SUDS. For infiltration SUDS, *clogging* is the most frequently observed failing mechanism, for conveyance SUDS *interference with obstacle* is observed most often, and for storage SUDS this is *limited freeboard* and *interference with obstacle*.

Looking at the failure locations and the root causes of these failures, the results show that interfaces between SUDS and other urban systems play an important role in both cases. These interfaces refer to the locations where urban water systems become connected to other urban infrastructures, such as roads and green areas. Almost 40 percent of the failures occur at such interfaces, and the causes underlying these failures are often related to "human factors." Such interfaces thus need careful attention in the different phases of the development process.

The failures and root causes identified in this study provide an initial insight into the socio-institutional changes that are required for the shift from traditional, sectoral urban water solutions to UWSI solutions (e.g., changes to routines, policies and guidelines that are still oriented toward traditional systems).

Chapter 5 focuses on the *organization* of UWSI. Drawing on case study research, the chapter analyzes initiatives around UWSI innovations in the cities of Amsterdam and Rotterdam. Development and implementation of such innovations is challenging due to the operational and sectoral mindset of organizations in which these initiatives take place. A desk study is combined with semi-structured interviews to analyze the types of initiatives and the mechanisms that play a role in managing the tension between innovation and operation.

Central to this study is the concept of ambidexterity. The essence of this concept is that organizations need both operation and innovation techniques to be successful. One way to achieve such ambidexterity is through dual organizational structures, in which one part focuses on innovation, and another part on operational activities. Such dual structures are also found in Amsterdam and Rotterdam: the initiatives focus on UWSI innovations, while the line organization focuses on the day-to-day operation of systems. Despite the structural separation of innovation and operation activities, the results also show close connections between both types. Network activities, both within and between organizations, play an important role in bridging the two. These networks allow work to be done across conventional disciplinary and organizational boundaries (which is typically required for UWSI innovations), and help spread the philosophy of integration and associated knowledge and skills.

From the 16 UWSI initiatives that are included in the study, four types of initiatives are differentiated: programs, movements, collaborations, and line-based initiatives. Each type is characterized by a different approach, organization, and role for hierarchy. Looking at the tension between innovation and operation activities, four mechanisms to manage this tension are identified: network mechanisms, hierarchical mechanisms, process mechanisms, and human resource mechanisms.

Network mechanisms dominate the connection between innovation (initiatives) and operation (the line organization). They play an important role throughout the entire innovation process, both in developing UWSI innovations, and in implementing them. Networks allow innovation activities to be separated from operation activities, while at the same time tightly connect them during the innovation process. This empirical finding differs from the literature on ambidexterity, which depicts two separated worlds (i.e., the world of operation, and that of innovation) connected at senior management level. Nonetheless, the results still point to an important role for executives: they can foster innovation, as well as formalize it.

These results are interesting for other cities worldwide that face the challenge of developing and implementing UWSI innovations in their operationally-oriented organizations: the identified mechanisms indicate possibilities for how the tension between exploitation and innovation could be managed.

Chapter 6 presents the general conclusions and the discussion of this thesis. The conclusions are summarized in four observations, followed by a reflection on each:

1. *UWSI is defined and understood in many different ways, thereby calling for a negotiated view on integration.*

The findings of this thesis show that UWSI is an ambiguous concept, involving many different *definitions* and *understandings* of integration. 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. This means that there is no alternative but to negotiate: rather than searching for a single truth, the involved actors require a process of interaction to negotiate and decide collaboratively how integration should be defined and operationalized, i.e., to arrive at a negotiated view on integration.

The discussion section reflects on what the ambiguity associated with integration means for decision-making. It is argued that, while ambiguity could be an important driver of the process of interaction by leaving room for individual interests and motivations, it could also hinder the implementation of UWSI by increasing the risk of people talking past each other. A process of interaction could play a balancing role in this respect: in earlier stages of decision-making, the ambiguity could act as a driving force for such a process, while at a later stage negotiations are needed to reduce ambiguity.

2. *Sustainability is a key driver for UWSI on paper, but in practice, many other competing factors come into play*

While in the urban water management literature on integration, as well as in policy documents, it is typically assumed that sustainability is the key driver of integration, the results of this thesis show that, in practice, sustainability does not always play a central role in decision-making on integration. Other values such as maintainability or esthetics turn out to be more relevant in some cases. These other values are, together with sustainability, part of the process of interaction in which the involved actors need to come to a negotiated view on integration.

The discussion section reflects on what this process of interaction may do for the (level of) sustainability of UWSI innovations. While the inclusion of other values may lead to the final solution becoming less sustainable, it may also benefit the level of sustainability by increasing the support for a solution. Since support and practicability are essential to the implementation of sustainability, including other values might be beneficial to achieving it.

3. *In practice, UWSI is often approached as a design challenge, and not as a continuous process that needs coordination across phases*

Urban Water Systems Integration is typically understood as a challenge to be addressed in the early stages of the development process, i.e., through using a cross-sectoral approach in the policy and design phase. The empirical results of this thesis show, however, that it is not only the connection between sectors that is essential for well-functioning UWSI systems (i.e., to prevent failures), but also the integration and coordination between the different phases of the development process. Without such coordination, integration may lose out on phases of implementation and management, despite a carefully integrated design. Urban Water Systems Integration is thus an infrastructure lifetime challenge, and not just a cross-sectoral design challenge.

The discussion section reflects on this issue and provides a few suggestions how the different phases of the development cycle could be better aligned, such as by including insights from the "people on the ground" in the early phases of the development process, or by making operators more aware of the values that are at play in the policy phase.

4. *While UWSI is generally considered an effort that requires a planned organization, emergent processes appear to be critical as well*

Given the extensive and radical changes that the transition to UWSI entails for organizations and institutions, systems integration is typically viewed as a phenomenon that requires a top-down, planned approach. However, the empirical results of this thesis reveal that systems integration is not only

developed in a planned way, but that it is also the result of incremental, emergent changes.

The discussion section reflects on the question what the emergence that comes with integration means for the planning for UWSI. It is argued that, although emergence is often thought to conflict with planning for UWSI, it can also be complementary to it. More specifically, while top-down integration initiatives allow executives to steer on systems integration, bottom-up initiatives enable people across an organization to become enthusiastic about it, such that they can develop relevant ideas using their expert knowledge and experience. Therefore, both processes are needed to arrive at supported, integrated solutions.

Samenvatting

Het stedelijk watersysteem is essentieel voor het leven in de stad: het voorziet de stad van schoon drinkwater, speelt een fundamentele rol in de bescherming van de volksgezondheid, en levert een grote bijdrage aan het voorkomen van wateroverlast. Door ontwikkelingen zoals klimaatverandering, bevolkingsgroei en verstedelijking komt er echter steeds meer druk te staan op stedelijke watersystemen. Veranderende weersomstandigheden, de uitbreiding van stedelijk gebied en een toenemende schaarste van energie en grondstoffen leiden tot volksgezondheidsproblemen, een afname van de water- en milieukwaliteit, en een verhoogd risico op wateroverlast.

De traditionele aanpak in het stedelijk waterbeheer, d.w.z. grootschalige, sectorale systemen voor drinkwatervoorziening, riolering en afvalwaterzuiveringsinstallaties, heeft de samenleving altijd veel gebracht. Deze systemen hebben bijvoorbeeld een grote bijdrage geleverd aan de bescherming van de volksgezondheid en aan het voorkomen van wateroverlast. De (mondiale) ontwikkelingen die op steden afkomen, brengen echter nu hun beperken aan het licht. Zo blijken deze traditionele watersystemen in beperkte mate bestand tegen extreem weer, hebben zij een hoog netto energieverbruik, en verminderen zij de milieukwaliteit.

Het wordt steeds duidelijker dat stedelijke watersystemen, in plaats van de sectorale oplossingen, sectoroverstijgende oplossingen nodig hebben om op de mondiale ontwikkelingen te anticiperen: zij hebben oplossingen nodig die het stedelijk watersysteem verbinden met andere stedelijke infrastructuren zoals wegen, parken en energie-infrastructuren. Deze integrale, sectoroverstijgende oplossingen zouden beter bestand zijn tegen de gevolgen van zware stormen, overstromingen en perioden van droogte; kunnen waardevolle grondstoffen zoals nutriënten, energie en water terugwinnen; en kunnen bovendien ook bredere sociale en milieuvoordelen opleveren.

In dit proefschrift worden dergelijke oplossingen aangeduid als als “Urban Water Systems Integration” (UWSI), wat in het Nederlands vertaald kan worden als “systeemintegratie voor stedelijk water.” De definitie van UWSI is “de fysieke, sociale en institutionele koppeling van (delen van) het stedelijk watersysteem met andere stedelijke systemen.”

Hoewel velen het erover eens zijn dat UWSI essentieel is om watersystemen voor te bereiden op de toekomst, blijkt het nog niet eenvoudig om UWSI in de praktijk succesvol uit te voeren. Het ontwerpen, aanleggen en beheren van integrale oplossingen is niet alleen een technisch-complexe, maar ook een sociaal-institutionele uitdaging. Zo vereist UWSI radicale veranderingen in organisaties en instituties, die maar moeilijk tot stand te brengen zijn. Organisaties die verantwoordelijk zijn voor stedelijk waterbeheer worden immers gekenmerkt door strikte richtlijnen, werkwijzen en procedures om de essentiële diensten die zij leveren te beschermen. Daarnaast kunnen UWSI-systemen niet alleen door waterprofessionals worden ontworpen, aangelegd en beheerd, maar is ook de inzet van andere stedelijke actoren zoals wegbeheerders, stedenbouwers en inwoners nodig. Dit vraagt om nieuwe vormen van samenwerking en afstemming tussen deze actoren. Bovendien kan elk van deze actoren totaal verschillende plan- en besluitvormingsprocessen, en verschillende institutionele structuren hebben, wat de besluitvorming over UWSI nog ingewikkelder maakt.

Het is duidelijk dat het ontwikkelen en uitvoeren van UWSI niet eenvoudig is. En hoewel algemeen wordt erkend dat de belemmeringen voor de implementatie van integratie van sociaal-institutionele aard zijn, is veelal door een technische bril naar het integratievraagstuk gekeken. Zo is bij het meeste onderzoek naar integratie gebruik gemaakt van technische methoden, en/of heeft men vooral gekeken naar de technologie voor integratie.

Dit proefschrift kijkt daarom vanuit een empirisch, sociaal-institutioneel perspectief naar UWSI, en onderzoekt de wijze waarop integratie in de praktijk wordt ontwikkeld en georganiseerd. Het doel van dit onderzoek is om een beter beeld te krijgen van de socio-institutionele processen die een rol spelen bij UWSI, en zo de verschuiving naar een integrale en duurzame aanpak in stedelijk waterbeheer te ondersteunen. In totaal zijn er vier deelonderzoeken gedaan, die elk vanuit een ander perspectief naar UWSI kijken. Samen geven zij een rijk beeld van de sociaal-institutionele processen die UWSI beïnvloeden. Op basis van deze vier perspectieven is de volgende onderzoeksvraag geformuleerd:

Hoe wordt integratie gedefinieerd, begrepen, uitgevoerd en georganiseerd in stedelijk waterbeheer?

Elk deelonderzoek richt zich op een van de vier onderdelen van de onderzoeksvraag en hanteert daarbij een andere benadering met een andere invalshoek. Een overzicht hiervan is te zien in Tabel S-1. Figuur S-1 geeft een visuele samenvatting van de vier deelonderzoeken en hun uitkomsten.

Tabel S-1. Overzicht van de vier deelonderzoeken in dit promotieonderzoek.

Deel-onderzoek	Hoofdstuk	Onderdeel van de onderzoeks-vraag	Perspectief op UWSI	Benadering van UWSI	Onderzoeks-methode
1	2	*gedefinieerd*	Theorie	Theoretisch concept	Interpretatieve literatuurstudie
2	3	*begrepen*	Praktijk	Perspectief van professionals	Q methode
3	4	*uitgevoerd*	Project	Hemelwater-voorzieningen	Veldonderzoek
4	5	*georganiseerd*	Organisatie	Innovatie	Casestudy

Opmerking. UWSI = Urban Water Systems Integration

Figuur S-1. Visuele samenvatting van de vier onderzoeken in dit proefschrift en hun resultaten.

Het eerste deel van **Hoofdstuk 2** richt zich op de *definitie* van integratie en introduceert het concept UWSI. Dit concept vormt de theoretische basis voor de rest van dit proefschrift. Aan de hand van een interpretatieve literatuurstudie zijn bestaande concepten voor een integrale aanpak in stedelijk waterbeheer geïdentificeerd en gestructureerd. Uit deze studie blijkt dat de stedelijk watermanagement literatuur veel verschillende concepten gericht op een integrale aanpak bevat. Elk van deze concepten heeft zijn eigen interpretatie van wat integratie is, en van de manier waarop men zou moeten omgaan met de complexiteit die erbij komt kijken. Wat opvalt aan de verschillende concepten is dat zij zich vaak beperken tot een bepaald onderdeel of thema in stedelijk waterbeheer. Bijvoorbeeld tot hemelwater, (de terugwinning van grondstoffen uit) afvalwater of waterinfrastructuur.

Het doel van de UWSI-conceptualisering is om tot een breder perspectief op integratie te komen – dus een die zich juist niet beperkt tot een bepaald deel of thema in de stedelijke watercyclus, zoals bij de meeste bestaande aanpakken van integratie. Er zijn vier typen van UWSI onderscheiden: geografische, fysieke, informatieve en projectmatige systeemintegratie.

- *Geografische UWSI* is gebaseerd op de ruimtelijke afstemming van verschillende stedelijke infrastructuursystemen. Het doel is dat zij elkaar niet tegenwerken met hun nabije ligging, maar juist rekening met elkaar houden.
- *Fysieke systeemintegratie* is de fysieke koppeling van twee of meer stedelijke systemen. De fysieke integratie kan zowel zijn gebaseerd op grondstoffen als op infrastructuren. Bij grondstoffen is het door het ene systeem gegenereerde of getransporteerde product nodig voor het functioneren van het andere. Bij integratie van infrastructuren maakt het ene infrastructuursysteem gebruik van het andere om zijn functie te vervullen.
- *Informatieve systeemintegratie* is gebaseerd op het combineren van gegevens van verschillende stedelijke systemen.
- *Projectmatige systeemintegratie* richt zich op samenwerking tussen verschillende stedelijke infrastructuren bij herstel- of constructiewerkzaamheden.

De UWSI typen zijn gebaseerd op de manier waarop verschillende systemen met elkaar verbonden zijn (respectievelijk via ruimte, grondstoffen, infrastructuren, gegevens of planning), en niet op subsystemen of deelstromen binnen de stedelijke watercyclus. De UWSI-typologie kan daardoor inzicht geven in de verschillende typen van integratie die naast elkaar voorkomen. Dit kan helpen onderlinge afhankelijkheden tussen deze typen, en mogelijke trade-offs die daarbij ontstaan, inzichtelijk te maken. Op die manier kan de UWSI-typologie de discussie over integratie, zowel in theorie als in de praktijk, structureren.

Het tweede deel van Hoofdstuk 2 richt zich op de consequenties van integrale systemen voor besluitvormers. Het identificeert de onzekerheden en uitdagingen die gepaard gaan met de verschuiving naar integrale oplossingen.

De resultaten van dit onderzoek laten zien dat een groot deel van de onzekerheid die met UWSI samenhangt is toe te schrijven aan (1) de *interfaces* tussen de gekoppelde systemen, d.w.z. de raakvlakken die ontstaan tussen voorheen niet gekoppelde systemen, en (2) de *multi-actor complexiteit*, d.w.z. de acties van andere actoren en de instituties die deze acties beïnvloeden. Deze bevindingen pleiten ervoor dat deze *sociale* en *institutionele interface onzekerheden* zorgvuldige aandacht behoeven bij de ontwikkeling van UWSI-oplossingen.

Hoofdstuk 3 bekijkt UWSI vanuit het perspectief van stedelijk waterprofessionals, en richt zich op de vraag hoe UWSI wordt begrepen door deze professionals. Met behulp van de Q-methode zijn vier verschillende perspectieven van Nederlandse stedelijk waterprofessionals op de rol van integratie in toekomstige stedelijk watersystemen geïdentificeerd. Deze laten zien dat integratie op veel verschillende manieren wordt geïnterpreteerd, maar dat er ook veel overeenkomsten zijn tussen de perspectieven. Hoewel de perspectieven verschillen wat betreft de kansen en uitdagingen waarop men zich zou moeten richten, erkennen ze allemaal dat de traditionele aanpak in stedelijk waterbeheer zou moeten veranderen om systemen voor te bereiden op de toekomst.

Om de perspectieven te verkennen en identificeren, zijn in totaal 30 waterprofessionals gevraagd om een set van 43 stellingen te sorteren in een tabel die de vorm heeft van een normale verdeling. De stellingen gingen allemaal over de rol van integratie voor toekomstige stedelijke watersystemen. Achteraf zijn de deelnemers geïnterviewd om een beter inzicht te krijgen in de wijze waarop zij hun beslissingen hebben genomen - en dus in hun perspectieven. Met behulp van factoranalyse zijn de individuele perspectieven vervolgens gegroepeerd in gedeelde perspectieven.

Voor perspectief 1 (*Toekomstbestendigheid door coördinatie: ruimte vinden voor stedelijke uitdagingen)* gaat integratie over de samenwerking tussen partijen in de stad om zo de vele uitdagingen, die op steden afkomen, te coördineren. In perspectief 2 (*Toekomstbestendigheid door klimaatadaptatie: leefbare steden creëren*) verwijst integratie naar klimaatadaptatie, waarbij adaptatiemaatregelen ook als de sleutel worden gezien om de sociale omstandigheden en ecologische kwaliteit in steden te verbeteren. Voor perspectief 3 (*Toekomstbestendigheid door terugwinning van grondstoffen: institutionele structuren uitdagen*) draait integratie om de terugwinning van grondstoffen, waarbij een belangrijke rol wordt gezien voor (nieuwe) samenwerkingsverbanden. In perspectief 4 (*Toekomstbestendigheid door efficiëntie: controle hebben*) verwijst integratie naar het efficiënt beheren van de ondergrond door goed inzicht te hebben in het systeem.

Uit de resultaten blijkt dat de perspectieven verschillende opvattingen hebben over integratie in toekomstige stedelijke watersystemen: zij zien verschillende drijfveren voor integratie en richten zich op verschillende ruimtelijke schalen. Toch zijn ze niet noodzakelijkerwijs tegenstrijdig; dat wil zeggen dat het ene perspectief het andere uitsluit. Inzicht in de overeenkomsten en verschillen tussen de perspectieven is nuttig om de discussie over integratie te structureren, maar ook om effectieve strategieën op te stellen die recht doen aan de verschillen die er zijn. Zo geven de vier perspectieven inzicht in met welke verschillende ruimtelijke schalen en motieven voor integratie rekening moet worden gehouden.

Hoofdstuk 4 kijkt naar de uitvoering van UWSI, en richt zich op ervaringen met een specifiek soort UWSI-systemen, namelijk Sustainable Urban Drainage Systems (SUDS), wat in het Nederlands vertaald kan worden als "nieuwe typen hemelwatersystemen." Op basis van locatiebezoeken en interviews met stedelijk water experts van elke gemeente zijn technische faalmechanismen van SUDS in kaart gebracht. Daarna zijn de onderliggende oorzaken van deze faalmechanismen geïdentificeerd.

De resultaten laten zien dat het falen van SUDS vaak te wijten is aan sociaal-institutionele aspecten, zoals slechte communicatie tussen actoren (van verschillende disciplines en/of fasen), en traditionele, ingesleten praktijken die integrale oplossingen niet ondersteunen. Dit toont aan dat niet alleen in de eerste fasen van het ontwikkelingsproces (d.w.z. de beleids- en ontwerpfase) aandacht moet worden besteed aan integratie, maar ook in latere fasen van het ontwikkelingsproces (d.w.z. de constructie- en beheerfase).

Voor het soort faalmechanismen maakt het onderzoek onderscheid tussen drie soorten SUDS op basis van hun (primaire) hydraulische functie: oppervlakkige afvoer, infiltratie en berging. Voor infiltratievoorzieningen is het *dichtslibben van systemen* het vaakst waargenomen faalmechanisme. Voor SUDS die gebruik maken van oppervlakkige afvoer is het functioneren het vaakst belemmerd door *obstakels* op het perceel of op de weg, en bij bergingsvoorzieningen is het falen het vaakst te wijten aan een *beperking in peilvariatie* en *obstakels* in de bergingsvoorziening.

Als wordt gekeken naar zowel de locaties waar het falen optreedt, als de onderliggende oorzaken van dit falen, blijken de systeemgrenzen tussen het watersysteem en andere stedelijke infrastructuren een belangrijke rol te spelen. Deze systeemgrenzen worden ook wel interfaces genoemd in dit proefschrift. Dit zijn de plekken waar het stedelijk watersysteem wordt verbonden met andere stedelijke infrastructuren, zoals de overgangsgebieden tussen wegen en groenvoorzieningen. Bijna 40% van de faalmechanismen doen zich voor op zulke interfaces. De oorzaken van deze faalmechanismen houden vaak verband met menselijke factoren. Interfaces vragen zorgvuldige aandacht in de verschillende fasen van het ontwikkelingsproces.

De geïdentificeerde faalmechanismen en oorzaken bieden een eerste inzicht in de socio-institutionele veranderingen die nodig zijn om UWSI-systemen te ondersteunen. Dit kunnen bijvoorbeeld veranderingen in routines, beleid en richtlijnen zijn, die nog altijd voornamelijk gericht zijn op traditionele systemen.

Hoofdstuk 5 richt zich op de organisatie van UWSI. Aan de hand van casestudyonderzoek analyseert dit hoofdstuk initiatieven tot UWSI-innovaties in Amsterdam en Rotterdam. De ontwikkeling en implementatie van dergelijke innovaties is een uitdaging door de operationele en sectorale mindset van organisaties waarin deze initiatieven zijn georganiseerd. In dit casestudyonderzoek is een bureaustudie gecombineerd met interviews, waarbij gekeken is naar de soorten initiatieven en de mechanismen die een rol spelen bij het omgaan met de spanning tussen innovatie en operatie.

Het concept ambidexteriteit (*ambidexterity)* staat centraal in het onderzoek. De essentie van ambidexteriteit in dit onderzoek is dat organisaties zowel operationele als innovatie activiteiten nodig hebben om succesvol te zijn. Eén manier om deze ambidexteriteit tot stand te brengen is door deze activiteiten gescheiden te organiseren (*structurele ambidexteriteit*), waarbij een deel van de organisatie zich richt op innovatie, en een ander deel op operatie. Zulke duale structuren komen ook voor in Amsterdam en Rotterdam: de initiatieven richten zich op UWSI-innovaties, en de lijnorganisatie richt zich op het dagelijks beheer van systemen. Ondanks de structurele scheiding van innovatie en operationele activiteiten, laten de resultaten ook sterke verbindingen zien tussen de twee typen activiteiten. Netwerken spelen hierin een belangrijke rol. Netwerken maken het makkelijker om over conventionele grenzen van disciplines en organisaties heen te werken – wat vrijwel altijd nodig is voor UWSI-innovaties. Ook helpen netwerken om het gedachtegoed over integratie en de bijbehorende kennis en vaardigheden te verspreiden.

Aan de hand van de 16 UWSI-initiatieven die in de studie zijn onderzocht, zijn vier typen initiatieven onderscheiden: programma's, bewegingen, samenwerkingsverbanden en lijngebaseerde initiatieven (d.w.z. initiatieven verbonden aan de lijnorganisatie). De vier typen initiatieven hebben verschillende eigenschappen: ze worden gekenmerkt door een verschillende aanpak, organisatie en rol voor hiërarchie. Voor het omgaan met de spanning tussen innovatie en operationele activiteiten, zijn vier mechanismen onderscheiden: netwerkmechanismen, hiërarchische mechanismen, procesmechanismen en HR-mechanismen.

Netwerkmechanismen domineren de verbinding tussen de innovatie en operatie. Zij spelen een belangrijke rol gedurende het gehele innovatieproces, zowel bij de ontwikkeling van UWSI-innovaties als bij de realisatie ervan. Zo maken netwerken het mogelijk innovatie activiteiten te scheiden van operationele activiteiten, en ze tegelijkertijd nauw met elkaar te verbinden tijdens het innovatieproces. Deze empirische bevinding verschilt van de literatuur over ambidexteriteit, die een beeld schetst van twee gescheiden werelden (d.w.z., de wereld van dagelijks beheer versus de wereld van innovatie) die verbonden zijn in de top van de organisatie. De resultaten wijzen niettemin nog steeds op een belangrijke rol voor leidinggevenden: zij kunnen innovatie zowel stimuleren als formaliseren.

Deze studie bevat relevante inzichten voor andere steden die worstelen met de ontwikkeling en uitvoering van UWSI-innovaties in hun operationeel-georiënteerde organisaties. De vier typen mechanismen geven een eerste idee van hoe met de spanning tussen innovatie en operatie om kan worden gegaan.

Hoofdstuk 6 presenteert de algemene conclusies en de discussie van dit proefschrift. De conclusies worden samengevat in vier kernobservaties, gevolgd door een reflectie op elk daarvan:

1. *UWSI wordt op veel verschillende manieren gedefinieerd en begrepen, waardoor een onderhandelde visie op integratie nodig is*

De resultaten van dit proefschrift laten zien dat UWSI een ambigu concept is, omdat integratie vaak verschillend wordt *gedefinieerd* en *begrepen*. Niet alleen tussen verschillende stedelijke domeinen, maar ook binnen het stedelijk waterdomein hebben actoren verschillende ideeën over (de noodzaak van) systeemintegratie. De betrokken actoren zullen daarom moeten onderhandelen over wat men onder integratie verstaat. Dit vraagt om betrokken actoren samen te brengen, een proces van interactie tussen hen te organiseren en hen samen te laten beslissen hoe integratie moet worden gedefinieerd en geoperationaliseerd.

De discussie gaat dieper in op wat de ambiguïteit die gepaard gaat met UWSI betekent voor het besluitvormingsproces. Hoewel ambiguïteit enerzijds een belangrijke aanjager van het proces van interactie zou kunnen zijn doordat zij ruimte laat voor individuele belangen en drijfveren, zou zij anderzijds ook de uitvoering van UWSI kunnen belemmeren doordat mensen langs elkaar heen praten. Een proces van interactie kan in dit opzicht een balancerende rol spelen: zo zou de ambiguïteit in eerdere stadia van de besluitvorming als drijvende kracht voor een dergelijk proces kunnen fungeren, terwijl in een later stadium het proces nodig is om door onderhandeling diezelfde ambiguïteit te verminderen.

2. *Op papier is duurzaamheid de voornaamste drijfveer voor UWSI, maar in de praktijk spelen vele andere factoren een rol*

Hoewel in de literatuur over stedelijk watermanagement en in beleidsdocumenten duurzaamheid vaak wordt gepresenteerd als de belangrijkste drijfveer voor integratie, blijkt uit de empirische resultaten van dit proefschrift dat duurzaamheid niet altijd een centrale rol speelt in de besluitvorming over integratie. In de praktijk blijken vaak ook andere waarden zoals beheerbaarheid of esthetiek bepalend te zijn in de besluitvorming. Samen met duurzaamheid, maken deze waarden deel uit van het proces van interactie dat nodig is om tot een onderhandelde definitie en aanpak tot integratie te komen.

De discussiesectie reflecteert op wat dit proces zou kunnen betekenen voor de uiteindelijke mate van duurzaamheid van UWSI-innovaties. Want hoewel het opnemen van andere waarden ertoe kan leiden dat de uiteindelijke oplossing minder duurzaam wordt, kan het ook de mate van duurzaamheid ten goede komen doordat het draagvlak voor een oplossing toeneemt. Aangezien draagvlak en uitvoerbaarheid essentieel zijn voor de implementatie van duurzaamheid, kan het opnemen van andere waarden dus gunstig zijn voor het bereiken van duurzaamheid.

3. *In de praktijk wordt UWSI vaak benaderd als een ontwerpuitdaging – en niet als een continu proces waarbij coördinatie tussen fasen essentieel is*

Integratie van stedelijke watersystemen wordt doorgaans gezien als een uitdaging die in de eerste fasen van het ontwikkelingsproces kan worden aangepakt, d.w.z. door een sectoroverstijgende aanpak in de beleids- en ontwerpfase. De empirische resultaten van dit proefschrift laten echter zien dat niet alleen de verbinding tussen sectoren essentieel is voor goed functionerende UWSI-systemen (d.w.z. om faalmechanismen te voorkomen), maar ook de afstemming en samenwerking tussen de verschillende fasen van het ontwikkelingsproces. Als deze afstemming niet op orde is, kan integratie, ondanks een zorgvuldig geïntegreerd ontwerp, het onderspit delven in latere fasen, zoals die van uitvoering en beheer. Systeemintegratie blijft dus tijdens de gehele levensduur van de infrastructuur een uitdaging – en is niet sectoroverstijgende ontwerpprobleem dat kan worden opgelost in de ontwerpfase.

In de discussie wordt gereflecteerd op dit punt en worden enkele opties gegeven om de verschillende fasen van de ontwikkelingscyclus beter op elkaar af te stemmen. Zo zouden (inzichten van) beheerders beter mee kunnen worden genomen in het ontwerpproces, of zou men beheerders meer bewust kunnen maken van de waarden die in de beleidsfase een rol spelen.

4. *Hoewel UWSI doorgaans wordt beschouwd als een inspanning waarvoor een geplande aanpak nodig is, blijken ook emergente veranderingen van cruciaal belang*

Vaak wordt gedacht dat systeemintegratie een top-down en geplande aanpak vereist. Dit komt door de omvangrijke en radicale veranderingen die systeemintegratie voor organisaties en instituties met zich meebrengt. De empirische resultaten van dit proefschrift laten echter zien dat systeemintegratie niet alleen op een geplande manier tot stand komt, maar ook het resultaat is van ongeplande, opeenvolgende veranderingen.

Wat betekent deze emergentie voor de planning van UWSI? Er wordt vaak gedacht dat emergentie in strijd is met planning, maar het kan ook complementair zijn. Waar top-down initiatieven leidinggevenden in staat stellen om te sturen op systeemintegratie, kunnen bottom-up initiatieven helpen om draagvlak te creëren voor systeemintegratie lager in de organisatie. Op die manier kunnen zulke initiatieven bijdragen aan de actiebereidheid van betrokkenen en kan het helpen om tot nieuwe ideeën te komen. Beide processen zijn nodig om tot gedragen, integrale oplossingen te komen.

Table of Contents

Chapter 1

Introduction

Global developments like climate change, population growth, and urbanization put increasing pressure on urban water systems, seriously threatening the livability of cities. In developed countries, urban water systems typically consist of centralized water supply systems, sewer networks, and large-scale water treatment facilities. Providing essential services like water supply, sanitation, and flood protection, these systems lie at the heart of cities' public health, well-being, and economy. The limits of traditional urban water systems, however, are increasingly coming to light. A growing body of literature has criticized traditional urban water systems for their limited capacity to respond to emerging urban water challenges (Ferguson et al., 2013a; Kiparsky et al., 2013; Rijke et al., 2008).

Rather than the sectoral approach that characterizes traditional practices, an integrated, cross-sectoral approach has been proposed to meet these challenges. Both in theory and in practice, it is widely acknowledged that such an integrated approach is essential to prepare urban water systems for the future. Integrated solutions are more resilient to the consequences of climate change, allow for the recovery of resources from wastewater, and provide broader social and environmental benefits.

Despite the numerous benefits of integration on paper, however, reality is stubborn: after waiting for many years, the Dutch Environmental and Planning Act – which aims to facilitate integrated spatial planning – has, at the time of writing, still not come into effect; aquathermal projects barely get off the ground due to a lack of clarity on the governance related to them; sewer replacement projects turn out to be difficult to combine with the construction of district heating networks, as they take much longer than expected; and while an increasing number of resources can be recovered from wastewater, there seems to be hardly any market for them.

This illustrates that there is a significant gap between theory and practice, as well as between the technology of integration and its organization: although the advantages of integrated solutions are evident, their implementation seems challenging. This thesis addresses this knowledge gap by taking an empirical, social science perspective on integrated solutions for urban water systems.

In this introduction, the rationale for this research is discussed. First, the relevance of integration to anticipate emerging developments is pointed out, and then the socio-institutional challenges of integration are outlined. Next, the scientific knowledge gap that this thesis aims to fill, as well as its research questions and approach, are presented. The final section gives the outline of this thesis.

1.1 Emerging urban water challenges and the need for integration

Developments like climate change and urbanization put increasing pressure on urban water systems and challenge organizations responsible for urban water management to maintain expected service levels. Conventional water management solutions appear limited in their ability to do so, as well as to meet new objectives such as regarding sustainability and environmental quality. On the one hand, urban water systems are thus seriously threatened by emerging developments, and on the other hand, they face sustainability challenges to which they have limited capacity to respond.

First, climate change threatens the performance of traditional urban water systems. Being designed to operate under normal weather conditions, traditional urban water systems have a limited capacity to deal with extreme weather events (Ashley et al., 2005). Developments like urbanization and the associated increase of impervious surfaces further exacerbate this situation by making cities more vulnerable to these weather extremes (Kleidorfer et al., 2014). Impermeable areas change the response to rainfall, leading to higher peak flows and reduced groundwater recharge. Over the last decades, several cities around the globe have suffered from heavy storms, leading to severe damage, such as in Copenhagen in 2011 (Garne et al., 2014) and Beijing in 2012 (Wang et al. 2013). Furthermore, cities worldwide have faced increasing drought and heat issues (e.g. Engel et al., 2011; X. Zhang et al., 2019). It is expected that in 2050, one third to nearly half of the global population will face water scarcity, seriously threatening human life, nature, and livability (He et al., 2021).

Second, traditional urban water infrastructure leads to environmental degradation (Chocat et al., 2007; Owolabi et al., 2022), which is further exacerbated by the consequences of climate change, i.e., rising temperatures and heavy rainfall. In addition, emerging compounds in wastewater and aquatic environments are a new concern (Parida et al., 2021): surface runoff and (industrial) effluent contain pollutants, like PFAS and pharmaceuticals, that can be harmful to animals and humans.

Third, traditional urban water systems have a limited ability to contribute to the wider sustainability agenda, such as net-zero greenhouse gas emissions, and a fully circular economy in 2050 (EU Commission, 2020; Fetting, 2020). Traditional treatment processes have a high net energy consumption (He et al., 2015), while a significant amount of chemical and thermal energy remains untapped (Hao et al., 2019). In addition, wastewater contains other valuable resources such as nutrients and water that are often not recovered. Urban water systems thus rely on linear economic models with a “take-make-consume-dispose” strategy (Ramírez-Agudelo et al., 2021), that do not fit circularity ambitions (EU Commission, 2020).

Clearly, traditional urban water systems need change to prepare them for the future. A large number of studies have called for a more sustainable approach to urban water management, paying more attention to the urban context in which the water system is embedded and exploiting potential interconnections with other urban systems (Chocat and Schilling, 2001; Fratini et al., 2012; Geldof, 1995; Harremoës, 2002; Mo and Zhang, 2013; Rijke et al., 2008; Tscheikner-Gratl et al., 2016a; P. Zhang et al., 2019). Various integrated principles and solutions have been developed, such as those focusing on storm water management and resource recovery from (waste)water:

- Storm water solutions have been designed that are integrated in the urban design, serving as an alternative to underground networks of pipes. Such integrated storm water solutions often deliver benefits beyond drainage alone. Relying on principles such as infiltration and storage, they typically contribute to other values such as ecology, esthetics and recreation (e.g. Ashley et al., 2013; Cohen-Shacham et al., 2016; Wong and Brown, 2009).

- Treatment plants have been designed that recover chemical energy, nutrients, and water (Mo and Zhang, 2013). In the Netherlands, for example, wastewater plants have been transformed into "energy and resource factories" that recover energy, cellulose, bioplastics, phosphate, alginate-like exopolymers and biomass (van Leeuwen et al., 2018). In addition, urban water in the form of wastewater, drinking water, ground water and surface water contains thermal energy that could be recovered (Elías-Maxil et al., 2014; van der Hoek et al., 2018). Combined with district heating networks, this thermal energy could be used both for heating and for cooling purposes (Đurđević et al., 2019).

These examples illustrate that urban water solutions that anticipate sustainability challenges are typically integrated, cross-sectoral solutions: they transcend the boundaries of traditional urban water systems, and extend to other urban infrastructures like streets, parks, and energy infrastructures. In this thesis, the concept of Urban Water Systems Integration (UWSI) is used to refer to such cross-sectoral urban water solutions. Urban Water Systems Integration is defined as "the physical, social, and institutional interlinking of (parts of) the urban water system with other urban systems." In Chapter 2 the concept of UWSI is further introduced.

Despite the broadly shared view that UWSI is key to prepare urban water systems for the future, developing and implementing UWSI has proved challenging (e.g. Dhakal and Chevalier, 2017; Koop et al., 2017; Qiao et al., 2018; Roy et al., 2008; van de Meene et al., 2011). Rather than being designed, built, and operated by water engineers solely, UWSI innovations need the involvement of other urban actors, such as urban planners, road authorities, utility companies and citizens. This means that UWSI requires new forms of collaborations and coordination between these actors, which challenges the implementation and organization of UWSI innovations.

1.2 Why is it so difficult? Socio-institutional challenges of UWSI

At least three factors challenge the implementation and organization of UWSI innovations: the multi-actor complexity that is inherent to UWSI, traditional processes and structures that are oriented toward sectoral solutions, and the dependency on other sectors that UWSI involves.

First, the multi-actor complexity that comes with integrated solutions challenges their implementation (Fratini et al., 2012). Compared with traditional solutions, integrated solutions inevitably involve more actors, such as urban planners, road authorities and energy infrastructure planners. These actors have different interests and agendas, and they work from different institutional backgrounds (van Broekhoven and Vernay, 2018). This could hinder communication, and make interactions as well as decision-making more difficult (Klijn and Koppenjan, 2004).

Second, integrated solutions need to be incorporated into existing systems; into the physical networks, but also into the organizations. The departmental silos that characterize these organizations, however, are typically oriented toward sectoral solutions. This means that, to support the development and implementation of integrated solutions, guidelines and procedures that are deeply embedded in the organizations need to be adapted (van Broekhoven and Vernay, 2018). Making such changes in sectors such as the urban water sector, however, is challenging, given the low tolerance for failure and the fact that traditional strict processes and procedures have been instrumental to the safe and reliable urban water services of today (Farrelly and Brown, 2011; Marlow et al., 2013). Current organizational processes and structures thus form a socio-institutional challenge to the development and implementation of UWSI innovations.

Third, initiatives around integrated solutions do not only emerge within the urban water sector, but also in other sectors. The actions taken in those sectors will be taken from the perspective of those sectors. This challenges a planned approach to UWSI, as the moment at which these initiatives arise, as well as their aim and scope are hard to predict by urban water managers. Nonetheless, the initiatives developed in those other sectors could have implications for processes and procedures of the urban water sector (Hoang and Fenner, 2016). Compared to traditional solutions, sectors can thus operate less autonomously as their performance become highly dependent on that of other sectors. This makes the process to develop and implement integration unpredictable and challenging.

These factors demonstrate why developing and organizing UWSI is not an easy matter. Nonetheless, an integrated approach is widely recognized as an important means to address sustainability challenges. There is thus a clear tension between the need for UWSI on the one hand, and the complexity of implementing and organizing it in practice, on the other. This field of tension forms the starting point of this research. In the next section, I relate this practical challenge to the urban water literature on integration, identifying the scientific knowledge gap that this thesis aims to fill.

1.3 Scientific knowledge gap: a social-science, empirical perspective on UWSI

Over the last decades, integration has received increasing attention in the urban water literature. Such as outlined in Section 1.1, a multitude of integrated approaches to urban water management has been developed in response to sustainability challenges like climate change and resource limitations – challenges that traditional, sectoral solutions have only a limited ability to deal with. Without going into detail on the urban water literature here (see Chapter 2 for this), I argue that much of these studies focus mainly on the technology for integrated solutions and/or are based on engineering methods. For example, they focus on technologies for resource recovery from wastewater (e.g. Deng et al., 2021), use hydrodynamic models to determine the impact of integrated storm water solutions (e.g. Mikovits et al., 2017), evaluate the in-situ performance of such systems (e.g. Boogaard et al., 2014), or look at the energy recovery potential of wastewater (e.g. Hao et al., 2019).

As I have argued, however, not only the technology, but also the governance that comes with UWSI challenges the development and implementation of integration. Since integration requires new forms of collaboration and organization, it is essential to look at UWSI from a socio-institutional perspective. After all, technological innovations cannot succeed without adapting organizations and institutions to these innovations (Kiparsky et al., 2013). And while various studies have indicated that barriers to the implementation of integration are typically related to the governance of urban water systems (Brown et al., 2017; Dhakal and Chevalier, 2017; Roy et al., 2008), little research is done that has investigated how integration comes about in practice – thus looking at how it is developed and organized on the ground.

Clearly, an empirical, social-science perspective on UWSI, which looks at integration from different angles, is needed to fill this knowledge gap. I see four research opportunities that, together, could provide a rich picture of the socio-institutional processes that come with the shift to integrated solutions:

- First, a better understanding of how integration is defined is needed. In the urban water literature, a wide diversity of approaches to integration has been developed, demonstrating that there is no shared definition of integration. This could hinder the discussion on UWSI and trouble knowledge exchange between different bodies of literature on integration. To structure this discussion and take the urban water literature on integration to the next level, research is needed to investigate what is meant by UWSI.

- Second, the diversity in viewpoints on integration in the literature suggests that in practice, too, urban water practitioners understand (the need for) systems integration differently. For example, differences in knowledge, values or interests could result in different views on what integration is and why it is needed. Clearly, an empirical approach is needed to explore and identify these practitioner's perspectives. This is valuable, as it could support practitioners in the discussion on integration, and in creating strategies that accommodate these differences.
  Furthermore, an empirical exploration of these perspectives would add to the literature on systems integration: in the field of urban water management research, but also in related fields such as that of industrial ecology (see van Broekhoven and Vernay, 2018) or sustainability transition research (e.g. Brown et al., 2009; de Haan et al., 2015; Ferguson et al., 2013b), integrated approaches are typically centered around sustainability. More specifically, the studies advocate for a change towards more sustainable urban systems and see integration as the way to achieve this. It can be questioned, however, whether this could be taken for granted; i.e., whether sustainability is always the central driver of integration, given the urban complexity and the multitude of urban challenges that water managers are facing. There may be other drivers for UWSI, such as space limitations or financial constraints, that might be more important for practitioners in their considerations. An empirical approach could help identifying the different drivers for integration and investigate the role of sustainability in that.

- Third, to better understand the socio-institutional processes involved in systems integration, insights are needed into how UWSI has been operationalized in practice. It is to be expected that the different views that practitioners have on integration, affect how systems have been implemented and used. Furthermore, since UWSI involves innovations, i.e., novel technologies and configurations, it is likely that organizations and institutions have not yet been adapted to these new technologies, and that this leads to new failures. Insight into these failures and the role that socio-institutional factors play in them, helps to anticipate these failures, e.g., learning about routines, policies and guidelines that need change. To the best of my knowledge, no such an analysis has been done before.

- Fourth, to gain a richer understanding of the socio-institutional processes involved in systems integration not only the operationalization of UWSI needs to be investigated, but also its organization. Getting insights into this organization is particularly interesting, as, despite the clear need for UWSI, realizing the shift to integrated practices seems to be difficult such as highlighted in Section 1.2: organizations responsible for urban water management are challenged to manage the tension between, on the one hand, the need for socio-institutional innovation, and on the other hand the focus on operational processes to guarantee the provision of safe and available water services. An empirical approach that looks at ongoing UWSI initiatives could provide insights into how organizations responsible for urban water management deal with this tension.

To summarize, there are four important knowledge gaps with respect to UWSI: how integration for urban water systems is *defined*, *understood*, *operationalized,* and *organized*. This thesis addresses these four gaps, with the aim of getting a better understanding of the socio-institutional processes involved in UWSI, and thereby supporting the transition to more integrated urban water management practices.

1.4 Research questions and approach

Based on the knowledge gaps identified in Section 1.3, the following main research question is formulated:

How is integration defined, understood, operationalized, and organized in urban water management?

To answer this question, this thesis presents four studies that each look at UWSI from a different perspective, examining how UWSI is defined, understood, operationalized, and organized, respectively (see Table 1-1 for an overview of the perspectives and the corresponding chapters).

Since I am particularly interested in how UWSI comes about in reality, a predominantly empirical approach is used. Only for the first study (Chapter 2) a literature-based, conceptual approach is adopted. This is done as the urban water literature lacks a clear and coherent definition of integration. For this reason, I first want to clarify what is meant by integration and arrive at a conceptualization of UWSI. The other studies (presented in the Chapters 3, 4 and 5) use an empirical approach, focusing on practitioners' perspectives, UWSI projects and organizations, respectively. For each study, one or two sub-questions are formulated that, together, help me to answer the main research question.

Table 1-1. Overview of the studies and chapters in this thesis.

Study	Chapter	Part of research question addressed	Perspective on UWSI	Looking at UWSI as…	Research Method
1	2	*Defined*	Theoretical	Theoretical concept	Interpretive review
2	3	*Understood*	Practitioner's	Practitioner's perspective	Q methodology
3	4	*Operationalized*	Project	Implemented SUDS	Field study
4	5	*Organized*	Organizational	Innovation	Case study

Note. SUDS = Sustainable Urban Drainage Systems
UWSI = Urban Water Systems Integration

Below, the approaches and sub-questions that guided these studies are presented:

I. The first study takes a conceptual perspective on UWSI, thereby drawing on the urban water literature. The aim is to get a better understanding of the different definitions of integration in the literature. Existing approaches to integration in the urban water literature are defined and synthesized, and their implications for decision-makers are explored. This results in the concept of UWSI. The following two sub-questions are asked to focus the study:

   1. *How can the different approaches to integration in the urban water literature, i.e., Urban Water Systems Integration (UWSI), be conceptualized?*

   2. *What uncertainties and decision-making challenges are introduced by UWSI?*

II. Subsequently, the second study looks at UWSI from an empirical perspective: it focuses on urban water practitioners and their understandings of an integrated approach. Using Q methodology, the aim is to identify different perspectives that Dutch urban water practitioners have on the role of integration for future urban water systems. The following sub-question is central to the study:

   3. *What perspectives do Dutch urban water management practitioners have on integration for future urban water systems?*

III. The third study focuses on the operationalization of UWSI, looking at specific cases of implemented integrated storm water solutions (Sustainable Urban

Drainage Systems, also referred to as SUDS). Using site visits, the aim is to get a better understanding of the failures occurring in integrated systems in practice and the role of socio-institutional factors therein. The following sub-question is addressed:

4. *What, where and wherefore do technical failures occur in UWSI, more specifically, failures in implemented SUDS?*

IV. Lastly, the fourth study focuses on how UWSI is organized and is based on case study research. Looking at UWSI as an innovation that is developed through initiatives such as programs and movements to UWSI, the following sub-question is addressed:

5. *How do urban water management organizations manage the tension between innovation (i.e., UWSI initiatives) and operation (i.e., day-to-day activities undertaken by the line organization)?*

A visual summary of the four studies in this thesis, the methods used, and the outcomes is presented in Figure 1-1.

1.5 Thesis outline

Figure 1-2 provides an overview of the four perspectives that this thesis takes on UWSI (presented in the chapters 2 to 5) and how these are connected.

Chapter 2 introduces the concept of UWSI and thereby provides the theoretical basis for the rest of this thesis. Based on the urban water literature, it conceptualizes

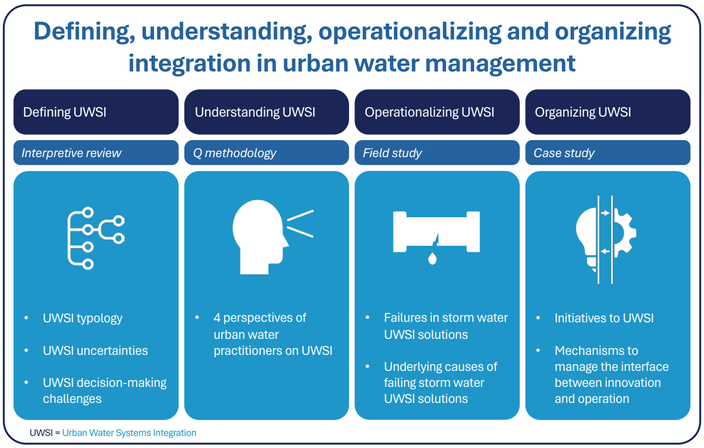

Figure 1-1. Visual summary of the four studies conducted in this thesis and their outcomes.

integrated approaches to urban water management into four types of Urban Water Systems Integration. Chapter 2 also explores the implications that such integrated solutions bring for decision-makers, identifying the uncertainties and challenges specific to UWSI. Chapter 3, 4 and 5 subsequently build on the findings presented in Chapter 2, focusing on empirical cases of UWSI.

Chapter 3 looks at UWSI from the perspective of practitioners, focusing on the diversity in understandings of UWSI in practice. Using Q methodology, different perspectives that Dutch urban water practitioners have on the role of integration for future urban water systems are explored and identified.

Chapter 4 focuses on experiences with a specific case of UWSI, namely implemented Sustainable Urban Drainage Systems (SUDS). Using site visits, the technical failures that have occurred in these systems and their underlying root causes are identified.

Chapter 5 focuses on the organization of UWSI. Using a case study research approach, this chapter analyzes initiatives around integration in the cities of Amsterdam and Rotterdam. It com nsiders UWSI as innovation and looks at how UWSI is developed and implemented in an established organization.

Finally, **Chapter 6** presents and discusses the conclusions of this thesis, including the recommendations for further research.

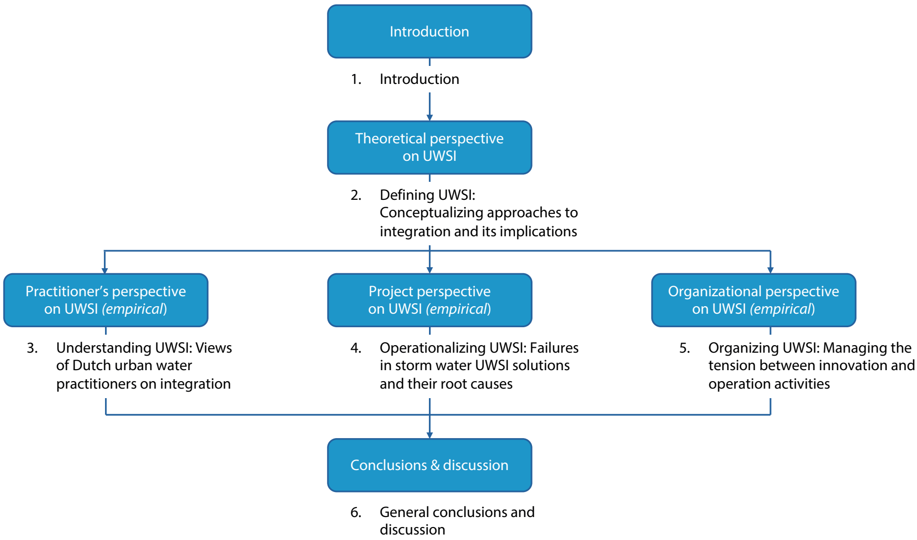

Figure 1-2. Structure of this thesis.

Chapter 2

Defining UWSI: Conceptualizing approaches to integration and its implications[1]

[1] This chapter is based on: Nieuwenhuis, E., Cuppen, E., Langeveld, J., & de Bruijn, H. (2021). Towards the integrated management of urban water systems: Conceptualizing integration and its uncertainties. Journal of Cleaner Production, 280, 124977.

2.1 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 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., 2019a) 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., 2019a). 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 chapter 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 study 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 chapter, we have used an interpretive 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 study 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 2.2, in Section 2.3 we go on to develop our typology of Urban Water Systems Integration. In Section 2.4 we discuss the uncertainties involved in systems integration and their implications for decision-making. Section 2.5 presents our conclusions and recommendations for research to foster further realization of systems integration.

2.2 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.

2.2.1 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, esthetics, 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).[2] 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 one meter 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 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).

2.2.2 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

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

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 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).[3]

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,[4] and is expected to meet more than half of the city state’s water demand in the future (Lee and Tan, 2016).

2.2.3 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., 2016b). 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).

[3] 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.

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

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).

2.2.4 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.

2.2.5 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) (2000/60/EC), 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).

2.2.6 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 2-1 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 2-1 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 2-1). 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 2-1). 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 2.2.1), but also needs to consider the integration of rehabilitation management (Section 2.2.3). Moreover, the local processing of storm water relates to the possibilities for resource recovery from wastewater (Section 2.2.2), as well as influencing the receiving water quality; for example, by bringing microplastics (Bollmann et al., 2019) into the environment (see Section 2.2.4).

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

Table 2-1. 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.

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 2.2.2), 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 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.

2.3 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 2.2). 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.

2.3.1 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."[5] To conceptualize the urban water approaches to integration (see Section 2.2) 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 2-1). 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 2-2).[6]

For each of these types, we briefly describe their objects of integration and their link to the existing approaches to integration (see Table 2-1). 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 2.2.1 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,

[5] 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.

[6] 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.

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 2.2.4). 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-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 2.2.2).

    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 cab(Langeveld et al., 2013). 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 2.2); however, the examples we have provided here do show some overlap with the integrated approach to asset management (Section 2.2.3) and with integrated storm water management (Section 2.2.1).

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 2.2.5). 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 2.2.3). 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

Table 2-2. Characteristic 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).

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.

2.4 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.

2.4.1 Exploring systems integration uncertainty

If we look at the four types of systems integration (Table 2-2), 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[7] 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 2-3). 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.

[7] 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 behaviour, and normative uncertainty to values and norms.

Table 2-3. 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.	

2.4.2 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 chapter, we have identified the following challenges that urban water professionals face when anticipating the future.

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 2-3), 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).

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.

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 2.4.1 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.

2.5 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 chapter 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 chapter 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 2.4.2) 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.

Chapter 3

Understanding UWSI: Views of Dutch urban water practitioners on integration[8]

[8] This chapter is based on: Nieuwenhuis, E., Cuppen, E., & Langeveld, J. (2022). The role of integration for future urban water systems: Identifying Dutch urban water practitioners' perspectives using Q methodology. Cities, 126, 103659.

3.1 Introduction

Urban water systems worldwide are seriously threatened by climate change, population growth and urbanization: changing weather patterns, increasing anthropogenic activities and more impervious surfaces lead to degradation of environmental quality and increased risk of urban flooding. In addition, existing urban water infrastructure is deteriorating, and resource limitations and tightening regulations further challenge urban water management (Butler et al., 2016). The ongoing changes put pressure on service levels for urban water systems. To prepare these systems for the future, the traditional urban water paradigm requires a shift (Brown and Farrelly, 2009; Pahl-Wostl et al., 2011).

Traditionally, urban water management has focused on providing safe, reliable, and cost-effective water services. In cities, water infrastructure has been gradually expanded in response to prevailing ideological and technological conditions. In developed countries this has resulted in urban water systems with centralized water supply systems, sewer networks, and large-scale water treatment facilities (Brown et al., 2009). While these traditional systems have been very effective in the past – i.e., significantly contributing to public health and protecting cities from flooding – current sustainability challenges now reveal their limitations (Wong and Brown, 2009). For example, they seem to have a limited ability to cope with extreme climate conditions (e.g. Ashley et al., 2005; Rijke et al., 2013), have a high net energy consumption (e.g. Mo and Zhang, 2013), and lead to the deterioration of the environmental quality (e.g. Chocat et al., 2007).

Alternatively, urban water systems can also be designed in such a way that they are more resilient to the consequences of heavy storm events, flooding, and periods of drought, enable the recovery of valuable resources like nutrients, energy, and water, and provide wider social and environmental benefits. Rather than another (technological) add-on, the future-proofing of urban water systems calls for a change to the socio-technical system: current challenges need innovations that extend to other urban disciplines, such as urban planners and road authorities (Brown et al., 2009; Kiparsky et al., 2013). Accordingly, both scholars and practitioners agree that we need a more integrated approach to prepare the urban water system for the future (Brown and Farrelly, 2009; Ferguson et al., 2013a; Pahl-Wostl et al., 2011).

Although an integrated approach is clearly needed for the future-proofing of urban water systems, there is no consensus on how such integration should look like. We see at least three issues that contribute to this lack of consensus:

- First, there is no agreed definition of what an integrated approach to urban water management is (Nieuwenhuis et al., 2021a). This complicates communication about the role that integration could play for future-proofing.

In response to the multiple sustainability challenges, different approaches to integration have been developed. The approaches focus for instance on storm water, resource recovery from wastewater, the rehabilitation of water infrastructure, the urban water cycle [9], and the optimization of urban wastewater systems (Nieuwenhuis et al., 2021a). This diversity in focus illustrates the lack of consensus on what a more integrated approach means.

- Second, even *if* actors have shared understanding of what is meant by integration, it is likely that they disagree on matters such as the drivers of integration, the level of urgency or the means for integration. Integrated urban water solutions involve many different actors, each of them having their own responsibilities, perspectives and interests (e.g. Fratini et al., 2012; Roy et al., 2008). Molenveld et al. (2020), for example, studied the viewpoints among non-governmental stakeholders on the governance of integrated storm water management – more specifically, on the governance of climate adaptation. They found that actors have fundamentally different views on the need and sense of urgency, as well as how to realize climate adaptation (Molenveld et al., 2020). This illustrates the "wicked" (Rittel and Webber, 1973) or "unstructured" (Hisschemöller and Hoppe, 1995) nature of integration, with different parties disagreeing not only about the solutions, but also about the nature of problems.

- Third, and related to the wicked nature of the issue, uncertainty about the future (e.g., climate change, and technological and institutional developments) contributes to the lack of consensus on integration in future urban water systems (Nieuwenhuis et al., 2021a). The inherent uncertainty may make that actors hold different views on the requirements that future systems need to meet, which in turn influences their view on (the need for) integration.

These three issues imply that among urban water practitioners, i.e., professionals involved in the management of (various parts of) the urban water cycle who work at water boards, municipalities, drinking water companies, knowledge institutes, and consultancy firms, there will be different views about integration in future urban water systems. These differences could stem from practitioners' organizations, local conditions, or other issues. To work towards future-proof urban water systems, practitioners have to cope with this diversity and wickedness in decision-making on integration. To foster the implementation of integration, and thus to contribute to

[9] The urban water cycle includes the "man-made" changes to the natural water cycle, such as the infrastructures developed for drinking water supply and the collection and treatment of wastewater.

the future-proofing of urban water systems, we need a systematic understanding of the different perspectives on integration that exist among practitioners.

This chapter explores the different perspectives of Dutch urban water practitioners on the role of integration for future urban water systems. We use Q-methodology to empirically identify the perspectives, and subsequently analyze the role of integration therein based on a typology of Urban Water Systems Integration (Nieuwenhuis et al., 2021a). Analyzing real-world perspectives allows us to reflect on the extent to which predominant perspectives in the literature mirror reality, and to go beyond preconceived viewpoints that are commonly juxtaposed in urban water literature, such as the sustainable and technocratic viewpoint (see e.g. Chocat et al., 2007).

This chapter is structured as follows. Section 3.2 explains the concept of Urban Water Systems Integration and briefly describes the context of the Dutch urban water sector. Section 3.3 explains the theory of Q methodology and how it was applied in this study. Section 3.4 presents the four perspectives. In Section 3.5, we analyze the perspectives based on the concept of Urban Water Systems Integration. Additionally, we discuss them in the light of the current literature. We conclude with the implications of our research, as well as ideas for future research in Section 3.6.

3.2 An integrated approach to future-proofing urban water systems

3.2.1 Urban Water Systems Integration

Urban Water Systems Integration (Nieuwenhuis et al., 2021a) is defined as “the physical, social, and institutional interlinking of (parts of) the urban water system with other urban systems.” Nieuwenhuis et al. (2021a) introduced a typology of Urban Water Systems Integration based on analysis of urban water literature. This typology distinguishes four types of Urban Water Systems Integration: geographical, physical, informational, and project-based systems integration. Each of the types are related to specific object(s) of integration (Table 3-1).

- *Geographical systems integration* is based on the spatial alignment of different urban infrastructure systems, and aims at preventing the (undesirable) interference between them. This alignment is of particular importance for high-density urban areas where many functions have to be combined in the same urban space. Moreover, emerging sustainability challenges, like the energy transition and climate adaptation, are expected to put even greater pressure on this space. Solutions, such as district heating, (additional) storm water sewers and infiltration facilities require space on top of what is already demanded today (Merkx, 2020). This illustrates the variety of (conflicting) spatial interests involved. Geographical systems integration aims to address these, focusing on the coordinated spatial organization of urban systems.

- *Physical systems integration* involves the physical linkage of two or more urban systems, and can be based on either resources or infrastructures.
    - In the case of integration based on resources, the product generated or transported by one system (output) is required for the functioning of another (input). An example is the recovery of resources from wastewater, such as the local reuse of municipal wastewater effluent for industrial purposes (Majamaa et al., 2010).
    - In the case of infrastructure-based integration, one infrastructure uses the other to fulfill its function. Examples include multi-utility tunnels that co-locates cables and ducts in one tunnel (Hunt et al., 2014), and storm water solutions that are integrated into other urban systems, such as living walls (Riley, 2017).

- *Informational systems integration* is based on combining data from different urban systems, also referred to as a smart-city or digital-city initiatives. Such initiatives are typically aimed at increasing the efficiency of systems, through integrating information and communication technology (ICT) and physical infrastructures. An example is that of smart roofs, which provide dynamic water storage based on real-time weather data and remote-control operation (Rainproof, 2018).

- *Project-based systems integration* focuses on the possible synergies between urban infrastructure systems in rehabilitation and construction planning. This comprises, for instance, the planning of replacement and maintenance

Type of systems integration	**Object of integration**	**Description**
Geographical	Space	Spatial alignment of urban systems in the same area
Physical	Resources	Shared use of a resource for multiple functions
	Infrastructures	Shared use of an infrastructure system
Informational	Data	Use of data from different urban systems in operating those systems
Project-based	Planning	Alignment of rehabilitation and construction plans for multiple urban systems

Table 3-1. Characteristics of the different Urban Water Systems Integration types (from Nieuwenhuis et al., 2021).

projects for different infrastructures such that they take place at the same time, or immediately after each other (see e.g. Tscheikner-Gratl et al., 2016b).

3.2.2 Urban water management in the Netherlands

As a background to our empirical analysis, we briefly discuss the context of the Dutch urban water sector. The Netherlands is a flat, densely populated delta area, with large parts of the country below sea-level. Fifty-nine percent of the country is susceptible to flooding, and flood control has therefore long been a national priority (PBL, 2010). There are two main types of landscape: low-lying, flat polders in the western and northern part of the country, and slightly higher sandy areas towards the east and south. While specific urban water challenges depend on local conditions, both areas are facing similar issues: practitioners have to find solutions for increasing drought, heat and extreme storm events in complex, built-up urban areas. In addition, they are faced with deteriorating infrastructure (RIONED Foundation, 2013).

When it comes to the management and operation of urban water systems, drinking water companies, municipalities and water boards are the key actors, while the central government is in charge of protecting the country from flooding from the sea and main rivers.

- Drinking water companies are responsible for the production and distribution of water, including the operation and maintenance of the infrastructure required for this purpose. The service areas of the ten drinking water companies in the Netherlands range from about 350 km^2 to 15.000 km^2.
- Municipalities are responsible for the collection and transport of wastewater, as well as the management of storm water and groundwater in public space (residents and businesses carry the responsibility for their own properties). Dutch municipalities range in population size from about 1.000 to 870.000.
- Water boards are in charge of the quantity and quality of surface water, the management of polder water levels and flood defenses, and wastewater treatment. The water boards are among the oldest local government bodies in the Netherlands and operate independently from the national government. In total, there are 21 waterboards throughout the Netherlands.

3.3 Method

We applied Q methodology (Brown, 1980; Stephenson, 1936) to identify the different perspectives of Dutch urban water practitioners on integration for future urban water systems. Q methodology is a useful method for our study because it allows researchers to identify the variety of shared perspectives in a certain policy discourse (Molenveld, 2020). This makes Q methodology particularly suitable to investigate wicked policy issues, such as the future-proofing of urban water systems. In contrast to conventional survey research, Q methodology allows the researcher to explore the perspectives without hypothesizing them in advance, and thus to go beyond preconceived viewpoints. In the field of water management, Q methodology has been previously used to identify different perspectives on future flood management (Raadgever et al., 2008), public participation processes (Webler and Tuler, 2006), governance of storm water (Cousins, 2017), as well as that of climate adaptation (Molenveld et al., 2020).

In a Q study, a diverse group of participants is selected and asked to rank a set of statements on a particular subject into a prearranged, normally distributed, grid (see Figure 3-1). First, each participant sorts the set of statements according to his or her own perspective. Then, the individual sorts are grouped into shared perspectives using factor analysis. To give researchers an in-depth understanding of the perspectives, each participant is subsequently interviewed to elaborate on their sorting. By so doing, Q methodology combines the strengths of both quantitative and qualitative research techniques: while its quantitative character allows the diversity of perspectives to be statistically analyzed, the qualitative character of the Q methodology allows researchers to stay close to the perceptions of participants.

Q methodology is an adaption of Spearman's method of factor analysis. Stephenson inverted the factor technique by applying by-person factor analysis instead of by-variable factor analysis (Stephenson, 1936). As such, Q methodology focuses on correlations between Q sorts. It treats individuals as if they are "the variables," creating factors that explain the variation among particular Q sorts (Stephenson, 1936). Rather than a relationship between particular statements, correlations in Q indicate a relationship between the entire sets of statements.

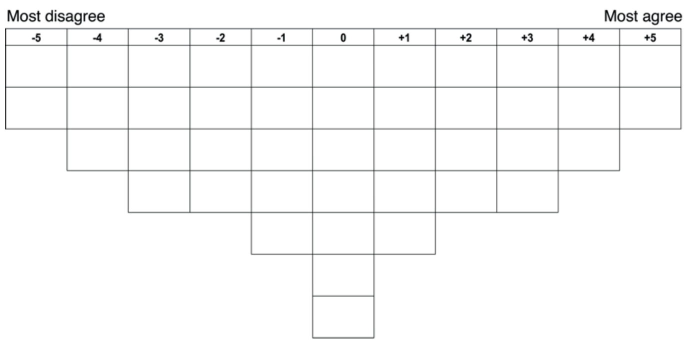

Figure 3-1. The sorting grid used for this study. Each participant received 43 statements and had to rank them. The Q distribution ranged from -5 to +5 and indicated the number of statements that can be assigned a particular ranking value.

The method consists of 5 steps: (1) selecting the Q statements, (2) selecting the participants, (3) conducting the Q interviews, (4) performing the factor analysis, and (5) interpreting the factors (Cuppen, 2010; Watts and Stenner, 2012). Below, we will discuss each of these steps, and explain how we carried them out in this study.

3.3.1 Step 1: selecting the Q statements

The first step comprises the concourse definition and the Q sample selection. The concourse is the full range of discussions and discourses on the particular issue under study (McKeown and Thomas, 1988). It is constructed by collecting statements that represent the wide array of subjective viewpoints on the issue. Thereafter, the final set of statements, the Q sample, needs to be selected. This Q sample must be "broadly representative of the opinion domain" and should "demonstrate good coverage in relation to the research question" (Watts and Stenner, 2012, p. 67). Watts and Stenner (2012, p. 59) distinguished a structured and an unstructured Q sample, either developed using a deductive or an inductive approach. Irrespective of the approach employed, it is key that participants understand and recognize the statements (and thereby the meaning of statements). Preferably, the wording of Q statements should therefore stay close to the wording of participants (Brown, 1980).

In this study, the concourse covered all subjective viewpoints on the role of systems integration in preparing the urban water system for the future. We used an inductive approach to develop our concourse. Statements were collected from six semi-structured interviews with urban water practitioners, as well as from workshops and presentations attended by the first author, scientific articles, Dutch newspapers, industry magazines and columns. During the interviews, we noticed that the concept of integration was not always understood by practitioners. Although practitioners stressed the need for cooperation and alignment with other urban systems, they were often confused by the word integration, suggesting it did not fit their language. Hence, we decided to collect both statements explicitly about integration, and statements about future-proofing in general. This included topics such as future urban water challenges, expectations about future service levels and changes required to meet these levels. In the next step, we subsequently identified the statements that were either implicitly or explicitly about integration. This approach allowed us to explore the concept of integration in an empirical way. Statements were collected until saturation was reached. This resulted into a concourse of 649 statements.

For the Q sample selection, we then took a semi-structured approach. We evaluated for each of the 649 statements whether it was about integration. We searched for words with a similar meaning, such as "collaboration" or "cooperation", and for statements describing integration in a more implicit way. All 649 statements were categorized into three sub-themes: the meaning of integration, drivers for integration (or drivers for non-integration), and the challenges and opportunities to integration. Statements that did not fit one of these categories were rejected, and duplicates were removed, reducing the set to 150 statements. By iteratively categorizing the statements based on their subject (e.g., financial matters, human resources, public health, and guidelines and regulations) and merging similar statements, the set was further reduced to 65 statements. We then repeatedly discussed the statements with five urban water professionals and a Q researcher, resulting in a preliminary Q sample of 48 statements. After piloting this sample in five interviews, we made a few more alterations to the statements. This resulted in a final Q sample of 43 statements.

To further check the validity of our sample, we asked the participants after each interview whether they felt the Q sample covered the relevant issues. Most participants were satisfied and did not wish to add anything. Those who did want to add something elaborated on an issue they had already mentioned in relation to one of the other statements. This confirmed that the Q sample included the variety of relevant issues and ideas.

3.3.2 Step 2: selecting the participants

Step 2 consists of sampling the P set: the group of participants. Earlier it was explained that Q research aims to discover and explicate relevant viewpoints on a particular topic. This implies that a P set needs to be diverse, capturing the different viewpoints that participants have on a particular topic, rather than a representative sample that accurately reflects particular characteristics of a population (Brown, 1980). Q methodology therefore typically relies on a strategic sampling strategy, in which participants are selected if they have a defined and relevant viewpoint on the issue at stake (Watts and Stenner, 2012, p. 70). In addition, a Q study does not require a large number of participants: there are generally fewer participants than statements, with interviews continuing until no new perspectives emerge (Watts and Stenner, 2012, p. 73). This is supported by the inverted factor analysis that is part of Q methodology (see Step 4), in which participants are the variables rather than the statements.

We defined our P set as follows: Dutch urban water practitioners who are actively involved in policy-making, such as policy-makers, strategic advisors and policy practitioners, working in (semi-)governmental and private organizations. Aiming to include all relevant perspectives, we used a strategic heterogenous sampling approach. We selected participants from different organizations and backgrounds, and from across the county, maximizing diversity with respect to contextual variables (e.g. geographical location, soil conditions, municipality size, and local taxes for urban water services). Participants were selected in three ways: we approached people via our own network (*n*=18), we used LinkedIn (*n*=5), and we approached referrals based on the snowball sampling technique (n=7) [10]. This resulted in a final group of 30 participants, employed at water boards, municipalities, drinking water companies, knowledge institutes, and consultancy firms (Table 3-2).

3.3.3 Step 3: conducting the Q interviews

Step 3 comprises the Q interviews. First, the participants sort the set of statements, from their own perspective, into a fixed normal distribution (see Figure 3-1). This forces them to reflect on each statement and to prioritize which statements they find most important with respect to the issue at stake. Thereafter, a post-sorting interview is conducted to get a more profound and qualitative understanding of the participant's perspective.

The first three interviews were conducted face to face in December 2019. The remaining 27 interviews were conducted via video conferencing from April to August 2020 due to covid-19 restrictions. For the online interviews, we sent a printed set of statements together with the sorting grid (Figure 3-1) in advance, and subsequently guided the participants through the Q sort during the video call. Both the in-person and the online interviews were performed in a similar way and each participant received the same instructions. All interviews were recorded and transcribed.

We first introduced the aim of our project. We explained that we were interested in the different perspectives of practitioners on future urban water systems, and that we were particularly interested in the role integration could play in future systems.

Table 3-2. Overview of participants per actor type.

Type of organization	Number of participants
Municipality	12
Water board	7
Drinking water company	3
Knowledge institute	3
Advisory company/Consultancy firm	5
Total	30

[10] Snowball sampling is a technique in which interviewees suggest other potential interview candidates. Each participant was asked to suggest other urban water practitioners with a defined, either similar or different, viewpoint on the future-proofing of urban water systems.

We then asked the participants to sort the statements according to the question: “which statements do you (dis)agree most with regarding a future-proof urban water system?” We formulated this question in terms of “future-proof” rather than “integration,” as we had learned early in the project that the term integration was not well understood by all practitioners (see Section 3.3.1). By using “future-proof,” which is a common term in Dutch (“toekomstbestendig”), in combination with our introduction about integration, we made sure that each participant would understand what was meant.

The participants subsequently read through the 43 statements one by one, and sorted them into three piles: those they agreed with, those they felt neutral about and those they disagreed with. We then asked them to return to the piles, and to sort them into the sorting grid, starting with the statements they agreed with (at the rightmost side of the grid), then the ones they disagreed with (at the leftmost side of the distribution), and lastly, the statements they felt “neutral” about. After the sorting, we asked the participants if they felt the Q sort reflected their point of view, or if they wanted to make any last adjustments.

In the post-sorting interviews, we asked the participants about the positions of statements, in particular the most (dis)agreeable ones – thus the statements sorted into the two outer columns at +/- 4 and 5 (see Figure 3-1). In addition, we asked them how they viewed an integrated approach to urban water management, and the role this could play in preparing the system for the future.

3.3.4 Step 4: factor analysis

The aim of the fourth step (factor analysis of the Q sorts) is to look for participants who have sorted the statements in a similar way, and thus who have a shared perspective on the issue at stake. In Q method, factor analysis is an iterative process, in which researchers identify and evaluate different factor solutions, aiming for factors that could be interpreted as meaningful perspectives. There are two methods of factor extraction: centroid factor analysis and principal component analysis. Although these are two different methods of extraction, they are found to produce similar factor results (Harman, 1976). The next step in factor analysis comprises factor rotation, which can be done using varimax rotation or by hand (manual rotation). Varimax rotation uses statistical criteria that maximizes the amount of study variance that the factors altogether account for. In Q methodology, however, the best mathematical solution is not always the most meaningful solution, i.e., the solution that best explains and explicates the variety of perspectives. It is therefore suggested to use varimax rotation at the outset, followed by a manual rotation using the substantive knowledge of the data gained during the process of Q analysis (Watts and Stenner, 2012, p. 126). To facilitate the evaluation of different factor solutions, a weighted average ranking of the statements is computed for each of the rotated factors – a so-called *factor array*. This factor array shows the "ideal" Q sort for that factor, i.e. how someone with a Q sort that would load 100% on that factor would have ranked the statements. The factor arrays could be used for interpretation of the factors, each representing a perspective that is shared by the participants who load uniquely and significantly on that factor.

To analyze our Q sorts, we used the open-source software Ken-Q v.1.0.6 (Banasick, 2020). We defined the most meaningful clustering of Q sorts, using an iterative approach: we looked into various factor extraction and rotation options, and went back and forth between the quantitative and qualitative data. Eventually, we used principal component analysis and varimax rotation, followed by three by-hand adjustments[11]. This resulted into four interpretable factors. The decision for a four-factor solution was supported by two criteria that are commonly used to evaluate how many factors to keep after extraction: each of the factors had at least two Q sorts that loaded significantly upon that factor alone (Brown, 1980, pp. 222–223); and the cross-product of the two highest loadings on that factor (ignoring signs) exceeded twice the standard error of that factor, also known as Humphrey's rule (Brown, 1980, p. 223).

In the final four-factor solution, 29 out of 30 Q sorts loaded significantly on one or more of the factors, of which 18 were *defining* ones, i.e., Q sorts that were uniquely associated with a particular factor (see Appendix B for an overview). Factor 1 had the highest number of defining Q sorts, with eight participants loading significantly. Both Factor 2 and 3 had four participants loading significantly, and Factor 4 had two.

3.3.5 Step 5: factor interpretation

The fifth step is the interpretation of the factors into unique perspectives. The output from the factor analysis (step 4) generally forms the basis for the perspective descriptions. Additionally, the post-sorting interviews (step 3) facilitate the in-depth interpretation of the perspectives and is used to enrich the descriptions.

[11] We first used varimax rotation to explore the dominant viewpoints among our participants. This resulted into 15 Q sorts with a significant factor loading ($p<0.01$) on a single factor; loadings exceeding ± 0.3934 are significant at the 0.01 level (for the formula, see van Exel and de Graaf, 2005). The varimax rotation was evaluated by an initial interpretation of the factors, looking at all Q sorts that loaded significantly on one or more factors. It then emerged from the qualitative data that three Q sorts that loaded (borderline) significantly on two factors, namely Q sorts 1, 12 and 13, actually had a better fit with only one of these factors. In accordance with the rotation procedure outlined by Watts and Stenner (2012, p. 126), we therefore decided to make three by-hand adjustments: we rotated factor 1 and 4 two degrees clockwise, factor 2 and 3 three degrees anti-clockwise and factor 3 and 4 two degrees anti-clockwise. This raised the number of Q sorts associated with our four factors from 15 to 18 out of 30, with Q sort 1 loading significantly on Factor 3 (with a factor loading of 0.49), and Q sort 12 and 13 on Factor 1 (with factor loadings of 0.58 and 0.59, respectively). Other than these three Q sorts, the by-hand adjustments had no further impact on the composition of the factor groups.

Section 3.4 presents the descriptions of our four perspectives. To develop the descriptions, we drew on the *defining* and *distinguishing* statements. The defining statements are the most (dis)agreeable statements, i.e., those ranked at +/- 4 and 5. The distinguishing statements are those ranked significantly different at the 0.05 level (for the formula, see S. Brown, 1980, p. 300), and ranked highest or lowest compared to any other factor. In addition, we used quotes from the post-sorting interviews to further explicate the perspectives.

3.4 Results: four perspectives on integration for future urban water systems

This section presents the four perspectives identified with Q methodology*: Future-proofing through coordination: finding space for urban challenges* (perspective 1), *Future-proofing through climate adaptation: creating livable cities* (perspective 2), *Future-proofing through recovery: challenging institutional structures* (perspective 3), and *Future-proofing through efficiency: being in control* (perspective 4). For each factor, we provide a narrative, together with the defining and distinguishing statements. We end the section with a summary of the perspectives. The factor scores per statement could be found in Appendix A. Appendix B provides an overview of the participants and their factor loadings.

3.4.1 Perspective 1. Future-proofing through coordination: finding space for urban challenges

Table 3-3 provides an overview of the defining and distinguishing statements for perspective 1, *Future-proofing through coordination: finding space for urban challenges*. This perspective is represented by eight participants, working at municipalities (*n*=3), consultancy firms (*n*=2), a knowledge institute (*n*=1), a water board (*n*=1) and a drinking water company (*n*=1).

At the heart of this perspective is better coordination of different urban challenges: working beyond organizational boundaries and finding space for challenges related to water, whilst not overlooking those related to other domains. Hence, these practitioners are conscious of the urban complexity in which the urban water system has to be managed. They believe that new technologies could play an important role (28), but they stress, above all, that we need to change the way we work. The practitioners argue that the implementation of integrated solutions is currently hampered by a lack of collaboration, both between sectors (5) and between phases (37). As such, the urban water sector should operate beyond traditional roles (1,10,20). It should not only rely on the cooperation with water partners (29), but also actively engage with the various parties in the city (39), not forgetting its inhabitants (13). This issue is reflected by respondent 26:

> The traditional management duties are, of course, very important, but those will all work out. We are so good at it in the Netherlands that these traditional management tasks can be carried out easily. The next step is simply to collaborate.

This perspective sees (timely) coordination as an effective means of dealing with contemporary urban water challenges, irrespective of the challenge. The coordination extends, for example, to climate adaptation projects for which a major challenge lies in spatial planning (39), but also to that of the subsurface, such as with respect to the energy transition and the space needed for district heating (26). The practitioners see cooperation as a means, as the vehicle, of identifying what is at stake, negotiating with the different parties involved, and collaboratively deciding on the trade-offs. This is illustrated by respondent 12:

> It is all about space. ... So, you will have to make choices. ... In fact, as a city, we have to learn to… just as much as we look at a particular area for the water system, we should look at the whole urban area for the city and think of our priorities: what are the priorities for the different systems?

In this context, this perspective does not see a role for generic rules, as these do not acknowledge this urban complexity (40). Instead, they argue that a process of interaction should provide input for (location-specific) solutions. They believe that such a process will eventually result in a design that could safeguard different urban interests. They, however, see a hurdle for the final implementation, i.e., the planning (7). Respondent 12 reflects on this issue*:*

> I believe that in terms of content, when it comes to technical matters, you can always find a solution – you can always come up with things. But the discussions are always about planning ... especially if there are different organizations involved.

Table 3-3. Overview of the defining statements (+/- 4 and 5) and distinguishing statements (at p<0.05) for perspective 1. Statements significantly different at the 0.01 level are indicated with an asterisk. Rel.position stands for relative position, indicating if the ranking value is, on average, higher (>) or lower (<) compared to other factors.

Type of statement	Ranking value and rel.position		Statements (including their number)	
Defining statements *(most agree)*	+5	>	39	The only way to climate-proof our city is making connections to other projects and parties in the city, and linking climate adaptation to their goals.
		>	5	Separate budgets for maintenance of green facilities, roads and water hinder the implementation of integrated solutions.
	+4	>	37	The careful transfer between the various phases of policy, design, implementation and management remains a challenge to successfully integrating the design of the public space.
		>	7	The challenge of collaboratively achieving a future-proof public space is not so much agreeing on the actual design, but rather in agreeing on the moment of replacement.
		>	13	Creating support and awareness among residents is crucial to achieve a future-proof urban water system.
Other disting. statements	+1	>	38*	By dwelling on larger issues, such as defining risk profiles, we miss obvious opportunities for improvement.
	0	>	26	The future of the urban water system depends on how the energy transition is implemented and how fast.
	-1	<	40*	To achieve future-proof urban water management, clearer rules are needed about who is responsible for damage and how to prevent it.
Defining statements *(most disagree)*	-4	<	29	In order to prepare our urban water system for the future, agreements between the various water partners is more important than between the parties involved in spatial planning.
		<	10*	Everyone talks about climate proofing and circularity, but we should first ensure that our gullies, the sewage system and the receiving water system function properly.
		<	1	The water sector's ambition to be sustainable comes at the expense of its core business: caring for public health, guaranteeing dry feet and protecting water quality.
	-5	<	28	We should not apply innovative solutions until we have identified their risks.
		<	20	The focus on climate adaptation diverts attention away from traditional management tasks.

* Distinguishing statements at $p < 0.01$

3.4.2 Perspective 2. Future-proofing through climate adaptation: creating livable cities

Table 3-4 shows the defining and distinguishing statements for perspective 2, *Future-proofing through climate adaptation: creating livable cities*. The perspective has four significantly loading Q sorts. The participants are employed at a municipality (*n*=3) and at a water board (*n*=1).

In this perspective, future-proofing relates to climate adaptation and an integrated approach to storm water management. The practitioners see an important role for including urban water infrastructure in the spatial design to improve the livability, as well as the biodiversity of cities. To this end, they are in favor of "non-piped", preferably nature-based, urban drainage solutions that process the water locally by means of infiltration, delay, and/or storage (31). Respondent 4 explains that such future systems preferably have other social and environmental benefits as well:

> In my view, a future-proof water system is one that is able to deal well with our future climate and all the weather conditions associated with it. So, it should be able to resist a warmer climate, but also to other weather extremes. … Furthermore, I think it is very important that it serves a wide range of societal goals, and preferably it should be a system that proves its added value already now.

Hence, next to preparing for a changing climate, this perspective finds healthier urban ecosystems important. This is reflected by respondent 6: "I really see it [the urban water system] much more as an ecosystem that needs to be in some kind of balance so that it functions well." Healthy surface water is part of such a balance, for which this perspective sees a shared responsibility for the water authorities and the municipalities (29). Above all, however, this perspective stresses the need for an integrated approach to spatial planning – and thus taking climate adaptation measures – to keep the city ecosystem in balance. The practitioners underline that the urgency of climate adaptation requires connecting with other projects and parties in the city (39), seeing the rehabilitation of whatever type of infrastructure as an opportunity to design the public space in a climate-proof way (7). In addition, they argue that a broader framing of climate adaption could contribute to a future-proof city, such as reflected by respondent 7:

> In my opinion, you should not use climate adaptation to summarize it, but rather the livability of the city, so then you have "healthy urban planning," that kind of slogans. … Only if you say you're going to make the city more attractive, and pleasant, and livable, then you can make people enthusiastic.

Table 3-4. Overview of the defining statements (+/- 4 and 5) and distinguishing statements (at p<0.05) for perspective 2. Statements significantly different at the 0.01 level are indicated with an asterisk. Rel.position stands for relative position, indicating if the ranking value is, on average, higher (>) or lower (<) compared to other factors.

Type of statement	Ranking value and rel.position		Statements (including their number)	
Defining statements *(most agree)*	+5	>	9*	Strict regulation of spatial developments, such as the "compensation rule" for water storage or a minimum construction level, are essential to create more space for water.
		>	31*	Any storm water solution that reduces the amount of water in the sewerage system is a step in the right direction and will help to change our way of thinking.
	+4	>	18*	To prepare the urban water system for the future, we have to discard the idea that this should not cost more than our current system.
		>	39	The only way to climate-proof our city is making connections to other projects and parties in the city, and linking climate adaptation to their goals.
		>	34	Climate adaptation needs a clear captain who can combine issues like flooding, heat stress and drought.
Other disting. statements	-1	>	29*	In order to prepare our urban water system for the future, agreements between the various water partners is more important than between the parties involved in spatial planning.
	-3	<	7*	The challenge of collaboratively achieving a future-proof public space is not so much agreeing on the actual design, but rather in agreeing on the moment of replacement.
Defining statements *(most disagree)*	-4	<	28	We should not apply innovative solutions until we have identified their risks.
		<	32	Using legislation to enforce climate adaptation measures is undesirable.
		<	26	The future of the urban water system depends on how the energy transition is implemented and how fast.
	-5	<	17	At street level, it is best to work on an individual basis – because coordinating with other sectors costs too much time and money.
		<	3*	Municipalities do not have sufficient knowledge and experience to properly manage the process towards a future-proof urban water system.

* Distinguishing statements at p < 0.01

As climate adaptation is so urgent to these practitioners, they are not bothered by the potential higher costs the integration of storm water infrastructure in the spatial planning brings along (18, 17). There is no time to wait until future innovative solutions can be implemented, neither to wait for the energy transition (26, 28). Hence, municipalities have to come into action, and appoint someone who can take the lead to accelerate actual implementation (34). According to this perspective, municipalities are the right and the only party to organize the transition to a more climate-robust urban water system (3), using regulation to steer on the objectives for the water system (9,32).

3.4.3 Perspective 3. Future-proofing through recovery: challenging institutional structures

The defining and distinguishing statements for perspective 3 (*Future-proofing through recovery: challenging institutional structures*) are presented in Table 3-5. Perspective 3 has four participants loading significantly, working at a water board (*n*=2) and a drinking water company (*n*=2).

In this perspective, future-proofing is about closing cycles, making a “sponge” of urban areas and recovering the resources that are present in wastewater. Water management practices need a fundamental change according to this perspective. The urban water sector should put its ambitions high (35) and think twice before renovating systems that in fact are outdated already now (21). To prevent decisions that lead to technological lock-in, the water sector should focus on long term goals and make a strategic plan that looks at a bigger spatial scale (23). Rather than sticking to traditional systems and roles, it should look for innovative solutions (28) and be open to new types of institutional arrangements, for example local initiatives together with companies. As such, respondent 9 believes that “you need to start thinking on a smaller scale and apply more small-scale solutions, and then you will automatically arrive at the level of residents or companies.” Hence, this perspective sees a role for decentralized solutions in future urban water systems (25), and finds support from residents essential, because local solutions can also require effort from them (13). Along these lines, participant 24 reflects on the position of large-scale treatments plants that we have today:

> If we look at the future, perhaps we should change our system, and that means that we deal with our wastewater in a different way, or that there is perhaps a much more logical place to recover resources. Hence, we should not pin ourselves down on that-end-of-pipe too much, by doing all kinds of things there. There may well be other places where we can do much better.

Increasing drought is a strong new driver to focus on recovery, and the replenishment of aquifers is therefore key to these practitioners (33). They underline that drought does not only decrease the water availability, but also changes the patterns of demand. Accordingly, they argue that drought-related issues cannot be solved with the water partners alone, and that they should therefore shift their attention to parties involved in spatial planning (29,17). They argue that this needs central coordination. Hence, they see an important role for a captain who could pull the different disciplines and organizations together (34), combined with legislation to support change towards more sustainable urban water solutions (32). This is reflected by respondent 24:

> There are people who say that you will make it, but you need leadership and the right stimuli to make that change happen. It does not happen by itself. It is not going to come slowly. … There has to be some pressure, there has to be urgency and there has to be leadership, regulation, otherwise you cannot get it done.

This quote also explains why this perspective is critical to the new Environmental and Planning Act (8), which will be effectuated in January 2022 as to facilitate integrated spatial planning, and focuses on a decentralized approach. The practitioners doubt whether the new law can really bring about the change required, such as reflected by Respondent 24: “I hear all kinds of things about the Environmental and Planning Act, that it is going to change everything. … But then one is talking about the instrument, but not about the purpose behind it.”

Table 3-5. Overview of the defining statements (+/- 4 and 5) and distinguishing statements (at p<0.05) for perspective 3. Statements significantly different at the 0.01 level are indicated with an asterisk. Rel.position stands for relative position, indicating if the ranking value is, on average, higher (>) or lower (<) compared to other factors.

Type of statement	Ranking value and rel.position		Statements (including their number)	
Defining statements *(most agree)*	+5	>	34	Climate adaptation needs a clear captain who can combine issues like flooding, heat stress and drought.
		>	33	Active management of groundwater, both in terms of the replenishment and discharge of groundwater, is a requirement for a future-proof urban water system.
	+4	>	35	Knowing that everything we build now will have to last for many decades, our ambitions for a future-proof system should be much higher.
		>	13	Creating support and awareness among residents is crucial to achieve a future-proof urban water system.
		>	23	In order to make our system future-proof, shifting to a district-oriented approach is vital; replacing at the neighborhood level rather than street level.
Other disting. statements	+3	>	21	When choose to renovate sewers, we are indirectly opting to maintain our current system; continuing to develop renovation technologies, such as relining, is thus a threat to future-proof urban water systems.
	+3	>	25*	Decentralized wastewater systems are better able to meet the objectives of a future-proof urban water system than centralized ones.
	0	<	27*	If we want to achieve our spatial ambitions in the future, the space under the ground needs to be the starting point for the above-ground design.
	-1	<	37*	The careful transfer between the various phases of policy, design, implementation and management remains a challenge to successfully integrating the design of the public space.
Defining statements *(most disagree)*	-4	<	32	Using legislation to enforce climate adaptation measures is undesirable.
		<	28	We should not apply innovative solutions until we have identified their risks.
		<	17	At street level, it is best to work on an individual basis – because coordinating with other sectors costs too much time and money.
	-5	<	29	In order to prepare our urban water system for the future, agreements between the various water partners is more important than between the parties involved in spatial planning.
		<	8*	The Environment and Planning Act will improve the coordination between different urban infrastructures.

* Distinguishing statements at p < 0.01

3.4.4 Perspective 4. Future-proofing through efficiency: being in control

Table 3-6 provides an overview of the defining and distinguishing statements for perspective 4, *Future-proofing through efficiency: being in control*. The perspective has two Q sorts uniquely associated with it. Its participants are working at a consultancy firm (*n*=1) and at a municipality (*n*=1).

In this perspective, asset management is the main priority: the practitioners have a strong focus on managing the subsurface space efficiently (27), and thereby take a technical-financial view with respect to future-proofing. According to respondent 20, "future-proof is simply that you are in control, that you know what is going on, that you have your act together." Hence, these urban water practitioners are not bothered by deeply rooted habits that prevent change (6), as they find it most important that we operate the system in a smarter way, thereby considering all phases of the development process (37). Digital tools could contribute to this (16), as well as clearly defined responsibilities (40). A future-proof system is thus by no means about setting higher ambitions (35), but rather about a better management of the current system (10).

Saving costs and efficiency is important to this perspective (18). One of the reasons that these practitioners do not see a role for decentralized wastewater infrastructure (25), nor for local storm water measures (31), is based on the principle of "economies of scale". To this end, the perspective is in favor of collective solutions. This also explains why support from residents is less important to them (13), Respondent 6 reflects on this issue:

> In my view, there are already a lot of possibilities underground. And in that case, indeed, depending on the situation, it is not an absolute necessity to involve residents, as they are not bothered by it at all. Moreover, I have more faith in district-focused measures than in street-focused measures, and the larger the scale, the less important it is to involve individual residents.

Additionally, respondent 20 explains that collective solutions allow the sector to be in control, which is at the heart of this perspective:

> Most above-ground solutions require quite a lot of maintenance and also require people who live there to be careful. … That means that, if it works now, it does not have to work in five years' time. … Yet, I believe that, on the long run, we will look for it [space] in the underground again, because this is easier, as a government, to keep the control.

Table 3-6. Overview of the defining statements (+/- 4 and 5) and distinguishing statements (at p<0.05) for perspective 4. Statements significantly different at the 0.01 level are indicated with an asterisk. Rel.position stands for relative position, indicating if the ranking value is, on average, higher (>) or lower (<) compared to other factors.

Type of statement	**Ranking value and rel.position**		**Statements (including their number)**	
Defining statements *(most agree)*	+5	>	23	In order to make our system future-proof, shifting to a district-oriented approach is vital; replacing at the neighborhood level rather than street level.
		>	27	If we want to achieve our spatial ambitions in the future, the space under the ground needs to be the starting point for the above-ground design.
	+4	>	16*	The water sector should adopt digital advances and fully exploit the opportunities that smart technology offers.
		>	37	The careful transfer between the various phases of policy, design, implementation and management remains a challenge to successfully integrating the design of the public space.
		>	40	To achieve future-proof urban water management, clearer rules are needed about who is responsible for damage and how to prevent it.
Other disting. statements	+2	>	10*	Everyone talks about climate proofing and circularity, but we should first ensure that our gullies, the sewage system and the receiving water system function properly.
	0	<	13*	Creating support and awareness among residents is crucial to achieve a future-proof urban water system.
	-1	>	28*	We should not apply innovative solutions until we have identified their risks.
	-1	<	18	To prepare the urban water system for the future, we have to discard the idea that this should not cost more than our current system.
	-2	<	6*	In the final analysis, deep-rooted habits are what prevent the realization of future-proof systems.
	-3	<	33*	Active management of groundwater, both in terms of the replenishment and discharge of groundwater, is a requirement for a future-proof urban water system.
	-3	<	9*	Strict regulation of spatial developments, such as the “compensation rule” for water storage or a minimum construction level, are essential to create more space for water.
Defining statements *(most disagree)*	-4	<	26	The future of the urban water system depends on how the energy transition is implemented and how fast.
		<	29	In order to prepare our urban water system for the future, agreements between the various water partners is more important than between the parties involved in spatial planning.
		<	31	Any storm water solution that reduces the amount of water in the sewerage system is a step in the right direction and will help to change our way of thinking.
	-5	<	25	Decentralized wastewater systems are better able to meet the objectives of a future-proof urban water system than centralized ones.
		<	35	Knowing that everything we build now will have to last for many decades, our ambitions for a future-proof system should be much higher.

* Distinguishing statements at p < 0.01

The focus on efficiency, which characterizes this perspective, is also reflected in the call for the collective replacement of systems. For example, this enables the implementation of climate adaptation measures at little additional costs. The practitioners argue for taking a good look at the subsurface and the existing infrastructures, preferably on a district level, to facilitate collective replacement (23, 27) – and thus to save costs. Moreover, they underline that coordination with parties in charge of these infrastructures becomes even more important (29), since the pressure on the subsurface is only increasing further in the future. They find collective replacement important; nevertheless, own goals and targets should not lose sight of. For instance, other parties should invest as well (e.g., green authorities), and they do not want to pay for the energy transition, nor want to wait for it, if the need for (sewer) replacement is high in a particular area (26).

3.4.5 Summary of the perspectives and their understanding of future-proofing

Table 3-7 presents the key characteristics for each perspective. This reveals that the perspectives have different understanding of future urban water management. Perspective 4 (*Future-proofing through efficiency: being in control*) is most distinctive from the other perspectives. This is also shown by the factor score correlations (Table 3-8), as these were considerably lower for factor 4 than for the other factors. We first provide a recap of perspective 4 and subsequently summarize the other three perspectives, for which the differences are more nuanced.

Perspective 4 (*Future-proofing through efficiency: being in control*) has a clear idea of the way to become future-proof; i.e., being in control, having good insights into the

Table 3-7. Overview of the perspectives. The table provides the key characteristics for each perspective. P stands for perspective.

Perspectives	Key characteristics
P1: Future-proofing through coordination: finding space for urban challenges	- Finding space for urban sustainability challenges - Dealing with urban complexity - Putting a collaborative process central
P2: Future-proofing through climate adaptation: creating livable cities	- Climate-proofing urban space - Creating livable cities and healthy ecosystems - Using regulation to accelerate climate adaptation
P3: Future-proofing through recovery: challenging institutional structures	- Closing cycles and dealing with increasing drought - Challenging current institutional structures - Guiding change through leadership
P4: Future-proofing through efficiency: being in control	- Operating urban water infrastructure in a smarter way - Putting a better understanding of the system central - Increasing efficiency through collective replacement and solutions

Table 3-8. Factor score correlations. KenQ automatically calculates the correlations between factor arrays. A higher factor score correlation indicates a greater similarity in content between two factors – and thus the perspectives.

	Factor 1	Factor 2	Factor 3	Factor 4
Factor 1	1.00	0.47	0.41	0.31
Factor 2	0.47	1.00	0.41	0.11
Factor 3	0.41	0.41	1.00	0.00
Factor 4	0.31	0.11	0.00	1.00

system and opting for efficiency. At the same time, it also has an idea of how future systems should look like, with centralized solutions dominating future urban water systems. They only see a minor role for decentralized solutions in future urban water systems, as they argue that the drainage capacity of decentralized storm water solutions cannot be guaranteed, making them financially unattractive. This does not imply, though, that these practitioners do not see the need for climate adaptation, or do not acknowledge other (non-water-related) benefits decentralized storm water solutions could bring. According to them, however, other involved parties (e.g., green authorities) should contribute to these solutions as well.

Perspective 1 (*Future-proofing through coordination: finding space for urban challenges*) acknowledges that climate adaptation is essential for future-proofing, but it puts climate adaptation next to other urban challenges. The main concerns of this perspective are the many urban challenges that have to be addressed simultaneously, and the limited space available. Rather than strict regulation, the practitioners see a collaborative process as the critical means of future-proofing. They believe that regulation in fact threatens the room for negotiation with other parties, arguing that a proper process will yield a proper solution. They consider the physical solution thus subordinate to the collaborative process, and mainly have a strong vision of the way to become future-proof (coordination), rather than what the future urban water system should look like.

Perspective 2 (*Future-proofing through climate adaptation: creating livable cities)* has its main focus on climate adaptation and sustainable storm water measures when it comes to future-proofing. The perspective considers climate adaptation key to improve the social and environmental conditions of cities. Hence, it has a strong focus on processing storm water locally, and the practitioners have a clear picture of how future systems should look like; i.e., a climate-proof urban space, for which the urban water infrastructure is included in the spatial design. They argue that regulation is key to enforce that much needed adaptation measures will be taken in time, and see a key role for municipalities to take the lead.

Perspective 3 (*Future-proofing through recovery: challenging institutional structures*) displays some similarities with both the first and second perspective: it emphasizes the need for climate adaptation to become future-proof (perspective 2), and thereby sees an important role for (new) collaborations (perspective 1). Different from perspective 1, however, this perspective is less concerned with urban complexity and mainly focuses on the urban water system, also in relation to the wider, regional, water system. Increasing drought is a central theme, and according to perspective 3, the urban water system can only become future-proof if we treat both storm and wastewater more carefully: storm water should be utilized, and the resources present in (industry) wastewater should be recovered.

In addition, compared to perspective 2, perspective 3 has a different view on climate adaptation: rather than redesigning urban space to create livable cities, perspective 3 focuses on "redesigning" the urban water cycle to address the consequences of drought. Perspective 3 thus operates at a larger spatial scale than perspective 2. This may be related to the fact that perspective 3 is only represented by water authorities (n=2) and drinking water companies (n=2); i.e., organizations with service areas extending beyond city boundaries, and that are primarily concerned with water-related issues. This could account for the perspective's strong focus on the water system itself, rather than how the water system needs change in relation to other urban challenges (perspective 1); how and when infrastructures need to be replaced (perspective 4); or how public space should be redesigned (perspective 2). For the other perspectives, we did not find any surprising results with respect to the participants defining that perspective.

None of the perspectives were represented by participants from only one organization, or by participants from organizations with similar contextual variables (e.g., geographical location or municipality size). This suggests that perspectives are not (only) dictated by the practitioner's organization or other local conditions. Further research, e.g. involving a larger group of practitioners and using quantitative methods, is needed to determine the influence of these factors.

Altogether, we found that the perspectives on future-proofing mainly differ with respect to their view on future systems, i.e., which sustainability challenges should be addressed, and the means to be used. Despite these differences, our results reveal a basis of mutual agreement among urban water practitioners: practitioners generally agree that traditional urban water management practices need to change to prepare the system for the future. Furthermore, we could not identify clear conflicts between the perspectives. So, despite their different values and interests, our results suggest that the intentions of one perspective do not necessarily rule out those of the other perspectives.

3.5 Discussion

This section first discusses the role each of the perspectives sees for integration in future urban water systems, using the typology of Urban Water Systems Integration (Section 3.2.1). Second, we analyze how each of the perspectives relates to the literature.

3.5.1 The different views on the role of integration in future urban water systems identified

The different understandings that the perspectives have of future-proofing (Section 3.4.5) are reflected in the role they see for integration in future urban water systems (Table 3-9).

In perspective 1 (*Future-proofing through coordination: finding space for urban challenges*) integration is viewed as a means to safeguard different urban interests, and thereby to become future-proof. This is also reflected in the types of integration identified for perspective 1: geographical, physical, and project-based integration. For perspective 2 (*Future-proofing through climate adaptation: creating livable cities*), all types of integration are focused on climate adaptation. They either relate to the measures themselves (geographical and physical integration), or to the path towards it (project-based integration). Perspective 3 (*Future-proofing through recovery: challenging institutional structures*) sees integration as a vehicle for future-proofing: geographical and physical integration can serve as a solution to address the increasing drought, by closing resource and/or water cycles. In perspective 4 (*Future-proofing through efficiency: being in control*), integration is viewed as a way to increase efficiency, e.g. in the case of project-based integration to bring financial gain; or to have more control, for example with geographical integration to get better insights into (the location of) various physical systems.

Some types of integration are more commonly referred to than others. We did not identify the informational type of systems integration, for example, while the geographical type of systems integration was identified in each of the perspectives. This suggests that urban water practitioners have a common understanding that the spatial alignment of systems is key to future-proofing. Likewise, one could argue that practitioners do not see a role for the integration of information (yet); however, we only included the types of integration that were explicitly mentioned in the interviews. For instance, in the research project of which this study was part, we identified a project in Amsterdam (the RESILIO project) involving smart climate adaptation measures that combine real-time weather forecasts with dynamic water storage. This example of informational systems integration would fit the description of perspective 2, yet it was not mentioned in the interviews, and therefore not included.

Table 3-9. Overview of the different types of Urban Water Systems Integration that are identified for each perspective. P stands for perspective and UWSI for Urban Water Systems Integration.

Type of UWSI *(and object of integration)*	P1: Future-proofing through coordination: finding space for urban challenges	P2: Future-proofing through climate adaptation: creating livable cities	P3: Future-proofing through recovery: challenging institutional structures	P4: Future-proofing through efficiency: being in control
Geographical *(space)*	Alignment of various urban infrastructure systems to fit in all demands	Designing streets in a climate-robust way, e.g., to prevent damage due to urban flooding	Fitting in storm water infrastructure across urban areas, allowing for natural replenishment	Better insights into the location of (planned) infrastructures to prevent costs from unnecessary damage or interventions later on
Physical *(resources)*	-	Green storm water solutions that provide social and environmental benefits as well	Resource recovery, e.g. decentralized water recovery in collaboration with companies	-
(infrastructures)	Multifunctional solutions as a means to align the various interests and to utilize all urban space available	Climate-proof solutions on roofs and buildings	-	-
Informational (*data)*	-	-	-	-
Project-based *(planning)*	Collective replacement through better coordination, creating a moment to balance between the different interests and objectives	Collective replacement to gain momentum for a climate-proof redesign of the street	-	Collective replacement, preferably on a district level, to save money and time

Furthermore, we found that a single type of integration could be characterized differently. For the geographical type of systems integration, for example, the drivers for integration, as well as their relevant spatial scale, are specific to each of the perspectives. In perspective 1, geographical integration is mainly about spatial alignment of the different urban infrastructures, considering the variety of interests and fitting in various system demands. Perspective 2 focuses on the inclusion of storm water infrastructure in the urban design, for instance, to prevent that other infrastructures interfere with the storm water flow and cause damage. Hence, while perspective 1 focuses on the scale of urban infrastructures and their challenges, we identified a smaller relevant spatial scale for perspective 2 (e.g. street-level). Likewise, the spatial scale and drivers differ for the perspectives 3 and 4: perspective 3 aims to fit in storm water infrastructure across urban areas to allow for natural replenishment, while in perspective 4, geographical integration is mainly about better insights into the location of physical infrastructures to prevent, for example, unnecessary damage.

3.5.2 Representation of the perspectives in the literature

All perspectives were, to some extent, reflected in the urban water literature. Perspective 1 (*Future-proofing through coordination: finding space for urban challenges*) resembles the literature that takes a systems approach to urban water management, for example Dunn et al. (2017). In addition, it has a link with the literature on urban (underground) space planning, concerning urban space limitations (Hooimeijer and Maring, 2018; von der Tann et al., 2019).

Perspective 2 (*Future-proofing through climate adaptation: creating livable cities*) corresponds to the body of literature that takes a more holistic approach to storm water management (see e.g. Fletcher et al., 2015). Various concepts such as urban drainage systems (SUDS) (Fletcher et al., 2015), sponge cities (Jiang et al., 2018) and blue-green systems (BGS) (Deletic et al., 2020) have been developed, all of which are based on integrating storm water infrastructure into the urban landscape in order to process water in a more sustainable way than conventional solutions do. Since perspective 2 sees climate adaptation as a means to create livable cities, it also bears similarities with the ideas of de Graaf and van der Brugge (2010) and Fratini et al. (2012), who argue that climate adaptation is actually key to improve the social and environmental conditions of cities.

The future-system depicted in perspective 3 (*Future-proofing through recovery: challenging institutional structures*) resembles the water cycle city state (Wong and Brown, 2009), which is the fifth of six developmental states that cities move through on their path toward increased water sensitivity. Likewise, the perspective overlaps with the literature on integrated urban water management (IUWM), aiming for a better physical and institutional integration of the water supply, storm water, and wastewater components of the urban water cycle (Mitchell, 2006). Similar to perspective 3, IUWM emphasizes the need for highly coordinated management to achieve such integration.

Perspective 4 (*Future-proofing through efficiency: being in control*) bears similarities with the view expressed by Marlow et al. (2013), who criticized the discourse on sustainable urban water management. They argued that consideration for changing urban water management practices should be based on "evidence-based arguments" and needs "valid economic assessments". This does not imply, though, that they are against change. They highlight, however, that the risks and benefits of innovations should be clear and that future systems should, in any case, be financially viable. Hence, similar to perspective 4, knowledge and efficiency are key to them. Along these lines, the perspective corresponds to the sewer asset management literature as well (e.g. Tscheikner-Gratl et al., 2019b). For instance, with regard to risk-based management, but also concerning collaborative rehabilitation of infrastructures (Tscheikner-Gratl et al., 2016b), as this offers financial benefits and provides the opportunity for future-proofing systems in a more efficient way.

Relating the perspectives to the literature, our results suggest that real-world perspectives are less conservative (i.e., less averse to change) than the traditional, technocratic viewpoint that is still depicted as the dominant perspective (see e.g. Dunn et al., 2017; Fuenfschilling and Truffer, 2016). We found that the ideas about more sustainable practices have a lot of support on the ground. Dutch practitioners generally agree that traditional urban water management practices need to change to prepare the system for the future, and they also have clear ideas about that. Moreover, perspective 4, which could be called the most conservative, is represented by the lowest number of participants (n=2). So, while the urban water literature typically portrays the conservative viewpoint as the dominant perspective in urban water practices, our results show differently. In addition, the literature commonly juxtaposes the sustainable viewpoint and the traditional, technocratic viewpoint (see e.g. Chocat et al., 2007; Marlow et al., 2013). Our results indicate, however, that practitioners' views are less dichotomous: the discussion is not so much about conservative versus sustainable, but rather about which sustainability challenges are most important to address.

3.6 Conclusions

Urban water systems are under increasing pressure, facing challenges such as climate change, urbanization, and population growth. Clearly, an integrated approach is needed to address these challenges and to prepare systems for the future. As integration is a wicked problem, practitioners disagree about the meaning of integration, as well as the opportunities and challenges they should focus on – for example, climate adaptation, resource recovery or collective replacement. A first step in future-proofing is, therefore, to gain a better understanding of the different perspectives that practitioners have about such integration. This could facilitate communication and structure the discussion about future urban water systems. In addition, insights into the differences between practitioner's viewpoints could help to build effective strategies that accommodate these differences, for example, by incorporating the various drivers that practitioners see for integration and considering different spatial scales.

This chapter has used Q methodology to study these viewpoints: a group of 30 urban water practitioners ranked a set of 43 statements about integration in future urban water systems into a normally distributed grid. In addition, we conducted interviews to get a better understanding of how participants made their decisions – and thus of their viewpoints. Using factor analysis, we subsequently grouped the individual perspectives into shared ones.

This resulted in four real-world perspectives of Dutch urban water practitioners on the role of integration for future water systems. For each perspective, at least two out of the four Urban Water Systems Integration types (Nieuwenhuis et al., 2021a) were identified, demonstrating that practitioners see an important role for integration in future systems. Furthermore, while the perspectives differ as to the opportunities and challenges to focus on, they all recognize that traditional water management practices need to change to prepare for the future. Perspective 1 focuses on coordination, perspective 2 on climate adaptation, perspective 3 on recovery, and perspective 4 on efficiency. We identified five key differences between the perspectives: their view on future systems, the meaning of integration, the role of it in future urban water systems, as well as the drivers and means to realize it. Despite these differences, we also see common ground between the perspectives. All perspectives recognize that sustainability challenges should be addressed, with collaboration shifting beyond sectoral boundaries. For example, practitioners generally agree that climate adaptation is needed, yet the sense of urgency, their motivation and the proposed means differ.

Further research is needed to generalize our findings, for instance, performing studies in different contexts (i.e., different environmental, technological and/or institutional conditions), or using quantitative methods like surveys, involving more practitioners and/or from outside policy-making, to understand how widely held each of these perspectives is. In addition, since Urban Water Systems Integration typically extends to other urban sectors, we recommend including practitioners from these related sectors (e.g., urban planners, architects, and road authorities), and identifying their perspectives as well. Despite this, our study provides promising insights for the scientific debate on future urban water systems, as well as for decision-making on integration:

- First of all, the four real-world perspectives suggest that the urban water sector is less averse to change than the literature portrays. For future research, we therefore suggest shifting away from the dichotomy of conventional versus sustainable, and rather address the decision-making challenges related to the implementation of integration. An in-depth case study involving different urban actors and looking at successful strategies to deal with the wicked nature of integration could provide useful insights.

- In addition, the perspectives, both their similarities and differences, provide fruitful ground for developing negotiated knowledge (De Bruijn et al., 2010, p. 146) or collaborative learning (Cuppen, 2012), where the various parties collaboratively explore the perspectives, seeking a common interpretation of the policy problem and its solution. Although such collaborative processes might be cumbersome, the basis of mutual agreement among urban water practitioners looks promising. As such, developing negotiated knowledge could be an effective way to deal with the wicked nature of integration (Nieuwenhuis et al., 2021a). Practitioners would collaboratively explore how integration can be defined and operationalized, while being aware that they may have different views of reality ("agree to disagree"). Recognizing the different perspectives of urban water practitioners presented in this chapter contributes to reaching such a negotiated view.

The four viewpoints empirically identified in this chapter provide valuable insights for both practitioners and scholars, and represent a substantial step towards future-proofing urban water systems.

Chapter 4

Operationalizing UWSI: Failures in storm water UWSI solutions and their root causes[12]

[12] This chapter is based on: Vollaers, V., Nieuwenhuis, E., van de Ven, F., & Langeveld, J. (2021). Root causes of failures in sustainable urban drainage systems (SUDS): An exploratory study in 11 municipalities in The Netherlands. ***Blue-Green Systems, 3***(1), 31-48.

4.1 Introduction

Traditionally, urban water management has focused on providing safe, reliable, and cost-effective water services. The protection of public health was at the heart of the development of sewer systems, and their construction has been a key development to modern city life. Together with centralized water supply, and large-scale water treatment facilities, sewer systems have become the dominant urban water system (Wong and Brown, 2009). Growing societal attention to pollution control and environmental protection, however, has led to the questioning of the effectiveness of traditional sewer systems (Chocat et al., 2007). In response to these environmental concerns, a push towards more integrated storm water solutions has emerged in the past decades (Qiao et al., 2018). This shift to novel integrated storm water solutions has received growing attention all over the world, and has led to the parallel development of new storm water concepts. Examples include sustainable urban drainage systems (SUDS), low impact development (LID) (Fletcher et al., 2015), and a more recent one, sponge cities (Jiang et al., 2018). These concepts are often used interchangeably, and sometimes together referred to as blue-green systems (BGS) (Deletic et al., 2020). Throughout this thesis, we use the term SUDS, which can be broadly defined as technologies and techniques used to manage storm water and surface water in a manner that is more sustainable than conventional solutions (Fletcher et al., 2015). These SUDS use principles such as infiltration and storage, thereby not only processing water, but also contributing to the urban environment in an environmental, as well as a social and economic sense (Zhou, 2014; Cohen-Shacham et al., 2016).

Over the past three decades, SUDS have been widely implemented in both newly developed and existing urban areas. They have become a viable alternative to the traditional sewer infrastructure. This does not imply, however, that SUDS always function appropriately (Marlow et al., 2013). We see at least three issues attributing to the malfunctioning of SUDS:

- First of all, SUDS make use of different technologies than conventional solutions, and thus also require different knowledge and skills for their implementation, their operation and maintenance (Brown and Farrelly, 2009). This shift to new technologies, to which practitioners are not yet familiar, potentially increases the risk of failure.

- Second, SUDS inevitably require crossing of conventional system boundaries, and there is only limited knowledge of what is happening at the interfaces between the previously unconnected systems (Veeneman, 2004). Unlike sewer pipes, SUDS are often located above the ground, extending to both public and private spaces such as streets, parks, and gardens. Sustainable urban drainage systems therefore set different requirements for other urban systems, which have not been designed for drainage functions previously (Hoang and Fenner, 2016). While the domains in charge of each of the other urban systems have much knowledge about their own system, there is only limited knowledge of what is happening at the interfaces between these systems, increasing the risk of failure (Nieuwenhuis et al., 2021).

- Lastly, the relational complexity introduced with SUDS adds to the likelihood of its malfunctioning (Fratini et al., 2012). Compared with decision-making on conventional drainage solutions, decision-making on SUDS inevitably involves actors from multiple disciplines (Hoang and Fenner, 2016; Cotterill and Bracken, 2020). These actors all have their own responsibilities and interests, as well as their system logics. This makes decision-making less straight forward, complicates communication, and fosters misunderstandings.

These issues illustrate that the malfunctioning of SUDS is not only a technical issue, but also relates to socio-institutional aspects: the different actors involved and the institutions that direct the perceptions and actions of these actors. How do these observations relate the urban water literature? So far, the malfunctioning and performance of SUDS has mainly been described in technical studies, often on a lab or pilot scale (Geiger et al., 2010; Scholz and Grabowiecki, 2007; Xie et al., 2019) or in clearly defined experimental settings. In addition, much of the available research focused on only a few issues, such as hydraulic performance (Chu and Fwa, 2019) or clogging of infiltration facilities (Boogaard et al., 2014; Scholz and Grabowiecki, 2007; Abbott and Comino-Mateos, 2001). A few studies looked at the socio-technical interactions between SUDS and the wider urban landscape (e.g. Hoang and Fenner, 2016; Fratini et al., 2012); however, these did not investigate the malfunctioning of SUDS in practice. Research on the overall performance of SUDS is thus scarce (Cotterill and Bracken, 2020).

Besides, while the management of SUDS has received little attention in the literature, sewer asset management, i.e., the maintenance and rehabilitation of sewer infrastructure to prevent malfunctioning, has received extensive attention (see Tscheikner-Gratl et al., 2019 for an overview). In addition, asset management practices are deeply embedded in institutions, with legal frameworks and guidelines that prescribe how to manage and operate sewers (and NEN-EN 13508-2:2003+A1:2011 nl (2020), see e.g. the standards NEN-EN 752:2017 (2017)). Since the 1980s, there has been a shift away from constructing new sewer infrastructure, towards the rehabilitation and maintenance of existing systems (Oomens, 1992). A similar shift is required for SUDS now, i.e., towards the management of SUDS.

Practitioners need to acquire new knowledge and develop their skills for the successful management of SUDS. The traditional socio-technical urban water system, comprising the infrastructure and all organizations and people directly and indirectly (researchers, education etc.) involved in operation and maintenance, has evolved over decades. This has resulted in well described and defined procedures. However, the socio-technical system has changed because of the implementation of SUDS (Cotterill and Bracken, 2020). Sustainable urban drainage systems have different design, operation, and maintenance requirements, and thus also need a different management approach. To foster the learning of practitioners, and to anticipate the malfunctioning of SUDS, it is crucial to better understand the failures that occur in SUDS, as well as their underlying causes.

This chapter works towards a better understanding of failures occurring in SUDS, adopting a socio-technical systems perspective. We use an exploratory case-study approach, (1) to identify technical failures of SUDS occurring in practice, and (2) to explore the root causes underlying the malfunctioning of these SUDS based on interviews with professionals. These insights serve to anticipate failing systems, aiming to improve the functioning of SUDS and to add to their reliability. As such, this study has the objective to contribute to a renewed socio-technical urban water system with more sustainable water management practices.

4.2 Methods

4.2.1 Site selection

This study investigates failures in SUDS using a case study approach. In total, 70 cases in eleven different municipalities throughout the Netherlands were collected. Table 4-1 provides an overview of the municipalities and the site characteristics. Selection criteria were the presence of SUDS and the willingness of an urban water professional to participate in the research, as well as the geographical location and the type of area (greenfield or brownfield areas).

4.2.2 Data collection

In each municipality, we collected cases of technical failures in SUDS through site visits. Additionally, we conducted semi-structured interviews with urban water professionals who were involved in the implementation and/or operation of the SUDS.

The cases were collected based on what the professionals identified as malfunctioning SUDS, i.e., where the system failed to achieve its intended function according to the urban drainage professionals. Every single location where the professional indicated a failure in the SUDS constitutes a unique case. These cases were photographed, and a short description of the situation was added based on the information given by the professionals.

Table 4-1. Overview of the site characteristics. The type of area indicates whether the SUDS were built in a greenfield area, or in a redeveloped brownfield area. In case of a greenfield area, the specific neighborhood is provided in parentheses.

Municipality (neighborhood in parentheses)	Type of area	Type of SUDS	Number of failures
Eindhoven (Meerhoven)	Greenfield	Subsurface storage	4
Nijmegen (Centrum)	Green- and brownfield	Bioswales	2
Nijmegen (Waalsprong)	Greenfield	Bioswales	10
Utrecht (Leidsche Rijn)	Greenfield	Bioswales, permeable pavement	10
Almere (Homeruskwartier)	Greenfield	Bioswales, permeable pavement	7
Zwolle (Stadshagen & Centrum)	Green- and brownfield	Permeable pavement, soakaway crates	10
Gouda	Brownfield	permeable pavement, soakaway crates	3
Tilburg	Brownfield	Facade gardens	1
Diemen	Brownfield	Above-ground storage, soakaway crates	1
Dordrecht	Brownfield	Underground storage	2
Rotterdam	Brownfield	Permeable pavements, soakaway crates, bioswales, subsurface storage	10
Amsterdam	Brownfield	Bioswales, subsurface storage, permeable pavement	10

To maintain a clear scope in this exploratory research and to enhance consistency between the analyzed cases, we decided to interview urban drainage professionals only. The interview questions focused on three main issues: the general experiences that these professionals had with SUDS, the failures of SUDS in the specific study site(s), and their view on the underlying reason for these failures.

4.2.3 Data analysis

4.2.3.1 Failure characteristics

All failures were analyzed based on four SUDS characteristics: technical failure, failing function, failure location and phase of failure. Table 4-2 provides an overview of these characteristics and their corresponding categories. During the site visits, we iteratively refined the categories. To ensure they properly describe the data set, we subsequently verified them during the interviews.

Technical failure

The categories for technical failures were primarily based on previous research. The technical failures most prevalent in the literature are the following: clogging (Abbott and Comino-Mateos, 2001; Boogaard and Wentink, 2007), low maintainability of SUDS (Boogaard and Wentink, 2007; McDonald, 2018), insufficient slope for the conveyance of water (Pötz and Bleuzé, 2016), and illicit connections in subsurface infiltration systems (Boogaard and Rombout, 2008; Heppenhuis, 2020). In case these categories were not able to describe the failure properly, new technical failures were added after consulting with the professionals.

Failing function, failure location and phase of failure

The other case characteristics, which are more descriptive in nature, are documented according to the categories presented in Table 4-2. The categories for the case characteristic *failure location* were grouped into *internal* and *interface locations*. *Internal* refers to failures occurring within a single urban system, and *interface* refers to failures occurring at the physical interface between two systems.

4.2.3.2 Root causes

To find the underlying reasons for the technical failures occurring in each of the SUDS, eleven interviews with urban drainage professionals were conducted. During these interviews, one or more causes were identified for each case. To come to a comprehensible list of root cause, we subsequently removed double causes and rephrased overlapping ones. We used a socio-technical systems perspective to

Table 4-2. Overview of the four case characteristics and their initial categories. These categories were further refined during the site visits. The case characteristic failure location is subdivided into internal and interface locations.

Case characteristics	Description	Categories
Technical failure	The technical issue that causes malfunctioning	Clogging; Poor maintainability; Insufficient slope; Illicit connections
Failing function	The main hydraulic function of the system	Conveyance; Infiltration; Storage
Failure location	The location of the failure	Internal locations: roof; house; private plot; street; public open space; water body Interface locations: Between roof and house; Between house and private plot; Between private plot and street; Between street and public open space; Between public open space and surface water body
Phase of failure	The project phase where the failure originated from	Design phase; construction phase; user/maintenance phase

develop a balanced set of causes; i.e., comprising both causes with a technical nature, and causes related to the behavior of actors and their institutions. When root causes had only one or two cases, we looked for a more general description of that root cause, such that it could be assigned to at least three cases, whilst each case could (still) be well described by one of the root causes.

4.2.3.3 Analysis of the technical failures and root causes

In order to explore the relationship between the technical failures and the other case characteristics, we combined data on the technical failures with those on the other case characteristics. In addition, we combined data on the causes underlying the technical failures with data on the four case characteristics of SUDS.

4.3 Results & Discussion

In total 70 cases of failure were identified in 11 municipalities throughout the Netherlands. The database of all cases is provided as supplementary material to the article that this chapter is based on (see Supplementary Material: Database of 70 failure cases in Vollaers et al. (2021))

4.3.1 Technical failures

Eighteen different technical failures were identified, eight of which were mentioned earlier in literature and ten of which followed from the empirical data (see Table 4-3).

4.3.2 Failing function

Table 4-4 gives an overview of the number of cases for each failing function. The most commonly observed technical failures for each of the three functions of SUDS (infiltration, transport or storage) are the following:

- **Infiltration:** *Clogging* (9 out of 36 cases*)* was identified as the most common technical failure occurring in infiltration systems. This is in line with previous research, as clogging has been frequently associated with the failing of swales, permeable pavements, and infiltration crates (Bergman et al., 2011; Hatt et al., 2009; Scholz and Grabowiecki, 2007).
- **Conveyance:** The most common technical failure identified for conveyance systems was *Interference with obstacle* (7 out of 25 cases) (see Figure 4-1 for an example). This technical failure was previously mentioned by Boogaard et al. (2006). The second most common failure is *Insufficient slope* (4 out of 25 cases), which is also in line with previous studies.
- **Storage:** The most common technical failure of storage systems were *limited freeboard* and *interference with obstacle* (both 2 out of 9 cases). We did not find relevant literature about these failures.

Table 4-3. Overview of the number of cases for each technical failure. The gray color highlights the technical failures that are based on empirical research. The other ones are found in the literature.

Technical failure	Number of cases
Interference with obstacle	11
Clogging	10
Incomplete design	8
Wrong construction material	6
High groundwater table	6
Outlet not fitted correctly	5
Insufficient slope	4
Local sagging	3
Wrong construction elevation	3
Poor maintainability	3
Limited freeboard	2
Poor walkability	2
Accessibility of drainage system	2
Poor split binding (wrong material used)	2
Pollution	1
Illicit connections	1
Unfavorable roof design	1
Total	70

Table 4-4. Overview of the number of cases for each failing function

Failing function	Number of cases
Infiltration	36
Conveyance	25
Storage	9
Total	70

Figure 4-1. Two cases (#13 and #15) of technical failures in SUDS with a failing function of conveyance. Left: an obstacle interferes with the transport of water by an open gutter. Right: due to insufficient slope of the garden, the storm water flows into the shed.

4.3.3 Failure location

Table 4-5 presents an overview of the failure locations observed in the 70 cases, differentiating between *internal locations* and *interface locations*. *Internal* refers to failures occurring within a single urban system, and *interface* refers to failures occurring at the physical interface between two systems. See Figure 4-2 for an illustration of the failure locations per type of SUDS.

Table 4-5 reveals that almost 40% of the failures occur at the physical interfaces of urban systems, i.e., where the physical infrastructures of two urban systems meet. These failures are thus not related to internal processes of SUDS, such as their hydraulic performance. Figure 4-2 shows that such interfaces are typically associated with physical changes in surfaces (e.g., paved surface to vegetation), height differences (e.g. a sidewalk) and structures (e.g. a fence), suggesting that these make them prone to failure. In addition, physical interfaces often mirror the boundaries of ownership and/or responsibility (e.g., private vs. public ownership, or between two different public domains). Ambiguity as to who is responsible for maintenance at such interfaces could therefore be the reason for the malfunctioning of these SUDS.

The observation that interfaces play an important role in the malfunctioning of SUDS is also supported by previous research: Nieuwenhuis et al. (2021a) looked at integrated urban water solutions, and found that interfaces, which emerge at the locations where previously unconnected systems become interconnected, are an important source of uncertainty. These make it more difficult to understand the overall system behavior, and thereby increase the risk of failure. They explained that such interfaces involve many potential mismatches, which could be both technical and socio-institutional in nature – thus mismatches related to physical changes in surfaces, and those related to the boundaries of responsibility and ownership, respectively.

Table 4-5. Overview of the number of cases for each failure location.

Failure location	Number of cases
Internal locations	44
Public open space	21
Street	19
House	2
Private plot	1
Roof	1
Water body	0
Interface locations	26
Between private plot and street	11
Between street and public open space	5
Between private plot and water body	4
Between house and private plot	4
Between public open space and water body	2
Total	70

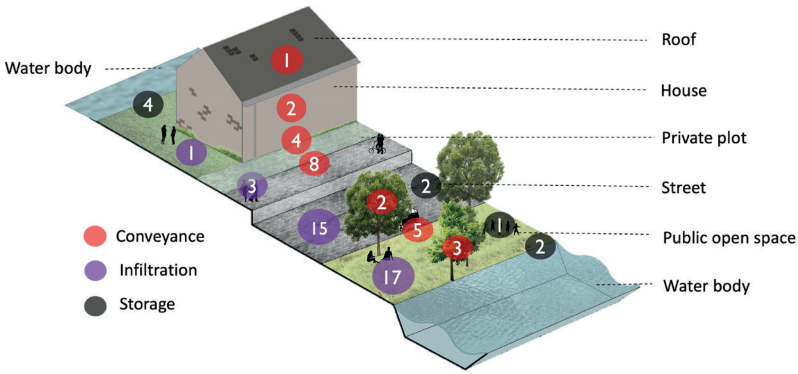

Figure 4-2. Overview of the number of technical failures of SUDS that occur at different locations in the urban area. The colors indicate the hydraulic functions of the SUDS.

4.3.4 Phase of failure

Table 4-6 provides an overview of the phases where the failures originate from. Fifty percent of the failures (35 cases) originated from the design phase. The construction (19 cases) and the user/maintenance phase (16 cases) together accounted for the other 50%. Hence, in each of the project phases a significant proportion of failures finds its origin, meaning that each project phase needs attention to develop well-performing SUDS. This is supported by the research of Rijke et al. (2008) who concluded that all phases of the development process are important to successfully implement innovative water systems.

4.3.5 Root causes

This section provides an overview of the root causes identified for the technical failures occurring in the 70 SUDS. Based on the interviews with urban water professionals, an initial list of 36 causes was identified (see Appendix C). This was subsequently reduced to a final set of 11 unique root causes, based on the procedure outlined in Section 4.2.3.2. For 21 cases we assigned two root causes, and for the remaining cases (49) only one cause was assigned. Table 4-7 shows the final list of root causes. The grey highlights indicate the most prevalent root causes, which are discussed in more detail. For the other ones, only a brief description is provided. We subsequently discuss the final set of root causes as a whole, reflecting on their nature.

4.3.5.1 The final eleven root causes

Root cause 1: embedded practices of involved actors

This root cause relates to the dominant and traditional thoughts, knowledge, and skills of practitioners in various urban sectors (e.g., water, green or roads), leading to the incorrect design, construction, or maintenance of SUDS, and ultimately its malfunctioning. Sometimes, these embedded practices are based on guidelines, but they could also be routines. Four interviewees explained that particular ways of

Table 4-6. An overview of the number of cases for each phase of failure.

Phase of failure	Number of cases
Design phase	35
Construction phase	19
User/maintenance phase	16
Total	70

Table 4-7 Overview of the final set of 11 root causes. The five root causes that are highlighted in grey are the most common root causes.

Root causes	Number of cases
Embedded practices of involved actors	13
Poor communication between different actors	12
Incomplete knowledge about the interactions of SUDS with other urban systems	11
Incomplete knowledge about the technical performance of SUDS	11
Lack of experience in constructing SUDS	10
Fitting SUDS to unforeseen circumstances	8
Actual use of SUDS by humans	6
Poor communication between phases	6
Lack of knowledge how to maintain SUDS	6
Poor maintainability of SUDS	5
Ambiguity about the maintenance responsibilities	3
Total	91

working or traditional measures can be so deeply embedded in practices that they are hard to change. They mentioned, for example, the construction of raised edges around green spaces (see Figure 4-3) and that of convex-shaped roads. Both hamper the handling of storm water above ground, and thus limit the functioning of SUDS.

Figure 4-3. Case #30: a facade garden, which has been assigned the root cause embedded practices of involved actors. A facade garden is typically constructed surrounded by raised borders. Preventing runoff to be drained into the garden, this reduces the effectiveness of the SUDS.

Our findings are supported by the work of Roy et al. (2008), who found that standards and engineering guides sometimes prevent the use of SUDS in a way that their advantages are actually utilized; for example, they noticed that codes prescribe the installation of gutters and curbs alongside roads, and thus also alongside those with permeable pavement. This illustrates that the urban drainage system is a socio-technical system, and that new SUDS technologies therefore also require changing the socio-institutional system. Sustainable urban drainage systems impose new demands on the people in charge of designing, constructing, and maintaining such systems, and practitioners therefore need to develop new knowledge and skills, e.g., through training. In addition, policies, guidelines, and standards need change, to make sure they support the proper design, implementation, and use of SUDS. Kiparsky et al. (2013) refers to this as *institutional innovation,* and argues this is of similar importance to technological innovation.

In addition, the multifunctionality of SUDS implies that SUDS set different requirements for other urban systems, which have not been designed for drainage functions previously (Hoang and Fenner, 2016). Besides the municipal urban drainage department, there are many other actors involved. These all work according to their own rules and practices, whilst influencing the performance of SUDS. Hence, not only the physical interfaces (see Section 4.3.3) that emerge with the shift to SUDS should be managed, but the urban drainage sector should also deal with the socio-institutional interfaces; i.e., the other actors in the urban environment and the institutions that guide these actors.

Root cause 2: poor communication between different actors

This root cause concerns both the communication between actors belonging to a specific group, such as between actors within the municipal sewer department, and the communication between different actor groups, e.g., between two different departments at the municipality, or between the municipality and external parties such as project developers, civil engineering consultants and/or architects.

The multifunctionality of SUDS implies that decision-making on the design, implementation and maintenance of SUDS involves actors from different disciplines. These actors all have their own responsibilities and interests, as well as their (sector-specific) terminology. Hence, they are not always naturally aware of the water function of SUDS, neither do they have the “urban water vocabulary.” This complicates communication, thereby increasing the risk of failure.

An example of such poor communication leading to malfunctioning SUDS is illustrated in Figure 4-4. The interviewee explained that architects typically want to minimize the distance between the ground-floor level of the house and the water level (in this case 0.15 meter), aiming for a closer connection with the water – a so-called "living-on-water-experience". The municipality, however, generally designs water systems with a large freeboard (in this case 0.70 meter) to increase the storage capacity of the water, which could prevent urban flooding after heavy rainfall, as well as water shortage in case of drought. These requirements, however, were not communicated clearly in the decision-making process, which eventually resulted in the houses being constructed with little freeboard. As the storage capacity now had to be realized elsewhere in the urban water system, this brought along high costs.

Figure 4-4. Case #60 has been assigned the root cause poor communication between different actors. Due to lacking communication between the architect and the municipality, the houses were built only 0.15 meter from the water level. This minimized the storage capacity of the surface water, while the water was initially designed as a storm water detention pond with a freeboard of 0.70 meter.

Root cause 3: incomplete knowledge about the interactions of SUDS with other urban systems

This root cause refers to the lack of knowledge of urban practitioners about the interactions of SUDS with other urban systems in public space. Several interviewees indicated that interactions of SUDS with other systems are hard to predict beforehand. They explained that there are many different types of SUDS, and that their functioning highly depends on local conditions. This makes it very challenging to predict the interactions that will take place at the interfaces with other urban systems.

Figure 4-5 presents an example of the unexpected impact of car traffic on the performance of permeable pavement. After the implementation of the pavement, it turned out that car traffic resulted in friction between the stones. This damaged the joint fillings between the bricks, and eventually led to their disappearance. As the practitioners had no experience with permeable pavement yet, they did not anticipate the long-term effects of cars on this type of porous pavement construction.

Previous research pointed out that implementing SUDS in a complex urban environment results in new system interactions, and could potentially pose negative impacts on the functioning of both SUDS and other urban systems (Hoang and Fenner, 2016). Such interactions emerging at the interfaces between previously

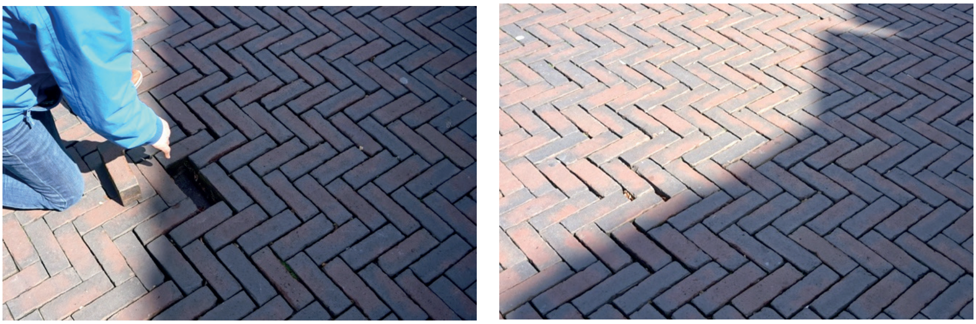

Figure 4-5. Case #29 has been assigned the root cause Incomplete knowledge about the interactions of SUDS with other urban systems. Due to the impact of cars as well as street sweeping, the joints of the permeable pavement bricks vanished. This decreased the overall performance of the SUDS; i.e., the stability of the road surface.

4

unconnected systems are an important source of uncertainty: they increase the complexity, making it more difficult for decision-makers to understand the overall system behavior (Nieuwenhuis et al., 2021a).

Root cause 4: incomplete knowledge about the technical performance of SUDS

This root cause represents the lack of knowledge about the internal processes that occur within SUDS. Four interviewees explained that this incomplete knowledge typically stems from the limited monitoring that is carried out in SUDS. They argued this prevents learning, and results in unnecessary failures. In addition, one interviewee reported that in some cases, designers do not have the knowledge and/or experience to properly understand the internal processes occurring in SUDS. This relates, for example, to incomplete knowledge about the subsoil. As compared to sewers, the subsoil forms an important part of SUDS, particularly in the case of infiltration facilities. The design is then often based on the very limited information available about the subsoil, if at all. When SUDS are then constructed in practice, the subsoil sometimes has other characteristics than expected, resulting in malfunctions. For instance, the soil contains more clay, or groundwater levels are higher than expected, decreasing the permeability of the soil, or reducing the subsurface storage capacity, respectively. An example is provided inFigure 4-6.

These findings are supported by the empirical study on Dutch SUDS of Boogaard et al. (2006), who found that the technical knowledge on SUDS is often still limited when implemented.

Root cause 5: lack of experience in constructing SUDS

As SUDS are relatively new and still developing, the interviewees mentioned that constructors often have limited experience in the installation of such systems. Moreover, the construction of SUDS is less straight-forward than that of sewer networks: there are many different types of SUDS and their construction depends on

Figure 4-6. Case #33 has been assigned the root cause incomplete knowledge about the internal technical processes. The pavers were separated by joints filled with a permeable material, allowing water to infiltrate. Even after a small rainfall event, however, water remained ponding for at least one hour. As such, it was thought that the permeable material had become clogged, leading to a malfunction of the SUDS.

case-, as well as location-specific conditions. The lack of experience makes it harder for constructers to anticipate the diverse conditions, and at the same time, the diversity complicates the gaining of general construction experiences with SUDS.

In addition, one of the interviewees explained that municipalities frequently hire external consultants to represent the municipality for construction supervision. This increases the risk of construction failures, as the external people often have limited background knowledge of the systems and their requirements. Hence, in addition to the experience of constructors, the experience of contractors and/or supervisors is crucial to the proper functioning of SUDS (Moglia et al., 2011).

Root cause 6: fitting SUDS to unforeseen circumstances

This root cause relates to the adjustment of the layout or design of SUDS due to circumstances that were not anticipated in the design phase. Existing urban infrastructure, both below and above the ground (e.g., cables, pipelines, or trees), could physically limit the construction possibilities. This problem is particularly severe in areas without detailed geological surveys or systematic infrastructure records. To deal with the "unpleasant surprises," workers could then decide to make small adjustments to the design, such that they can continue the construction process. These adjustments, however, could, significantly reduce the functionality of SUDS.

This root cause was also found in previous research of Moglia et al. (2011)who stated that in the construction phase of SUDS the conditions often turned out to be different than expected. Based on, for instance tacit knowledge, (experienced) contractors then decided to change the design.

Root cause 7: actual use of SUDS by humans

This root cause relates to the actual use of SUDS in practice: after implementation, people could use the SUDS in a way that was not accounted for in the design. They could, for example, put a flowerpot in the gutter (Figure 4-7). The rain pipe collects the storm water from the roof and discharges the storm water into the gutter at street level. The water is then transported overland, and thus kept visibly (as opposed to the traditional subsurface lateral house connection), towards the infiltration facility. When placing a flowerpot in the gutter, the intended flow path of the storm water is blocked.

This root cause may stem from the fact that citizens are only limitedly aware of the concept of SUDS, as well as their role in the functioning of SUDS (Roy et al., 2008). In addition, Zhang and Chui (2018) showed that the willingness of the (uninformed) public to be involved in SUDS practices is not self-evident: they identified *lack of public interest* and *lack of public support* as two significant barriers to the implementation of SUDS.

Root cause 8: poor communication between different project phases

This root cause refers to the poor communication between actors involved in different phases of the development process, i.e., the design, construction, and user/maintenance phase. One interviewee mentioned that it sometimes happened that, although technical drawings displayed the new design, e.g. a road design that ensures proper drainage of the runoff to an infiltration facility, it was still built according to traditional means.

This also relates to the fragmentation of the current urban planning process, resulting in the loss of information or knowledge during the transition from one project phase to the next (see e.g. de Graaf and van der Brugge, 2010).

Figure 4-7. Case #8 has been assigned the root cause actual use of SUDS. A flowerpot was placed in front of a dwelling's water outlet, preventing water to be discharged properly.

Root cause 9: lack of knowledge how to maintain SUDS

Root cause 9 refers to the incomplete knowledge of operators on how to properly maintain SUDS. Five interviewees stated that operators are not always acquainted with the maintenance required for new systems. This could lead to incorrect or too little maintenance, ultimately resulting in the malfunctioning of SUDS. The work of Boogaard and Rombout (2008) supports this finding: they concluded that Dutch municipalities are often not aware of the maintenance requirements of SUDS.

Root case 10: poor maintainability of SUDS

This root cause refers to the sometimes-limited possibilities for maintenance, for instance, due to the inaccessibility of (some parts of) SUDS. This finding is in line with previous empirical research: Boogaard and Rombout (2008) stated that many infiltration facilities are difficult to inspect and clean. They argued that the maintainability of SUDS is key to their functionality, and that it should therefore be considered in the design phase.

Root cause 11: ambiguity about the maintenance responsibilities

It is often unclear who is responsible for the maintenance of SUDS. This ambiguity typically stems from the system interfaces (see Section 3.3) that emerge with the shift to integrated urban water solutions. In addition, the construction of SUDS may lead to shifting responsibilities. This implies that a significant role in the maintenance of SUDS could be with parties whose key-priority is not water-related, like road authorities in the case of permeable pavement.

4.3.5.2 Reflection on the nature of the root causes

Looking at the list of root causes as a whole, Table 4-7 on page 80 reveals that the root causes are mainly socio-institutional, rather than technical in nature. Hence, root causes typically relate to behavior of actors or the institutions that direct the perceptions and actions of these actors, concerning issues such as communication, responsibility, knowledge, experience, routines, and guidelines.

On the one hand, this finding could result from the phrasing of the root causes. For example, for the root cause 3, 4 and 10 (respectively, *incomplete knowledge about the interaction of SUDS with other urban systems*, *incomplete knowledge about the technical performance of SUDS,* and *poor maintainability of SUDS*) one could argue that the root causes are (mainly) related to the physical infrastructure. However, also for these root causes, we see a clear relationship with actors and institutions; i.e., that failures could be prevented, by e.g. better instructions, communication between actors or through evaluation.

On the other hand, the reason that we mainly identified root causes related to actors and institutions might be that SUDS are still relatively new. Most of the SUDS in our database are not yet at the end of their technical lifetime, suggesting that our list is not (yet) exhaustive. While our list of root causes could thus be further extended, Table 4-7 nevertheless shows that the socio-institutional system is a significant contributor to malfunctioning SUDS. This suggests that the socio-institutional infrastructure is not always properly aligned with the techniques and technologies used in SUDS, and that failures could be prevented if matters such as communication and guidelines would be given more attention.

4.3.5.3 Relationship between the root causes and case characteristics

Root causes versus failing function

Figure 4-8 gives for each of the root causes a breakdown of the number of cases by the different hydraulic functions of SUDS (*conveyance*, *infiltration,* and *storage*). This reveals that the different SUDS types are not equally affected by the root causes.

On the one hand, Figure 4-8 shows that ten out of the 11 root causes have been assigned to more than one of the SUDS' functions, illustrating that root causes are not necessarily function specific. On the other hand, Figure 4-8 reveals that some causes were frequently assigned to particular types of systems, while these causes were not (or not often) identified for the other systems. This suggests that there is a relationship between specific root causes and the hydraulic principles of SUDS (i.e., infiltration systems process storm water by means of infiltration, and conveyance systems process water through draining it via above-ground structures).

Based on this information, specific recommendations for each of the system types could be made. For example, root cause 4, *incomplete knowledge about the technical performance of SUDS,* is the most common root cause for infiltration systems (n=10), while this root cause has not been assigned to conveyance systems (and has only been assigned to one failing storage system). Hence, information on technical performance is of particular importance for infiltration SUDS.

In addition, Figure 4-8 shows that the root causes 1, 2, 3 and 5 (respectively, *embedded practices of involved actors, poor communication between different actors, incomplete knowledge about the interaction of SUDS with other urban systems* and *lack of experience in constructing SUDS)* are the most common root causes for failing conveyance systems. These four root causes are all related to the interaction and involvement of non-water-related actors, suggesting that the performance of conveyance SUDS is dependent on the actions of other actors. Conveyance systems process storm water through above-ground drainage, and therefore interact with many other infrastructures in the urban environment (e.g., roads, curbs, gardens, speed bump, lampposts), as well as their responsible actors. This suggests that, to minimize failures in conveyance systems, both the physical and socio-institutional interfaces between SUDS and other urban systems deserve extra attention.

Root causes versus phase of failure

Failures can origin from the design or construction phase, or sometimes they arise later during the user/maintenance phase. Figure 4-9 maps, per root cause, the number of failures that origin from each of the project phases, providing insights into which issues need most attention in particular project phases.

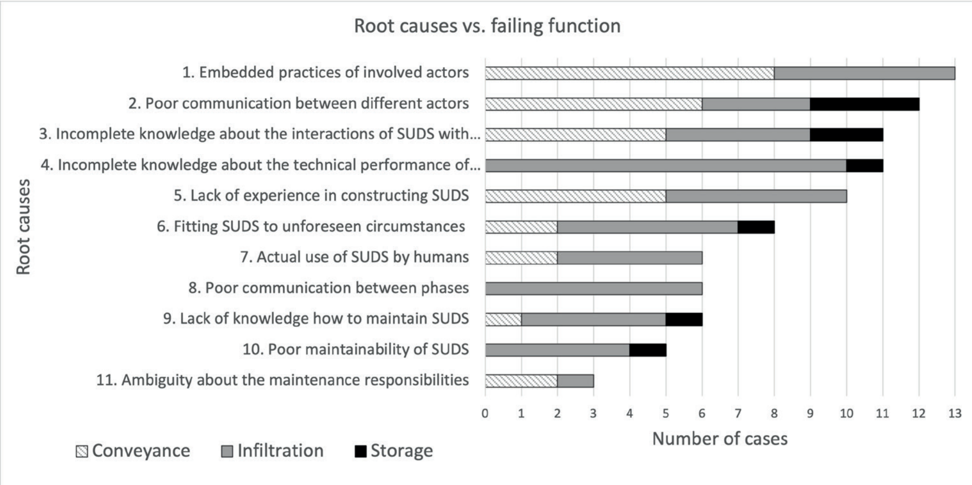

Figure 4-8. Number of failures in SUDS of a certain failing function for each root cause.

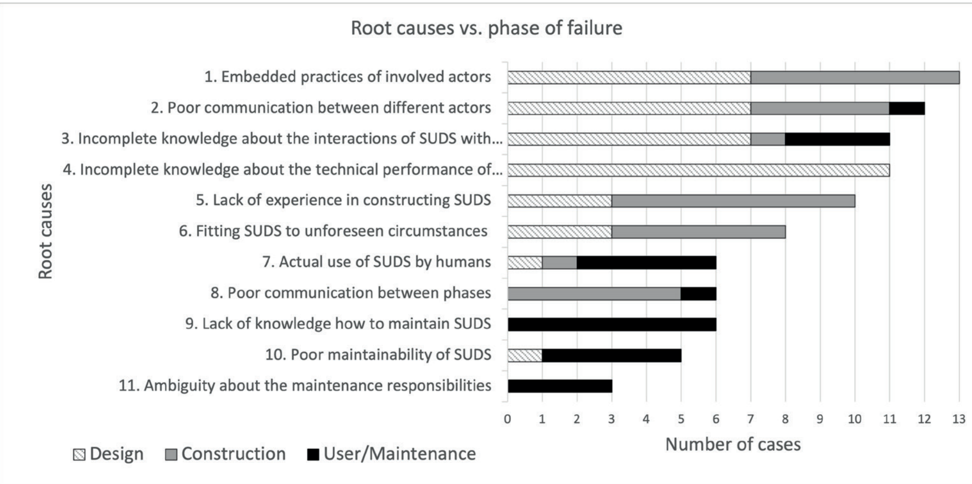

Figure 4-9. Number of failures that origin from each of the project phases, per root cause.

For the design phase, four root causes (number 1, 2, 3 and 4) were identified as the most common causes underlying technical failures: *Embedded practices of involved actors, Poor communication between different actors, Incomplete knowledge about the interactions of SUDS with other urban systems* and *Incomplete knowledge about the technical performance of SUDS*. These four root causes mainly relate to the interaction of actors with the technical system. Conventional storm water systems are well-developed from a socio-technical perspective, which is still progressing for SUDS. This suggests that, for the design of SUDS, it is crucial that the social system is interconnected with the technical system.

With respect to the construction phase, we found that technical failures are most often caused by the *Lack of experience in constructing SUDS* (root cause 5). This illustrates the importance of involving constructors in the implementation of SUDS: new systems do not only require advanced knowledge from engineers and designers, but also require different skills and knowledge from constructors. Hence, more attention should be paid to educate constructors about, e.g., what the new techniques and technologies entail, why new requirements are set and what the critical issues for construction are.

With respect to the failures originating from the user and maintenance phase, Figure 4-9 reveals that the most dominant root causes are 7, 9 and 10: A*ctual use of SUDS, lack of knowledge how to maintain SUDS* and *poor maintainability of SUDS*, respectively. All these root causes relate to a certain lack of knowledge from users and operators on how to handle SUDS. Actors in charge of maintenance have to be well-involved such that they know what maintenance is required for certain types of systems and how these maintenance practices should be performed.

Overall, Figure 4-9 reveals that all three project phases are important to consider for the development of new systems: root causes have been assigned in the same order of magnitude to each of the project phases, and eight out of the eleven root causes appear in two or more project phases. Hence, root causes can, in many cases, not be attributed to just one project phase. For example, *Poor communication between different actors* (root cause 2) can lead to failures in the design phase, but also in the construction and maintenance phase. In addition, root cause 9, *Lack of knowledge how to maintain SUDS*, which (in this research) has only been assigned to failures in the maintenance phase, illustrates that even if SUDS are well designed and implemented, failures can still occur in the user and maintenance phase.

Root causes versus failure location

Technical failures occur at several locations within SUDS (see Figure 4-2 at page 78). We identified 11 failure locations (see Table 4-5 at page 78), and grouped these into two categories: internal failure locations (failures occurring within a single urban system) and interface failure locations (failures occurring at the physical interface between two systems). Figure 4-10 combines these data with data on the root causes, showing that nine out of the 11 root causes occurred at both internal and interface locations. This reveals that to prevent the malfunctioning of SUDS, both these locations deserve attention in preventing SUDS failures.

In addition, with respect to the interface locations, Figure 4-10 shows that the most dominant root causes are number 1, 2, 3 and 5 (*Embedded practices of involved actors, Poor communication between different actors, Incomplete knowledge about the interactions of SUDS with other urban systems* and *Lack of experience in constructing SUDS)*. All these root cause relate to social aspects (i.e., skills and knowledge), suggesting that the failures at the interfaces of SUDS are often socio-institutional in nature, rather than strictly technical.

For the internal locations, we found that root cause 4 (*Incomplete knowledge about the technical performance of SUDS)* was clearly the most dominant one: it was assigned to 11 cases. Apparently, due to a lack of information about their functioning, SUDS frequently fail. To prevent such failures, we argue that malfunctioning should be anticipated; i.e., through investigating the failure and evaluating the SUDS in its real-world environment. Such evaluation is key to improve the performance of SUDS, providing information on how to adapt the SUDS. Documenting and sharing this information fosters learning, eventually contributing to the reliability of SUDS.

4.4 Conclusion and outlook

Sustainable urban drainage systems are widely implemented systems that form an essential part of contemporary storm water management. Like any other part of the

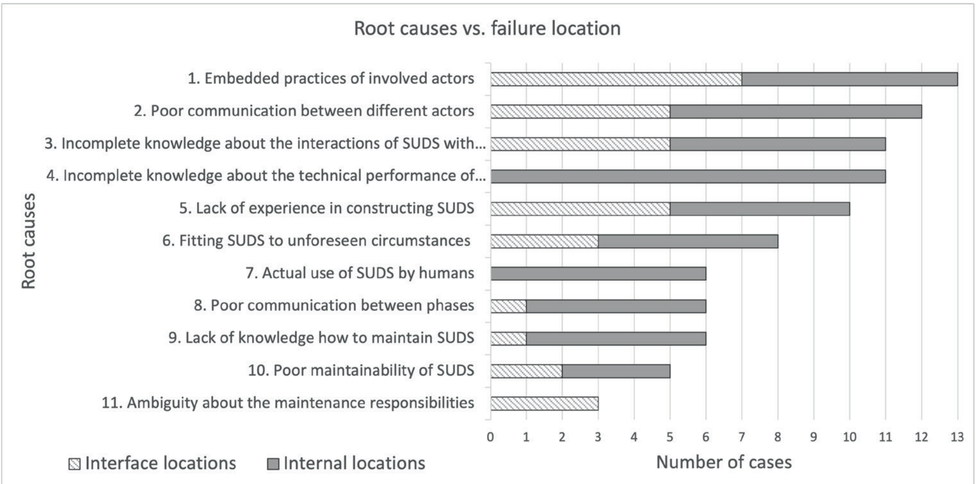

Figure 4-10. Number of failures in SUDS failure location, for each root cause.

urban water infrastructure, piped or non-piped, SUDS are subject to failure. Based on observations, this exploratory study has identified 70 failure cases in various types of SUDS in 11 Dutch municipalities. The analysis of these failure data reveals that

- failures often (more than one third) occur at the interfaces of different urban systems; i.e. where the physical infrastructures of two urban systems meet, such as at the interface between a private plot and a public street.
- failures affect each of the defined hydraulic functions of SUDS: infiltration, conveyance, and storage, with respectively, *clogging*, *interference with obstacle*, and *limited freeboard* and *interference with obstacle*, as the most noticed failing functions.
- failures can origin from the design phase, construction phase, as well as the user/maintenance phase.

4

These findings suggest that a decent SUDS construction check upon completion (thereby also considering the user/maintenance phase, as well as the transfer between phases) has the potential to reduce the number of failures. Special attention should be paid to the interfaces with other urban systems (e.g. green, roads and private plots).

Based on interviews with urban water professional, we have identified a final list of 11 causes underlying these failures, with all failures being linked to one or two of the root causes. The most common root causes identified are

- *embedded practices of involved actors*
- *poor communication between different actors*
- *incomplete knowledge about the interactions of SUDS with other urban systems*
- *incomplete knowledge about the technical performance of SUDS*
- *lack of experience in constructing SUDS.*

Several of the most common root causes are merely socio-institutional, rather than technical in nature. This suggests that not only the physical interfaces that arise with the shift to SUDS, but also the socio-institutional changes that this shift requires should be addressed. To define *how* they should be addressed (for instance, by implementing new guidelines and standards, or particular policy instruments, or by changing decision-making processes), further research should identify what the socio-institutional nature of causes can be attributed to. For example, to the time it takes for institutions to become embedded, i.e. to develop new practices, skills and knowledge, or to the inherently more integrated character of SUDS compared to traditional sewer systems; i.e., next to water managers, various other "professional" actors, as well as inhabitants play an important role in SUDS. Furthermore, we argue that additional interviews with professionals from other disciplines and sectors, such as landscape architects and urban planners, could provide valuable insights, and may lead to other, new, root causes that our approach has not been able to reveal.

Finally, we encourage further research on the performance of SUDS in practice, with, for instance, different viewpoints, levels of detail, and/or local conditions. Our study provides valuable insights into the occurrence and root causes of failures in SUDS, and thereby contributes to a renewed socio-technical urban water system with more sustainable water management practices. We invite other researchers to analyze other sustainable storm water systems, to foster learning, anticipate failures and improve the performance of SUDS in practice.

Chapter 5

Organizing UWSI: Managing the tension between innovation and operation activities[13]

[13] This chapter is based on: Nieuwenhuis, E., Cuppen, E., Langeveld, J., & de Bruijn, H. (2023). Understanding crosssectoral innovations for urban water management through the lens of organizational ambidexterity. *Urban Water Journal*.

5.1 Introduction

Urban areas are highly dependent on their urban water systems, providing essential services such as access to clean drinking water, public health protection and flood control. Global developments like climate change, population growth and resource limitations increasingly threaten the provision of these services: changing weather patterns, increasing anthropogenic activities, and depleting natural resources lead to environmental and public health issues and increase the risk of urban flooding (e.g. Lee et al., 2017; Miller & Hutchins, 2017). The traditional approach to urban water management has aimed to address these issues using a sectoral approach – thus through (additional) urban water infrastructure. This has resulted in large-scale water systems that are based on linear models with a "take-make-dispose" strategy, i.e., centralized water supply systems, sewer networks and large-scale wastewater treatment facilities (Wong and Brown 2009). It is becoming increasingly clear, however, that urban water systems need, rather than sectoral solutions, cross-sectoral solutions to adapt them to these global developments: they need solutions that extend to other urban systems like roads, green infrastructures (e.g. parks) and energy infrastructures (Hoek et al., 2017; Nieuwenhuis et al., 2021; Wan Rosely & Voulvoulis, 2022). There are numerous examples of the benefits of such cross-sectoral solutions. Storm water solutions could contribute to values such as ecology, aesthetics and recreation (e.g. Gogate et al., 2017; Skrydstrup et al., 2020). Thermal energy could be recovered from wastewater, drinking water, ground water and surface water (van der Hoek et al. 2018). Energy, nutrients and water could be recovered from wastewater (Mo and Zhang 2013). Clearly, integrated solutions have the potential to increase the resilience and sustainability of urban water systems; i.e., to prepare them for future changes, and increase the efficiency in their use of energy, water and resources, while avoiding the production of waste.

We refer to such integrated innovations as urban water systems integration (UWSI). This is defined as "the physical, social, and institutional interlinking of (parts of) the urban water system with other urban systems" (Nieuwenhuis et al., 2021). Urban Water Systems Integration involves integration that is based on, for instance, space, resources, infrastructures, data and planning. In Nieuwenhuis et al. (2021) we introduced a typology of urban water systems integration that distinguishes between geographical, physical, informational, and project-based forms. In practice, these forms of UWSI often occur simultaneously. For example, the implementation of climate adaptation measures typically requires spatial alignment with other urban infrastructures (*geographical UWSI*), and often takes place together with construction or rehabilitation works of other urban infrastructures (*project-based UWSI*).

Not only scientists, but also policy makers and politicians recognize the need for UWSI innovations to adapt urban water systems to global developments.

Supranational governments such as the European Union have introduced water legislation to steer toward integrated planning, management, and operation of water systems. Examples include the Water Framework Directive (2000/60/EC), the Water Reuse Regulation (2020/741) and, recently, a proposed revision of the Urban Wastewater Treatment directive (1991/271/EEC). Such supranational laws put pressure on central governments and local organizations that are responsible for urban water management to develop and implement UWSI innovations in a timely manner to prepare for the future. The question is, however, how these organizations can put the challenge of an integrated approach to urban water management into practice; i.e., how these organizations can organize the development and implementation of UWSI innovations. On the one hand, the sectors involved in UWSI often have a strong operational orientation that challenges the development and implementation of innovation. In sectors such as water, transportation and energy, processes of construction and maintenance require an operational mindset, with precise, often linear, and long-term planning. The tolerance for failure in these sectors is typically low, as failures could lead to large social costs. It is clear that such an operational mindset is not conducive to innovation. On the other hand, innovation is needed, not only within sectors, but also across sectors. This will influence the operational processes of these sectors, as well as the boundaries between them: an innovation in one sector can have a major impact on the other sectors (Vollaers et al. 2021; Nieuwenhuis et al. 2021). Innovation thus requires a completely different mindset of organizations: innovation processes are non-linear, need flexibility, assume a high tolerance for failure, and may overhaul the operational practices of an organization. This means that there are two worlds: the world of operation and that of innovation. When organizing innovation, these two worlds require a balancing act between preventing that the operational mindset dominates so strongly that innovations get no room to develop, and preventing that the attention to innovations leads to distraction and serious disruption of the operation.

This chapter aims to provide insight into how organizations responsible for urban water management could perform this balancing act – after all, worldwide cities are challenged to develop and implement UWSI innovations to prepare urban water systems for the future, while also making sure that systems are properly maintained and operated. In this study, we use the theory on organizational ambidexterity to get a better understanding of this balancing act (Duncan 1976; O'Reilly and Tushman 2004). Ambidextrous organizations are organizations that balance exploration and exploitation activities – i.e., operation and innovation activities, respectively, which are the terms we use in this study. One way to achieve this balance is through creating organizationally distinct units, one for operation and one for innovation, which are tightly integrated at senior management level (O'Reilly and Tushman 2004). This study seeks to contribute to the theory on ambidexterity by exploring how the units of operation and innovation are connected, and the role of top management therein. The research question is: “how do urban water management organizations manage the tension between innovation (i.e., initiatives to UWSI) and operation (i.e., day-to-day activities undertaken by the line organization)?”

To answer this question, we focused on Amsterdam and Rotterdam (the Netherlands) and looked at the key organizations in charge of urban water management in each city: Waternet and the Municipality of Rotterdam, respectively. We expect the cases to be a rich source of practical information on how UWSI innovations are organized, and that they could provide valuable lessons for other cities worldwide: the two cities are characterized in the literature as "global frontrunners" in implementing an integrated approach (see e.g. den Exter, Lenhart, and Kern 2015; Koop et al. 2017; Mees et al. 2013). In addition, both organizations have started various cross-sectoral and cross-organizational initiatives such as programs and collaborations that co-exist alongside their regular organizational activities to adapt urban water governance to more integrated approaches; i.e., initiatives to UWSI. The analysis consisted of two steps. First, we identified the different initiatives to UWSI and empirically explored how these were used to develop UWSI. Second, we investigated how the initiatives to integration interacted with operational processes. In each city, we analyzed a diverse set of initiatives. Combining a desk study with semi-structured interviews, we looked at the types of the initiatives and the mechanisms that played a role in managing the interface between initiatives and the line organization.

The structure of this chapter is as follows. Section 5.2 introduces the concept of ambidexterity in relation to this study. In Section 5.3, we outline our research approach and introduce the cases. Section 5.4 presents the results, which are subsequently discussed in Section 5.5. We conclude with the implications of our research and ideas for further research in Section 5.6.

5.2 Organizing UWSI innovations in parallel to line organizations: viewing through the lens of ambidexterity

In this chapter we use the concept of organizational ambidexterity to understand how innovations are organized in hierarchical organizations that are defined by strict procedures for operation. Ambidextrous organizations have the ability to both explore new opportunities, and at the same time exploit existing capabilities (Gibson and Birkinshaw 2004). The research on ambidexterity originates from organizational science (Duncan 1976; March 1991; Tushman and O’Reilly 1996) and has shown that both components, i.e., exploitation and exploration, or operation and innovation, are key to success of organizations: they allow adaption to a changing environment, while being aligned with the management of today’s demands (Gibson and Birkinshaw 2004; O’Reilly and Tushman 2004). Finding the right balance between operation and innovation activities, however, could be challenging, due to the potential tension between both activities (March, 1991; O'Reilly & Tushman, 2004).

To deal with this tension, O'Reilly and Tushman (1996; 2004) suggested that organizations should segregate their innovation units from their operational units, giving the autonomy to the innovating units to develop their own processes, structures and cultures, while operational units could focus on ongoing operational processes. Leaders of the innovation units should be able to operate independently and have the willingness to challenge the status quo (O'Reilly and Tushman 2004). At the same time, however, both autonomous units should also be tightly integrated at the senior management level, with executives managing the tensions between innovation and operation, being fully committed to operating ambidextrously. They are responsible for maintaining an overall consistency, for example, through letting innovation managers report to a single executive that manages the trade-offs and conflicts between both activities, as well as inviting innovation managers to executive team meetings (O'Reilly and Tushman 2004).

From the perspective of systems integration, the approach to ambidexterity has two potential strengths. First, it indicates how to deal with the tension between the line organization that is characterized by their fixed processes and procedures on the one hand, and the need for innovation which fundamentally challenges these processes, on the other hand. Second, it provides space for a variety of cross-sectoral innovations – from initiatives to innovation that have a more planned character, as well as those that follow a more emergent approach, resulting from bottom-up initiatives.

Since the publication of these first insights on ambidexterity (Duncan 1976, March 1991, Tushman & O'Reilly, 1996), much research has been published that leads to a richer, and sometimes more nuanced, picture of the management of the tension between innovation and operation. We summarize these in four observations.

- *Contextual versus structural ambidexterity*. O'Reilly and Tushman translated ambidexterity mainly into the structure of an organization: they aim to solve the tension between exploration and exploitation through creating two autonomous subunits. This mode of ambidexterity is also referred to as *structural ambidexterity* (O'Reilly and Tushman 2004). An alternative is what Gibson and Birkinshaw (2004) called *contextual ambidexterity*. The idea is that rather than the structure of an organization promoting ambidexterity, the entire organizational context should be oriented towards it; i.e., that the systems and processes of an organization encourage ambidextrous behavior of individuals. Such a context means that each individual employee is aware of the tension between innovation and operation and can make its own choices in this respect. As ambidexterity is in the case of this contextual approach not achieved through physically separating operation and innovation units with individuals assigned to either, the separation between operators and innovators becomes a bit more blurred than in the structural approach.

- *Senior leadership versus leadership at all levels.* Within both the structural and contextual approach to ambidexterity, leadership plays a key role, yet at different hierarchical levels. The approach of O'Reilly and Tushman is underpinned by a top-down way of thinking: innovation and operation activities are organized separately, with senior management taking care of the connection between them (O'Reilly and Tushman 2004). From this perspective, supporting senior executives play a decisive role in creating an ambidextrous organization (Jansen et al. 2008). Later studies point to the importance of leadership at other organizational levels. Taylor & Helfat (2009), for example, found that the role of middle management was key to eventually implement innovation. Nemanich and Vera (2009) looked at transformational leadership of team managers.

- *Leadership versus networks*. Rather than leadership, there is a research stream that looks at the role of social relationships and networks to connect innovation and operation activities. Especially when many innovations are generated, with many potential applications, it is almost inconceivable that the bridge that only goes through leadership teams will lead to sufficient integration (see Brockner et al. 2015; Stadler, Rajwani, and Karaba 2014). The underlying idea is that network activities expose employees to different perspectives, providing them the opportunity to learn from each other, and that this contributes to ambidexterity (Brockner et al. 2015).

- *Internal networks versus external networks.* So far, the focus has been on a single organization and the ambidexterity of that organization. However, systems integration needs the involvement of multiple organizations. Until now, only few studies have been conducted that looked at this inter-organizational level, yet it is suggested that relationships across organizations is required for ambidexterity (see Brockner et al. 2015, Stadler et al. 2014). Page (2021), for example, extended the concept of organizational ambidexterity to cross-sector collaborations, and showed how collaborations could link knowledge exploration and exploitation activities to create innovative solutions. In addition, Tiwana (2008) looked at alliance ambidexterity and found that in project alliances, strong ties were needed to integrate knowledge, while bridging ties contributed to generating new ideas. Ambidexterity is thus no longer a matter of a single organization, but also comes about in inter-organizational partnerships.

While most of these observations were conducted at private firms, the concept of ambidexterity is also highly relevant for public organizations (e.g. Boukamel and Emery, 2017; Cannaerts et al., 2020). Public organizations are under constant pressure to operate their systems in an efficient way and to produce more value for their citizens, while they also must be innovative to overcome emerging sustainability challenges. Several studies have successfully applied the concept of ambidexterity to public service organizations (e.g. Gieske et al., 2020; Matheus and Janssen, 2016). Overall, research has identified fairly similar antecedents of ambidexterity for public organizations and private firms (Page et al., 2021). Commonly mentioned differences are the influence of politics and the lack of competitive pressure in public organizations (Choi and Chandler 2015; Boukamel and Emery 2017). Whereas political pressure may induce a conservative response from risk-averse public managers, it could also require ambidexterity instead, such as Page et al. (2021) found in the case of political mandates. This shows that the concept of ambidexterity is potentially fruitful to get a better understanding of how organizations responsible for urban water management deal with the tension between innovation and operation.

5.3 Method

This study used an exploratory, multiple case-study design. We focused on two largest cities in the Netherlands: Amsterdam and Rotterdam.

5.3.1 Case study description

Amsterdam and Rotterdam are of comparable size (872.757 and 651.157 inhabitants, respectively (Statistics Netherlands (2020)), and face similar challenging local urban water systems conditions: i.e., high ground water levels, poor soil conditions, located in delta areas, and vulnerable for both river flooding and inundation due to rainfall runoff. Since their establishment, both cities have dealt with urban water issues. The two cases have thus much in common; however, they differ in the way they have organized their urban water management:

In the Netherlands, responsibility for urban water systems (i.e., surface water, groundwater, storm water, drinking water and wastewater) lies primarily with municipalities, district water boards[14] and drinking water companies. Table 5-1 provides an overview of the responsibilities of the urban water management organizations, as well as the executing organizations in Rotterdam and Amsterdam.

[14] Dutch water boards are decentralized public authorities in charge of water management with boundaries that are primarily defined by hydro-geographical properties such as river basins and drainage areas.

For Rotterdam, we only included UWSI initiatives of the municipality, which is the key organization in charge of urban water management. Rotterdam lies in the management areas of three different waterboards (Hoogheemraadschap van Schieland en de Krimpenerwaard, Hollandse Delta, and Hoogheemraadschap van Delfland). To manage and coordinate the activities of the municipality and the different water boards, the organizations initiated the Rotterdam wastewater cycle collaboration in 2013 (RoSA, or Rotterdamse Samenwerking in de Afvalwaterketen, in Dutch).

For Amsterdam, we focused on the initiatives of Waternet and those of the municipality if Waternet had a key role in them. Waternet is the executive organization of the municipality of Amsterdam and that of the water board Amstel, Gooi and Vecht (AGV). Waternet takes care of the "water tasks" of both these organizations (see Table 5-1 for a description of these water tasks), but is also in charge of drinking water supply and the operation of many bridges and sluices in Amsterdam (Municipality of Amsterdam, 2016). As such, it is the only water company in the Netherlands that covers the whole water cycle.

Table 5-1. Key urban water management actors in the Netherlands, their responsibilities, and the responsible parties in Rotterdam and Amsterdam. Waternet (Amsterdam) is a water cycle organization, i.e., it is a drinking water company, and it is also the executive agency of the municipality and the water board.

Urban water management actors	Main responsibilities ("water tasks")	Responsible organization in Rotterdam	Responsible organization in Amsterdam
Municipalities	Collection and transport of wastewater, and the management of storm water and groundwater in public space (residents and businesses carry the responsibility for their own properties).	Municipality of Rotterdam	Waternet (on behalf of the municipality of Amsterdam)
District water boards	Control of polder water levels and flood defenses, management of the quantity and quality of surface water, as well as the treatment of wastewater.	Hoogheemraadschap van Schieland en de Krimpenerwaard; Waterschap Hollandse Delta; Hoogheemraadschap van Delfland	Waternet (on behalf of Waterschap Amstel, Gooi en Vecht)
Drinking water companies	Production and distribution of drinking water, including the operation and maintenance of the infrastructure required for this purpose.	Evides	Waternet

5.3.2 Data collection

The data collection consisted of two steps. As a first step, we identified the organizational structure of the Amsterdam and Rotterdam urban water organizations and their initiatives to integration related to the "municipal water tasks" (see

Table 5-1). Secondly, we analyzed a set of initiatives in more depth. We defined initiatives as ideas with an organized structure that were characterized by organized activities addressing urban water sustainability issues such as climate adaptation or circularity. The initiatives could be organized top-down, taking a planned approach, or have developed in a more emergent way. Based on their organization and approach, we inductively differentiated between four types of initiatives: programs, movements, collaborations and line-based initiatives. The characteristics of each of the types are provided in the results section (Section 5.4.1).

For the first step of data collection, we conducted six exploratory telephone interviews with urban water policy practitioners working at a strategic position at one of the municipalities or at Waternet in August and September 2020. Due to COVID-19 restrictions, the interviews for this study were not conducted face to face. All interviews were conducted in Dutch. We asked the interviewees about the organizational structure and ongoing initiatives to UWSI. This resulted in an initial list of 7 initiatives in Rotterdam and 9 in Amsterdam. We further expanded this list by a desk study. We collected general policy and strategy documents about urban water management and documents about initiatives that focused on an integrated approach to urban water management. This resulted in a final list of 18 and 16 initiatives for Rotterdam and Amsterdam, respectively. Based on policy documents, legislation, internal and industry reports, and scientific literature we collected key-information on the initiatives, such as their goals, ambitions, and drivers. We subsequently mapped the initiatives, categorizing them by the following urban water management themes: asset management, climate adaptation and resource recovery[15]. We used this subdivision as it allowed to effectively map the approach to urban water management for both cities. In addition, it very well represented the themes in the urban water world, and was in line with the integrated approaches to urban water management that can be found in the literature (Nieuwenhuis et al., 2021a). We validated the list of initiatives in our next research step. We asked the interviewees whether they had any suggestions for initiatives that we might had overlooked. This did not result in any new initiatives.

[15] For Amsterdam, we also included an initiative on the recovery of aquathermal energy in the category of resource recovery. In Rotterdam, there was not such an initiative; only a few small, occasional aquathermal projects had been implemented.

For the second step of data collection, we selected 8 initiatives for each city and conducted semi-structured interviews to analyze them in more depth. We decided to focus on interviews rather than observations, as the initiatives typically spanned periods of years. Observations were therefore considered not feasible. Aiming to provide a rich base of empirical knowledge, we selected initiatives that varied both in type (programs, collaborations, movements and line-based initiatives, see Section 5.4.1 for more information on these types) and in theme (asset management, climate adaptation and resource recovery). See Table 5-2 and Table 5-3 for an overview of the selected initiatives.

Table 5-2. Overview of the selected Rotterdam UWSI initiatives.

Initiative	Type of initiative	Urban water management theme	Aim
Rotterdam Reyeroord+	Program	Asset management, climate adaptation	Changing current asset management practices: involving inhabitants and using system renovation as the start of a transition.
Rotterdam Multifunctional roofs	Program	Climate adaptation	Creating multifunctional roofs and contributing to sustainability.
Rotterdam Strat. asset management	Program (line-based initiative)	Asset management	Implementing uniform asset management practices and the joint replacement of urban infrastructures.
Rotterdam Next SB-SO	Line-based initiative	Asset management	Changing current approaches of the departments of City management and City renewal.
Water Sensitive Rotterdam (Club of 36)	Movement	Climate adaptation	Implementing climate adaptation measures on a neighbourhood level through linking urban professionals, residents and civil servants with each other.
Rotterdam Weerwoord	Program	Climate adaptation	Making Rotterdam climate-proof through a citywide and neighbourhood-specific approach.
Rosa Consortium	Collaboration	Resource recovery	Making the Rotterdam urban water cycle climate-proof, circular and effective.
Rotterdam Circularity	Program	Resource recovery	Closing material cycles through increasing circular-thinking and facilitating a circular economy.

In total, 25 video-conferencing interviews were conducted with 27 persons, in the period from February to September 2021 (see Supplementary Material I for an overview of the respondents). All interviewees had provided informed consent for recording and using the interview data, as well as for the use of anonymized quotations. Ethical approval for the study was obtained from TU Delft's Human Research Ethics Committee. All interviewees were knowledgeable about the initiatives: they were practitioners involved as manager or advisor, or they worked at a more strategic level at the organization and knew more about initiatives in general. One interviewee was an independent researcher who was involved in a study that looked at two initiatives that were included in this study (see Willems et al., 2022). In the interviews, we explored the concepts and themes that were relevant for the organization of innovation. Questions focused on two main issues: the development of the integration initiatives (i.e., how the initiatives developed over time, which

Table 5-3. Overview of the selected Amsterdam UWSI initiatives.

Initiative	**Type of initiative**	**Urban water management theme**	**Aim**
Amsterdam Rainproof	Movement	Climate adaptation	Preparing Amsterdam for heavier rainfalls together with citizens, entrepreneurs, and knowledge workers.
Amsterdam Climate adaptation	Program	Climate adaptation	Preparing Amsterdam for a changing climate (heat, drought, (urban) flooding).
Waternet Climate adaptation	Program	Climate adaptation	Making the Waternet area climate proof and resilient.
Koppelkansen	Program (collaboration)	Asset management, Climate adaptation	Addressing multiple sustainability challenges in public space through smart, integrated solutions, both above and below ground.
Amsterdam Future-proof assets	Line-based initiative	Asset management	Preparing assets in Amsterdam for the future through concrete projects together with knowledge institutes and industry.
Waternet Circular economy	Program	Resource recovery	Reducing the environmental impact trough reorganizing the Waternet urban water cycle.
Waternet Energy transition	Program	Resource recovery (aquathermal energy)	Contributing to the heat transition through aquathermal energy projects and making Waternet carbon neutral/energy positive.
Waternet New sanitation	Program	Resource recovery	Developing knowledge and gaining experience with (local) resource recovery through concrete projects.

challenges were faced and how practitioners dealt with these challenges) and the organization of these initiatives (i.e., how they were initiated, what role executives had in the innovations, how the initiatives were financed and what strategies the practitioners involved in the initiatives used to establish the innovations). All interviews were recorded and transcribed.

5.3.3 Data analysis

To analyze our data, we used the software atlas.ti9 (version 9.1.2.). We defined our coding scheme combining a deductive and inductive approach. See Supplementary Material II for a description of our coding scheme and process. We combined the data of the two cities to get a rich understanding of how Waternet and the Municipality of Rotterdam organized UWSI innovations. We first looked at a more descriptive level; i.e., the type and theme of the initiatives, and their approach. We subsequently looked at a more analytical level, looking into how the organizations dealt with the interface between the initiatives (innovation) and the line organization (day-to-day operation). This resulted into four types of mechanisms to manage this interface: network mechanisms, hierarchical mechanisms, process mechanisms and human-resource mechanisms. A detailed description of these mechanisms is provided in the results section (Section 5.4.2). To interpret our results, literature on ambidexterity was used.

5.4 Results

In this section we first discuss the different types of initiatives. Then we look at how the connection between the initiatives and the line organization was organized.

5.4.1 Different types of initiatives: their organizations and approach to integration

Based on our data, we identified four types of initiatives to UWSI: programs, movements, collaborations and line-based initiatives.

5.4.1.1 Programs

Eleven of the initiatives were programs. Overall, the programs had a formal character: they were planned and top-down initiated vehicles to innovation, , with a predefined goal and scope. Programs ran typically for a set period (e.g., 4 years, connected to the council's tenure), with budget available for doing pilots and innovations. Several respondents mentioned that the formal status of a program helped them to develop innovation. Two respondents said that by calling something a program, executives indicated to the line organizations that the issues the program addressed had a certain priority.

While the formal character of programs and having a dedicated team to work on the issue could speed up innovation, it was also mentioned as an obstacle to getting new practices embedded and to reaching people in the line organization.

5.4.1.2 Movements

We identified two movements: Water Sensitive Rotterdam and Amsterdam Rainproof. A common thread of these movements is their bottom-up approach. Executives were only involved at a distance, supporting the movements by giving space to develop their own identity and approach. Both movements presented themselves as non-associated with the government: they built their own identity, characterized by, for example, their own logo, website, and communication. They heavily relied on enthusiastic, and thus intrinsically motivated people, both from inside and outside the organization.

5.4.1.3 Collaborations

A third type of initiative is the collaboration, of which we included two in our dataset. The essence of a collaboration is its network-like character, with strong ties to other organizations. An example is the RoSA consortium in Rotterdam, which connects the municipality with the drinking water company and the three waterboards that are active in Rotterdam. Collaborations also had some top-down characteristics. For example, the establishment of the RoSA consortium followed a national agreement (the National Water Agreement (Ministry of Infrastructure and the Environment, 2011)). In addition, higher management and administrators of the various organizations played a prominent role in the collaborations, such as with defining the projects.

With respect to the mobilization of resources, a collaboration has the advantage that costs could be shared among the participating parties. According to two respondents, this facilitated the development of innovations. Additionally, having multiple parties involved made it more interesting for international (research) investments, such as from the European Union (respondent 10).

5.4.1.4 Line-based initiatives

We identified three initiatives to integration that were based in the line organization. According to the theory on structural ambidexterity, innovation should take place in distinct units that are not part of the line organization. However, as several practitioners involved in the line-based initiatives described a similar tension between innovation and operation, we decided to include these initiatives in our dataset, referring to them as "line-based initiatives."

All line-based initiatives originated within the line organization. Their main characteristic was that they focused on innovation of regular activities, yet going beyond the optimization of day-to-day tasks. In the case of Next SB-SO, for example, civil servants aimed to reorganize and integrate the approaches of the department of City management and that of City renewal. Practitioners involved in the line-based initiatives typically divided their time between regular tasks and innovation. The initiatives often developed gradually and did not have a clear starting point. They started with little or no involvement from higher levels in the organization. Instead, lower-level managers, such as department heads, or civil servants who saw the relevance of changing current practices, were closely involved in the establishment of these initiatives. At a later stage, support from higher management was sought. Line-based initiatives had thus both some bottom-up and some top-down aspects.

5.4.2 Mechanisms to manage the interface between initiatives and the line organization

Looking into our data, we found different mechanisms to protect innovations on the one hand, and integrate them with the line organization on the other. We inductively categorized the mechanisms into four groups: network mechanisms, hierarchical mechanisms, process mechanisms and human-resource mechanisms.

5.4.2.1 Network mechanisms

We found that networks played an important role throughout the entire innovation process, both to develop UWSI innovations as well as to implement them. As sustainability challenges do not comply to disciplinary and organizational boundaries, initiatives typically relied on a network approach to be able to work across these boundaries. Additionally, networks were used to spread the philosophy of integration and associated knowledge and skills. Networks had thus a double use in the innovation process: they contributed to the development of UWSI initiatives, as well as to their implementation. As a consequence of this, we noticed that both processes merged into each other.

We identified network structures on different scales and with different purposes (see Table 5-4). For each of them, we provide a brief description, including an empirical example from the cases.

Intraorganizational networks

Within organizations, intraorganizational networks were used to facilitate working across departmental boundaries and spread innovative thinking. Respondent 23 described how she approached civil servants who were enthusiastic about circularity and initiated the Blue Rebel network. The Blue Rebels had regular meetings for brainstorming and talking about possible interventions to promote circular practices. Respondent 13 explained that such a network of intrinsically motivated people could have a knock-on effect on adopting innovative practices: "In every department you have people, colleagues, who are happy to help … And, because they are in the same department, they can often convince their own colleagues more easily about something."

Networks of initiatives

In addition to ties between departments, we found connections between initiatives. Multiple respondents mentioned that they, on purpose, looked for these connections, to save costs, but primarily to strengthen the position of individual initiatives. By pairing up, they could create a "critical mass" such that innovative practices were adopted more easily. Civil servants who were involved in diverse initiatives and networks across the organization played a key role in the connections between initiatives. These "bridging actors" could work at different levels; i.e., at the operational or tactical level, e.g. involved in diverse projects, or at a more strategic level.

Another way to establish networks of initiatives was via initiative managers: for Rotterdam, several respondents mentioned that most of the sustainability initiatives were led by young, highly motivated people who knew where to find each other, and that this contributed to alignment between initiatives. Additionally, we noticed that in each program plan, relationships with other programs were mentioned, highlighting the overlap between challenges and goals. At Waternet, two respondents indicated that the organizational positioning of the three programs (climate adaptation, circularity and energy transition) was mainly beneficial for the collaboration between them. Recently, the programs were restructured, now falling all directly under the responsibility of the executive board, rather than each having their own position in the line organization. Facing the same struggles, respondent 23 explained that this shared position helped to join forces on several issues:

> All three of us actually have to fight a bit of the same battle against the existing organization, just on different themes. ... So we are now preparing a management proposal together ... as we are actually running into the same kind of problems.

External networks

Network activities outside the organization were primarily undertaken to establish either short-term or long-term relationships with external parties that were essential to integration. Pairing up with these parties could help to get innovations adopted more easily by the internal organization. Multiple respondents indicated that urban water organizations rely on other parties to achieve the goals of UWSI initiatives.

Table 5-4. Overview of the different type of network activities and their objectives such as identified in the cases.

Types and scales of network activities	Identified objectives of network activities
Intraorganizational networks	- Working across departmental boundaries - Creating a knock-on effect
Networks of initiatives	- Saving costs - Strengthening the position of initiatives - Pairing up to build a critical mass
External networks	- Gaining support from parties that are vital for the innovation (dependency) - Getting innovations more easily adopted within the organization
Knowledge platforms	- Sharing of knowledge - Putting pressure on parties operating at a larger scale, e.g. trade associations

Respondent 20 described this on the basis of climate adaption: "Climate adaptation is a problem you really can't solve on your own; not just as a water authority, but actually not even as government ... more than half of the city is private property." This dependency of others was mentioned an important reason for building external relationships. Rainproof even decided to hire someone who was specifically in charge of managing and maintaining external relationships, i.e., a community manager – a role that was completely new to Waternet at the time. While addressing sustainability challenges required on the one hand many different collaborations and coalitions, several respondents also underlined the need for long-term partnerships, such as between water boards and municipalities, like the RoSA consortium: these pave the way for cooperation on other topics.

Local, regional, national and international knowledge platforms

Another form of external network activities that we identified was joining local, regional, national or international knowledge platforms. In addition to knowledge-sharing, these platforms could be helpful in jointly putting pressure on parties operating at a larger scale. For example, they facilitate approaching higher tier governments (to change prohibitive regulations) or trade associations that operate at a regional or national scale.

5.4.2.2 Hierarchical mechanisms

While network activities were the dominant mechanism for managing the interface between the initiatives and the line organization, our data showed that hierarchical mechanisms played an important role as well. Rather than being in conflict with each other, we found that networks and hierarchy could complement each other.

Hierarchy as a vehicle for integration

Our data showed that committed executives were beneficial to UWSI innovations: they could play a key role in the establishment of initiatives, and thereby protect and fuel the innovation process. For example, a (temporary) director at Waternet positioned the Waternet innovation programs directly below the board of directors. Before, the initiatives were part of the line organization. Respondent 23 explained that this director's decision strengthened the position of the programs with respect to department heads: “At the position we now have in the organization, we are at the same level of authority with those department heads. Thus, it was a strategic move; we are now colleagues.”

Another finding related to the role of hierarchy, was that the support of executives could help to get line organizations moving. Respondent 14 attributed this to hierarchy and the chain of command: "There are certain departments and colleagues, and sometimes organizations as well, very susceptible when something is organized much more top-down. That, if the management says: “it [the innovation] is good,’ they will take part in it." In addition, we found that the support of a certain executive could help to get the support of other executives: since UWSI initiatives involve cross-sectoral innovations that need the involvement of different executives, one could “use” the executives that are already enthusiastic about the initiative to get the other executives on board as well.

5

Institutionalizing innovations

Besides fueling the innovation process, we found that hierarchical mechanisms played a role in institutionalizing innovative practices through incorporating them in guidelines and official documents. Initiative practitioners could play a part in this as well, actively searching for opportunities to formalize innovative practices.

This was, for example, the case in Rotterdam for the four-years policy plans for urban water management (municipal sewerage plan). Since these plans need to be approved by the municipal councils and provide the basis for daily operations and practices, multiple respondents explained that establishing innovative management principles in these plans could help mainstreaming innovative practices. Respondent 7 elaborated on how the ideas of the Weerwoord program about climate adaptation now have been established in the newest sewerage plan of Rotterdam, which is entitled *From pipe to outdoor space*: “In principle, we were already doing that [from pipe to outdoor space], but it is now much more formalized and has really become a guiding principle." Another example of institutionalizing UWSI innovations that was observed in the case studies related to design guidelines: in both cities, steps were taken to include climate adaptation measures in municipal design guidelines for public space.

5.4.2.3 Process mechanisms

A third set of mechanisms revolves around the interactions between practitioners who focus on innovation and those who focus on day-to-day operation of systems, hereinafter referred to as initiative practitioners and line-organization practitioners, respectively. Rather than innovations first being fully developed within the initiatives and then being connected to the line organization, we saw that developing and implementing innovation was more of a process of interaction, with line-organization practitioners (gradually) becoming co-producers of the innovation. This also relates to our findings about networks: in Section 5.4.2 we showed that UWSI innovations are typically developed in close collaboration with other practitioners and organizations.

We identified different ways in which people across the line organization were involved, differentiating between informing, inspiring, motivating and encouraging them to action:

Informing people in the line organization

In all initiatives, we could identify some form of *informing* line-organization practitioners about the initiatives, such as sharing information through platforms like LinkedIn or intranet. In Rotterdam, programs officially belonged to a department, which was, according to several respondents, beneficial for information-sharing. In Amsterdam, two respondents mentioned that practitioners in the line organization were trained to learn about new practices, such as through the course System Innovation, which was related to the Koppelkansen program.

Inspiring people in the line organization

Informing often went hand in hand with *inspiring*. For movements in particular, inspiration was an important part of the initiative. Rather than just providing information about what climate adaptation is and how it could be done, movements focused on making people enthusiastic about climate adaption, such as through presentations and one-on-one conversations throughout the organization. Additionally, movements organized social events, such as the “Water Sensitive Cafes” in Rotterdam and coffee breaks. These social events were organized to bring people from different organizations together, to get to know each other, share ideas and have fun.

In the same vein, respondent 1 (Reyeroord+ program) organized guided tours through the Reyeroord neighborhood for colleagues to talk about the initiative and make people enthusiastic about the “Reyeoord approach.” The Blue Rebel network (see Section 5.4.2.1), which was part of the circularity program of Waternet, was also a form of reaching the line organization through inspiration. That same program also introduced "roving reporters" ("razende reporters" in Dutch) who made vlogs about successful circular cases and shared those with the rest of the organization.

Motivating and encouraging people in the line organization to action

Motivating and *encouraging to action* focused on convincing people in the line organization of the need for change and persuading them to contribute to the solution. Several respondents emphasized that, within initiatives, one should make the translation from (sustainability) ambitions to everyday practices. For example, respondent 21 (Circularity program) mentioned that one must break down the complexity into smaller bits:

> So when you see the long-term horizon, with the complexity that comes with it, that you break it [the complexity] down [translating it] to the here and now, so that the small steps that are taken now, give people the energy right away, and that it fits into their processes.

Two other respondents highlighted the importance of "problem ownership," making line-organization practitioners part of the innovation challenge through involving them directly in activities of initiatives, such as in pilots and in the development of artifacts like models and maps that support innovative practices. Involving people in such activities could give them the confidence to incorporate innovative practices in their daily work, such as elaborated on by respondent 21:

> What we see is that also people in the line [organization] get a kind of daring and realization: "okay, so I can do something, I may do something, I can convince [other] people now, and I know that there is also a large group of people supporting me, including the management and board, to go and do that".

5.4.2.4 Human-resource mechanisms

The last category of mechanisms to organize the connection between initiatives and the line organization relates to human resources. The results showed that individuals and their skills could play an important role in managing the tension between innovation and operation.

The human factor: initiative managers contributing to integration

The skills of initiative managers, i.e., individuals that led the initiatives, played an important role in managing the interface between innovation and operation, such as in networks (see Section 5.4.2.1) and in facilitating the process of interaction (see Section 5.4.2.3). Multiple respondents related these actions to a certain skill set; i.e., that initiative managers had certain skills that were beneficial for the innovation process. These included networking and convincing others, as well as creating an open and positive atmosphere, stimulating creativity, allowing for errors, and with a lot of emphasis on what is possible rather than what is not possible.

We also found actions, taken by initiative managers, drawing on hierarchy: initiative managers actively approached executives to get their support, knowing their support was beneficial to innovation (see Section 5.4.2.2). For example, they invited executives to successful cases, indicated and translated the added value of and initiative for the (various) directors/aldermen involved, and translated abstract, long-term goals to goals with a shorter time horizon that were more attractive for directors in charge. For Rotterdam, several respondents attributed the necessary skills to the type of people leading the initiatives: they explained that most of the program managers were young, highly motivated people with strong interpersonal skills, who had often first done a traineeship at the municipality.

Creating new roles and hiring external people

Multiple respondents highlighted that developing UWSI innovations required different capacities than traditional urban water management. Our data showed that this knowledge gap was typically dealt with by educating people, creating new roles and/or hiring external people for initiatives. For example, for the Waternet Circularity program, initiative practitioners followed a course on transition management to gain knowledge about accelerating transitions. Amsterdam Rainproof and Waternet's Climate Adaptation Program both employed a community manager. These were responsible for managing (external) relationships (see Section 5.4.2.1), and thus contributed to a culture that was more externally oriented, fostering integration.

Another reason for hiring external people that was mentioned by two respondents, was that these external people could more easily bring winds of change. Respondent 16 explained that Rainproof on purpose recruited a program manager from outside the organization to prevent that Amsterdam Rainproof would become "just another Waternet story." On the other hand, many respondents emphasized that initiative managers who came from inside the organization and who had an established reputation were beneficial to an initiative, getting support from senior management more easily.

5.5 Discussion

In this section, we use the concept of ambidexterity to reflect on the results of our study. With the early studies on ambidexterity emphasizing the connection between innovation and operation activities at senior management level (Duncan, 1976; March, 1991; Tushman and O'Reilly, 1996), and later research highlighting that these connections take place at various hierarchical levels of the organization(e.g.

Nemanich and Vera, 2009; Taylor and Helfat, 2009), we found an even more nuanced picture. In our study, the interface between innovation and operation was dominated by networks, and complemented by hierarchy. In Section 5.5.1 we interpret our findings about networks, and in Section 5.5.2 we discuss the role that hierarchy could play in managing the interface between innovation and operation activities.

5.5.1 Networks dominating the connection between initiatives and the line organization

We have made four observations related to networks in managing the tension between innovation and operation:

First, our results show that innovation and operation activities did not take place completely isolated from each other, such as specified in the studies on structural ambidexterity (O'Reilly and Tushman, 2004; Tushman and O'Reilly, 1996). According to those prior studies, innovations need to be developed in separated organizational units, and then transferred to the organizational units that are responsible for the operational process. We found, however, that, although most initiatives were accommodated in separated organizational units (i.e., programs, collaborations and movements), there was a continuous interaction between the initiatives and the line organization. For example, practitioners in the line organization were continuously informed about innovation initiatives, they were part of informal networks, and they were also directly involved in pilots and projects.

Second, the continuous interaction with the line organization means that innovation is not like a project that is carried out in isolation and which is then rolled out, but that innovation is a co-creation with the line organization. This suggests that initiative practitioners should not define the innovation too early in the process, but rather give the line organization the space to become co-producers of the innovation. These first two observations relate to the literature on learning alliances, which focuses on the engagement of multiple stakeholders to develop and scale up innovations (Darteh et al., 2019; Lundy et al., 2005). In learning alliances there is often a shared desire to address an underlying problem, and the alliances should preferably be represented by multiple actors in the horizontal dimension (multiple stakeholders working at city level), as well as the vertical dimension (e.g. working at community, city and national level) to develop creative solutions for complex problems such as related to urban water governance (Verhagen et al., 2008). These characteristics of learning alliances were also observed in networks were UWSI innovations came about.

Third, we observed a prominent role for the connections *between* innovations – thus the network of initiatives (see Section 5.4.2.1). This means that there is not a single innovation unit (see Section 2), but there are many. This observation also has implications for the interface between operation and innovation: the network of initiatives is used to get the ball rolling; i.e. to create a critical mass such that the innovation cannot be avoided anymore (Caniëls and Romijn, 2008). Actors with a bridging position, i.e., *bridging actors* (Spekkink and Boons, 2016), play a key role in creating these networks.

Fourth, and also related to the other three observations, the role for networks, interactions and co-creation means that the boundaries between initiatives and the line organization are less clearcut. Different than the literature on ambidexterity suggests, we did not find a clear distinction between the world of innovation and that of operation.

Based on these observations and the many connections between innovation and operation that we found, the question is what is left of the concept of ambidexterity. After all, with a dominant role for networks and with innovations also emerging in the line organization (i.e., line-based innovation), the idea that there are autonomous subunits for innovation and operation which are connected at the top does not hold for UWSI innovations.

We argue, however, that the (conceptual) distinction between operation and innovation remains relevant, as the concept could be helpful to understand the *essence* of the innovation challenge: it makes individuals alert to the tension between the need for UWSI on the one hand, and the focus on safety and operability on the other. Being alert to that tension allows for anticipating it. For example, it could help initiative practitioners think about how to organize the interface between innovation and operation such as through undertaking network activities or actively involving executives. The same applies to top executives: by being alert to tension between operation and innovation, executives could act upon it. For example, they could give initiatives a strategic position in the organization or facilitate a network approach. This is supported by the finding of Lewis et al. (2018) who found a relationship between leadership and networking and their effect on innovation capacity.

We therefore argue that the concept of ambidexterity could be helpful in understanding and dealing with the innovation challenge (i.e., the tension between innovation and operation), yet organizations should not stick too much to it. After all, the results of this study show that organizational separation between innovation and operation goes hand in hand with interconnectedness through networks – and we argue that exactly this combination of separation and connection is the key to success.

5.5.2 Bringing about UWSI: smart combinations of hierarchy and networks

In this section we revert to the role of senior executives – an element that is central to the original theory: top management connects the world of innovation and operation and resolves the tension between the two worlds. As mentioned earlier, we observed a smaller role for senior executives and identified all kinds of other connections between innovation and operation (Section 5.4.2.1 and 5.4.2.3). At the same time, however, many respondents stressed the pivotal role of executives in the innovation process (Section 5.4.2.2).

Bringing about UWSI is a complex and hard-to-predict process: there are many different initiatives to UWSI that occur in parallel, of which some of them have a more planned character and others a more emergent one. Furthermore, these initiatives are connected to each other as well as to the line organization, in which networks are important, but in which we also identified a role for senior management. Organizations are challenged to connect hierarchy and networks, linking top-down planning with the emergent process that characterizes networks. Based on our results and previous work about using hierarchical interventions in networks (de Bruijn, 2005), we see two ways to do this:

- To catalyze the innovation process: rather than a top-down decision that strictly defines what has to be done and how it should be done, a top-down decision should leave room for emergence, giving space to practitioners to anticipate emerging developments and opportunities. This could be done through, for example, defining an initiative, such as a program or collaboration, and select motivated practitioners, without defining how these practitioners should operate. By starting the initiative, executives indicate to the line organization that the innovation has priority, strengthening its position with respect to operational activities. The added value of the executive lies in timely identifying innovation opportunities and defining initiatives. If the initiative would not have been started from top down, there might not have been a process, or it may had taken much longer before a line-based initiative would have emerged. Executives could thus play an important role in speeding up innovation.

- Or to complete the innovation process: executives could formalize innovations that were developed in an emergent way. For example, they could embed innovative practices into guidelines or procedures, or they could start a program in parallel to a movement, allowing to reach practitioners that are more sensitive to hierarchy. By doing so, executives could take a determining role in strengthening or completing the innovation process.

5.6 Conclusion

Aiming to get a better understanding of how organizations responsible for urban water management can deal with tension between the need for innovation on the one hand, and the focus on operation on the other hand, this study used a case study approach to analyze 16 UWSI initiatives in Amsterdam and Rotterdam. Semi-structured interviews (n=25) were combined with desk study research. We looked at the types of initiatives as well as the mechanisms to organize the interface between initiatives and the line organization.

This resulted into the identification of four types of initiatives: programs, collaborations, movements and line-based initiatives. Each initiative has its own characteristics, and the specific challenges and context determine the type of initiative that is considered most appropriate. In addition, we found four mechanisms that shaped the connection between innovation and the line organization: network mechanisms that focused on network activities between organizations, as well as within organizations and between initiatives; hierarchical mechanisms that drew on hierarchy to foster the development or implementation of innovation; process mechanisms that focused on the process of interaction between the line organization and initiatives; and human-resource mechanisms that related to human aspects.

The main finding that followed from our empirical results was that the connection between innovation and operation was not primarily achieved through top executives such as mentioned in the literature on structural ambidexterity, but mainly through networks. Nonetheless, we found that executives could play an important role in the connection between the line organization and initiatives: their support could strengthen the organizational position of initiatives. In addition, they could guide and structure the bottom-up processes that occur in the organization by taking a systems perspective.

This study gives valuable insights for both practice and theory. We provide valuable lessons for other cities worldwide that are struggling to develop and implement UWSI in their hierarchical organizations to become more sustainable. We give insights into different initiative types and their characteristics, as well as the mechanisms that enable managing the tension originating from the innovation challenge. In addition, regarding the theory on ambidexterity, this study gives relevant insights on the pivotal role of networks. Our empirical findings are supported by more recent studies on ambidexterity that argue that the tension between innovation and operation should be managed at different hierarchical levels – thus not just at the top (see Brockner et al., 2015; Stadler et al., 2014). We show that this happens by all kinds of actors throughout the organization and during the entire innovation process; i.e., through networks. The organization of innovation in urban water organizations is thus much more nuanced than the original literature on ambidexterity suggests, and we show that networks deserve further attention in this field of research.

For future research, we recommend taking a closer look at the role of networks and agency in bringing about UWSI innovations. Our results show that individuals such as initiative managers could have an important contribution to managing the tension between innovation and operations, such as through their role in networks or by engaging executives. Insights from the literature of institutional entrepreneurship may be valuable here, such as by looking at the direct strategies and activities that individuals use to bring about change, and/or at the skills and abilities that are required to carry out these activities (e.g. Klein Woolthuis et al., 2013). In addition, the role of networks in developing and implementing innovations should be further investigated. We found a large role for networks, but these findings could be specific to the Dutch context. A comparative case study, looking at different geopolitical contexts, that examines possible inhibitors or barriers to networks supporting innovation initiatives, could provide valuable insights into the role of networks in innovations.

Another suggestion for further research relates to the influence of organizational structures on the effectiveness of UWSI initiatives. Our results show that, despite the large organizational differences regarding urban water management in Amsterdam and Rotterdam, both organizations have started comparable initiatives. In addition, we found similar mechanisms that were at play. Given the explorative character of this study, we did not look at the role of organizational structure and their effectiveness. Future research should address this, for example through a case study with multiple organizations and/or different types of initiatives.

Chapter 6

General conclusions and discussion

6.1 Intermediate conclusion: answering the sub-questions

This section summarizes the conclusions from previous chapters, answering the sub-questions such as presented in Section 1.4.

6.1.1 Conceptualization of approaches to integration

Chapter 2 addressed the first sub-question:

1. *How can the different approaches to integration in the urban water literature, i.e., Urban Water Systems Integration (UWSI), be conceptualized?*

Based on an interpretive review of the concept of integration in the urban water literature, the following five approaches to integration were distinguished: integrated storm water management, resource recovery from wastewater, integrated rehabilitation management, integrated urban water management, integrated optimization of urban wastewater systems.

While all these approaches are legitimate, and together they provide valuable insights into the different aspects that need to be considered for a truly integrated approach, their main limitation is that they are typically limited to a particular flow or subsystem in the urban water cycle. As a consequence of this, the approaches do not provide insights into the relationships with other flows or subsystems, nor in the trade-offs that need to be made between the many different interests and functionalities that are inevitable involved with integrated solutions.

To overcome this issue, a more comprehensive perspective on integration was taken that conceptualized the different approaches into four types. This resulted in the concept of Urban Water Systems Integration (UWSI), which was defined as “the physical, social, and institutional interlinking of (parts of) the urban water system with other urban systems.” As such, UWSI thus focuses not only on the interconnection of different physical infrastructures, but also on the connection between the actors involved and the institutions that guide the perceptions and actions of these actors. Four types of UWSI were distinguished: geographical, physical, informational and project-based UWSI (see Table 6-1). The advantage of this concept over the existing approaches to integration, is that the UWSI typology provides insight into the different types of integration that could occur in parallel, and thereby helps to manage the trade-offs that could arise with that.

The typology was based on cross-cutting objects of integration, i.e., objects that did not focus on a particular sub-system or flow within the urban water cycle such as most of the existing approaches to integration did, but general objects of integration that were irrespective of such subsystems or flows (see Table 6-1). As such, the UWSI

Table 6-1. Characteristics of the different Urban Water Systems Integration types

Types of systems integration	Objects of integration	Description
Geographical	Space	Spatial alignment of systems in the same area
Physical	Resources	Shared use of a resource for multiple functions
	Infrastructures	Shared use of an infrastructure system
Informational	Data	Use of data from different systems in operating those systems
Project-based	Planning	Alignment of rehabilitation and construction plans for multiple urban systems

typology could help structuring the discussion on integration. The following five objects of integration were identified: space, resources, infrastructures, data, and planning.

6.1.2 Implications of UWSI – uncertainties and challenges

The second sub-question was also addressed in Chapter 2:

2. *What uncertainties and decision-making challenges are introduced by UWSI?*

The concept of UWSI was used to explore the implications that UWSI brings along for decision-making. We first looked at the uncertainties that were specific to UWSI, and then formulated three implications these uncertainties have for decision-making.

The results showed that much of the uncertainty associated with UWSI could be attributed to (1) the *interfaces* between the coupled systems, i.e., where the previously unconnected systems became interconnected, and (2) multi-actor complexity, i.e., the actions of other *actors* and the *institutions* guiding these actions. To provide insight into these specific UWSI uncertainties (i.e., social interface and institutional interface uncertainties), the uncertainties that emerge due to systems integration were conceptualized in such a way that they highlighted these UWSI uncertainties. To do so, the socio-technical systems perspective (technical, social, and institutional uncertainty) was combined with the concept of UWSI (internal, interface, and external uncertainty). This resulted in the conceptualization of UWSI uncertainties that is presented in Table 2-3 on page 32, with the social and institutional interface uncertainties highlighted in grey.

Based on the systems integration uncertainties, three implications for decision-making on integration were formulated:

- First, given the many actors involved in integrated solutions, all of whom have different understandings of what integration is and how it should be operationalized, actors need to come to a negotiated view on integration. This means that the involved actors should agree together on what they mean by integration, as well as on the actions needed to achieve it.

- Second, and inherent to integration as a negotiated concept, is that decision-making on integration typically needs a process approach rather than a project approach. This is a fundamental difference: while a project approach is characterized by a precise problem definition, a clear goal, and a fixed-linear planning, in a process approach, a problem definition needs to be broad, goals are dynamic, and decision-making takes place in rounds. These characteristics of a process approach will facilitate negotiations. On the contrary, precise problem definitions, clear goals and a fixed-linear planning that characterize a project approach would hamper such negotiations.

- And third, as institutions fit the current systems and processes, and are thus always behind on state of the art, practitioners need to operate in an institutional environment that does not (yet) support integration. This is an even greater challenge in the urban water sector, a sector that is heavily regulated and characterized by fixed processed and procedures to protect important values such as public health and flood safety.

6.1.3 Views of Dutch urban water practitioners on UWSI

Chapter 3 provided the answer to the third sub-question:

3. *What perspectives do Dutch urban water management practitioners have on integration for future urban water systems?*

Q methodology was used to empirically explore and identify perspectives of Dutch urban water management practitioners on integration for future urban water systems. In total, 30 respondents were included in the study, and four shared perspectives were identified (see Table 6-2 for an overview).

Perspective 1 saw an important role for coordination and collaborative process, given the many urban challenges that need to be addressed simultaneously, and the limited space available. Perspective 2 focused on climate adaptation and saw this as the key to better social and environmental conditions of cities. Perspective 3 aimed for the recovery of resources and thereby saw an important role for (new) collaborations. Perspective 4 was all about being in control, having good insights into the system and opting for efficiency.

To identify what these perspectives implied for integration, we looked at the types of UWSI in each of the perspectives (see Table 6-2). For each perspective, at least two of the UWSI types were identified. This demonstrates that practitioners saw an important role for integration in future urban water systems. However, the results also showed that the perspectives had different understandings of what integration exactly is and why it should be used. Even for a single type of integration these differences were found. For example, the geographical type of UWSI was identified in each of the perspectives, but they looked at it from a different spatial scale and had different motivations to use it. For instance, perspective 1 focused mainly on considering the variety of interests and geographically to fit in various system demands, while for perspective 4, geographical UWSI was mainly about a better understanding of the location of physical infrastructures to avoid unnecessary damage.

Insight into the differences between perspectives is useful to structure the discussion on integration, but also to build effective strategies, for example, regarding what different spatial scales and motivations for integration should be taken into account for these strategies.

Table 6-2. Overview of the perspectives and the UWSI types identified in each of the perspectives.

Perspectives		**UWSI types identified**
Perspective 1	Future-proofing through coordination: finding space for urban challenges	- Geographical - Physical (*resources*) - Project-based
Perspective 2	Future-proofing through climate adaptation: creating livable cities	- Geographical - Physical (*resources)* - Physical (*infrastructures)* - Project-based
Perspective 3	Future-proofing through recovery: challenging institutional structures	- Geographical - Physical (*resources*)
Perspective 4	Future-proofing through efficiency: being in control	- Geographical - Project-based

6.1.4 Failures in storm water UWSI solutions and their root causes

Sub-question 4 was answered in Chapter 4:

4. *What, where and wherefore do technical failures occur in UWSI, more specifically, failures in implemented SUDS?*

To answer this question, we looked at the specific case of implemented integrated storm water solutions, i.e. Sustainable Urban Drainage Systems (SUDS). Site visits were used to identify failures in SUDS, and interviews with practitioners who were involved in the implementation and/or operation of these SUDS were conducted to determine the causes underlying these failures. Insight into the failures and their causes is relevant to improve the technical designs of SUDS, but also to help understanding how organizations and institutions, which are oriented toward traditional sewer systems, must be adapted such that they support SUDS.

To define the kind of failures, three types of SUDS were distinguished based on their hydraulic function: infiltration, conveyance, and storage. This distinction was made, as the hydraulic function turned out to be a determining factor for the failures that could occur. For example, *clogging* did not occur in storage SUDS, but it was the most frequently observed failure mechanism for infiltration SUDS. For conveyance SUDS *interference with obstacle* was observed most often, and for storage SUDS this was *limited freeboard* and *interference with obstacle*.

Analysis of the failure locations and the root causes of these failures indicated that interfaces between SUDS and other urban systems played an important role in both cases. With respect to failure locations, the results showed that more than one third of the failures occurred at such interfaces. In addition, the interviews that were conducted showed that the causes underlying these failures were often related to “human factors” such as communication or embedded practices. This demonstrates that the malfunctioning of SUDS is not just a technical issue, but is often related to socio-institutional aspects.

Why and how did these socio-institutional aspects play a role in the failures occurring in SUDS? As SUDS are often located above the ground, they typically extend to other infrastructures such as streets, parks, and gardens. This means that there are more actors involved in the design, construction and/or maintenance phase of SUDS than just water managers, think for example of road authorities and inhabitants. The results showed that the occurrence of failures in SUDS could often be linked to the multiple and diverse actors involved, for example, because this introduced ambiguity about maintenance responsibilities, but also since the main priority of these other actors was typically not related to water, which made them less alert to the water function of SUDS.

Hence, interfaces that arise with the shift to UWSI involve uncertainty about actions and institutions, and could lead to new failures. The identified failures and root causes provided an initial insight into the socio-institutional changes required for the shift from traditional, sectoral urban water solutions to UWSI solutions (e.g., changes to routines, policies and guidelines that are still oriented toward for traditional systems).

6.1.5 Organization of UWSI innovations in Amsterdam and Rotterdam

In chapter 5 the answer to the fifth sub-question was provided:

5. *How do organizations responsible for urban water management manage the tension between innovation (i.e., UWSI initiatives) and operation (i.e., day-to-day activities undertaken by the line organization)?*

To answer this question, we looked at two Dutch cities, Amsterdam and Rotterdam, and analyzed the initiatives they started to develop and implement innovation. Central to the study was the concept of organizational ambidexterity. The essence of this concept is that organizations need both operation and innovation techniques to be successful. Combining a desk study with semi-structured interviews, we looked at the types of the initiatives and the mechanisms that played a role in managing the interface between initiatives and the line organization.

In total, 16 UWSI initiatives were analyzed. Based on the empirical data, four types of initiatives were identified: programs, movements, collaborations, and line-based initiatives. Each of the initiatives was characterized by a different approach, organization, and role for hierarchy. Programs had the most official character, typically having an assigned team and using a top-down approach, while movements were organized most freely, using a bottom-up approach and relying on intrinsically motivated people.

Looking at the tension between innovation and operation activities, four mechanisms that shaped the connection between UWSI initiatives and the line organization were identified: network mechanisms, hierarchical mechanisms, process mechanisms and human resource mechanisms.

Network mechanisms, which comprise network activities on many different organizational levels, dominated the connection between initiatives and the line organization. Such network mechanisms played an important role throughout the entire innovation process, both in developing UWSI innovations, and in implementing them. This empirical finding differed from the literature on ambidexterity, which depicts two separated worlds (i.e., the world of operation, and that of innovation) that are connected at senior management level. The empirical findings revealed a smaller role for hierarchy. Hierarchical mechanisms relied on authority to foster the development or implementation of innovation. While executives did not play a dominant role in managing the interface between initiatives and the line organization, they were still important: they could foster UWSI during the process of innovation or play a role in the formalization of UWSI practices. Process mechanisms related to the process of interaction between practitioners involved in initiatives and those that focus on day-to-day operation of systems, i.e., line-organization practitioners. With respect to human resource mechanisms, i.e., mechanisms related to human aspects, the results showed that the personal skillset and capabilities of practitioners also played an important role in managing the tension between innovation and operation.

As Amsterdam and Rotterdam are considered “global frontrunners” in urban water management, the identified initiatives and integration mechanisms could be useful for other cities worldwide that are struggling to develop and implement UWSI in their hierarchical organizations to become more sustainable.

6.2 General conclusion: answering the main-research question

This section presents the general conclusion of this thesis, and thereby answers the main research question:

How is integration defined, understood, operationalized, and organized in urban water management?

To answer this question, the different perspectives on UWSI (see Section 1.2) are combined and compared. This has resulted in 4 key observations that are presented below.

6.2.1 UWSI is defined and understood in many different ways, thereby calling for a negotiated view on integration

The results of this thesis showed that there are many different views on integration: both in theory (Chapter 2) and in practice (Chapter 3) a variety of *definitions* and *understandings* of UWSI were identified. Regarding the *organization* of UWSI (Chapter 5), similar results were found: the multiplicity and diversity of UWSI initiatives reflect that integration can be understood in different many ways. This diversity means that integration could also be described as a wicked problem: parties disagree not only about the solutions, but also about the definition of problems. Looking at what this wickedness means for decision-making, it calls for a *negotiated* view on interaction: rather than searching for a single truth – which is not possible for wicked problems – a process of interaction is needed such that involved parties could decide collaboratively how integration should be defined and operationalized. I expect fruitful grounds for such negotiations as no significant conflicts between different understandings of integration were found – thus that one understanding excluded the other.

For example, in Chapter 3 four practitioner's perspectives on integration for future urban water systems were identified. These perspectives focused on different spatial scales and saw different drivers for UWSI, but rather than excluding each other, the perspectives could be used in a complementary way. Each perspective contained valuable information that could be used to make effective strategies for future-proofing. Nonetheless, in terms of desired means of achieving UWSI, the results did show some potential conflicts between the perspectives, such as whether stormwater management measures should be enforced or only encouraged. These conflicts, however, concerned mostly the implementation of UWSI, rather than the core ideas on it.

Similarly, for the *organization* of UWSI (Chapter 5), no clear conflicts between the initiatives were found, but rather interconnections. Although the initiatives were typically organized in a separated way, i.e., targeting a single sustainability issue such as climate adaptation or circularity, the results showed that, during implementation, there were also many relationships between the initiatives. For example, the Waternet programs (i.e., the Program Energy transition, Program Circularity and Programs Climate adaptation) closely collaborated on many topics: together they created a "critical mass" for UWSI innovations that could no longer be stopped by the line organization. This suggests that pairing up gives them an advantage, rather than leading to conflict, despite their different focuses.

Why and how does the diversity in understandings serve as a driver for a process of interaction? And why is such a process essential for the operationalization of UWSI? As UWSI is a cross-sectoral challenge, it inevitably requires the involvement of many different actors, each with their own resources and responsibilities. Obviously, these actors have different perceptions and interests regarding UWSI. This means that there is no single truth on integration, but there are many: all the identified perspectives are legitimate and understandable, but different in their approach. A process of interaction could be instrumental to bring the perspectives together and *negotiate* on how UWSI should be defined and operationalized: such a process allows to accommodate the different views and connect them. Since we did not find clear conflicts between the perspectives, negotiations could enrich the approach to integration and lead to synergy and a supported outcome. The connections between initiatives are an example of such negotiations: the different goals and approaches could be combined, even though there were different views and motivations for UWSI.

6.2.2 Sustainability is a key driver for UWSI on paper, but in practice, many other competing factors come into play

While in the urban water literature on integration as well as in policy documents it is typically assumed that sustainability is the key driver of integration, the empirical results of this thesis showed that in practice, sustainability did not always play a central role in decision-making on integration. Other values such as operability and esthetics could also play a role, and sometimes a trade-off between these values could not be avoided.

More specifically, the results in Chapter 2 showed that many of the integrated approaches to urban water management have been formulated in response to sustainability challenges such as climate change, water quality issues and resource limitations. As such, the theoretical concepts on integration are typically based on the assumption that sustainability is the key driver for integration. Similarly, in the policy documents that we studied for Chapter 5 about the organization of UWSI, sustainability ambitions seemed to be the main driver for UWSI initiatives.

Looking at the practitioners' *understandings* of UWSI (Chapter 3), however, the results showed that sustainability did not always play a central role in decision-making on integration. In perspective 1, for example, an integrated approach was mainly viewed as a means to address the many spatial challenges that are at hand and deal with the limited space available – thus as a necessity. The emphasis in this perspective was on coordinating and accommodating different interests, but also on making trade-offs and choices about what is most important at a certain location, rather than coming up with the most sustainable solution. Likewise, for perspective 4 we found that UWSI was not so much about sustainability, but rather about saving costs and working efficiently. Thus, while all of the perspectives agreed that sustainability challenges needed to be addressed and that integration could play a role in this, not all of them saw sustainability as the central driver to UWSI.

Similarly, in Chapter 4, we found that sustainability was no leading principle for the *operationalization* of UWSI. For example, the results showed that in some cases the design of SUDS was adjusted to improve their maintainability or safety, although this decreased their sustainability. In other cases, we found that esthetics was more critical than sustainability.

These examples show that, when it comes to UWSI, there are other values (e.g. safety, affordability, livability) at play than just sustainability. This implies that, in some cases, a compromise needs to be made between those other values and sustainability. And the mere fact that it requires a trade-off means that, in some cases, sustainability will be of less weight than the other values. There is thus a paradox in the fact that although sustainability is often the driver of integration, our results show that the process of negotiation that is required to arrive at UWSI may lead to lower levels of sustainability.

6.2.3 In practice, UWSI is often approached as a design challenge, and not as a continuous process that needs coordination across phases

Whereas the results about the *definition, understanding* and *organization* of UWSI (Chapter 2, 3 and 5) indicated that primarily the collaboration between sectors is key to UWSI, the results on the *operationalization* of UWSI (Chapter 4) revealed that coordination between the different phases of the development process is highly relevant as well. When this coordination was not in place, it could lead to failing UWSI systems – thus resulting in the loss of integration.

In the urban water literature on integration (see Chapter 2), as well as in the practitioners' perspectives (Chapter 3), UWSI is viewed as a cross-sectoral challenge that inevitably needs a cross-sectoral approach. This attention for connection between sectors was also reflected in the *organization* of UWSI (Chapter 5): the policy documents that were analyzed typically emphasized the need for a cross-sectoral approach. In addition, the initiative teams typically comprised practitioners from different departments, together forming an interdisciplinary team. This attention to a cross-sectoral approach was mainly found in the earlier stages of the development process, such as during the policy and design phase.

The *operationalization* of UWSI in Chapter 4, however, revealed that the attention to integration is also relevant for the later stages of the development process. We found that failures in integrated systems originated in all phases of the development process. For example, failures originated in the construction phase due to constructors not being informed about new system designs, and in the user/maintenance phase due to operators not being aware of the maintenance requirements of new systems.

This illustrates the importance of paying attention to integration in (and between) all phases of the development process to achieve successful systems – just paying attention to the collaboration between sectors in the policy and design phase is thus not enough. In this respect, UWSI could be seen as an infrastructure lifetime challenge, rather than an integrated design challenge.

This finding seems obvious, yet we observed that there was relatively little attention to considering implementation and operational processes for UWSI systems. Nonetheless, careful operation is extremely important for critical infrastructure sectors such as the urban water sector considering their low tolerance for failure and the long infrastructure lifespans. While this holds true for traditional, sectoral solutions, it is equally, if not more, important for integrated solutions. After all, UWSI can lead to new failures such as at the interfaces of previously unconnected systems (see Chapter 4), but also makes the “whole" of systems more vulnerable: failures in one part of the system may trigger other, bigger, failures in connected systems – i.e., cascading failures. Furthermore, UWSI innovations require radical changes in the “do's and don'ts” of constructors and operators. For instance, the construction of UWSI innovations may require counter-intuitive actions from constructors that contradict traditional practices and guidelines, such as constructing road surfaces with a concave shape rather than a convex shape to drain storm water via the road surface. Clearly, the processes of implementation and operation require careful attention to ensure that UWSI solutions function well.

6.2.4 While UWSI is generally considered an effort that requires a planned approach, emergent processes appear to be critical as well

Given the extensive and radical changes that the transition to UWSI entails for organizations and institutions, systems integration is typically viewed as a phenomenon that requires a top-down, planned approach such that various changes could be coordinated and aligned. The empirical results of this thesis show, however, that unplanned actions also played an important role in the processes of developing and implementing UWSI.

To be more specific, looking at the *organization* of UWSI in Chapter 5, we found that most of the integration initiatives were organized in a top-down way (i.e., programs and collaborations). Their establishment typically resulted from sustainability goals imposed by higher governmental tiers (e.g. the European Union or the national government). To meet these goals, executives started initiatives in parallel to the line organization that were not hindered by the focus on day-to-day operational activities and that allowed a dedicated team to work on the development and implementation of UWSI. These initiatives thus took a planned approach to integration so as to meet sustainability ambitions and targets.

The emphasis on integration as a deliberately planned phenomenon to sustainability was also reflected in the literature on systems integration: systems integration concepts such as urban metabolism, closed loops, city as ecosystem and circular urban systems (van Broekhoven and Vernay, 2018) typically viewed integration as a strategy for sustainability. While these concepts have a different focus, they are all based on the same principles that move away from linear "take, make, dispose" processes, and put an integrated approach central to achieve sustainability. This means that the desired form of integration was already defined beforehand (for instance, a closed loop or circular urban system) and then planned for. Both in theory and in practice, systems integration is thus typically understood as an endeavor that needs a planned organization.

Drawing on our empirical results about the *understanding* and the *organization* of UWSI, however, we found that UWSI was not realized through top-down planning alone, and largely depended on unplanned (patterns of) actions. For example, UWSI innovations resulted from interactions in networks (see Chapter 5 on the *organization* of UWSI). Even for initiatives with a planned character (i.e., programs and collaborations), connections with other initiatives, departments and organizations strongly influenced whether and how UWSI came about. For example, we found that within such networks, unexpected UWSI innovations were developed, such as those related to the textile industry at Waternet and within Bluecity in Rotterdam.

Similarly, in Chapter 3 on the *understanding* of UWSI, the perspectives 1 and 2 illustrated the role for emergence. For example, perspective 1 stressed that one should view water challenges in the perspective of the many urban challenges that lie ahead, and be more responsive to the goals and projects of other parties in the city, rather than only setting one's own sectoral targets and work towards them. In practice, this means that deliberate plans cannot always be realized and will have to give way to ideas and issues that pop up and are considered more important at that moment.

Perspective 2 focused on climate adaptation, thereby viewing adaptation measures as an opportunity to improve the livability of the city. It emphasized the importance of responding to what is already happening in the city and linking to ongoing (small-scale) projects, even though climate adaptation was not always the top priority in those projects. In both perspectives there is thus much attention for emergence rather than planning: instead of following a well-defined and deliberate plan that is established by top management, one continuously adapts to a changing environment in which decisions are typically taken one at a time, often by individuals in the organization.

Although seemingly counterintuitive, the empirical findings of this dissertation thus show that bottom-up, emergent innovations were instrumental in achieving systemic changes like UWSI. After all, the development and implementation of UWSI depends on many other parties and organizations in the city. This means that one cannot achieve UWSI alone but is dependent on the actions of these other actors – and these have their own ideas about how integration should be developed and implemented. As a result, UWSI cannot always be realized through a project approach which is linear and plannable, but typically evolves as a process of interaction that is subject to serendipity.

6.3 Discussion: reflecting on the findings of this thesis

This section puts the findings of this thesis in a broader context, reflecting on the four conclusions drawn in section 6.2 one by one.

6.3.1 Leaving room for broad interpretation versus talking past each other: what does the ambiguity associated with integration imply for decision-making?

In section 6.2.1 it was concluded that UWSI is an ambiguous concept, involving many different definitions and understandings of integration. What does this ambiguity mean in practice? I argue that the ambiguity associated with UWSI involves two sides:

On the one hand, the ambiguity is an important driver to the process of interaction. Since UWSI can be defined in many different ways, it leaves room for individual interpretations, interests and motivations. As such, ambiguity facilitates identification with UWSI and offers space for the process of interaction that is needed to come to a negotiated view on integration. Ambiguity can thus play a mobilizing role in this process, being helpful in engaging actors to arrive at an integrated and widely supported solution. In this respect, I see an advantage for the concept of integration over that of sustainability, which leaves less room to accommodate other values such as livability and financial concerns (Section 6.2.2).

On the other hand, while a certain tolerance for ambiguity is needed, it should not be too high, as this could hinder the implementation of UWSI. The plurality of definitions and concepts for UWSI increases the risk of people talking past each other. Furthermore, it could slow down decision-making, given the many actors involved in UWSI, all having their own perspective on what needs to be integrated, as well as on why and how this should be done.

These two sides demonstrate that, while the ambiguity associated with UWSI could thus be helpful for arriving at a collaborative solution that safeguards different public values, it could also be counterproductive, preventing that UWSI actually comes about. The question is thus how the benefits of ambiguity could be exploited while its adverse effects could be limited. In this respect, a process of interaction (see Section 6.2.1) can play a vital role: in earlier stages of decision-making the ambiguity associated with UWSI can act as a driving force for the process of interaction, while it could help reducing ambiguity at a later stage.

6.3.2 Sustainability versus integration: to what extent is UWSI concerned with sustainability?

The results in Chapter 2 showed that many integrated approaches to urban water management have been formulated in response to sustainability challenges such as climate change, environmental issues, and depleting resources. In Section 6.2.2, however, I concluded that sustainability challenges are not the only driver of integration. Typically, other values such as esthetics or livability play a role in decision-making for UWSI as well, being part of the process of interaction that is needed to arrive at a negotiated view on integration (Section 6.3.1). The question is what such negotiations mean for the (level of) sustainability of UWSI innovations.

On the one hand, the inclusion of other values may lead to the final solution becoming less sustainable. More specifically, the fact that there are other values at play, means that in some case trade-offs need to be made – and this may be at the expense of the degree of sustainability of UWSI innovations. For example, changing the design of UWSI innovations to improve their maintainability could decrease their sustainability. While in some cases clever design could overcome those limitations, in other cases it could not. This illustrates that integration and sustainability, in terms of content, do not always go hand in hand.

On the other hand, the inclusion of other values may well be beneficial to the process of achieving sustainability: it could increase the support for a solution, and thereby facilitate the implementation of UWSI innovations. This is illustrated by perspective 2 in Chapter 3, and the initiative type “movements” in Chapter 5: in both cases, climate adaptation was framed as a means to improve the livability of cities. Such positive framing could also be used as a strategy to develop a shared understanding and willingness to act. For example, rather than emphasizing the need for climate adaptation measures, the opportunities to improve social cohesion and individual well-being could be highlighted (Willems et al., 2022). Focusing on these other values can thus increase support for UWSI innovations. And looking at the construction and user/maintenance phases of systems (Chapter 4), the inclusion of values related to the maintainability and practicability of UWSI innovations in the design phase may prevent that later major modifications must be made that greatly reduce the sustainability of solutions. This illustrates that including other values thus might be beneficial to the final level of sustainability of UWSI innovations.

Yet, this “level of sustainability” can also be questioned; i.e., the way sustainability is defined can be questioned. I would like to make two comments on this. First, the level of sustainability of a solution can be evaluated in different ways. For example, while the final UWSI solution can be found highly sustainable, it could also lead to the early replacement of infrastructure that has not yet reached its technical lifetime. This may be the case, for example, with an integrated redesign of a street for climate adaptation purposes or joint rehabilitation works (van Riel et al., 2016). Rather than only evaluating whether the final solution is (more) sustainable in itself, the environmental costs of such early replacement of traditional infrastructure should be included in the evaluation of sustainability as well. Second, one could argue that UWSI is a means to keep doing what we are doing, focused on doing “more more

more," rather than looking at what we already have and using that in the most optimal, sustainable, and durable way.

It is thus debatable to what extent UWSI is concerned with sustainability and whether UWSI innovations always lead to sustainable solutions. Nonetheless, I found that, through the collaborative processes of interaction by which UWSI innovations typically came about, and thus the inclusion of different interests and values, final solutions often addressed different sustainability challenges.

6.3.3 Operation versus policy: how can the different phases of the development process be aligned with regard to UWSI?

The results of this thesis showed that, although UWSI involved significant changes for operators, processes of implementation and operation often received only little attention in policy-making (Section 6.2.3). This illustrates that the different phases of the development process are not always well aligned, with the operational phase seeming to lose out on the policy phase.

Nonetheless, the processes of construction and operation in a sector such as the urban water sector are essential, given the vital services urban water systems deliver and the long infrastructure lifetimes. To work towards reliable integrated solutions, implementation and operation issues must therefore be given sufficient priority in the development process. I provide a few suggestions how this could be done.

One way is to include "people on the ground" in the development process so that their knowledge and experience can be incorporated in the design of UWSI solutions. For example, one could make those people, and the values that are important to them, part of the process of interaction (Section 6.3.1). This means that operators should be involved at the front end of the process, i.e., in the policy phase, to make sure that their ideas and values are included in the systemic changes that are required for the shift to more integrated solutions. Furthermore, one could make operators more aware of the values that are at play in the policy phase, such as sustainability (see Section 6.2.2), by actively reaching out to them. I found an example of this in Chapter 5 in the case of the "roving reporters" ("razende reporters" in Dutch) in the Circularity Program of Waternet. Those reporters made vlogs about successful circular cases to tell the "circularity story" to operators and others in the organization. While this may not directly lead to including operational values and issues in policy-making, it could help making operators more alert to the changes that are required for UWSI, and if needed, communicating potential mismatches to policy makers.

Another way to better align the different phases of the development process would be, the other way around, to include people who were involved in earlier phases and know more about the “master plan” on UWSI in later phases of the development process. By doing so, attention to UWSI could be safeguarded in those later phases, which is more difficult to achieve in the case of traditional, document-based project handovers.

These examples illustrate that there are various possibilities to better integrate operational challenges into front-end decision making. Rather than being exhaustive here or presenting the best solution how to do so, my aim is to highlight the need to take those challenges into account – and thus the need to consider those challenges for further research.

6.3.4 Planned versus emergent: what does the emergence that comes with integration mean for the planning of UWSI initiatives?

While it is often thought that systems integration develops in a planned way, I found that emergent innovations played an important role in UWSI as well (Section 6.2.4). For example, the results in Chapter 5 revealed a large role for networks, and in two of the four practitioners' perspectives presented in Chapter 3, it was emphasized that water should be connected to other ongoing (infrastructure) initiatives rather than just focusing on one’s own planning. What does the role for emergence mean for decision-making in practice and the planning for UWSI?

Emergence may seem to conflict with planning for UWSI. Based on the results presented in this thesis, however, I argue that emergent processes are also essential to achieve UWSI. While top-down initiatives allow executives to steer on systems integration, bottom-up initiatives enable people across the organization to become enthusiastic. As such, they could contribute to servants’ willingness to act and support idea development (Chapter 5). The latter is essential, since UWSI involves radical changes across the organization, and thus affects practices of civil servants in all layers of the organization. While not all these practitioners may come up with systemic ideas and changes, they could provide valuable insights based on their knowledge and experience. By providing space for emergence, these bottom-up initiatives are given a chance and allow unexpected ideas to develop.

On the one hand, emergence is thus needed and should be facilitated. On the other hand, in some cases, emergent actions may also hinder planned UWSI initiatives – for example, if during the process of implementing planned initiatives new ideas arise that cause planned initiatives to be discontinued. This suggests that emergent initiatives should be monitored such that showstoppers for UWSI could be blocked, while actions that fit planned UWSI initiatives or that could take place in parallel, are supported. In this way, emergent processes have the potential to contribute to supported, integrated solutions that are much needed to prepare urban water systems for the future.

To conclude, the four studies conducted in this thesis (Chapter 2, 3, 4 and 5) and the key observations presented in the conclusions and discussion sections (Chapter 6) provide valuable insights into how integration is defined, understood, operationalized, and organized, and thereby support the transition to more integrated urban water management practices.

6

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Appendices

Appendix A: Factor scores per statement

Table A-1. Overview of the statements (in English) and their factor Q sort values (the factor arrays). The original statements were in Dutch. F stands for Factor.

#	Statement	F1	F2	F3	F4
1	The water sector's ambition to be sustainable comes at the expense of its core business: caring for public health, guaranteeing dry feet and protecting water quality.	-4	-2	1	0
2	It is undesirable that solutions for waste and storm water depend on the correct use and maintenance by residents or businesses.	-2	1	-3	1
3	Municipalities do not have sufficient knowledge and experience to properly manage the process towards a future-proof urban water system.	-3	-5	1	3
4	Continuously implementing innovative solutions leads to an unmanageable system at the city level due to the great variety of solutions.	0	0	0	1
5	Separate budgets for maintenance of green facilities, roads and water hinder the implementation of integrated solutions.	5	1	3	0
6	In the final analysis, deep-rooted habits are what prevent the realization of future-proof systems.	2	2	2	-2
7	The challenge of collaboratively achieving a future-proof public space is not so much agreeing on the actual design, but rather in agreeing on the moment of replacement.	4	-3	1	3
8	The Environment and Planning Act will improve the coordination between different urban infrastructures.	0	0	-5	2
9	Strict regulation of spatial developments, such as the “compensation rule” for water storage or a minimum construction level, are essential to create more space for water.	-1	5	2	-3
10	Everyone talks about climate proofing and circularity, but we should first ensure that our gullies, the sewage system and the receiving water system function properly.	-4	-1	-2	2
11	The local processing of storm water seems like a good idea, but in reality, without a storm water system, all undesired storm water, ground water and flushing water of aquifer thermal energy storage systems will be discharged to sanitary sewers – which would cause even more problems.	-2	-1	-3	0
12	By intelligent clustering of cables and pipes, we will be able to better manage public space in the future.	1	2	0	0
13	Creating support and awareness among residents is crucial to achieve a future-proof urban water system.	4	3	4	0
14	Municipal guidelines, for example for the design of public space, do not leave sufficient space to actually implement innovative solutions.	0	0	0	-1
15	If pipes are ready for replacement, we must focus on extending their lifespan to enable an integrated approach at neigbourhood level.	0	-2	-2	2
16	The water sector should adopt digital advances and fully exploit the opportunities that smart technology offers.	0	1	-1	4
17	At street level, it is best to work on an individual basis – because coordinating with other sectors costs too much time and money.	-3	-5	-4	-3
18	To prepare the urban water system for the future, we have to discard the idea that this should not cost more than our current system.	2	4	1	-1
19	The parties involved will not take the measures necessary to make our system future-proof, unless there are financial incentives.	-1	0	2	3
20	The focus on climate adaptation diverts attention away from traditional management tasks.	-5	-1	-3	-2

21	When choose to renovate sewers, we are indirectly opting to maintain our current system; continuing to develop renovation technologies, such as relining, is thus a threat to future-proof urban water systems.	-3	1	3	-2
22	Measures to prepare the system for the future, such as systems for local (re)use of water or water-permeable pavement, are often too demanding in terms of use and maintenance.	-1	-2	0	1
23	In order to make our system future-proof, shifting to a district-oriented approach is vital; replacing at the neighborhood level rather than street level.	3	3	4	5
24	More stringent privacy legislation hinders the optimal usage of sensors and data, thereby threatening the future-proofing of our systems.	-2	0	-2	-2
25	Decentralized wastewater systems are better able to meet the objectives of a future-proof urban water system than centralized ones.	-3	-3	3	-5
26	The future of the urban water system depends on how the energy transition is implemented and how fast.	0	-4	-1	-4
27	If we want to achieve our spatial ambitions in the future, the space under the ground needs to be the starting point for the above-ground design.	3	3	0	5
28	We should not apply innovative solutions until we have identified their risks.	-5	-4	-4	-1
29	In order to prepare our urban water system for the future, agreements between the various water partners is more important than between the parties involved in spatial planning.	-4	-1	-5	-4
30	If we want to achieve integrated solutions, we should put objectives, like circularity, climate resilience or energy neutrality, in the tendering process, rather than focusing on the instruments one should use.	3	0	3	-1
31	Any storm water solution that reduces the amount of water in the sewerage system is a step in the right direction and will help to change our way of thinking.	0	5	-3	-4
32	Using legislation to enforce climate adaptation measures is undesirable.	3	-4	-4	1
33	Active management of groundwater, both in terms of the replenishment and discharge of groundwater, is a requirement for a future-proof urban water system.	2	3	5	-3
34	Climate adaptation needs a clear captain who can combine issues like flooding, heat stress and drought.	1	4	5	0
35	Knowing that everything we build now will have to last for many decades, our ambitions for a future-proof system should be much higher.	2	-2	4	-5
36	Removing pharmaceuticals from wastewater will be a gamechanger for the reuse of effluent.	1	2	-1	0
37	The careful transfer between the various phases of policy, design, implementation and management remains a challenge to successfully integrating the design of the public space.	4	2	-1	4
38	By dwelling on larger issues, such as defining risk profiles, we miss obvious opportunities for improvement.	1	-3	-2	-3
39	The only way to climate-proof our city is making connections to other projects and parties in the city, and linking climate adaptation to their goals.	5	4	2	3
40	To achieve future-proof urban water management, clearer rules are needed about who is responsible for damage and how to prevent it.	-1	1	1	4
41	A future-proof urban water system requires a more business-oriented approach to the wastewater chain.	-1	-3	0	2
42	To prepare for the future, we need solutions that connect different systems, like aquathermal systems.	1	0	0	-1
43	Removing micropollutants from wastewater will have major consequences for how we deal with storm water.	-2	-1	-1	1

A

Appendix B: Factor loadings per participant

Table A-2. Overview of the participants in the Q study, the organization they are working for, and their (rotated) factor loadings. The gray boxes indicate the defining sorts, i.e. the Q sorts that loaded significantly upon that factor alone.

#	Organization	Factor 1	Factor 2	Factor 3	Factor 4
1	Water board	0.2696	0.3872	0.4898	0.3022
2	Water board	0.5570	0.5915	0.1140	0.0613
3	Water board	0.5238	-0.0066	0.4876	0.0991
4	Municipality	0.2294	0.6096	0.0945	0.2522
5	Municipality	0.4287	0.2622	0.3531	0.5219
6	Consultancy firm	0.1335	0.2762	-0.1286	0.4561
7	Municipality	-0.0633	0.6768	0.0979	-0.0125
8	Knowledge institute	0.1699	0.0240	0.4950	0.6465
9	Drinking water company	-0.2165	-0.0772	0.7051	0.1179
10	Consultancy firm	0.2089	0.2365	0.3565	0.3805
11	Municipality	0.2454	0.6961	0.2651	0.2317
12	Municipality	0.5759	0.2790	0.1671	0.3832
13	Water board	0.5934	0.3811	0.3783	-0.0124
14	Municipality	0.5583	0.0246	-0.0962	0.175
15	Municipality	0.0171	0.4008	0.1815	0.5876
16	Water board	-0.0317	0.4376	0.3759	0.0425
17	Consultancy firm	0.5847	0.3652	0.2656	0.2422
18	Municipality	0.4820	-0.1383	0.1581	0.0545
19	Knowledge institute	0.5754	0.1280	0.2986	0.2795
20	Municipality	0.2081	-0.1942	-0.1188	0.7391
21	Municipality	0.4953	0.4769	0.1312	0.0736
22	Consultancy firm	0.6083	-0.1689	-0.1341	0.1645
23	Consultancy firm	0.2417	0.2939	0.4019	0.534
24	Water board	0.3624	-0.0162	0.6837	0.0004
25	Drinking water company	0.1425	0.3304	0.5600	-0.102
26	Drinking water company	0.5491	0.3519	0.0925	-0.0473
27	Water board	0.6624	0.4477	0.1296	-0.0782

28	Municipality	0.4202	0.3836	0.4633	0.1624
29	Knowledge institute	0.4453	0.0981	0.4102	0.2665
30	Municipality	-0.0016	0.7082	-0.1119	0.4209
Explained variance (%)		17	14	12	10

Appendix C: Long list of root causes

Table A-3. Long list of root causes

Number	Root cause (Step 1)
1	Transfer from 3D to 2D design
2	Lack of standards for SUDS
3	The traditional way of separating traffic from greenery and water bodies
4	The traditional design of the public spaces in the Netherlands
5	The unfamiliarity of integrating SUDSs in spatial design
6	The norm-oriented mindset in the Netherlands
7	Esthetical considerations in design
8	Adaptation of system to temporary “construction” situation
9	Unforeseen changes in construction phase
10	Lack of experience of contractors on SUDSs
11	Lack of supervision from municipality during construction
12	Hiring external agencies for supervision practices
13	Traditionally constructing green with raised sites
14	Traditionally constructing on 1 height level
15	Traditionally constructing curb lower than street
16	The phased construction of plots
17	Unfamiliarity of responsible maintenance party
18	Unfamiliarity of residents about the responsibility for maintenance
19	Lack of maintenance standards of SUDSs
20	Lack of maintenance
21	Maintenance budgets not adapted to SUDS maintenance
22	The degree of maintainability not included in the design
23	Uncertainty about the SUDS functionality
24	Insufficient confidence in SUDS
25	Unfamiliarity about the social impacts of the SUDS
26	Unforeseen side effects of SUDS
27	Lack of knowledge about the performance of SUDS in practice
28	Lack of knowledge of long-term performance SUDS

29	Lack of social understanding about the role of SUDS
30	Poor communication between actors
31	Uneven level of knowledge among actors
32	Unfamiliarity of residents about the function of SUDSs
33	Lack of information about the subsoil conditions (only point information)
34	Lack of knowledge about the impact on the groundwater characteristics
35	Lack of experienced staff
36	Lack of monitoring and evaluating the performance of SUDS

A