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Socio-technical challenges towards smart urban water systems

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Abstract

Globally, urbanization, climate change, and ageing assets affect urban water management. One potential solution is recognized in smart urban water systems, which rely on monitoring data from infrastructure elements, e.g., combined sewer overflows (CSOs). Such monitoring data provides evidence on system functioning and performance and allows a dynamic control to exploit all existing infrastructure capacities, for example during heavy rainfalls. As a result, smart urban water systems hold the potential to improve performance outcomes, to reduce environmental impacts on surface waters, and to manage infrastructures more efficiently.

However, despite the availability of digital technologies for monitoring, data transfer, and control, only few examples of smart urban water systems exist. Where monitoring data is already obtained, it is often not optimally handled. Potential reasons cannot be found at the technical level only, but require an understanding of smart urban water systems in their social and socio-technical dimensions. To achieve smart urban water systems, not only technical innovation, but also adaptations of the surrounding social system are needed.

Therefore, this PhD thesis raises the research question: "*What are challenges to the development towards smart urban water systems from a socio-technical perspective?*" By combining literature from multiple disciplines, including environmental engineering, public policy, and urban water governance, a socio-technical perspective on smart urban water systems is acquired. The research question is addressed in the context of urban water management in Switzerland.

In publication 1, the perspective of Swiss sub-state authorities is chosen to investigate barriers to the utilization of data in public organizations. A general model of barriers at individual, organizational, and institutional levels is developed and applied to the comparative setting of 23 (out of 26) sub-states in Switzerland. Drawing on empirical data from semi-structured interviews and a qualitative comparative analysis (QCA), barriers such as a *lack of vision* or a *lack of resources* were identified at the individual and organizational levels, respectively.

In publication 2, the actor perspective is extended to include all social actors (e.g., operators, engineers, authorities) involved in urban water management as well as all technical elements within the boundaries of a catchment area of a wastewater treatment plant (WWTP), such as the WWTP itself, CSOs, and pumping stations. Based on considerations from socio-technical system theories, social network analysis, and social-ecological network studies, the conceptual approach of structurally explicit socio-technical networks (STN) of infrastructure management is developed. Further, concepts that allow for descriptive STN analyses are proposed, particularly related to the trends of digitalization, decentralization, and integrated management. The STN approach is applied to the context of urban water management, and more specifically, to an empirical case study urban water system in Switzerland. Drawing on

empirical STN data from semi-structured context interviews, document analyses, and an online-survey, findings from the descriptive STN analysis reveal challenges towards smart urban water systems in the form of *missing information exchange relations* between particular social actors. Further, the socio-technical degrees of digitalization and integrated management allow for determining the progress of smart urban water systems in a socio-technical way. For example, a STN of urban water management not only illustrates which technical elements are already equipped with monitoring technologies, but also shows which social actors have access to data obtained from these elements.

In publication 3, based on the conceptual STN approach, inferential analyses are performed for three empirical case study STNs of urban water management in Switzerland. The analysis pursues two objectives: i) understanding how social interactions such as information exchange among social actors are influenced by underlying socio-technical dependencies, and ii) analyzing particular socio-technical challenges towards data-driven and integrated urban water management, such as *organizational fragmentation*, *access to data*, and *diverging perceptions*. Using exponential family random graph models (ERGMs), findings demonstrate that information exchange among social actors is dependent on how they are related to the infrastructure system and socio-technical challenges were identified in respective case studies.

To address identified challenges towards smart urban water systems, the thesis suggests specific recommendations for policy and practice derived from the three publications. These recommendations are mainly applicable to the case of Switzerland, but other countries faced with similar challenges might find results or methodological approaches useful.

As this PhD project is characterized by its interdisciplinary orientation and supervision, reflections on interdisciplinarity within the project are presented, particular in relation to the differences between (environmental) engineering sciences and social sciences. These learnings may be relevant for scientists or project supervisors in similar interdisciplinary situations.

Overall, the research as presented in this thesis bears several limitations that could be addressed in future research. First, overcoming challenges requires appropriate policies, which could be evaluated in terms of their effectiveness. Second, with the strong focus on actors, further aspects of social systems (e.g., regulations) are considered as contextual and are not explicitly covered in this thesis. These aspects, however, also play an important role regarding the development towards smart urban water systems. Third, more comparative settings — that go beyond the Swiss perspective — could provide insights on challenges and solutions across different countries or sectors.

Kurzfassung

Urbanisierung, Klimawandel und alternde Infrastrukturen fordern die heutige Siedlungswasserwirtschaft heraus. Eine mögliche Lösung sind intelligente Abwassersysteme, die auf der Verwendung von Messdaten aus einzelnen Infrastrukturelementen, z.B. Regenüberlaufbecken (RÜB), beruhen. Solche Messdaten geben Aufschluss über die Funktionsweise und Leistungsfähigkeit der Abwassersysteme und ermöglichen eine dynamische Steuerung, um alle vorhandenen Infrastrukturkapazitäten zu nutzen, z.B. insbesondere bei Starkregenereignissen. Intelligente Abwassersysteme haben daher das Potenzial, die Leistungsfähigkeit der Infrastrukturen durch eine effizientere Bewirtschaftung zu verbessern und Umweltauswirkungen auf Gewässer zu reduzieren.

Trotz verfügbarer digitaler Technologien für die Überwachung, Datenübertragung und Steuerung gibt es in der Praxis nur wenige Beispiele intelligenter Abwassersysteme. Dort, wo bereits Messdaten erhoben werden, werden sie zudem oftmals nicht optimal genutzt. Mögliche Gründe dafür sind nicht nur auf der technischen Ebene zu suchen, sondern erfordern ein Verständnis von intelligenten Abwassersystemen in ihren sozialen und sozio-technischen Dimensionen. Intelligente Abwassersysteme erfordern nicht nur die Implementierung technischer Innovationen, sondern bedürfen gleichzeitig auch nötigen Anpassungen entsprechender sozialer, politischer oder organisatorischer Gegebenheiten.

Deshalb untersucht diese Dissertation die Forschungsfrage: "*Welche Herausforderungen stehen der Entwicklung zu intelligenten Abwassersystemen aus sozio-technischer Perspektive entgegen?*" Anhand von Literatur aus verschiedenen Disziplinen, darunter Umweltingenieurwissenschaften, öffentliche Politik und Governance, wird eine sozio-technische Perspektive auf intelligente Abwassersysteme erarbeitet. Die Forschungsfrage wird im Kontext der Schweizer Siedlungswasserwirtschaft behandelt.

In Publikation 1 wird die Perspektive der kantonalen Fachstellen in der Schweiz gewählt, um mögliche Hindernisse für die Nutzung von Messdaten in öffentlichen Organisationen zu untersuchen. Dazu wird ein allgemeines Modell zu Hindernissen auf individueller, organisatorischer und institutioneller Ebene entwickelt und auf 23 (von 26) Kantonen in der Schweiz angewendet. Gestützt auf empirische Interview-Daten und einer qualitativen vergleichenden Analyse werden zwei Hindernisse identifiziert: eine *fehlende Vision* auf individueller Ebene oder *fehlende Ressourcen* auf organisatorischer Ebene.

In Publikation 2 wird die Akteurs-Perspektive auf alle in der Siedlungswasserwirtschaft beteiligten Akteure (z.B. Betreiber, Ingenieure, Behörden) sowie auf alle technischen Elemente innerhalb eines Einzugsgebiets einer Kläranlage, d.h. zum Beispiel die Kläranlage selbst, RÜB und Pumpwerke, erweitert. Basierend auf Theorien zu sozio-technischen Systemen, der

sozialen Netzwerkanalyse sowie Studien zu sozial-ökologischen Netzwerken wird ein konzeptioneller Ansatz zu strukturell expliziten sozio-technischen Netzwerken (STN) entwickelt, die das Infrastrukturmanagement auf sozio-technische Weise abbilden. Darüber hinaus werden Konzepte vorgeschlagen, welche deskriptive STN-Analysen ermöglichen, insbesondere in Bezug auf Infrastruktur-Trends wie Digitalisierung, Dezentralisierung und integrierte Bewirtschaftung. Der STN-Ansatz wird auf den Kontext der Schweizer Siedlungswasserwirtschaft angewendet und in einer empirischen Fallstudie untersucht. Die Ergebnisse der deskriptiven STN-Analyse, die sich auf Daten aus Kontextinterviews, Dokumentenanalysen und einer Online-Befragung stützt, zeigen Herausforderungen auf dem Weg zu intelligenten Abwassersystemen in Form von *fehlendem Informationsaustausch zwischen beteiligten Akteuren* auf. Weiterhin lässt sich durch die beschriebenen sozio-technischen Masse für Digitalisierung und integrierte Bewirtschaftung, der Fortschritt intelligenter Abwassersysteme auf sozio-technische Weise bestimmen. So zeigt ein STN nicht nur auf, welche technischen Elemente bereits mit Messtechnik ausgestattet sind, sondern auch, welche Akteure Zugriff auf die erhobenen Messdaten haben.

In Publikation 3 werden auf Grundlage des konzeptionellen STN-Ansatzes erklärende Analysen für drei empirische Fallstudien in der Schweiz durchgeführt. Die Analyse verfolgt zwei Ziele: i) zu verstehen, wie soziale Interaktionen, z.B. der Informationsaustausch zwischen Akteuren, durch zugrundeliegende sozio-technische Abhängigkeiten beeinflusst werden, und ii) den Einfluss bestimmter sozio-technischer Herausforderungen auf dem Weg zu intelligenten Abwassersystemen zu analysieren, wie z.B. *organisatorische Fragmentierung, Zugang zu Daten* oder *unterschiedliche Wahrnehmungen über das technische Abwassersystem*. Ergebnisse aus der Analyse von 'exponential family random graph models' (ERGMs) zeigen, dass der Informationsaustausch zwischen Akteuren davon abhängt, auf welche Weise sie mit den jeweiligen Infrastrukturelementen verbunden sind. Zudem wurde der Einfluss der untersuchten sozio-technische Herausforderungen in den jeweiligen Fallstudien bestimmt.

Zur Bewältigung der identifizieren Herausforderungen in Bezug auf intelligente Abwassersysteme werden in dieser Dissertation spezifische Empfehlungen für Politik und Praxis vorgeschlagen. Diese Empfehlungen betreffen hauptsächlich die Schweiz Siedlungswasserwirtschaft. Jedoch könnten auch andere Länder, die mit ähnlichen Herausforderungen konfrontiert sind, von den Erkenntnissen oder methodischen Ansätzen profitieren.

Im Zuge der interdisziplinären Ausrichtung und Betreuung dieses Dissertationsprojekts werden Überlegungen zu interdisziplinären Erkenntnissen vorgestellt und auf die Unterschiede zwischen (Umwelt-)Ingenieurwissenschaften und Sozialwissenschaften hingewiesen. Diese Erkenntnisse könnten für Wissenschaftler:innen oder Projektbetreuende in ähnlichen interdisziplinären Situationen hilfreich sein.

Insgesamt weist die in dieser Dissertation vorgestellte Forschung mehrere Limitierungen auf, die sich in zukünftiger Forschung angehen lassen. Erstens erfordert die Bewältigung der Herausforderungen in Bezug auf intelligente Abwassersysteme geeignete politische Maßnahmen. Zweitens werden durch den starken Fokus auf Akteure weitere Aspekte sozialer Systeme (z.B. Gesetze oder Richtlinien) in dieser Dissertation nicht explizit behandelt. Diese weiteren Aspekte spielen jedoch ebenfalls eine wichtige Rolle bei der Entwicklung von intelligenten Abwassersystemen. Drittens könnten vergleichende Analysen — die über die Schweizer Perspektive hinausgehen — Einblicke in Herausforderungen und Lösungen in verschiedenen Ländern oder Sektoren bieten.

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If not in home office during the Covid-19 pandemic, I spent most of my time in the PEGO office in the ESS department. Here, I would like to thank Martin Huber for being a great colleague and friend, from the start to (more or less) the end of both our PhDs. I would like to thank Mert Duygan and Mario Angst, former PEGO office mates and co-authors of two of my PhD publications. It was great to have you for insightful discussions and valuable input, or of course, to share some office-made popcorn. Further thanks go to all colleagues in the PEGO group and the entire ESS department.

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The majority of my PhD research has had a spatial focus on Switzerland. Here, I would like to thank all survey participants and interview partners for giving their valuable time to provide me with data. Thanks to Hans Balmer for being a helpful and reliable contact person.

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List of abbreviations

CSO	combined sewer overflow
ERGM	exponential (family) random graph model
ICA	instrumentation, control, and automation
IMC	inter-municipal cooperation
QCA	qualitative comparative analysis
RTC	real-time control
STN	socio-technical network
UWM	urban water management
UWS	urban wastewater system / urban water system
WWTP	wastewater treatment plant

1. Introduction

1.1 Motivation and main research question

This PhD thesis focuses on the development of 'smart' urban water systems, which rely on the integration of available technologies related to instrumentation, control, and automation (ICA) into existing infrastructures. Utilizing data from such technologies could help operate and plan urban water systems in a more efficient way and reduce environmental impacts on surface waters. In this sense, smart urban water systems promise to save on additional 'hard, concrete' infrastructure as existing capacities in urban water systems are exploited in an optimized way.

However, despite these benefits, smart urban water systems remain a rarity in practice. Therefore, this PhD thesis explores and analyzes potential challenges that may impede the development towards smart urban water systems. To do so, this thesis adopts a socio-technical perspective that explicitly considers both social and technical aspects of (smart) urban water systems. For example, insufficient organizational resources or absent individual awareness of the benefits of smart urban water systems could hinder the effective utilization of data from urban water systems. Moreover, having technologies installed in specific urban water system elements does not immediately imply that all relevant actors can access and utilize obtained data. Therefore, research is needed to address the potential challenges that various actors, i.e., individuals or organizations involved in urban water management, face with respect to smart urban water system developments.

The following main research question guides this PhD research:

> ***What are challenges to the development towards smart urban water systems from a socio-technical perspective?***

The question is approached for the case of *smart urban water systems and their management in Switzerland*. Whereas empirical observations stem from data collected in Switzerland, theoretical considerations apply more generally and findings are placed into a larger context. In an interdisciplinary way, the thesis brings together multiple streams of literature from different disciplines, mostly from environmental engineering, public policy, and environmental and urban water governance. Overall, the PhD research demonstrates that improvements of surface water protection and stormwater management require more than technical innovation, namely social adaptations to overcome identified challenges that — in this case — would enable smart urban water systems on a larger scale.

1.2 Background

In the following, I present the idea of smart urban water systems from a technical point of view (*chapter 1.2.1*), followed by a description of important urban water governance aspects (*chapter 1.2.2*) relevant for acquiring a socio-technical perspective on (smart) urban water systems and their management (*chapter 1.2.3*). Based on these theoretical foundations, I provide information on the current state of smart urban water systems in Switzerland (*chapter 1.2.4.1*) and discuss urban water governance aspects specific to Switzerland (*chapter 1.2.4.2*). Drawing on the overall literature review, I summarize identified research gaps in *chapter 1.3*.

1.2.1 Smart urban water systems

The need for smart urban water systems

Both academic and grey literature have pointed towards the need for smart urban water systems (Ingildsen and Olsson 2016; Kerkez et al. 2016; Oberascher et al. 2022; Sarni et al. 2019). Although the term *smart urban water systems* has not (yet) been widely used in both science and practice, this thesis adopts it with the intention to follow similar notions, such as related to 'smart cities' or 'smart grids' in the electricity sector. In these contexts, 'smart' refers to the intelligent use of (real-time) data to actively respond to changing states of the system[1] (Al Nuaimi et al. 2015; Ighodaro et al. 2017; Nguyen et al. 2018).

Climate change, urbanization, and ageing infrastructures motivate the need for smart urban water systems, as these global challenges affect either the urban water infrastructure itself or the surrounding aquatic or human environments (Honti et al. 2017; Miller and Hutchins 2017; Salerno et al. 2018; Yazdanfar and Sharma 2015; Zhou 2014). For example, more frequent extreme rainfall events increasingly exceed existing infrastructure capacities and lead to untreated overflows into surface waters (Yazdanfar and Sharma 2015; Salerno et al. 2018). Anthropogenic pollutants that find their way into surface waters put additional stress on aquatic ecosystems (Mutzner et al. 2019; Schönenberger et al. 2022). To address these challenges, smart urban water systems hold the potential to reduce environmental impacts on surface waters and to achieve more resilient, flexible and efficient infrastructures and respective performance outcomes (Gruber et al. 2005; Lassiter and Leonard 2022; Montserrat et al. 2015).

Benefits of monitoring data in smart urban water systems

One aspect of smart urban water systems is that they rely on monitoring data obtained from specific elements within urban water systems, such as for example wastewater treatment plants (WWTPs), combined sewer overflows (CSOs), or pumping stations (s. Figure 1.1), among others, and related processes within these elements (Ingildsen and Olsson 2016; Oberascher et al.

[1] In operational engineering, 'smart' includes the option of 'control loops' as compared to the traditional 'feedforward loops'. Control loops allow for reaction, adaptation, or decision-making based on a current or past state of the system.

2022). In this thesis, *monitoring data* refers to data that is continuously collected, and depending on the context, also often labelled as 'real-time data' or sometimes 'big data', if data set sizes are large. In urban water systems, monitoring data stems from digital technologies ranging from low-maintenance sensors, wireless data transfer, to virtual data storage with ubiquitous access, and automated data evaluation (Blumensaat et al. 2017; Boyle et al. 2013; Mao et al. 2020). Scientists have started to encourage the utilization of monitoring data from urban water system elements for evidence-based operation, planning, and environmental impact assessment (Blumensaat et al. 2019; Boyle et al. 2013; Fletcher and Deletic 2007; Langeveld et al. 2013; Rieckermann et al. 2017; Yuan et al. 2019). Whereas processes in WWTPs are already largely supervised and controlled based on comprehensive monitoring data, the effective utilization of monitoring data from combined sewer systems, particular CSOs, is lagging behind (Naughton et al. 2021; Rieckermann et al. 2021).

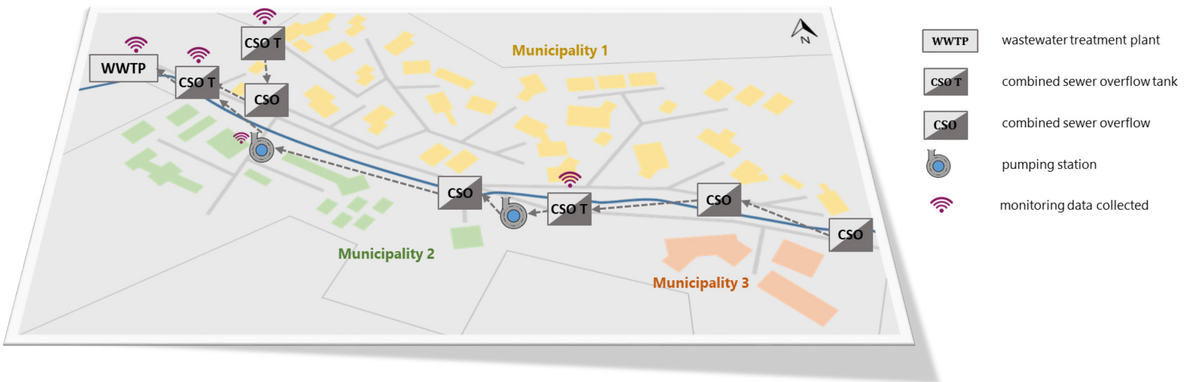


Figure 1.1: Simplified example of an urban water system with a WWTP and several CSO tanks, CSOs, and pumping stations. In the example, monitoring data is collected for selected urban water system elements.

Combined sewer overflows (CSOs)

This thesis puts a focus on CSOs, which are important elements of combined sewer systems and relevant in terms of surface water protection. During heavy rainfalls, a multiple of the dry-weather discharge exceeds the limited inlet capacities of WWTPs. CSOs directly discharge ('overflow' or 'spill') or hold back the excess volumes of combined wastewater and stormwater and later on release them into surface waters, e.g., rivers or lakes. In this thesis, the term *CSO* refers to the structural infrastructure element, i.e., a CSO discharging combined wastewater and stormwater. In many cases, a CSO includes a preceding CSO tank that allows for temporarily storing excess volumes. In the literature, the term CSO is also often used to describe the actual overflow (or 'spill') event.

From a scientific point of view, the application of integrated pollution load models as well as sporadic temporary measurement campaigns have improved the understanding of the impact of CSOs on surface water quality (Langeveld et al. 2013; Dirckx et al. 2011a). This non-negligible impact from CSOs on surface waters demands for continuous monitoring of overflow events (Dirckx et al. 2011b; Gruber et al. 2005; Montserrat et al. 2015). For example, monitoring data from CSOs provides information on, e.g., overflow frequency and duration. Such continuous monitoring data gives operators access to real-time information on the CSOs' performance. This information is key to immediate decision-making (e.g., in case of blockages or malfunctioning) and on the long run for a better understanding of the systems' behavior. By using good-quality, long-term data for model validation and calibration, uncertainties are reducible, which in turn could prevent unnecessary investments (Korving and Clemens 2002). Moreover, authorities who receive annual reports on the performance of CSOs could use this information as a basis for decision-making and environmental impact assessment regarding the systems' efficacy for surface water protection (Rieckermann et al. 2017).

Smart urban water systems and integrated urban water management

Real-time monitoring data from CSOs forms the basis for operating and dynamically controlling the entire urban water system including the WWTP and the combined sewer system. Such a dynamic control, or real-time control (RTC), particularly shows benefits during heavy rainfalls as all available sewer capacities can be used to distribute and balance urban stormwater discharges over the catchment area, thus preventing from over-polluting sensitive surface waters and reducing overflow events (Benedetti et al. 2013; Luo et al. 2021; Maiolo et al. 2020). In this sense, smart urban water systems imply an intelligent use of existing infrastructure capacities in an entire catchment area, which is often also referred to as integrated management of the urban water system (Fletcher and Deletic 2007; Seggelke et al. 2013; Benedetti et al. 2013). This integrated management allows, for example, actively deciding on "when and where CSO overflow events should occur?" or "how much urban stormwater should be directed towards the WWTP?" (Maurer et al. 2012). Such operational decisions can ultimately lead to higher total elimination capacities, i.e., reduced anthropogenic impacts from sewer systems and WWTPs on surface waters (Maurer et al. 2012).

A call for interdisciplinary research on smart urban water systems

Although digital technologies are available, CSOs continue to remain an unresolved and often ignored topic (Clifforde et al. 2006; Marine Conservation Society UK 2011; Rieckermann et al. 2021) in many countries. Given the benefits that smart urban water systems and integrated urban water management could bring, it is important to look beyond technical dimensions. Not only the development towards but also the actual management of smart urban water systems depend on social aspects, and particularly on people. Thus, understanding potential challenges, towards smart urban water systems requires interdisciplinary research (Blumensaat et al. 2019; Ighodaro et al. 2017) that includes social sciences perspectives (Hoolohan et al. 2021). For example, lacking resources, organizational fragmentation, or diverging perceptions and visions, could hinder establishing smart urban water systems. In the following, I therefore approach urban water systems from the point of urban water governance.

1.2.2 Urban water governance

What is (urban water) governance?

Governance, as a general concept, has many different definitions and interpretations, whereby a unifying element lies in the idea of an ensemble of practices, structures, and actors related to a specific context (Ansell and Gash 2007; Berardo and Lubell 2016; Emerson et al. 2011). For example, in the context of urban water governance, actors can be operators, engineers, or authorities. More generally, this includes all actors who are involved in particular practices, for example related to decision-making, policy implementation, or general day-to-day management activities, such as operation, planning, or monitoring of urban water systems (Fischer et al. 2022). Beyond actors and practices, governance incorporates political, social, economic, and administrative aspects (Rogers and Hall 2003). Examples of such aspects are the development and definition of regulations or standards, costs and pricing schemes, the organization of service provision, or the distribution of competencies, among others. From a structural perspective, governance can be understood as an arrangement or network of actors, such as individuals or organizational entities (Berardo et al. 2020; Fischer and Ingold 2020).

Traditionally, urban water systems have been governed in a state-centered way, which includes command-and-control structures, such as laws and rules that are enforced and monitored by powerful governmental authorities (Finewood and Holifield 2015; Pahl-Wostl 2015). However, particularly in the context of developing more sustainable urban water solutions, urban water governance has been opening up to include more non-state actors such as private companies, NGOs, or individual consumers (Finewood and Holifield 2015).

Given the variety of participating actors, urban water governance can be understood as a polycentric governance system (Ostrom 2010). Generally, polycentric governance refers to "many centers of decision-making", i.e., several different actors, which may function individually or in a collective manner (Ostrom et al. 1961). Within the technical boundaries of a local or regional urban water system, i.e., a catchment area, polycentric governance is reflected in that multiple decision-making actors interact in order to collectively provide urban water services (Fischer et al. 2022).

This thesis particularly focuses on actors involved in urban water governance. With this actor-centered focus, the research places other important governance aspects, e.g., related to institutions, policy design, decision-making, regulative or economic considerations, in the background (Franco-Torres et al. 2021). Nevertheless, this research implicitly incorporates parts of these aspects, as they define and implicitly influence particular actor roles or organizational configurations.

Organizational fragmentation

Polycentric urban water governance often results in the fragmentation of actors, be it individual decision-making entities or entire organizations (Feiock and Scholz 2009; Lubell et al. 2017). For example, decision-making often takes place related to different sub-sectors, such as wastewater treatment, urban drainage and stormwater management, or surface water protection. In addition, each urban water system catchment area is divided into various administrational jurisdictions (Kim et al. 2015; Ingold et al. 2016), as can be seen from the example of several municipalities owning and operating different parts of the urban water system. Such organizational fragmentation across sub-sectors and administrational boundaries challenges actors to address developments towards smart urban water systems, and particularly to achieve integrated urban water management. Integrated urban water management not only relies on the joint operation of many technical elements in a catchment area, but also requires coordination and collaboration among fragmented actors.

Learning from barriers to collaboration, innovation, and transitions

Collaboration or collaborative governance (Ansell and Gash 2007; Scott 2015; Ulibarri 2015; Kallis et al. 2009) of urban water systems is recognized as a potential solution to address organizational fragmentation. However, success or failure of effective collaboration depends on several factors. In the context of the broad field of water innovation, Porter and Birdi (2018) have identified 22 themes that influence collaboration. Among these themes are, for example, the need for clear roles and responsibilities, a strong or clear vision, or effective communication and data sharing. These selected themes show the importance of social and institutional aspects, not only hindering effective collaboration but also successful innovation in the water sector.

Similar to these themes, several studies have addressed barriers towards transformations in urban water management (Brown et al. 2009; Kiparsky et al. 2016; Roy et al. 2008; Speight 2015). Related to the transition towards more sustainable urban water management, Roy et al. (2008) identified seven major impediments, among them fragmented responsibilities, lack of institutional capacity, and resistance to change. These findings are in line with those obtained by Brown et al. (2009) who studied social and institutional barriers towards more sustainable and integrated urban water management and found that barriers include, for example, insufficient practitioner skills and knowledge, or organizational resistance, among others.

Given that these barriers were identified related to various phenomena in the context of urban water systems, considering them is important as similar barriers potentially challenge the development towards smart urban water systems. For example, barriers such as fragmented responsibilities, ineffective communication, the absence of data sharing, or organizational resistance, are also relevant in the context of smart urban water systems.

Digital transformation and governance

Related to smart urban water systems, digital transformation is reflected in the implementation and utilization of digital technologies and tools. However, digital transformation goes beyond technical aspects ('digitalization'), as it transforms the governance of urban water systems. Dunleavy et al. (2005) speak of this shift in governance towards "digital-era governance", which includes the integration of digitalization aspects into the governmental sphere, respective organizational structures, and administrative processes. Barns et al. (2016) suggest describing the implementation of digital components, e.g., sensor technologies, into existing infrastructure systems as a "digital infrastructure" in itself. Digital infrastructures pose challenges for urban governance, particularly due to increasing amounts of information that have not been available before. For example, even though specific infrastructure elements are equipped with digital technologies that transfer data, such data may not be accessible to all actors who could potentially utilize it.

Drawing on evidence from the energy sector: smart grid developments

Smart grid developments are transforming the energy sector. In this context, de Reuver et al. (2016) studied how operators could govern projects leading to smart grid innovation. Their findings suggest that grid operators increasingly need to collaborate with other actors to realize innovation projects for smart grids. However, Skjølsvold et al. (2015) argue that developments towards smart grids have mostly been approached from a technical perspective. By asking questions around smart grids from a social science perspective, their research explores how social scientists engage with smart grid developments. In the context of urban water systems, such a social science perspective on smart urban water system developments would also be useful to improve the understanding of potentially similar challenges.

Smart urban water systems from social or socio-technical perspectives

In the context of water infrastructures, Hoolohan et al. (2021) criticize that social and political dimensions in the 'digital water transformation' have so far mostly been forgotten. Therefore, the authors emphasize the need to incorporate social and political aspects in order to bridge the mostly techno-centric industry visions. Consequently, it is important to investigate social and political implications of the digital transformation on urban water governance.

This section outlined selected literature on urban water governance from a social science perspective. The overall PhD research, however, goes beyond individual technical perspectives (*chapter 1.2.1*) or social perspectives (*chapter 1.2.2*), and explicitly aims to consider urban water systems and their management from a socio-technical perspective (*chapter 1.2.3*). Thus, this thesis brings together technical aspects of smart urban water systems and social aspects of urban water governance to gain a more holistic understanding of potential challenges towards smart urban water systems.

1.2.3 Socio-technical urban water systems and their management

Urban water systems from a socio-technical perspective

Urban water systems have previously been studied from a socio-technical perspective, which includes both technical and social aspects of urban water systems (Fuenfschilling and Truffer 2016; Mao et al. 2020; de Haan et al. 2013; Jensen et al. 2015). Urban water systems can be understood as infrastructure systems that consist of technical infrastructure elements as well as social elements related to urban water governance. Examples for technical infrastructure elements are the WWTP or structures of (combined) sewer systems (e.g., CSOs, pumping stations, pipes). Examples for social elements are the social actors themselves (e.g., operators, engineers, authorities) as well as governance structures and processes ('social institutions') concerning regulation, planning, education, or financial aspects, among others (s. also *chapter 1.2.2*).

Both technical elements of the urban water system as well as social elements of urban water governance are interrelated (Guy et al. 2011; Künneke et al. 2010). For example, technical elements need to be planned or operated jointly, which requires coordination among social actors. If technological innovation occurs, in the urban water sector for example in the course of improving the elimination capacity of a WWTP, there is a need for adapting regulations and respective targets or for introducing financial incentives (Metz and Ingold 2014). Consequently, the technical functioning and performance of infrastructure systems depend on appropriate modes of urban water governance (Künneke et al. 2021). This further implies that developments related to urban water systems, such as the integration of digital technologies to make them smart, require coordination, coherence, and co-evolution between both social and technical aspects of urban water systems (Finger et al. 2005).

What is a socio-technical system?

Theory around socio-technical systems jointly considers social aspects and technical aspects of a system, e.g., related to an organization or even a society as a whole (Trist 1978). The idea is that both social and technical aspects need to change in parallel in order to achieve a desired outcome. In this sense, for example, technical infrastructure performance cannot be improved without adapting the surrounding social system, e.g., by changing organizational structures, by introducing educational measures, or by revising regulations and guidelines. In the context of innovation and transition studies, Geels (2004) conceptualized socio-technical systems differentiating between systems, actors, and institutions (or 'rules') that dynamically interact. This thesis does not investigate institutions or rules specifically, but recognizes actors as embedded social elements in an institutional context or a space of rules (Herzog et al. 2022).

Infrastructure systems have been conceptualized as socio-technical systems (Ottens et al. 2006), for example, to study resilience (Landegren 2017), technological developments (Ghaffari et al. 2019), or infrastructure transitions (Fuenfschilling and Truffer 2016). Examining transformations in energy distribution networks, Bolton and Foxon (2015) suggest a socio-technical understanding of infrastructure transformation and characterize infrastructure networks as "large-scale and complex technical systems" that require "mutual interaction between large numbers of individual components". More specifically, related to urban water systems, Jensen et al. (2015) adopt a socio-technical perspective to study transformations in wastewater treatment at the urban city level, and de Haan et al. (2013) developed a socio-technical model of urban water systems to produce different water scenarios depending on social and institutional conditions.

Why is a socio-technical perspective relevant for this thesis?

Smart urban water systems call for the implementation of new technological possibilities (e.g., sensors, data transfer, and data processing) that change technical aspects of urban water systems (e.g., real-time control). However, such technical changes also imply changes of social aspects of urban water governance. For example, in order to upscale the development of smart urban water systems, new or adapted regulations and guidelines might be needed (Manny et al. 2019). Various other policies, for example, financial incentives, educational measures, or a mix of these policies, could complement regulatory changes.

In contrast to these potential policies, this thesis research takes one step back and aims at improving the understanding of how smart urban water systems affect urban water management, i.e., how changes in the technical system affect changes in the social system, and in particular, how various actors deal with newly available data from urban water systems. In this sense, this thesis is less concerned with urban water governance, but rather with *urban water management*. While urban water governance embraces the full complexity of regulatory processes and includes multiple actors that help to design and implement policies, urban water management refers to regular activities that are required to plan, built, operate, monitor, or control urban water systems and related wastewater and stormwater resources (Pahl-Wostl 2009). Therefore, this PhD research focuses on actors in their urban water management roles. In their respective roles, actors potentially experience the development of smart urban water systems in different ways.

1.2.4 Case study: Switzerland

1.2.4.1 Current state of smart urban water systems in Switzerland

Switzerland's urban water infrastructure is characterized by a high fraction of combined sewer systems (70 percent)[2] and a high connectivity rate (ca. 97 percent) to more than 800 WWTPs.

[2] Combined sewer systems discharge both stormwater and wastewater in the same pipes, compared to separate sewer systems (or stormwater systems), which discharge stormwater and wastewater separately.

Sewer system assets comprise large replacement values of 55.2 billion CHF compared those of centralized WWTPs (10.1 billion CHF) (Maurer and Herlyn 2006).

Related to smart urban water systems, Maurer et al. (2012) pointed out the importance of (monitoring) data for urban water systems and encouraged establishing long-term data management. Whereas comparatively comprehensive amounts of data are available on the functioning and performance of WWTPs, only little is known on sewer systems in Switzerland. This lack of evidence implies that — despite huge investments in public sewer systems — their performance is mostly unknown (Rieckermann et al. 2017).

To this date, the total number of CSOs in Switzerland is undocumented and currently no national regulations are in place on the monitoring of CSOs. However, several operators have already started to experiment with and implement digital technologies in CSOs and urban water systems. Furthermore, several applied research projects in Switzerland have demonstrated the potential of smart urban water systems and integrated urban water management. One innovative example refers to a large-scale field experiment where dynamics in sewer systems are continuously monitored (Blumensaat et al. 2017).

However, Switzerland is only slowly making progress in terms of monitoring CSOs, smart urban water systems, and integrated urban water management. Whereas Swiss WWTPs are well monitored and equipped with the latest technological innovations due to strict guidelines and large subsidies (e.g., related to the removal of micropollutants), monitoring data on CSOs or sewer systems is often absent (Manny et al. 2019; Maurer et al. 2012; Rieckermann et al. 2017). Therefore, from a policy perspective, Switzerland has started to provide national technical guidelines, or recommendations at the sub-national level. Examples are the VSA (Swiss Wastewater and Water Protection Association) guideline "Abwasserbewirtschaftung bei Regenwetter" (2019) (Oppliger and Hasler 2019), the guideline "Wegleitung Daten der Siedlungsentwässerung" (2021) in the sub-state Berne or the guideline "Wegleitung und Musterpflichtenheft Datenbestand Siedlungsentwässerung" (2020) in the sub-state Solothurn (Battaglia 2020). These technical guidelines build on the basic urban drainage planning tool, the 'Genereller Entwässerungsplan (GEP)' that includes aspects of strategic planning, measures, and ways for implementation in each urban water system catchment area at the local or regional scale. 'GEPs' are regularly checked ('GEP check') regarding the successful implementation of measures and then consequently updated.

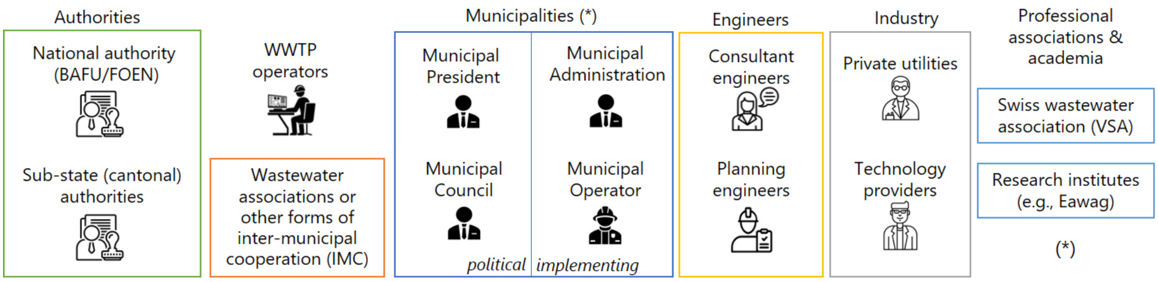
Compared to the situation in Switzerland, the monitoring of CSOs is mandatory in the US (US-EPA 2004, 2018). Several European countries have also started to address surface water pollution from overflow events, such as the UK (Benyon 2013) or France (Ministère de la transition écologique 2021). Nevertheless, there is no pan-European solution (yet) and respective European targets remain undefined (Rieckermann et al. 2021). Based on experience from Germany, the implementation of regulative requirements for the monitoring of CSOs has accumulated large amounts of 'useless data', as stakeholders often struggle with handling data or utilizing it purposefully (Hoppe et al. 2019). Such 'data waste' then makes it almost impossible to assess the impact of CSOs on surface waters by authorities. In Switzerland, stakeholders are largely in favor of regulative targets for CSOs and overflow events (Manny et al. 2019). However, it is questionable whether implementing such regulations would directly lead to truly smart urban water systems – for example, if actors do not have sufficient skills to handle and make use of monitoring data, or if they are unware or unconcerned with the associated benefits. Such potential challenges towards smart urban water systems from the perspective of individual actors remain unknown.

1.2.4.2 Urban water governance in Switzerland: competencies and actors

When it comes to urban water governance, specificities related to the context, case, and country matter (Ingold et al. 2016). In Switzerland, the Swiss Constitution and the national legislation (e.g., Water Protection Act) contain the overarching goals of water quality, security, and resource protection. Similar to the EU water framework directive, the core characteristic of the legislation addresses water quality, and not the infrastructure needed to ensure sufficient water quality. Therefore, from a legislative point, it is difficult to justify the need for smart urban water systems, or more specifically the relevance of quantifying CSO performance.

Switzerland is a federal state where competences for regulation and execution regarding urban water infrastructures are located at the sub-state level ('cantons'). Sub-state authorities are responsible to ensure that operators sufficiently meet the water protection targets. Operational competences for urban water systems are delegated to municipalities (Luís-Manso 2005). Since the 1990s, municipalities have started joining up to fulfill operational tasks beyond their individual administrative boundaries. This development refers to the process of horizontal integration leading to inter-municipal cooperation (IMC) (Blaeschke and Haug 2018; Ladner and Steiner 2003; Silvestre et al. 2018). For example, IMC allows for jointly operating a WWTP, which treats wastewater of an entire catchment area that includes several municipalities. In Switzerland, the term 'wastewater association' relates to an institutionalized organizational entity that guarantees IMC. Wastewater associations potentially have a positive effect on the development towards smart urban water systems, as a catchment-wide form of organization reflects the idea of a technically integrated urban water system. Besides wastewater associations, different organizational forms of IMC exist, such as contracting, intercommunal public institutions, or regional public institutions (Ladner et al. 2013; Lieberherr 2011). Clearly, the provision of Swiss urban water services is almost completely in public hands. Only few examples of public-private partnerships exist in Switzerland (e.g., Abwasser Uri AG, which is a public limited company, or SIG Geneva, which is a public law institution) (Lieberherr and Ingold 2022).

As many different actors are involved at local, regional, sub-state, and national levels, Swiss urban water governance faces organizational fragmentation (Lieberherr and Ingold 2019). This fragmentation not only affects overarching policy-design and political decision-making (Angst et al. 2018) but further impacts local environmental planning (Lienert et al. 2013), or the framing of long-term strategies (Lienert et al. 2006). Overcoming organizational fragmentation is also important in the context of smart urban water systems (s. *chapter 1.2.2*). Many Swiss urban water governance actors such as national and sub-state authorities, operators, representatives of municipalities, engineers, industry representatives and professional associations (s. Figure 1.2), need to deal with the integration of digital technologies and the availability of monitoring data in practice. However, it is unknown how these different actors do so and what challenges they face related to the development towards smart urban water systems.



** More actors are potentially relevant, e.g., «Schweizer Verband Kommunale Infrastruktur (SVKI)» (national professional association), or at the municipal level «Gemeindeschreiber» (municipal clerks) or the responsible cadastral offices, for example.*

Figure 1.2: Actors in Swiss urban water governance

1.3 Research gaps

Drawing on the literature about technical aspects of smart urban water systems (chapter *1.2.1*), social aspects of urban water governance (*chapter 1.2.2*), the idea of socio-technical systems in urban water systems (*chapter 1.2.3*) and the case of Switzerland (*chapter 1.2.4*), I summarize three main research gaps, i.e., 'research needs', which are addressed in this PhD thesis:

- The need for an interdisciplinary research perspective on the development of smart urban water systems that includes both social and technical aspects.
- The need to achieve a better understanding of challenges towards smart urban water systems.
- The need to address actors who are involved in urban water management and to understand how they deal with technological changes in the course of making urban water systems smart.

These three research gaps shape the overall research approach (*chapter 1.4.1*) that underlies this thesis as well as the definition of the research sub-questions (*chapter 1.4.2*) and the PhD publications (*chapter 1.4.3*).

1.4 Thesis Structure

1.4.1 Overall research approach

The three research gaps, as identified in *chapter 1.3*, shape the overall PhD research approach.

1) An interdisciplinary research perspective that includes social and technical aspects

Achieving smart urban water systems requires an understanding of infrastructure systems and their management in their technical and social dimensions as successful technological innovation requires aligning adaptations of the social system. The first part of the PhD thesis (i.e., publication 1) solely focuses on the social system at various levels, i.e., individual, organizational and institutional levels. The second part of the PhD research (i.e., publications 2 and 3) relies on *socio-technical system* theories (Ottens et al. 2006). From an analytical point of view, I draw on tools and concepts from *network analysis* to assess relations between social actors and infrastructure elements, which are relevant for a socio-technical understanding of infrastructure systems, such as urban water systems. Methodologically, I use concepts from social network analysis (Wasserman and Faust 1994), social-ecological network studies (Bodin 2017; Bodin et al. 2019), and more generally bipartite and multilevel networks.

2) A better understanding of challenges towards smart urban water systems

In order to support the development towards smart urban water systems with appropriate measures, the PhD research aims to improve the understanding of existing challenges. Multiple actors with various roles are and will be exposed to handling novel digital technologies and obtained data on urban water systems. Understanding their challenges is important for facing the development towards smart urban water systems.

3) A focus on actors who are involved in urban water management

The PhD research places a strong focus on the analysis of *actors* who are involved in the management of infrastructure systems, such as (smart) urban water systems. In this thesis, the definition of *actors* is equal to 'stakeholders' or 'social actors'. In the context of urban water systems, actors can be individuals or organizations who are directly or indirectly involved in the management of the urban water systems. For example, an individual actor can be an individual operator, an individual engineer, or an authority representative. Organizational actors are, for example, a municipality, a wastewater association, or an authority as an entire entity.

Such an *actor-centered focus* has two advantages. On the one hand, diverse actors have diverse needs related to the implementation of digital technologies and the utilization of data from smart urban water systems. Whereas, for example, operators rely on data to make real-time operational decisions, engineers rather use long-term data series to improve their modeling processes. Thus, actors deal in distinctive ways with the integration of data-related tasks and possibilities. Consequently, challenges towards smart urban water systems may unfold differently for respective actors. On the other hand, actors who are involved in managing urban water systems are part of collaborative governance settings. For example, operators exchange information with authorities or collaborate with consultant engineers. In this sense, actors are inherently related and dependent on each other in order to operate, plan, design, control, finance, and monitor ('manage') urban water systems. Regarding the development of smart urban water systems, multiple actors need to collaborate, share a vision, and collectively make use of digital technologies and obtained data. Therefore, challenges towards smart urban water systems may not only exist at individual actor levels. Rather, various interacting actors and their relations to other actors may affect respective challenges.

1.4.2 Research sub-questions

The main research question is divided into three research sub-questions that lead to the three PhD publications. Answers to the sub-questions are provided in the conclusions (*chapter 5*).

Figure 1.3 illustrates a structural overview of the three sub-questions that contribute to and cover different aspects of the main research question (*"What are challenges to the development towards smart urban water systems from a socio-technical perspective?"*).

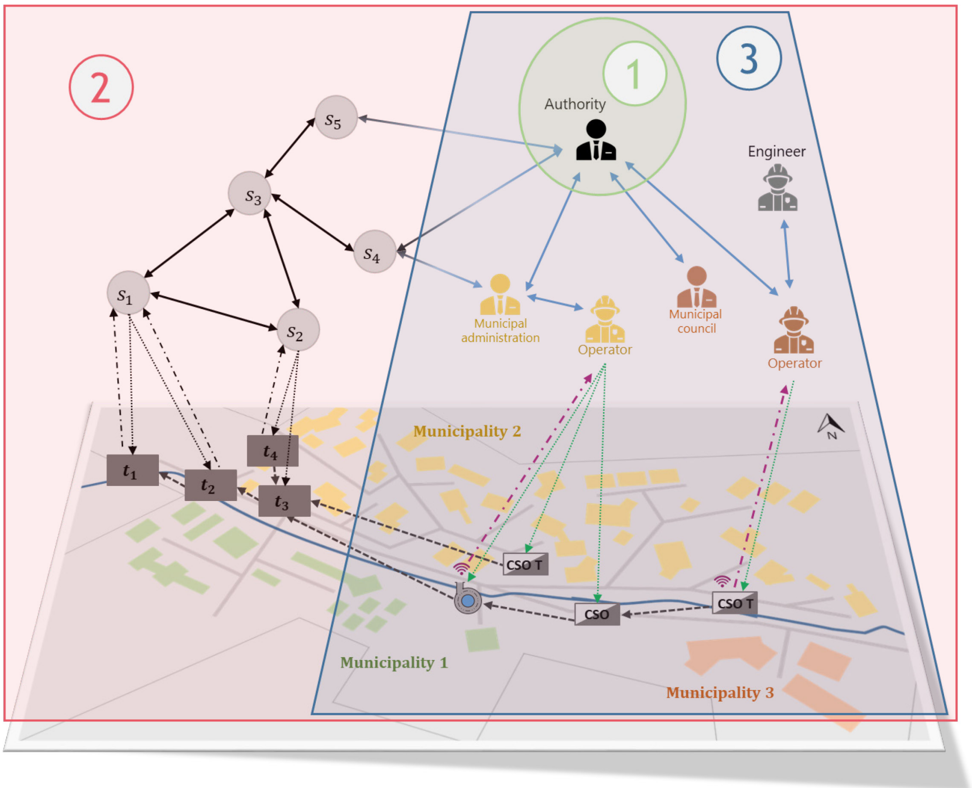


Figure 1.3: Overview of the thesis structure that illustrates which parts of a socio-technical urban water system are addressed. Here, the socio-technical representation consists of actors and technical infrastructure elements of urban water systems. RQ 1 (and publication 1) focuses on authorities (in green). RQ 2 (and publication 2) is concerned with the conceptual socio-technical network of actors and technical infrastructure elements, including empirical data on a single case study urban water system (in red). RQ 3 (and publication 3) looks at the socio-technical network of actors and technical infrastructure elements at the local or regional level of three case studies in Switzerland (in blue).

RQ 1	What are barriers to the digital transformation of urban water systems?

Research question 1 deals with barriers to the digital transformation of infrastructure systems. Looking at the case of urban water systems, it focuses on how authorities deal with newly available data from CSOs in Switzerland.

With respect to the main research question, research sub-question 1 looks at challenges related to the development towards smart urban water systems from the actor perspective of sub-state authorities in Switzerland.

RQ 2	How can a socio-technical network (STN) perspective of infrastructure systems, such as urban water systems, inform about challenges related to digitalization?

Research question 2 is concerned with improving the understanding of infrastructure systems and their management form a socio-technical network (STN) perspective drawing on a case-study urban water system in Switzerland. This includes technical infrastructure elements and social actors involved in urban water management, as well as multiple relations in-between. The concrete operationalization of a STN in the context of infrastructure systems provides a framework to study digitalization and associated integrated urban water management in a socio-technical way.

With respect to the main research question, research sub-question 2 provides the conceptual basis for studying smart urban water systems and respective socio-technical challenges from a multi-actor perspective through the conceptualization of STNs.

RQ 3	What are socio-technical challenges to managing smart urban water systems?

Research question 3 applies the STN approach to identify and analyze socio-technical challenges towards smart urban water systems. Drawing on empirical STN data from three case study catchment areas in Switzerland, the perspectives of all social actors involved in managing an urban water system are included.

With respect to the main research question, research sub-question 3 covers challenges related to the development towards smart urban water systems from a STN point of view.

1.4.3 Overview on publications

Each research sub-question feeds into a publication, peer-reviewed and published (publication 1 and 2), or submitted (publication 3). Table 1.1 gives an overview on the sub-questions that are addressed in the respective PhD publications.

Table 1.1: Overview on the research sub-questions and the respective publications

Research sub-question		Publication
1	*What are barriers to the digital transformation of urban water systems?*	Manny, L., Duygan, M., Fischer, M., Rieckermann, J. (2021) **Barriers to the digital transformation of infrastructure sectors**, *Policy Sciences, 54,* 943-983. https://doi.org/10.1007/s11077-021-09438-y.
2	*How can a socio-technical network (STN) perspective of infrastructure systems, such as urban water systems, inform about challenges related to digitalization?*	Manny, L., Angst, M., Rieckermann, J., Fischer, M. (2022) **Socio-technical networks of infrastructure management: Network concepts and motifs for studying digitalization, decentralization, and integrated management**, *Journal of Environmental Management, 318*, 115596, https://doi.org/10.1016/j.jenvman.2022.115596.
3	*What are socio-technical challenges to managing smart urban water systems?*	Manny, L., (submitted) **Socio-technical challenges towards data-driven and integrated urban water management: a socio-technical network approach**, *Sustainable Cities and Society*, preprint: http://ssrn.com/abstract=4168134.

The three publications speak to different audiences as the research itself unfolds multifaceted. For example, publication 1 mainly targets policy and political science audiences, whereas publications 2 and 3 speak to more interdisciplinary communities, around environmental management, socio-technical systems, and network sciences. Even though I provide detailed theoretical and methodological descriptions in the respective publications, the readers may find themselves confronted with unusual structures, unknown terminology, or theoretical concepts (s. also *chapter 5.3.2*). Therefore, I summarize each publication and the related steps of the respective research processes in a broadly understandable form below.

Publication 1: Barriers to the digital transformation of infrastructure sectors

Publication 1 deals with barriers to the utilization of data by public authorities in infrastructure sectors. Based on a combination of deductive and inductive approaches, we conceptualize potential barriers towards utilizing data at multiple levels: individual, organizational, and institutional. For example, at the individual level a lack of vision of an individual representative in a public authority may affect the utilization of data (Rogers and Hall 2003; Surbakti et al. 2019; Klievink et al. 2016). At the organizational level, we identify a lack of resources (Giest

2017; Clausen et al. 2019) or a lack of a digitalization culture (Schmid et al. 2018; Arduini et al. 2010) to be potentially relevant. Administrative fragmentation, particularly in public sector infrastructures with many different organizational entities, may further hinder the utilization of data (Austin 2018; Giest and Ng 2018). We apply our theoretical framing to the case of sewer systems in Switzerland and conduct semi-structured interviews with representatives from 23 (out of 26) sub-state authorities. Results from a qualitative comparative analysis (QCA) (Schneider and Wagemann 2012; Ragin 1987) indicate that mainly barriers at the individual and organizational levels hinder the utilization of monitoring data from sewer systems, i.e., lack of vision or lack of resources.

Figure 1.4 illustrates the steps in the research process in combination with the four potentially relevant barriers as well as the two resulting barriers from the analysis.

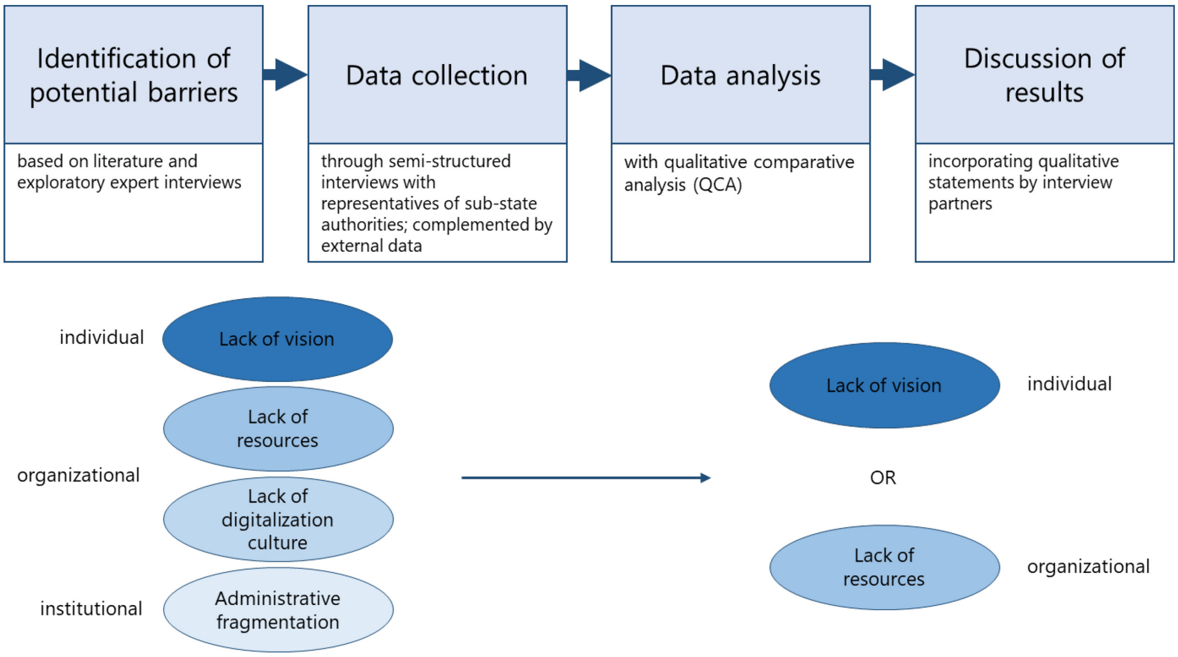


Figure 1.4: Visualization of the research process (top), and below the four potentially relevant barriers at three different levels (on the left) as well as the two resulting barriers after analysis (on the right).

Publication 1 goes beyond the case of urban water systems, as a general model of barriers towards digital transformation at individual, organizational, and institutional levels is suggested. These three levels are potentially relevant for other infrastructure sectors, particularly those managed by public organizations.

Publication 2: Socio-technical networks of infrastructure management: Network concepts and motifs for studying digitalization, decentralization, and integrated management

Publication 2 proposes a socio-technical network (STN) perspective (Elzen et al. 1996; Guy et al. 2011; Hu et al. 2010) to improve the socio-technical understanding of infrastructure systems and their management. This STN perspective further helps studying infrastructure trends, such as digitalization, decentralization, and integrated management in a socio-technical way. We developed a structurally explicit and formal description of STNs in the context of networked infrastructure systems, such as energy, transportation, water, or wastewater systems. Drawing on established concepts and methods from social network analysis and social-ecological network theory, we describe how STNs can be analyzed with network concepts (e.g., density, reciprocity, and centrality) and network motifs (i.e., network sub-structures). Based on these formal descriptions, we suggest how the socio-technical progress of infrastructure systems in terms of digitalization, decentralization, and integrated management can be measured. Our case study on urban water management illustrates an empirical application of the STN approach and demonstrates the potential of STNs to achieve a deeper understanding of socio-technical relations in urban water systems and similar networked infrastructure systems.

Figure 1.5 illustrates the research process as well as the conceptual and empirical STNs.

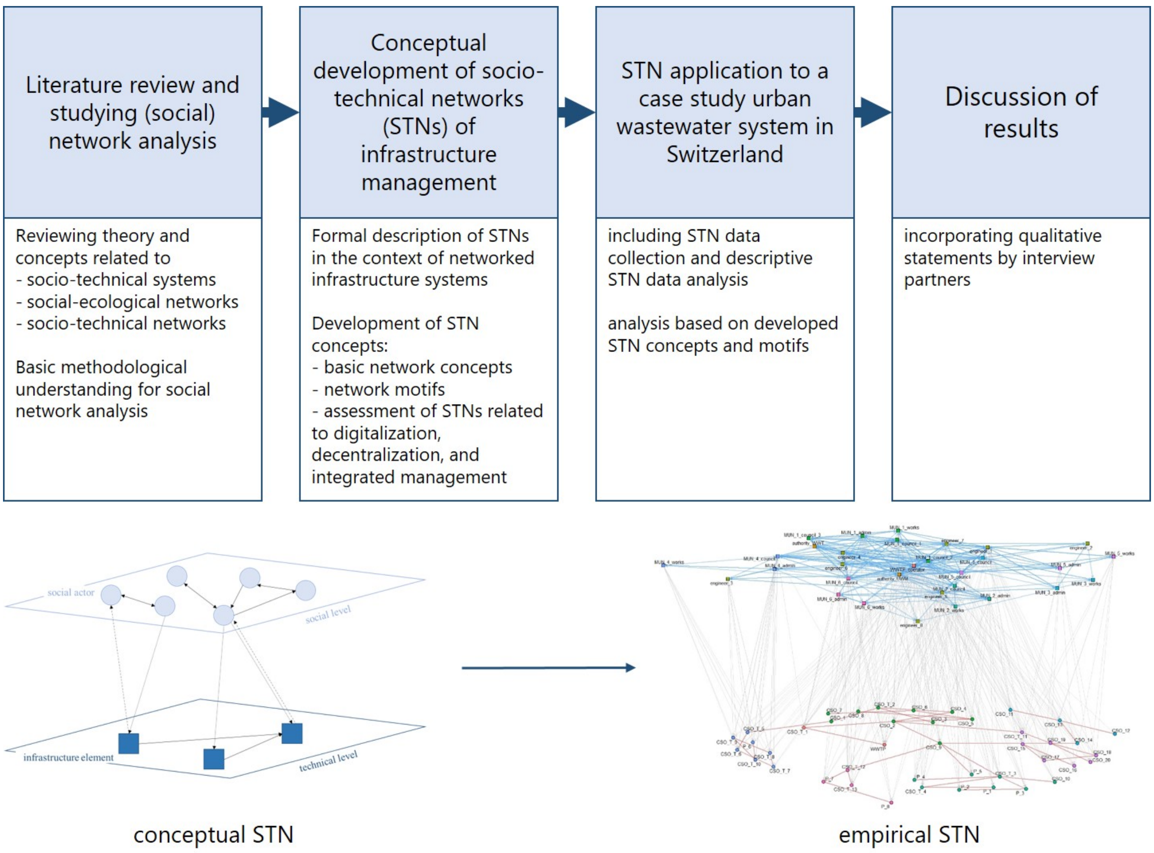


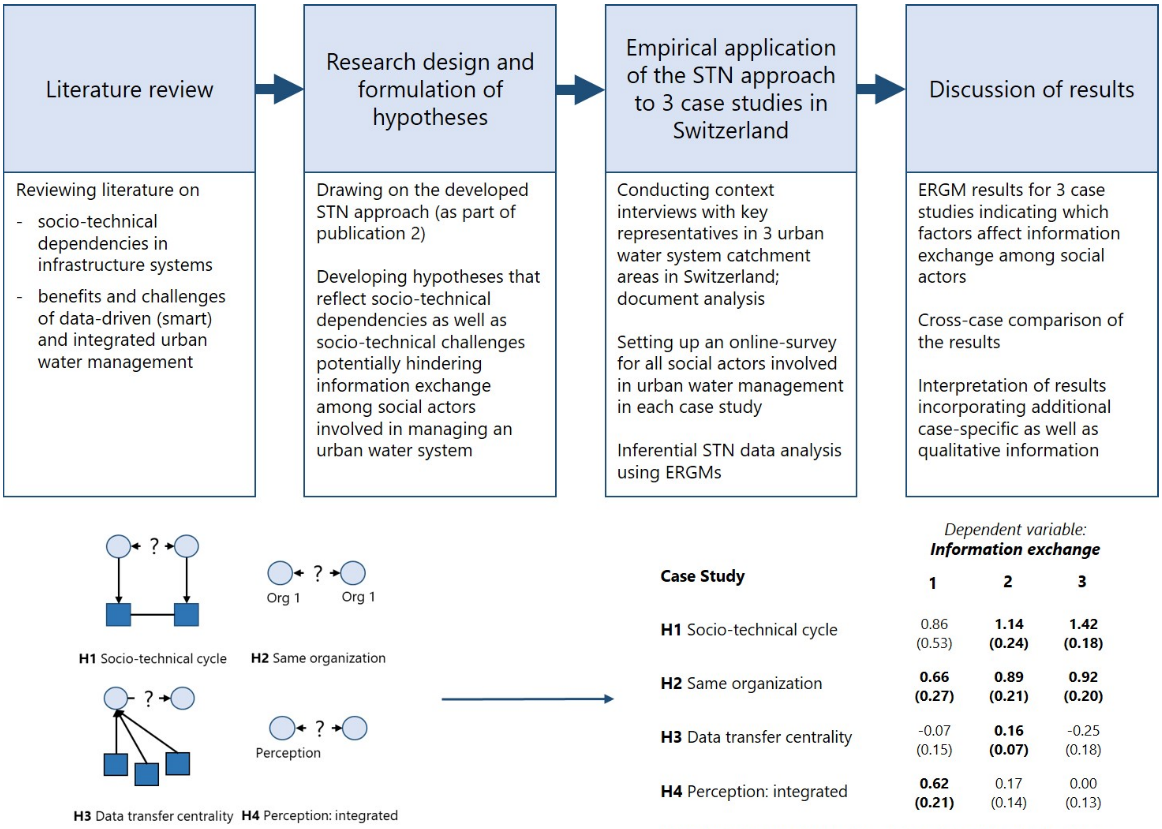
Figure 1.5: Visualization of the research process (top), and below a simple conceptualization of a STN (on the left) as well as an empirical STN of a case study urban water system in Switzerland (on the right).

Publication 2 goes beyond the case of urban water systems. The STN notation was developed in a more generic way and can be applied in the context of other networked infrastructure systems, such as drinking water, energy, or transportation systems. The publication further goes beyond the main topic of digitalization, smart (urban water) systems and integrated management, as another infrastructure trend related to decentralization is incorporated as well.

Publication 3: Socio-technical challenges towards data-driven and integrated urban water management: a socio-technical network approach

Publication 3 draws on the STN approach and suggests a case-specific operationalization to analyze socio-technical challenges towards data-driven (smart) and integrated urban water management (UWM). The STN consists of individual social actors (e.g., municipal operators, engineers, authority representatives) as social nodes and infrastructure elements (e.g., WWTP, CSOs, pumping stations) as technical nodes. Four different relations link these nodes: information exchange between social actors, physical connections between technical elements, operation from social actors to technical elements, and data transfer from technical elements to social actors. This operationalization allows for studying socio-technical challenges, such as organizational fragmentation, data access, and diverging perceptions, which may affect information exchange among social actors and thus potentially hinder data-driven and integrated UWM. Drawing on empirical STN data from three case study urban water systems in Switzerland, I provide results from an inferential analysis using exponential random graph models (ERGMs). Findings indicate that social interactions related to infrastructure systems (e.g., information exchange among social actors), not only depend on social factors, but are also influenced by socio-technical dependencies, i.e., how social actors are related to technical infrastructure elements. In addition, socio-technical challenges influence information exchange in particular case studies and are potentially contingent upon on the size of the urban water system, related socio-technical complexities, forms of organization, or the progress in terms of data-driven and integrated urban water management.

Figure 1.6 illustrates the steps in the research process, starting with a literature review, followed by the formulation of four specific hypotheses. Based on the collection of empirical STN data in three case study urban water systems in Switzerland, an inferential STN analysis was performed. The results from the ERGMs are presented as well.



Dependent variable: ***Information exchange***

Case Study	**1**	**2**	**3**
H1 Socio-technical cycle	0.86 (0.53)	**1.14 (0.24)**	**1.42 (0.18)**
H2 Same organization	**0.66 (0.27)**	**0.89 (0.21)**	**0.92 (0.20)**
H3 Data transfer centrality	-0.07 (0.15)	**0.16 (0.07)**	-0.25 (0.18)
H4 Perception: integrated	**0.62 (0.21)**	0.17 (0.14)	0.00 (0.13)

Bold values indicate significant effects at the level of p-values of 0.05 or lower.

Figure 1.6: Visualization of the research process (top), and below the four formulated hypotheses (on the left) as well as the ERGM results resulting from the inferential STN analysis (on the right).

1.4.4 Thesis structure

The following chapters of the thesis are structured as follows. Each publication 1, 2 and 3, is provided in a separate chapter, i.e., *chapters 2*, *3*, and *4*, respectively. In *chapter 5*, the overall conclusions from this PhD project are drawn. In *chapter 5.1*, I summarize all obtained results and provide answers to the research questions. Recommendations for policy-makers and practitioners are suggested in *chapter 5.2*. Research limitations and challenges in an interdisciplinary research context are provided in *chapter 5.3*, followed by an outlook on future research in *chapter 5.4*. The thesis closes with an additional chapter that critically discusses the need for smart urban water systems.

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2. Publication 1

Barriers to the Digital Transformation of Infrastructure Sectors

Policy Sciences

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Abstract

Digital technologies can be important to policy-makers and public servants, as these technologies can increase infrastructure performance and reduce environmental impacts. For example, utilizing data from sensors in sewer systems can improve their management, which in turn may result in better surface water quality. Whether such big data from sensors is utilized is, however, not only a technical issue, but also depends on different types of social and institutional conditions. Our article identifies individual, organizational, and institutional barriers at the level of sub-states that hinder the evaluation of data from sewer systems. We employ fuzzy-set Qualitative Comparative Analysis (fsQCA) to compare 23 Swiss sub-states and find that two barriers at different levels can each hinder data evaluation on their own. More specifically, either a lack of vision at the individual level or a lack of resources at the organizational level hinder the evaluation of data. Findings suggest that taking into account different levels is crucial for understanding digital transformation in public organizations.

Keywords: Digital transformation, Data utilization, Infrastructure, Wastewater, Switzerland, QCA

1. Introduction

Digitalization refers to a multiplicity of on-going processes in many different sectors, whereby the implementation of digital technologies and the utilization of obtained data constitutes a unifying element. Digital transformation goes beyond digitalization, as it additionally includes organizational and institutional changes, e.g., organizational culture, regulation, or service delivery, and affects the public sector, among other sectors (Mergel et al. 2019; Giest 2017). Digital transformation is also gaining ground in the domain of public infrastructure (Apráez and Lavrijssen 2019). An increasing number of municipal and regional authorities have started experimenting with applications that rely on information and communication technologies (Guenduez et al. 2018).

The increased application of sensors and data transmission technologies enables more sophisticated instrumentation and highly accurate measurements, and generate big data that is large in volume, features incoming real-time data streams, and requires employment of advanced analytics or algorithms (Klievink et al. 2016). Despite concerns over data security and over-reliance on data for the resolution of complex problems (Giest and Samuels 2020), big data is also acclaimed for providing an important potential for higher performance (Vydra and Klievink 2019; Rogge et al. 2017). For instance, the public water utility Denver Water has started to use big data to proactively identify trends that could point out to potential system failures before they arise as problems (Heaton 2013). Big data is also used by the public transportation authority of Singapore to reduce crowding in congested areas (Maciejewski 2016). Studies have further analyzed the rollout of smart meters for consumers in the energy sector (de Reuver et al. 2016).

Despite potential benefits, the utilization of big data is still limited and only recently gaining attention, especially in the public sector (Klievink et al. 2016). The literature focusing on social conditions influencing digital transformation has mostly studied just the adoption of new technologies, whereas conditions favoring or hindering the effective utilization of data have been overlooked (Sun et al. 2016; Surbakti et al. 2019; Maciejewski 2016). Digitalization per se does not often provide immediate benefits, especially if the resulting big data is not utilized, and leads to data wasting (Mergel et al. 2016). As the volume of data produced by new technology is increasing exponentially, the need for data analytics, processing, and interpretation of data is also growing (Ingildsen and Olsson 2016). However, the issue at hand goes beyond mere technical competence, but also involves organizational capabilities and readiness as the utilization of big data may require changes in roles (e.g., chief data officer as a new executive), routines, and decision-making within an organization (Klievink et al. 2016; Sun et al. 2016). For example, data from digital technologies may be included in performance indicators, therefore serving the purposes of reporting and the assessment of regulative targets

(Pollitt 2013; Lewis 2015). The formulation of multiple indicators that reflect interests of different actors, as well as increased transparency (e.g., through public participation in the reporting process), could help reduce the performance paradox (i.e., poor reporting) in the public sector (van Thiel and Leeuw 2002; Bolognesi and Pflieger 2019), and ultimately improve infrastructure management and reduce environmental impacts.

In order to understand how public authorities utilize newly available data of infrastructure systems and what challenges impede its effective use (Giest and Raaphorst 2018), we analyze and compare Swiss sub-states (Rieckermann et al. 2017). Our empirical focus lies on an oft-neglected and largely invisible infrastructure: sewer systems. Even though they involve high public investment costs, knowledge about the performance of these systems is only scarcely available as obtained data[1] is rarely utilized (Rieckermann et al. 2017). Understanding barriers to the utilization of data in Switzerland's urban water management practice is relevant for designing feasible policies for the handling of big data by public authorities, as well as on performance management of infrastructure systems. The digital transformation of sewer systems holds the potential to improve daily operational activities, the infrastructure planning process, as well as the protection of surface waters (Sarni et al. 2019).

Based on a combination of deductive and inductive approaches, the study identifies conditions that might act as barriers to the evaluation of data in Swiss sub-states. More specifically, we first discuss different strands of literature and deductively identify a general model with individual, organizational, and institutional levels, before relying on exploratory and semi-structured expert interviews to inductively specify four conditions applicable to our case. The four conditions and the outcome are operationalized based on in-depth interviews and document analysis, and — given that we expect conditions from the individual, organizational, and institutional levels to interact — cases are compared through Qualitative Comparative Analysis (QCA).

With this analysis, we make three contributions to the literature. First, we address a less researched but crucially important aspect of digital transformation, that is, the utilization of data (Sun et al. 2016; Surbakti et al. 2019; Maciejewski 2016). By discerning the conditions impeding data utilization, our study sheds light onto the social and institutional barriers to digital transformation, which can be considered a radical innovation (Hage 1980). Second, we bring together perspectives from policy and innovation studies, information technology, and environmental engineering in an interdisciplinary exercise. This results in a model of potential barriers to digital transformation including individual, organizational and institutional levels,

[1] In the entire text, the term «data» is used to refer to several, often used terms such as «monitoring data» or «sensor data». Such data is collected by digital technologies (e.g., sensors) which are installed within an infrastructure system. For sewer systems, data on water levels, flows, or discharges to surface waters can be measured. As such data is continuously collected, it reaches large volumes and can therefore also be described as big data.

and potential interactions across them (Klievink et al. 2016; Sun et al. 2016; Surbakti et al. 2019). With respect to technological change in public organizations, these have not been jointly analyzed in the existing literature to date. Third, while many conceptual articles with illustrative examples (Lavertu 2016; Giest 2017) or single case studies (Barns et al. 2017; Giest and Raaphorst 2018) deal with big data and politics, barriers to digital transformation have rarely been studied in a medium-N comparative setting with potentially important contextual variations across cases (Chatwin et al. 2019). Our empirical focus on urban water management provides an analysis of social and institutional barriers to the utilization of data by Swiss sub-state authorities. Overcoming such barriers could improve performance management of sewer systems, and may result in higher efficiency, with improved economic and environmental outcomes.

The remainder of this article is structured as follows. In the next section, we compile insights from the literature with a focus on digital transformation and barriers at different levels. After introducing our specific research context in "Empirical setting: utilizing data from sensors in Swiss sewer systems" section, we combine deductive logic with inductive reasoning, drawing on our case knowledge and findings from expert interviews. We identify potential barriers to the evaluation of data from sewer systems which we describe in "Methods" section, along with the analytical method. We then present the results of our analysis followed by a discussion. The article ends with conclusions that discuss the transferability of results, limitations of the analysis, and future research questions.

2. Politics, big data, and barriers to digital transformation

2.1 Potential benefits and critical voices

Digital transformation can affect the entire policy cycle (Höchtl et al. 2016), from the input side of policy processes, through innovations in democratic participation (Janssen and Helbig 2018), to its end, through the implementation of policies through public e-services or data-based evaluation of policies (Lavertu 2016). The digital transformation has often been said to pave the way for more evidence-based policymaking in public administrations (Höchtl et al. 2016; Giest 2017), or increased public infrastructure performance. For example, increased use of sensors and digital technologies enables real-time monitoring of traffic flow, public transportation, and air and water quality (Munné 2016). Furthermore, data sharing can increase transparency and facilitate the participation of stakeholders or the broader public, as this information can be used to provide feedback or suggestions (Matheus et al. 2020). Finally, digital transformation can influence principal-agent relations (e.g., Wood and Waterman (1991); Maggetti and Papadopoulos (2018)) by affecting information (a)symmetries between, e.g., utilities and authorities. For all these reasons, concepts such as "open government"

(Chatwin et al. 2019) or "digital-era governance" are argued to have replaced paradigms such as new public management (Dunleavy et al. 2005).

There is, however, a broad diversity of critical voices. As far back as 1972, Millar (1972) criticizes a potential bias towards mechanistic and abstract solutions for human problems, and a failure to properly take into account limited human and organizational abilities. Lavertu (2016) discusses the problems of potential misperceptions of organizational performance due to publicly available data to actors outside of public agencies. Likewise, complex, low quality, or inaccurate data can risk misinterpretation while data privacy issues can lead to mistrust (Matheus et al. 2020). Most recently, discussions have involved a potential bias against digitally illiterate or minority groups (Giest and Samuels 2020).

2.2 A general model of barriers to digital transformation

The disconnect between data production and data utilization (Giest and Ng 2018) is not only reflected in these critical voices, but is further exacerbated by the fact the digital transformation also requires human and organizational capacities for data analytics, processing, and interpretation of data (Ingildsen and Olsson 2016). While technical advancements in digital technologies promise a multiplicity of benefits, their implementation into existing organizational structures that would allow the actual reaping of the benefits is often challenging (Shearmur and Poirier 2016; Wang and Feeney 2014). Long established structures and procedures of policymaking and implementation tend to be "sticky", public administration actors generally rely on traditions and established "ways of doing things" (DiMaggio and Powell 1983), and the stable mind-set of any organization will support only a limited range of innovations (Walker 2006). Most innovations are in a continuum ranging from incremental to radical innovations rather than fully representing one (Hage 1980). Digital transformation driven by the utilization of big data can be considered as rather a radical innovation.

Previous findings in innovation studies, public administration, management and information technology show that similarly to the adoption processes of technological innovations, the utilization of big data in organizations is contingent upon several conditions that can be attributed to three levels: individual, organizational, and institutional levels (Klievink et al. 2016; Sun et al. 2016; Surbakti et al. 2019). Similarly, the technology-organization-environment (TOE) framework claims the adoption of an innovation to be dependent on technological, organizational and environmental contexts (i.e., institutional and geographical structures) that the organization in question is part of (Tornatzky et al. 1990). Finally, also actor-centered institutionalism in political science or public administration studies (Scharpf 2018) emphasizes that actors' (individuals or organizations) rational behavior is influenced by the institutional context and cultural norms. We thus jointly analyze conditions at all three levels of individuals, organizations, and institutions, and expect that conditions on the three levels potentially interact and produce complex configurations of conditions. For example, a specific individual-level condition might only matter in one given institutional context.

2.3 Individual-level conditions

Individual characteristics such as attitude, belief, and vision of managers can be highly important for organizational innovation (Rogers 2003), including the use of big data (Corbett and Webster 2015). Managers' cognitive orientation and vision towards the perceived value of data-driven management is also referred to as "technology acceptance" (Venkatesh and Davis 2000). Klievink et al. (2016) refer to this attribute as internal attitude of individuals, defined as "capability to develop internal commitment and vision for new processes and systems, especially openness towards data-driven decision-making" (p. 275). For example, a high level of employee engagement in terms of personal commitment and presence of championing figures who actively promote big data is important for its use in organizations (Surbakti et al. 2019). Taking into account the perceptions of public managers helps assess why uses of big data remain very limited in the public sector (Guenduez et al. 2018; Mergel et al. 2018).

2.4 Organizational conditions

The literature emphasizes two organizational conditions important for the innovativeness of an organization (Clausen et al. 2019). First, a lack of resource capacity to deal with data by relevant actors can represent a major bottleneck for digital transformation (Giest 2017). Human resources are found as one of the most important conditions affecting organizations' adoption of data utilization practices (Sun et al. 2016). More specifically, in case of big data, the adequacy of IT-literate personnel and availability of data science expertise are critical for organizations to develop a data use strategy (Klievink et al. 2016), and might be relevant to avoid disclosure biases and a performance paradox (e.g. Bolognesi and Pflieger (2019); van Thiel and Leeuw (2002); Lewis (2015)). Factors comprising human capital, such as the number of employees or presence of specialized personnel, are especially important for radical innovations which involve fundamental changes that embed a high degree of new knowledge (Dewar and Dutton, 1986).

In addition to human resources, a data oriented innovation culture is essential for successful initiatives of big data utilization (Surbakti et al. 2019; Marshall et al. 2015). For instance, municipalities advanced in e-government initiatives are more likely to be the ones with higher in-house ICT (information and communications technology) activities and intranet infrastructure (Arduini et al. 2010). An established digitalization culture across the entire organization can indicate not only the readiness but also the experience required for incorporating data into internal planning and decision-making processes. Civil servants benefit from organizational support for their potential interest in digital transformation through, e.g., training or sharing of data among government departments (Giest 2017). As many organizations still struggle to transition from paper-based management (Austin 2018), the lack of an established digitalization culture is likely to impede the utilization of data.

2.5 Institutional conditions

Organizations are embedded in several types of institutional contexts that influence them through expectations and cognitive frames and their social embeddedness and networks (DiMaggio and Powell 1983; Williamson 2000). Such institutional contexts and networks can also influence transaction costs (Williamson 2000; Andrews-Speed 2016), an important mechanism especially when dealing with data processing and interpretation. Increased diversity in size and number of partners with whom data is exchanged may correspond to an increased variety of data sources and formats, as well as different demands regarding organizational and coordinative efforts when it comes to receiving and treating data. This diversity may lead to a larger burden on authorities as one end user of data since merging data from diverse sources can require significant effort and time (Austin 2018), and could again lead to disclosure biases and performance paradox (e.g. Bolognesi and Pflieger (2019); van Thiel and Leeuw (2002); Lewis (2015)). This institutional barrier has also been described as stemming from existing administrative and institutional structures define the way data is collected, analyzed, and used, leading to "data silos" (Giest 2017).

3. Empirical setting: utilizing data from sensors in Swiss sewer systems

Smart metering, in the context of urban water management, refers to the installation of sensors and data transmission technologies in sewer systems (Apráez and Lavrijssen 2019). Such sensors allow obtaining real-time information on the system's actual performance (leakages, outages, etc.) and its impact on surface water quality, thus creating benefits for operators, planners and authorities (Fletcher and Deletic 2007; Langeveld et al. 2013). For operators, the information gained from sensors is key for real-time operational decision-making (e.g., in case of blockages or malfunctioning of pumps) and for a better understanding of the system's capacity and behavior. For planners, using available long-term data series for model validation and calibration, reduces uncertainties and thus prevents unnecessary investments, leading to an improved infrastructure planning process (Korving and Clemens 2002). Furthermore, responsible authorities who receive periodical performance reports could potentially use this information for compliance assessment and more evidence-based decision-making regarding both the operational performance and the systems' efficacy for surface water protection (Lewis 2015; Pollitt 2013; Rieckermann et al. 2017). Representatives from Swiss sub-states reported that, for example, sensor data reveals deficits in the operation of the sewer systems, which can be directly addressed with appropriate measures. The successful implementation of measures leads to an improved infrastructure performance, and therefore has a positive impact on the protection of surface waters. Only through evidence from data do the hidden underground sewer systems become visible, making it possible for the actual functioning of the built infrastructure assets to be examined. The availability of such evidence may also prove useful in moving forward in terms of open data practices and the releasing of public sector information (Conradie and Choenni 2014; Henninger 2013). Disclosure of information about sewer system performance ensures transparency and can contribute to an increasing awareness of the public.

In Switzerland, where sewer systems are mainly managed publicly, an increasing number of municipalities install sensors without being obliged to do so (Rieckermann et al. 2017). Swiss municipalities — or the wastewater associations that they create — are to a large degree autonomous in their decisions on how to manage their wastewater systems and whether to invest in digital transformation. Partly due to this autonomy, even in cases where data is available, it is currently often not shared with other beneficiaries such as authorities, or not analyzed for evaluating the system's performance (Manny et al. 2018).

In Switzerland, the overarching goals of quality, security, and resource protection are embedded in the Swiss Constitution and in the national legislation (such as the Water Protection Act). Given the federalist setting of Switzerland (Linder and Vatter 2001), the regulative and executive competences on water and infrastructure management are mostly at the sub-state level (alongside with other typical sub-state competences such as education or traffic infrastructure). Sub-state authorities are units of public administration of the sub-state and have the responsibility to check whether water protection targets are met as defined by law and directives. Operational competences for the discharge and treatment of wastewater have typically been delegated to municipalities who operate the infrastructure (Luís-Manso 2005), and — given again the federalist structure of Switzerland and far-reaching financial autonomy of Swiss municipalities — the coercive power of sub-states on municipalities on how to exactly perform their duties is limited (Ladner et al. 2016; Klaus 2020). In the Swiss federalist system, decisions are based on interactions between the sub-state authorities and municipalities. Furthermore, due to the newness of the issue, no clear responsibility has been established. So far, reporting data from sewer systems is not required by any form of sub-state law or directive, and the evaluation of available data by sub-state authorities is also not legally binding.

Our research design benefits from this federalist structure of Switzerland and compares 23 out of 26 Swiss sub-states (see Table 4 in Appendix 1).[2] Given that Swiss sub-states have important competencies in the domains of wastewater management and digitalization, we can observe different outcomes and related conditions for different sub-states. At the same time, we keep the basic legal and institutional structure of Switzerland constant. For these reasons, comparing Swiss sub-states has been a popular approach (Thomann 2015; Kammermann 2018; Klaus 2020). Furthermore, while the federalist structure might be a specificity of the country, we consider Switzerland as a typical case (Seawright and Gerring 2008) in terms of challenges related to digitalization of infrastructure sectors, comparable to other (Western, democratic) countries.

4. Methods

4.1 Data collection

We relied on a two-step approach for data collection. First, we conducted nine exploratory expert interviews (with operators, authorities, engineers, and researchers) in April 2017 that helped us to specify the conditions that may be particularly relevant for our analysis, based on the general model derived from the combination of existing theories. In our study context, we conceptualize these conditions as barriers to digital transformation (see Fig. 1). Our choice on analyzing barriers instead of driving or enabling conditions is partly driven by the collected data revealing that cases with absence of data utilization are overrepresented. Second, we gathered data from semi-structured face-to-face interviews with 23 sub-state representatives (data stems from questionnaires for three sub-states) in October 2017. Sub-states' representatives are affiliated to the sub-states' division of urban water management.[3] The interviews lasted between 1 and 3 hours, and included questions on the infrastructure, sensors, and using data, as well as the representative's preferences for given policy instruments (see Table 1 for detailed interview questions used in our analysis). The interview data was then used to calibrate the outcome and two conditions as part of applying a Qualitative Comparative Analysis (QCA).

[2] In the sub-states AI, BS and GE, the authority operates most parts of the sewer system. Any operational task, e.g. installation of sensors or data gathering, lies in the responsibility of the authority and not as usual in municipal hands. Consequently, we exclude these sub-states from the analysis.

[3] Examples of sub-state divisions responsible for urban water management in Swiss sub-state authorities are Amt für Wasser und Abfall (sub-state BE), Amt für Abfall, Wasser, Energie und Luft (ZH), Office de l'environnement (JU).

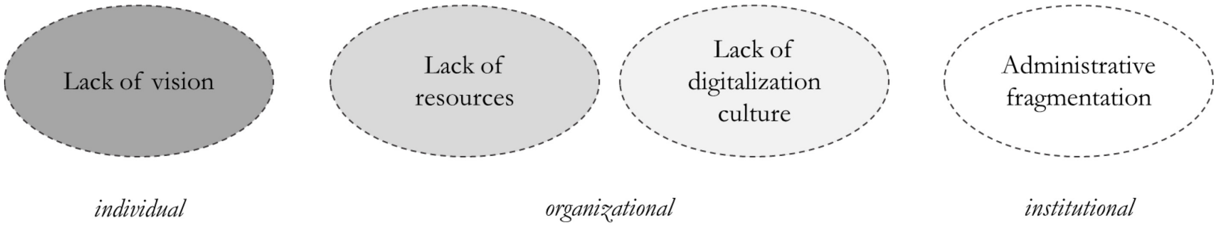

***Figure 1**: Identified conditions hindering the evaluation of data by Swiss sub-states: Lack of vision at the individual level, lack of resources and lack of digitalization culture at the organizational level and administrative fragmentation at the institutional level*

4.2 Qualitative Comparative Analysis (QCA)

We apply Qualitative Comparative Analysis (QCA) to identify configurations of barriers at different levels, given that we expect conditions from the three levels to interact. QCA is ideally suited for this task, because it identifies different combinations of conditions linked to an outcome (Ragin 1987; Schneider and Wagemann 2012; Rihoux and Ragin 2009). The method, which is based on set-theory and Boolean algebra, is typically utilized for the comparison of a medium (5-50) number of cases. Thus, the number of Swiss sub-states (26, from which we include 23 in our analysis) aligns well with the medium-N focus of QCA (Schneider and Wagemann 2012). In similar settings, scholars have used QCA to compare Swiss sub-states (Sager and Rielle 2012), to assess the influence of water stress, geographic and economic conditions on water recycling in Australia (Kunz et al. 2015), or the use of body-worn cameras policy in US states (Pyo 2020).

Fuzzy-set QCA (fsQCA) relies on data points on an interval scale (from 0 to 1) to identify their degree of membership in the sets of the outcome and the conditions. A so-called truth table is the basis of the analysis, and presents all observed and logically possible configurations of conditions. For each configuration of conditions (corresponding to a row in the truth table), the researcher then assesses the degree to which it is empirically related to the outcome. The assessment of this relation is based on fuzzy-set values of all cases and is indicated by a consistency score. Configurations that are consistently related to the outcome are included in the analysis. QCA then reduces the configuration of conditions that are related to the outcome by eliminating redundant conditions and finally identifies sufficient conditions — i.e., conditions that always lead to the outcome, but that are not the only explanations for the outcome. In this work, the analysis was performed using the R-packages "QCA" (Dusa 2019) and "SetMethods" (Oana et al. 2018).

4.3 From three levels to four conditions

From the literature, we have deductively identified a general model including three levels — individual, organizational, and institutional levels — important for understanding digital transformation. We now inductively combine this theoretical model with case knowledge and insights from expert interviews in order to specify conditions that are particularly relevant for our analysis. This results in four conditions assigned to the three levels identified based on the theoretical discussion (see Fig. 1).

First, at the individual level, the literature considers attitudes, beliefs, and vision of responsible individuals as critical in creating the impetus for innovation in general (Rogers 2003), and data-driven management more specifically (Corbett and Webster 2015). The role of those individuals responsible for the respective administrative divisions was also emphasized as a crucial condition for the evaluation of data in our exploratory interviews. For example, an expert stated that "evaluating data is often rather recognized as a hobby of those skilled to deal with data instead of generally acknowledging it as an important task that may reduce surface water pollution." Therefore, lack of vision about a future digitalized functioning and evaluation of the water infrastructure sector on the part of individuals such as division or department heads in sub-state authorities is considered a potential barrier for the evaluation of data from sewer systems.

Second, as suggested by the literature, a lack of personnel resources and capacities at the organizational level (Klievink et al. 2016) stands out as another potentially impeding condition. For example, an expert explained that "evaluating data requires additional administrative efforts". In line with the literature, findings from exploratory expert interviews indicate that personnel capacities are often insufficient, which may explain why authorities get into difficulties concerning time and workload management when it comes to regular evaluations of data.

Third, again on the organizational level, to complement quantitative aspects of available resources at the organizational level, we include a more qualitative condition, i.e., the digitalization culture in the sub-state, as a further condition influencing data evaluation. As suggested by both the literature as well as our exploratory interviews, an appropriate innovation culture is essential for successful initiatives of big data utilization (Surbakti et al. 2019; Marshall et al. 2015).

Fourth, on the institutional level, our insights from exploratory expert interviews suggest that one of the most important condition is institutional fragmentation. The higher the numbers of municipalities that a sub-state authority has to deal with, the higher the level of institutional or administrative fragmentation. Such higher fragmentation increases transaction costs of collaboration among the concerned organizations (Lubell et al. 2017). In our case, we argue that the higher the fragmentation, the more costly it is to exchange and jointly evaluate data among local municipalities and sub-state authorities. We rely on this specific condition in order to represent how institutional aspects can create barriers to innovation and digital transformation. In Switzerland, the operation of the majority of sewer systems lies in the hand of 2'222 municipalities (BFS 2018). However, sub-states differ strongly in terms of number of municipalities within their jurisdictions. In terms of data evaluation, sub-state authorities may be hindered by huge administrative burdens, as many municipalities imply many sources of data that need to be evaluated.

Along with our general theoretical model, we expect the four conditions at the individual, organizational, and institutional levels to interact and potentially jointly act as barriers to the utilization of data in Switzerland's urban water management practice. For example, it could be that the lack of vision at the individual level represents a barrier to digital innovation only if there is a simultaneous lack of digitalization culture. Or, institutional fragmentation might be a barrier only if resources at the organizational level are lacking. Also, it could be that there are several alternative sufficient conditions to a lack of digital transformation, pointing toward an equifinal solution, i.e., one aspect of configurational complexity emphasized by QCA (Ragin 1987). Whereas these examples illustrate the potential presence of configurational complexity, and thus justify the reliance on QCA, we have no strong configurational expectations and basically follow an abductive logic (Aliseda 2006; Fischer and Maggetti 2017): we have directional expectations for the influence of each condition on the utilization of data in Switzerland's urban water management practice, but identify configurations of conditions based on the inductive nature of QCA.

4.4 Operationalization and calibration

The following presentation of the calibration procedure — that is the assignment of fuzzy-set values to different states of the outcome and conditions — includes a discussion of the documentary sources for operationalizing each condition, as well as a discussion of our choices on fuzzy-set anchors for the outcome and each of the four conditions. Fuzzy-set anchors are based on the researchers justified decisions and were not discussed with experts or interviewees. Tables 5 and 6 in Appendix 1 provide an overview of the raw and calibrated data. At the level of data used for assessing the four conditions and outcomes describing the cases of sub-states, we rely on information from different sources. For example, the condition situated at the individual level is calibrated based on the perception of the individual representative in the sub-state authority drawn from the semi-structured interviews in 2017. The data describing the sub-state authority is used for the calibration of conditions at organizational level and the institutional level is represented by external data sources (BFS 2018; Schmid et al. 2018) describing the entire sub-state in the year 2018. The outcome is defined according to the indications of the individual representative within the respective sub-state authority. Therefore, our unit of analysis is the sub-state, but we rely on information from smaller units within that sub-state whenever that is appropriate for operationalizing the conditions. Consequently, we incorporate multiple levels of measurement, while the outcome of our analysis addresses sub-state authorities.

Outcome: no data evaluation (NO-EVA)

We describe the outcome by whether sub-state authorities do not evaluate data on the performance of sewer systems (NO-EVA). Due to the asymmetric distribution of the outcome, with more cases present where data is not evaluated, we focus on the absence of what we assume are "driving or enabling conditions" (i.e., barriers). In this sense, we can study how barriers could be approached to improve current practices.

The outcome NO-EVA is measured by an interval-scaled variable which is associated to the multiple-choice interview question: "How often is monitoring data evaluated by the sub-state authority?" Fuzzy-set calibration is then based on respective answers. A full set membership score (1.0) is assigned to cases where data is not evaluated. A full set non-membership score (0.0) is given to cases where sub-states' representatives evaluate data after relevant surface water pollution incidents (e.g., heavy rainfalls) and additionally in a periodic scheme, either monthly or yearly. Generally, both frequencies, i.e., monthly or yearly, would be a comparatively satisfactory state of practice and would provide useful evidence on the system's performance. We assume that evaluating data at least after relevant pollution incidents is already a step toward evidence-based management and thus assign a fuzzy-set score of 0.67, which is, for instance, the case in FR. The cross-over point of 0.5 is set for the shift from an incident-based toward a periodic data evaluation. If data evaluation solely occurs periodically without incident-based evaluation, we assign a fuzzy-set score of 0.33.

Condition 1: lack of vision (LACKVIS)

The condition *lack of vision* (LACKVIS) is calibrated based on an ordinal variable that reflects the openness of the sub-states' representative toward a specific future scenario of "data-driven management of (smart) sewer systems." The condition does thus not assess whether the sub-states have any vision for the future, but whether they have a specific vision that we assume would help them to work in the direction of relying on digitalization trends for data evaluation. The following scenario was presented to the interviewee: "[...] [the] sewer system [is] equipped with multiple sensors. Data is continuously transferred live and wireless to a central control system, automatically checked and then archived. Authorities receive automatically generated reports that they use a) to evaluate the functioning of the system, b) to make evidence-based decisions and c) to develop and implement necessary measures with the objective of meeting water protection targets." Full membership (1.0) for the set LACKVIS is assigned if the interviewee disagrees with the outlined scenario, full set non-membership (0.0) is given to a full scenario acceptance. An additional set membership score of 0.4 is introduced to consider if interviewees (e.g., FR, NE) agree only under specific preconditions, e.g., if competences and responsibilities are to be distributed more clearly. We assume that such a situation lies more within the set of agreement than disagreement, which is why a score of 0.4 is assigned. Some sub-state representatives (e.g., SO, TG) welcome data-based management of sewer systems. On the contrary, other representatives (e.g., GR, OW) argue that sensors in the challenging sewer environment are not yet state of the art technology and are rather convinced that either the technology is not leading to any form of improvement, or that the vision is impossible to ever materialize. Hence, such cases are assigned a score of 1.0.

Condition 2: lack of resources (LACKRES)

For the measurement and calibration of the condition *lack of resources* (LACKRES), we consider personnel capacities within the responsible division of urban water management of the sub-state authority. We rely on personnel capacities rather than financial resources due to limited data availability for the latter.[4]

However, we calculate the personnel capacities of each sub-state authority controlling for number of municipalities in each sub-state. This allows us to consider scale effects related to the different number of municipalities per sub-state, and thus the different number of potential interactions for sub-state authorities when dealing with data evaluation. Similar to the calibration procedure used by Kammermann (2018), we assume that by dividing the percentage of full-time job positions by the number of municipalities in a sub-state, we can provide a relative estimate of organizational capacities (*OC*). For instance, sub-states with many municipalities (e.g., BE (351 municipalities), ZH (168)) generally require more employees at the sub-state level to fulfill the same tasks than sub-states with fewer municipalities (e.g., GL (3), NW (11)). The cross-over point of 0.5 is fixed for an *OC* ratio of 2.0, which is chosen based on the following consideration. A value of 0.5 could, for instance, be generated if a case features a 100 percent full-time position who is responsible for 50 municipalities, solely in terms of urban water management. Set membership scores for LACKRES are assigned in the following scheme: full set non-membership (0.0) for an *OC* ratio > 4, full set membership (1.0) for an *OC*

[4] We have no information about the number of personnel specifically working on digitalization within the respective sub-state division, but consider the general personnel capacities as a proxy indicator for the capacity of a division to deal with issues of digitalization, and innovation more generally. Asking the division representative whether they consider they have enough resources would have been another possibility, but that perception would directly depend on what the representatives want to achieve or imagine themselves achieving, and thus depend on their vision, among others. Finally, we do not include personnel at the municipality level nor size of municipalities, given that our unit of analysis are sub-states.

ratio < 1. Assigning these fuzzy-set scores is based on a combination of visual inspection of the raw data distribution (see Fig. 4 in Appendix 1) and logical considerations on anchors as mentioned above. Therefore, our calibration procedure is characterized by the fact that it does not rely solely on mathematical measures such as mean or deciles.

Condition 3: lack of digitalization culture (LACKDIGI)

To operationalize the condition of a *lack of digitalization culture* (LACKDIGI) in the sub-state authority, we rely on a digitization index as calculated by Schmid et al. (2018) for Switzerland's sub-state authorities. The index includes variables on e-governance, e-voting and specific online services (Schmid et al. 2018). Thereby, it describes how engaged the sub-state authority is in adopting digital innovations within their service provision and indicates the general attitude toward digitalization among public actors. The measurement of the condition LACKDIGI corresponds to Schmid et al. (2018) digitization index which varies between values of 1.88 and -2.08. In the process of fuzzy-set calibration, a cross-over point at value 0 is defined as the mean of the values corresponds to -0.04 (see Fig. 5 in Appendix 1). Full set non-membership score (0.0) is assigned to digitization index values > 1, full set membership score (1.0) to values < -1. Further choices for fuzzy-set anchors are derived from the distribution of index values.

Condition 4: administrative fragmentation (FRAG)

The condition a*dministrative fragmentation* (FRAG) is operationalized based on the number of municipalities N_{mun} in a given sub-state. With respect to the variable distribution, we employ fuzzy-set scores in the following logic. A sub-state with a comparatively small N_{mun} is regarded as highly centralized in its administration, and hence not fragmented at all. A full set non-membership score (0.0) is therefore assigned to $N_{mun} \leq 25$. In contrast, a sub-state with many municipalities is presumably strongly fragmented regarding its administration. Thus, the full set membership score (1.0) is given to $N_{mun} > 250$. In the sub-state BE, the maximum number of municipalities ($N_{mun,\max} = 351$) is reached. The cross-over point (0.5) is chosen for $N_{mun} = 60$, based on the variables' distribution. Further differentiating fuzzy-set scores can be found in Table 1.

Table 1: *Calibration of outcome and conditions*

	Explanation	**Measurement**	**Operationalization**
NO-EVA	Frequency of data evaluation on the performance of sewer systems by the division of urban water management in a sub-state authority	Ordinal variable: "How often is monitoring data evaluated by the sub-state authority?" 0: no data evaluation 1: incident-based data evaluation 2: periodic data evaluation 3: incident-based and periodic data evaluation	Manual fuzzy-set membership scores: *0:* periodic data evaluation and after relevant incident *0.33:* periodic data evaluation *0.67:* incident-based data evaluation *1:* no data evaluation
LACKVIS	Lack of vision of the individual representative in the division of a sub-state authority	Ordinal variable: "Is the sub-state representative agreeing to a possible future digital scenario?" - agreement to vision - agreement under precondition - disagreement to vision	Manual fuzzy-set membership scores: *0:* agreement to vision *0.4:* agreement under preconditions *1:* disagreement to vision
LACKRES	Lack of (human) resources in the division of a sub-state authority	Organizational capacities (OC) are measured by the percentage of full-time jobs [%] in the authority's division of urban water management divided by the number of municipalities in each sub-state $OC = \frac{\text{Full-time jobs [\%]}}{N_{municipalities}}$	Manual fuzzy-set membership scores: *0:* $OC > 4$ *0.33:* $2 < OC \leq 4$ *0.67:* $1 \leq OC \leq 2$ *1:* $OC < 1$
LACKDIGI	Lack of digitalization culture in a sub-state authority	Schmid et al. (2018) provide an index on the digitization of Swiss sub-state authorities D_{index}	Manual fuzzy-set membership scores: *0:* $D_{index} > 1$ *0.33:* $0 < D_{index} \leq 1$ *0.67:* $-1 < D_{index} \leq 0$ *1:* $D_{index} \leq -1$
FRAG	Administrative fragmentation in a sub-state	Administrative fragmentation is measured by the number of municipalities N_{mun} in a sub-state	Manual fuzzy-set membership scores: *0:* $N_{mun} \leq 25$ *0.2:* $25 < N_{mun} \leq 50$ *0.4:* $50 < N_{mun} \leq 75$ *0.6:* $75 < N_{mun} \leq 150$ *0.8:* $150 < N_{mun} \leq 250$ *1:* $N_{mun} > 250$

5. Analysis and results

Table 2 presents the truth table for the outcome NO-EVA, that is, the fact that sub-states do not evaluate data on the performance of sewer systems. The combination of four conditions results in 16 possible configurations, from which 12 are empirically observed in the dataset and appear in Table 2 (that is, 12 configurations have empirically observed cases that are strong members in the respective set). This leaves us with four logical remainders that are not displayed in the truth table.

Table 2: *Truth table for the analysis of sufficiency for NO-EVA*

LACKVIS	LACKRES	LACKDIGI	FRAG	**NO-EVA**	Consistency	PRI	Cases
0	1	0	1	1	1.00	1.00	BE, LU, SO, TG
0	1	0	0	1	1.00	1.00	NE
1	0	0	0	1	1.00	1.00	OW
1	1	1	0	1	1.00	1.00	AR
1	1	1	1	1	1.00	1.00	GR
1	0	1	0	1	0.98	0.97	UR
0	1	1	0	1	0.98	0.96	JU
1	1	0	1	1	0.96	0.94	AG, SG
0	1	1	1	1	0.95	0.91	BL, FR, TI, VD, VS
0	0	0	1	0	0.88	0.74	ZH
0	0	1	0	0	0.86	0.67	GL, SH, SZ
0	0	0	0	0	0.70	0.33	NW, ZG

PRI = proportional reduction in inconsistency
Raw consistency threshold: ***0.9***

We set the consistency threshold for configurations leading to the outcome at 0.9, a choice that is based on two complementary criteria. First, this threshold corresponds to a major gap in consistency and PRI scores. A high consistency score of a configuration indicates sufficiency of that configuration for the outcome (see also Appendix 2). Second, this threshold clearly separates configurations covering cases that show the outcome from configurations covering cases that do not show the outcome. Two exceptions are SH and SZ, covered by a configuration non-sufficient for the outcome even though being a strong member in the outcome, and VS, covered by a configuration sufficient for the outcome even though not being a member in the set of cases with the outcome. An alternative threshold of 0.8 would be lower but still acceptable in terms of consistency, but the related result (LACKVIS + LACKRES + LACKDIGI + FRAG) would include more cases (three instead of one) that are only weak members in the outcome set (see also Appendix 4).

The first nine configurations thus all lead to the outcome NO-EVA, whereas the empirical evidence that the latter three also lead to such an outcome is not consistent enough. The last truth table column lists the empirical cases mainly covered by each configuration. Given that the analysis focuses on barriers, we only present and discuss results for the outcome NO-EVA, and refer to Appendix 2 for a presentation of results for sub-states where data is actually evaluated (no-eva[5]). For NO-EVA, the analysis of necessity reveals that there is no individually necessary condition (see Table 7 in Appendix 2).

The configurational information in the truth table is then subjected to the Quine-McCluskey algorithm, which returns different logical solution terms that vary in their complexity, depending on how they take configurations without information on the consistency for the outcome into account (Schneider and Wagemann 2012). We restrict the presentation of results to parsimonious solution (see Table 3). The parsimonious solution is equal to the intermediate solution[6], the conservative solutions appear in Table 11 in Appendix 2.

Table 3: *Parsimonious solution*

Solution term	**LACKVIS**	**+**	**LACKRES**	**→**	**NO-EVA**
Single case coverage	OW, UR; AG, SG; AR, GR		NE; BE, LU, SO, TG; JU; BL, FR, TI, VD, VS; AG, SG; AR; GR		
Consistency	0.96		0.92		
Raw coverage	0.58		0.70		
Unique coverage	0.17		0.29		
Solution consistency					**0.93**
Solution coverage					**0.87**

The raw consistency threshold was set at 0.9.

The solution consists of two alternative individual conditions sufficient for the non-evaluation of data.[7] The consistency and coverage scores express to what extent statements about set-theoretic relations between conditions and the outcome are supported by empirical evidence.

[5] Conditions and outcome written in lowercase letters stand for their absence, in uppercase letters for their presence.
[6] Directional expectations are LACKVIS → NO-EVA; LACKRES → NO-EVA; LACKDIGI → NO-EVA; FRAG → NO-EVA.
[7] In the Table, + represents logical 'or.'

An overall consistency score of 0.93 indicates that the solution is consistent with empirical evidence from the cases to a very large degree. An overall coverage value of 0.87 means that 87% of the outcome values are covered by the solution formula. Four out of 17 cases are covered by more than one of the two conditions (AG, SG, AR, GR). The case labels appear in the table together with each solution. Robustness of a) the fuzzy-set values to the exact calibration procedure and b) results to changes in the calibration procedure and fuzzy-set values are discussed in Appendix 4. The robustness tests revealed that our results are robust with respect to the calibrations of LACKVIS, LACKRES, and FRAG and more sensitive to the calibration of LACKDIGI (s. Appendix 4).

The findings reveal an equifinal solution, i.e., a situation where two alternative conditions can cause the outcome. They show that data is not evaluated in sub-states where individual representatives of the sub-state authority are lacking a vision (first term), or where the division of urban water management in the sub-state authority are lacking resources (second term). In the following, we interpret each solution through the lenses of case knowledge and insights, in order to complement and validate the results of the comparative analysis.

A first solution term for why sub-states do not evaluate data is given by the condition of a lack of vision at the individual level (LACKVIS) and covers six sub-states. Half of the six sub-states covered by this solution, OW, UR, AR, are some of the smallest sub-states of Switzerland by size and population. Indeed, digital transformation can have more relevance and value for larger sewer networks, as stated by the sub-state representative of AR. Size could thus partially correlate with a lack of vision at the individual level, potentially due to reduced professionalism and missing awareness for the necessity of evaluating data. However, according to the configurational nature of our approach, this is not the only important condition, given that another small sub-state (NW) is actually the most progressive regarding evaluating data from sewer systems. While the representative of the sub-state ZG claims that "the vision is already in realization, i.e., steps are undertaken to realize the presented future scenario", the representative of the sub-state UR rejects the scenario on the grounds that "it is not the authority's responsibility to evaluate data."

The second solution term (LACKRES) demonstrates that in most sub-state authorities (15 out of 18), personnel resources are generally limited and therefore may be lacking for the novel task of evaluating data from sewer systems. Thus, even though a vision for digital transformation of urban water management may be present, evaluation of data fails due to the unavailability of sufficient organizational capacities, i.e. human resources, at the level of the sub-state authority. For instance, the sub-state SO is generally very innovative and one of the most motivated sub-states in Switzerland when it comes to digitalization of urban water management. Since 2017, SO provides an online database where information on specific infrastructure elements is stored and openly available. In addition, together with the sub-state BE, SO created a digital data management concept to build up necessary IT infrastructures for a smarter management of sewer systems in the future. However, even though innovativeness and vision are clearly present, the sub-states SO and BE do not have sufficient personnel to evaluate data from sewer systems on a regular basis. In the sub-state TG, the situation is similar: though their openness toward digitalization is comparatively high (e.g., they conducted a survey on sewer data management among their municipalities in 2017), organizational capacities at the authority's level are lacking. In the sub-state GR, the division representative also expressed his concern about the lack of human resources. Finally, the representative from the sub-state TG emphasized a different aspect of human resources, saying that "it is not so much about capacities in numbers, but rather that the technical expertise of the personnel is currently inadequate."

The analysis reveals the sub-state VS as a contradictory case, in the sense that the sufficient condition LACKRES is present, but not the outcome NO-EVA. In fact, the sub-state VS represents a configuration where data are evaluated, but resources are lacking. Given our context knowledge, we assume that the individual representative of the sub-state VS has a comparatively strong vision toward data evaluation (lackvis) which may dominate the absence of resources (LACKRES) in this case. The individual sub-state representative has strong interests in water protection and therefore may act as a championing figure with high personal commitment (Surbakti et al. 2019) even though human resources are lacking.

Both conditions LACKDIGI and FRAG are not part of the solution as shown in Table 3. Therefore, the absence of data evaluation (NO-EVA) cannot be attributed to a lack of digitalization culture at the organizational level or administrative fragmentation at the institutional level. The additional analysis of the negated outcome, that is, the evaluation of data (see Table 10 in Appendix 2), reveals that authorities having a vision at the individual level (lackvis), having sufficient resources at the organizational level (lackres) and not being confronted with administrative fragmentation (frag) evaluate data.

6. Discussion

Based on the literature on digital transformation (Mergel et al. 2019), big data utilization (Apráez and Lavrijssen 2019; Giest 2017; Klievink et al. 2016; Maciejewski 2016) and organizational innovation (Mergel et al. 2016; Sun et al. 2016) as well as case knowledge and insights from expert interviews — thereby systematically combining deductive and inductive logics — we have tested the joint influence of four different conditions as hindering data evaluation by public authorities. Potential barriers in our model stem from individual (Corbett and Webster 2015; Rogers 2003), organizational (Klievink et al. 2016; Surbakti et al. 2019;

Marshall et al. 2015) and institutional (Lubell et al. 2017) levels, in line with literatures on technological innovation (Tornatzky et al. 1990) or public administration (Scharpf 2018). Results show that conditions at two levels affect data utilization in alignment with our expectations — the presence of a lack of vision (LACKVIS) or a lack of resources (LACKRES) hinders data evaluation, pointing towards an equifinal solution, with two alternative individually sufficient conditions leading to a lack of data evaluation.

The barrier with the highest coverage value, which also acts as an explanation for 15 out of 18 cases where data is not evaluated — a lack of resources at the sub-state level — might comparatively be easy to change for sub-state authorities. Of course, simply providing more financial resources to either sub-state authorities or municipalities might not help, but additional financial resources could help establishing relevant network, education or learning (Bennett and Howlett 1992) opportunities across and within sub-states and municipalities. These opportunities could also address the barrier of a lack of vision at the individual level. Furthermore, additional resources could be spent to specifically hire personnel with visions related to furthering digitalization and related data evaluation.

The conditions present in the solution term are also linked with other conditions across levels of our theoretical model. This is not a problem from a methodological point of view, given that QCA views cases as configurations of conditions (Ragin 1987; Mahoney 2004), and correlations between these conditions are moderate only.[8] Yet, it could be argued that the absence of digitalization culture (LACKDIGI) at the organizational level may influence a lack of vision (LACKVIS) at the individual level, a mechanism that should be tested in further studies. Our cases however show that lack of vision (LACKVIS) might be absent also in the presence of a digitalization culture (lackdigi) (e.g., BL, VS). Additionally, LACKRES and FRAG are related, as both include the number of municipalities in a given sub-state. However, only one condition appears in the solution term (LACKRES), meaning that LACKRES serves as a sufficient representation for cases with the outcome NO-EVA, whereas FRAG does not.

Among the four conditions, two conditions, i.e., the general digitalization environment (LACKDIGI) and administrative fragmentation (FRAG), are not sufficient conditions for data evaluation to happen. With respect to LACKDIGI, it could be that digitalization in the wastewater sector is not directly related to digitalization in other departments or sectors. Public authorities are silo-structured (Bouckaert et al. 2016), and some departments may be more advanced than others. The indicator by Schmid et al. (2018) refers to very general aspects, e.g., e-government or digital services, and might not represent particular departments within sub-state authorities and how they deal with novel digital solutions. With respect to FRAG, our

[8] Pearson correlation coefficients for conditions are:
LACKVIS, LACKDIGI: 0.01
LACKRES, FRAG: 0.57

results suggest reducing institutional fragmentation by municipal mergers (Steiner 2003) or the creation of wastewater associations among multiple municipalities (Hulst and Van Montfort 2007) per se — i.e., without an increase in relevant resources — might not be helpful to foster digitalization. Yet, if we apply a lower consistency threshold in the truth table (including 4 additional cases, from which only two are strong members in the outcome)[9], also FRAG and LACKDIGI are individually sufficient conditions for the lack of data evaluation (see Appendix 4).

Following previous studies have also identified several conditions from different levels to be important (Sun et al. 2016; Surbakti et al. 2019; Tornatzky et al. 1990), and based on a mix of deductive and inductive logics, that is, theoretical insights and in-depth case knowledge, we identify barriers to digital transformation at different levels. However, there may be other conditions potentially influencing the evaluation of data. For example, besides the vision of the individual responsible for data evaluation at the sub-state authority, the actual data science expertise of the sub-states' representatives might matter (Klievink et al. 2016). Taking organizational resources into account, we incorporated this condition to some degree — assuming that personal skills can be acquired through financial and personnel resources. However, data science and IT expertise remains an important condition that deserves more scientific attention in future studies.

Furthermore, we have analyzed public actors at the level of sub-states. Sub-state authorities can install strong incentive structures and provide knowledge, but data evaluation is at the end a joint task of sub-states, municipalities and other actors, such as engineering companies. Disentangling the network structures (Fischer 2017) among the different actors concerned by the challenge of digital transformation — and suggesting how exactly additional resources could foster network interactions — is another task for further studies. Studying the municipalities that are embedded within the sub-states in a hierarchical logic could also be done relying on combinations of QCA and hierarchical linear modeling (Meuer and Rupietta 2017). Also, other potentially important actors are other political entities acting as role models and creating mimetic pressure (DiMaggio and Powell 1983), as argued by the literature on innovation diffusion (Rogers 2003; Shipan and Volden 2008) or learning (Bennett and Howlett 1992). Individual case studies of selected cases could help in disentangling the more detailed mechanisms and processes over time that are responsible for why sub-states do or do not evaluate data. By comparing Swiss sub-state authorities to similar bodies, e.g., Water Boards in the Netherlands, Water Authorities in France, or Environmental Ministries of German Länder, which all demonstrate differences in terms of executive, regulative and operative competences,

[9] A lower consistency threshold implies that conditions with lower consistency scores will be included in the solution. For example, a consistency threshold of 0.7 dismisses conditions with consistency lower than 0.7.

novel explanations to the implementation of data evaluation may be elucidated, and the transferability of our results can be assessed.

7. Conclusion

The digital transformation of infrastructure sectors has many potential benefits, especially in urban water management, where only little is known about the performance of sewer systems (Fletcher and Deletic 2007). However, exploiting the full value of data is hindered by different barriers (Hoppe et al. 2019). This article focuses on digital transformation in the public sector, by studying the barriers to data utilization related to the performance of urban wastewater infrastructure in Swiss sub-states. Results from our fuzzy-set QCA reveal that two out of four conditions — namely lack of vision and lack of resources — indicate why data is not evaluated by sub-state authorities. We thus find evidence of hindering conditions at individual and organizational levels. The QCA method, focusing on causal complexity, has allowed us to identify two equifinal solution terms. Such equifinality is one aspect of configurational complexity (Ragin 1987). Results are robust in terms of frequency of cases linked to the configurations, as there are several cases for each solution term (Skaaning 2011). Calibration is grounded on theoretical considerations, case-specific knowledge and the distribution of raw data values. With some exceptions, results are robust to alternative choices of thresholds for conditions and outcomes; the related information appears in Appendix 4.

Our analysis contributes to the study of digitalization in organizations by elucidating barriers to utilizing data. The focus on barriers is primarily data-driven, but also allows us to study how deficits could be approached to improve current practices. In Switzerland, the evaluation of data by sub-state authorities is currently fully self-motivated, i.e. there is no coercive pressure (DiMaggio and Powell 1983) from the institutional context through national-level policies. In the absence of coercive pressure, normative pressure (DiMaggio and Powell 1983) could also play a role if the current state is suddenly perceived as insufficient (e.g., the lack of digitalization in relations between the national level and sub-states in the health sector has been heavily criticized during the COVID-19 pandemic).

Based on collected data, we explain a specific outcome — why sub-states do not evaluate data from sewer systems. This is an important outcome, as digitalization per se does often not provide immediate benefits, but rather produces large amounts of data leading to data wasting (Mergel et al. 2016), if not shared, treated, and analyzed appropriately (Sun et al. 2016). Conditions favoring or hindering the effective utilization of data have been overlooked in the literature (Sun et al. 2016; Surbakti et al. 2019; Maciejewski 2016). Our results could also indicate that the utilization of data for evaluation depends on factors on the individual (lack of vision) and organizational levels (lack of resources) directly relevant for hands-on implementation, rather than on more higher-level factors such as institutional fragmentation or digitalization of the public administration in a sub-state.

In terms of transferability, our results are applicable to the sector of urban water management in Switzerland. Yet, we think that our case is also a rather typical case (Seawright and Gerring 2008) for studying innovation and digitalization in other infrastructure sectors, also in other (rather Western, democratic) countries that face similar challenges. The theoretical model that consists of individual, organizational and institutional conditions is certainly useful for studying different settings and contexts related to innovation and data evaluation practices also in other sectors and countries, and our study should be seen as an effort of theory development in that regard (George and Bennett 2005). Yet, with respect to transferring the model to other countries, a study of sub-state authorities might be less relevant in non-federalist systems where digitalization and data evaluation might be more strongly steered by the central state.

Our results also speak to discussions about accountability, as data evaluation and the publication of evaluation results can increase transparency and, thus, the accountability of public authorities responsible for sewer systems. In the long term, utilizing data may also go in hand with higher efficiency, both in terms of economic efficiency (i.e. by preventing unnecessary investments due to more available evidence on the systems' performance) as well as environmental efficiency (i.e., better surface water protection through performance management).

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Appendix

Appendix A: Sub-states of Switzerland, raw data and fuzzy-set scores

Table A.1: *Sub-states of Switzerland and their abbreviations (case IDs)*

	Name of sub-state
AG	Argovia
AI*	Appenzell Inner-Rhodes
AR	Appenzell Outer-Rhodes
BE	Berne
BL	Basle-Country
BS*	Basle-City
FR	Fribourg
GE*	Geneva
GL	Glarus
GR	Grisons
JU	Jura
LU	Lucerne
NE	Neuchâtel
NW	Nidwald
OW	Obwald
SG	St. Gall
SH	Schaffhouse
SO	Solothurn
SZ	Schwyz
TG	Thurgovia
TI	Ticino
UR	Uri
VD	Vaud
VS	Valais
ZG	Zoug
ZH	Zurich

*We exclude sub-states AI, BS and GE from the analysis as in these sub-states, the authority itself operates most parts of the sewer system.

Table A.2: *Raw data matrix*

Case	Outcome: **NO-EVA** *Data evaluation*	Condition: **LACKVIS** *Vision*	Condition: **LACKRES** OC	Condition: **LACKDIGI** D_{index}	Condition: **FRAG** N_{mun}
AG	1	0	0.94	1.38	213
AR	0	0	0.75	-1.09	20
BL	1	1	1.74	-1.09	86
BE	0	1	1.28	0.89	351
FR	1	0.5	1.10	-0.85	136
GL	2	0.5	6.67	-0.10	3
GR	0	0	1.79	-0.60	112
JU	0	0.5	1.75	-0.10	57
LU	0	0.5	1.69	0.39	83
NE	1	0.5	1.39	1.38	36
NW	3	1	4.55	0.64	11
OW	0	0	3.57	0.14	7
SH	1	0.5	7.69	-0.10	26
SZ	1	0.5	3.33	-0.60	30
SO	0	1	0.92	0.64	109
SG	0	0	1.17	1.88	77
TI	1	0.5	1.74	-1.09	115
TG	1	0.5	1.25	0.39	80
UR	0	0	2.50	-1.59	20
VD	0	0.5	1.29	-1.09	309
VS	2	1	0.20	-2.08	126
ZG	2	1	9.09	1.38	11
ZH	2	1	2.38	0.39	168

Key of case IDs: Abbreviations for sub-states in Switzerland

Data stems from semi-structured interviews in October 2017, BFS (2018) and Schmid et al. (2018).

Table A.3: *Fuzzy-set scores*

Case	Outcome: **NO-EVA**	Condition: **LACKVIS**	Condition: **LACKRES**	Condition: **LACKDIGI**	Condition: **FRAG**
AG	0.67	1	1	0	0.8
AR	1	1	1	1	0
BL	0.67	0	0.67	1	0.6
BE	1	0	0.67	0.33	1
FR	0.67	0.4	0.67	0.67	0.6
GL	0.33	0.4	0	0.67	0
GR	1	1	0.67	0.67	0.6
JU	1	0.4	0.67	0.67	0.4
LU	1	0.4	0.67	0.33	0.6
NE	0.67	0.4	0.67	0	0.2
NW	0	0	0	0.33	0
OW	1	1	0.33	0.33	0
SH	0.67	0.4	0	0.67	0.2
SZ	0.67	0.4	0.33	0.67	0.2
SO	1	0	1	0.33	0.6
SG	1	1	0.67	0	0.6
TI	0.67	0.4	0.67	1	0.6
TG	0.67	0.4	0.67	0.33	0.6
UR	1	1	0.33	1	0
VD	1	0.4	0.67	1	1
VS	0.33	0	1	1	0.6
ZG	0.33	0	0	0	0
ZH	0.33	0	0.33	0.33	0.8

Key of case IDs: Abbreviations for sub-states in Switzerland

Fuzzy-set scores are based on the calibration procedure of the individual conditions and the outcome as shown in Table 1.

Plots on the distribution of raw data values and fuzzy-set scores

In the following figures, the x-axis shows the alphabetical order of cases (AG to ZH), the left y-axis shows the raw data used (as listed in Table A.2) and the right y-axis shows the fuzzy-set scores (as listed in Table A.3).

***Figure A.1.1**: Outcome NO-EVA*

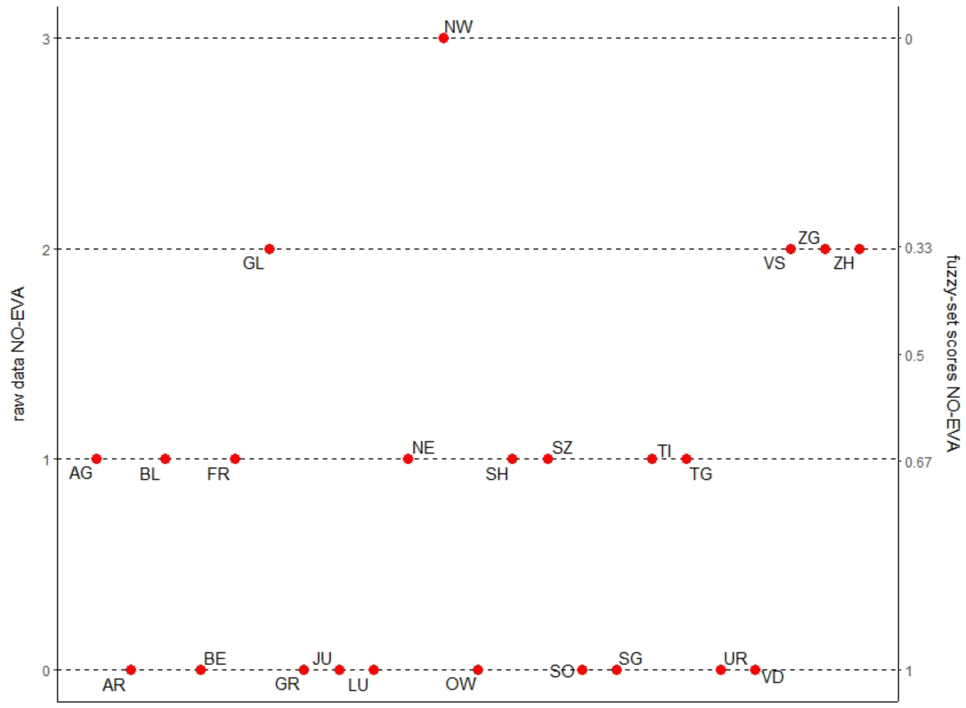


***Figure A.1.2**: Condition LACKVIS*

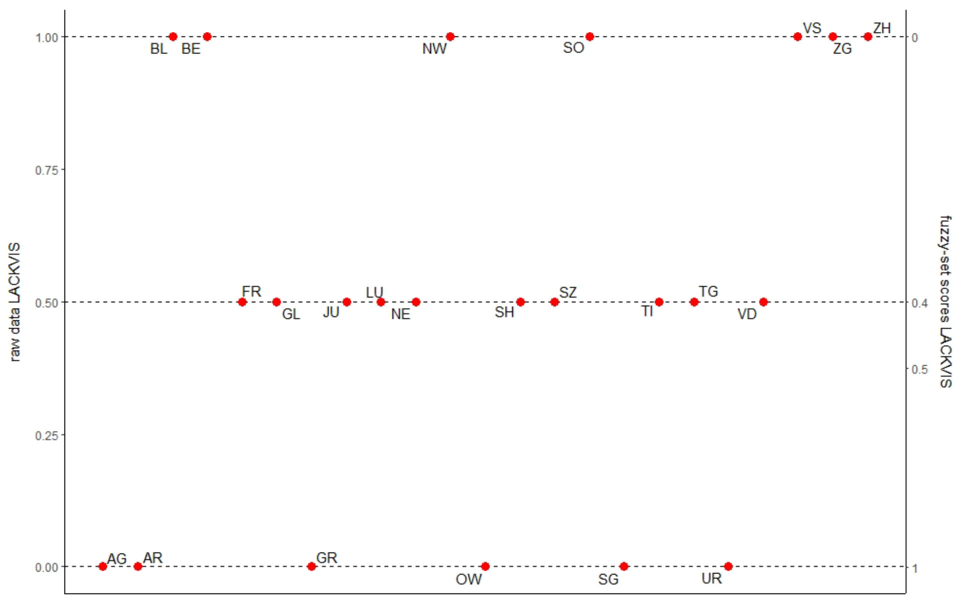


Figure A.1.3*: Condition LACKRES*

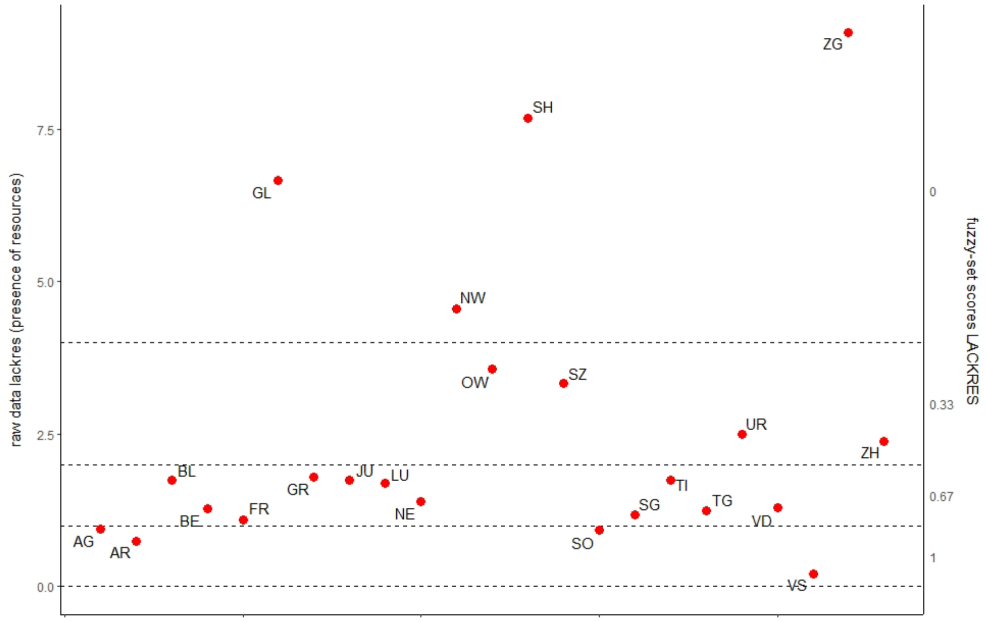


Figure A.1.4*: Condition LACKDIGI*

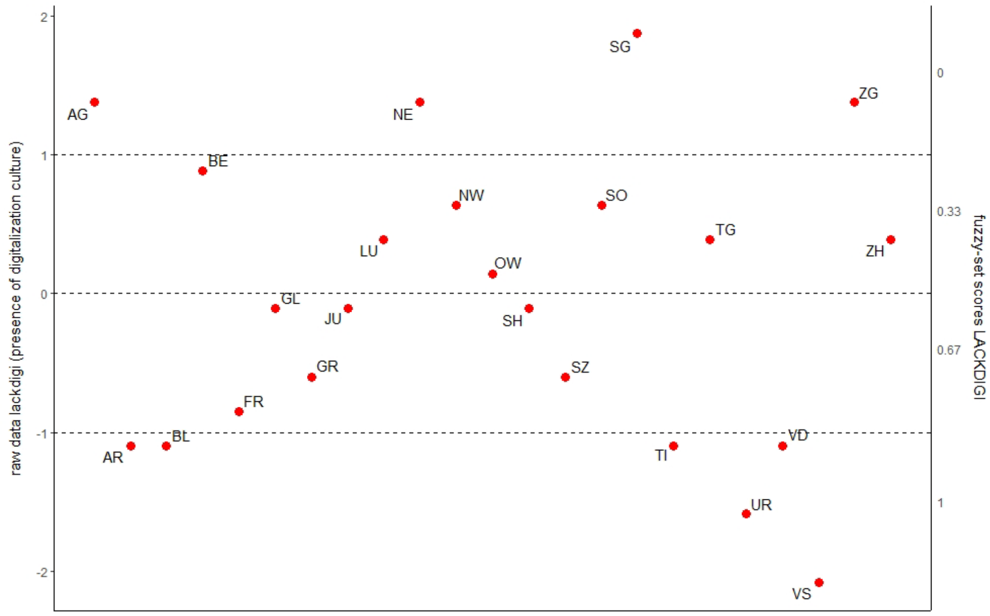
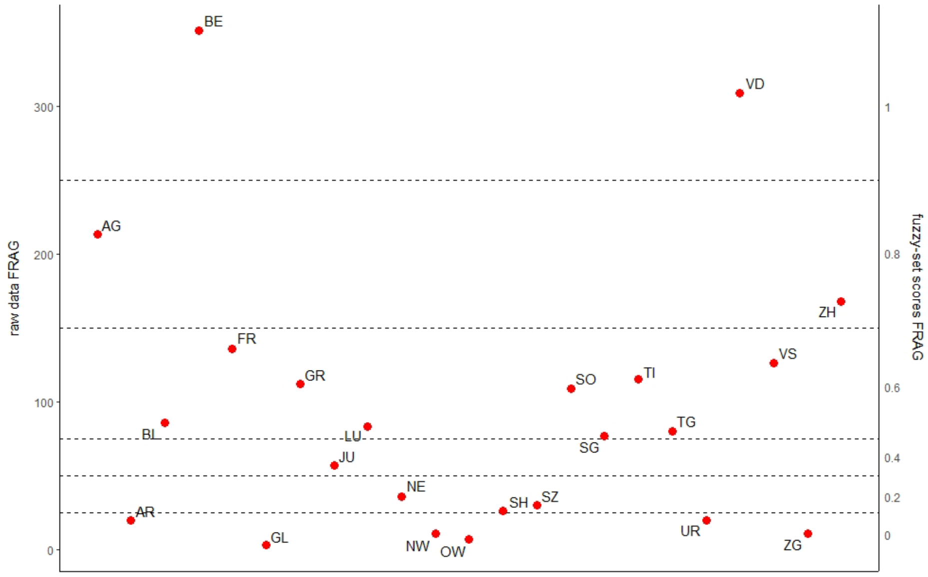


Figure A.1.5*: Condition FRAG*



Appendix B: Analysis of Necessity and Solution Terms

Analysis of Necessity

The analysis of necessity compares one condition and the outcome in terms of set membership scores. For a condition to be 'necessary', its set membership requires to be larger or equal to the set membership of the outcome, across all empirical cases. In the following tables, we provide an overview on resulting parameters for the analysis of necessity that are:

- **Consistency of necessity** states whether the presence of the outcome implies the presence of the condition. The parameter is calculated by $Y_i \leq X_i = \sum(\frac{\min(X_i,Y_i)}{\sum Y_i})$.
- **Coverage of necessity** expresses the empirical importance of a condition for explaining the outcome, i.e. measures how much of the outcome is covered by the condition. The parameter is calculated by $Y_i \leq X_i = \sum(\frac{\min(X_i,Y_i)}{\sum X_i})$.
- **Relevance of necessity (RoN)** indicates whether a condition is trivial or relevant. The parameter is calculated by $\frac{\sum(1-X_i)}{\sum(1-\min(X_i,Y_i))}$.

Table B.1: *Results of the analysis of necessity for the occurrence of the outcome (NO-EVA)*

Condition	**Consistency**	**Coverage**	**Relevance of Necessity (RoN)**
LACKVIS	0.58	0.96	0.97
LACKRES	0.70	0.92	0.91
LACKDIGI	0.62	0.84	0.84
FRAG	0.55	0.91	0.94
lackvis	0.56	0.74	0.74
lackres	0.44	0.81	0.81
lackdigi	0.50	0.84	0.84
frag	0.61	0.78	0.78

No individual condition is meeting the thresholds for consistency (0.9), coverage (0.5) and relevance (0.5), thus there is no single necessary condition for the outcome NO-EVA.

Note that a condition written in uppercase letters marks its presence, in lowercase letters its absence.

Table B.2: *Results of the analysis of necessity for the non-occurrence of the outcome (no-eva)*

Condition	**Consistency**	**Coverage**	**Relevance of Necessity (RoN)**
LACKVIS	0.43	0.27	0.64
LACKRES	0.52	0.26	0.52
LACKDIGI	0.63	0.32	0.56
FRAG	0.56	0.35	0.67
lackvis	0.94	0.46	0.59
lackres	**0.84**	**0.52**	**0.72**
lackdigi	0.68	0.41	0.66
frag	0.86	0.42	0.57

Necessary conditions meeting the thresholds for consistency (0.7), coverage (0.5) and relevance (0.5). Thus, lackres (in bold) is a necessary condition for the non-occurrence of the outcome no-eva.

Note that a condition written in uppercase letters marks its presence, in lowercase letters its absence.

Analysis of Sufficiency

The analysis of sufficiency follows the analysis of necessity. The heart of the analysis is the so-called 'truth table' that we present and explain in detail within the text. For each row in the truth table (a 'configuration'), the following parameters describe the measures of fit:

- **Consistency** measures to which degree a condition is a subset of the outcome. The parameter is calculated by $X_i \leq Y_i = \sum(\frac{\min(X_i, Y_i)}{\sum X_i})$.
- **Proportional Reduction in Inconsistency (PRI)** indicates to which degree a condition is a subset of the occurrence of the outcome rather than a subset of the non-occurrence of the outcome. The parameter helps to identify whether the condition is sensitive to being a subset of the occurrence of the outcome and the non-occurrence thereof. It is calculated by $\frac{\sum \min(X_i, Y_i) - (\min(X, Y, 1-Y)}{\sum \min(X_i,) - (\min(X, Y, 1-Y)}$.
- **Raw coverage** expresses how much of the outcome is covered by each solution path. The parameter is calculated by $X_i \leq Y_i = \sum(\frac{\min(X_i, Y_i)}{\sum Y_i})$.
- **Unique coverage** states how much of the outcome is covered by only one specific solution path.
- **Solution consistency** measures to which degree the solution path is sufficient for explaining the outcome.
- **Solution coverage** measures how much of the outcome is covered by the entire solution term.

Configurations that pass specified thresholds are then subjected to the Quine-McCluskey algorithm that returns configurations in three types of solutions:

- **Conservative (or complex) solution** includes only configurations that are empirically observed. No assumptions are made about any logical remainders, that is, logical configurations that are not covered by empirical cases.
- **Intermediate solution** considers logical remainders only if they correspond to the assumptions ('directional expectations') as defined by the researcher. In terms of complexity, the solution lies in-between conservative and parsimonious solutions.
- **Parsimonious solution** takes into account assumptions about logical remainders in order to return a solution term with the minimum of conditions (least complex solution).

Truth table and Solution Terms

Table B.3 *Truth table for the non-occurrence of the outcome (no-eva)*

LACKVIS	LACKRES	LACKDIGI	FRAG	**no-eva**	Consistency	PRI	Cases
0	0	0	0	1	0.78	0.51	NW, ZG
0	0	1	0	1	0.72	0.33	GL, SH, SZ
0	0	0	1	0	0.66	0.26	ZH
0	1	1	0	0	0.61	0.05	JU
0	1	0	0	0	0.51	0.00	NE
1	0	0	0	0	0.50	0.00	OW
1	0	1	0	0	0.49	0.03	UR
0	1	1	1	0	0.47	0.09	BL, FR, TI, VD, VS
1	1	1	1	0	0.39	0.00	GR
1	1	0	1	0	0.39	0.00	AG, SG
0	1	0	1	0	0.36	0.00	BE, LU, SO, TG
1	1	1	0	0	0.31	0.00	AR

PRI = proportional reduction in inconsistency
Raw consistency threshold: ***0.7***

Table B.4: *Conservative, parsimonious and intermediate solution for the non-occurrence of the outcome (no-eva)*

Solution term	**lackvis * lackres * frag**	**→**	**no-eva**
Single case coverage	NW, ZG; GL, SH, SZ		
Consistency	0.76		
Raw coverage	0.76		
Unique coverage	-		
Solution consistency			**0.76**
Solution coverage			**0.76**

The raw consistency threshold was set at 0.7. Number of multiple-covered cases is 0.

Table B.5: *Conservative solution for the occurrence of the outcome (NO-EVA)*

Conservative Solution						
Model 1	lackvis*LACKRES +	LACKRES*FRAG	+ LACKVIS*lackres*frag	+ (LACKRES*LACKDIGI)		→ NO-EVA
Model 2	lackvis*LACKRES +	LACKRES*FRAG	+ LACKVIS*lackres*frag		+ (LACKVIS*LACKDIGI*frag)	→ NO-EVA
Single case coverage	NE; BE, LU, SO, TG; JU; BL, FR, TI, VD, VS	BE, LU, SO, TG; BL, FR, TI, VD, VS; AG, SG; GR	OW; UR	JU; BL, FR, TI, VD, VS; AR; GR	UR; AR	
Consistency	0.92	0.95	0.99	0.92	0.99	
Raw coverage	0.45	0.50	0.31	0.48	0.34	
Unique coverage	M1: 0.04 M2: 0.06	M1: 0.06 M2: 0.07	M1: 0.09 M2: 0.02	M1: 0.08	M2: 0.08	
Solution consistency						**0.94**
Solution coverage						M1: **0.77**, M2: **0.78**

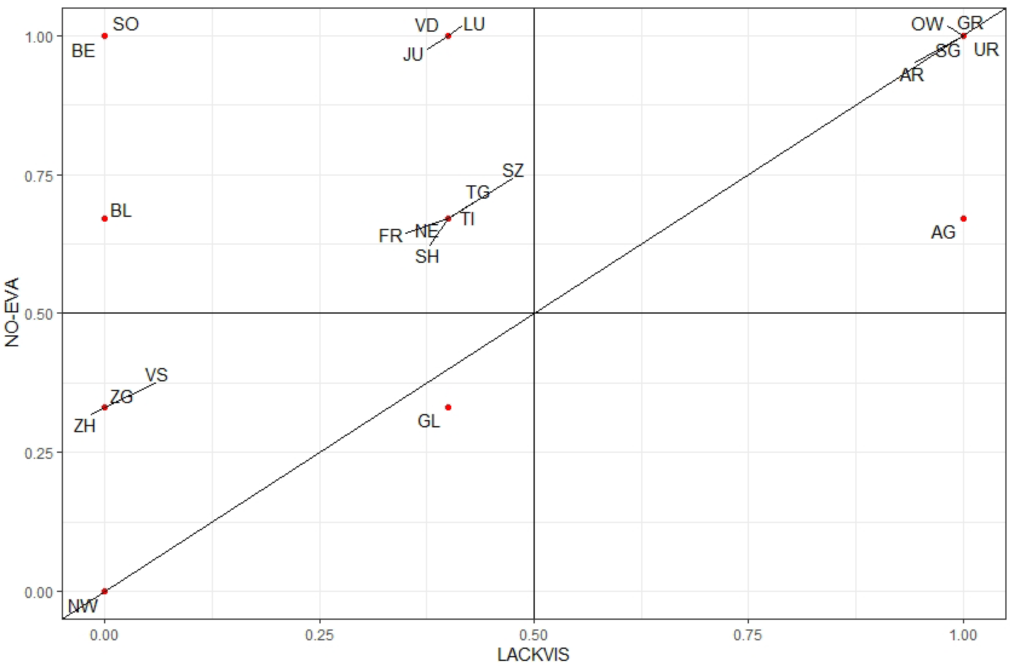
The raw consistency threshold was set at 0.9. Number of multiple-covered cases is 13.

Appendix C: Visual interpretation of the relation between conditions and outcome

The following Figures C.1 to C.4 present plots of fuzzy-set scores of each individual condition and the outcome NO-EVA. This form of visualization allows to make additional interpretations to those in Appendix B on necessity and sufficiency.

When taking a look at the upper left quadrant in Figure C.1, we observe many empirical cases where the condition LACKVIS is not present (below the cross-over point of 0.5) yet the outcome NO-EVA occurs (e.g. cases BE, SO, BL, LU, etc.). This is contradictory to our assumption that LACKVIS is necessary for the outcome NO-EVA, which makes the cases in the upper left quadrant so-called "deviant cases inconsistent in degree". For the analysis of sufficiency, we consider the lower right quadrant where no case is plotted. NO-EVA is not observed, if LACKVIS is not present. Thus, in terms of sufficiency, we do not have any "deviant case inconsistent in degree". Only the case AG can be classified as a "deviant case inconsistent in kind", as the fuzzy-set score of NO-EVA is lower than the one of LACKVIS.

Figure C.1: *Condition LACKVIS and outcome NO-EVA*



Interpretations for Figures C.2 to C.4 can be carried out in the same way as explained above. Figure C.2 illustrates that the four cases SH, SZ, OW, UR are "deviant cases inconsistent in degree" when it comes to the necessity of LACKRES for NO-EVA. In terms of sufficiency, the case VS represents such a deviant case. Even though resources are lacking (LACKRES), the sub-state authority evaluates data (no-eva).

Figure C.2: *Condition LACKRES and outcome NO-EVA*

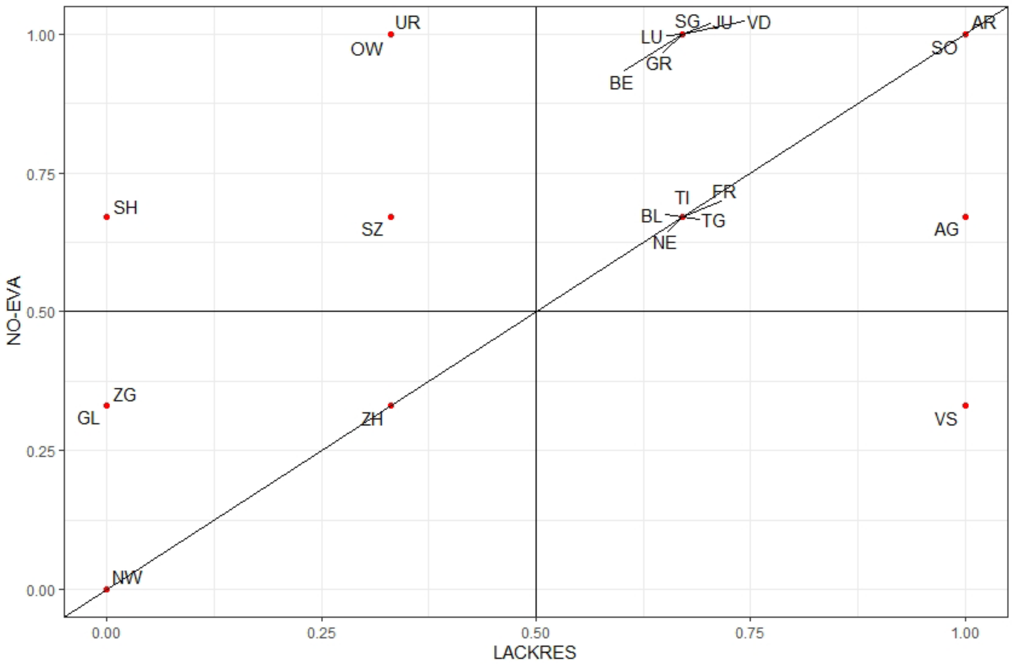


Figure C.3 shows that several cases are "deviant cases inconsistent in degree" regarding the necessity of LACKDIGI for NO-EVA (SG, BE, OW, LU, SO, AG, NE, TG). In these sub-states, even though data is not evaluated (NO-EVA), a digitalization culture is not lacking (lackdigi) at the organizational level. Regarding sufficiency, the cases GL and VS represent such deviant cases.

In Figure C.4, seven cases are "deviant cases inconsistent in degree" regarding the necessity of FRAG for NO-EVA. In these sub-states, data is not evaluated (NO-EVA) while they are not administratively fragmented (frag). For the analysis of sufficiency, the cases ZH and VS are "deviant cases inconsistent in degree".

Overall, these findings are in line with the calculated parameters of fit in Appendix B.

Figure C.3: *Condition LACKDIGI and outcome NO-EVA*

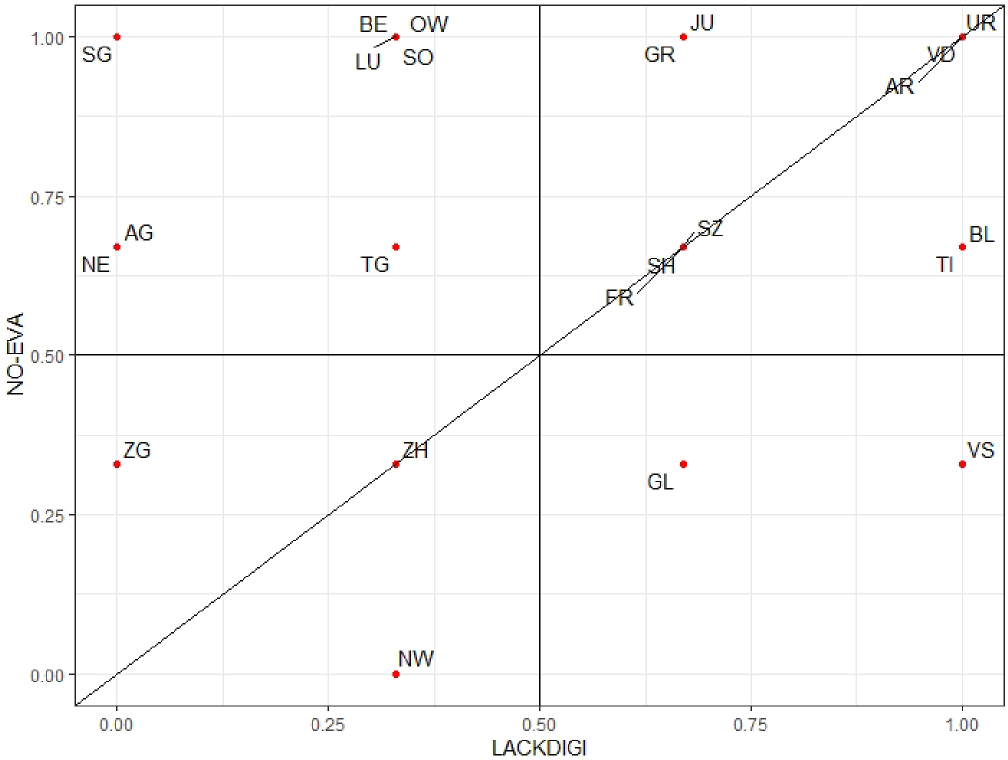
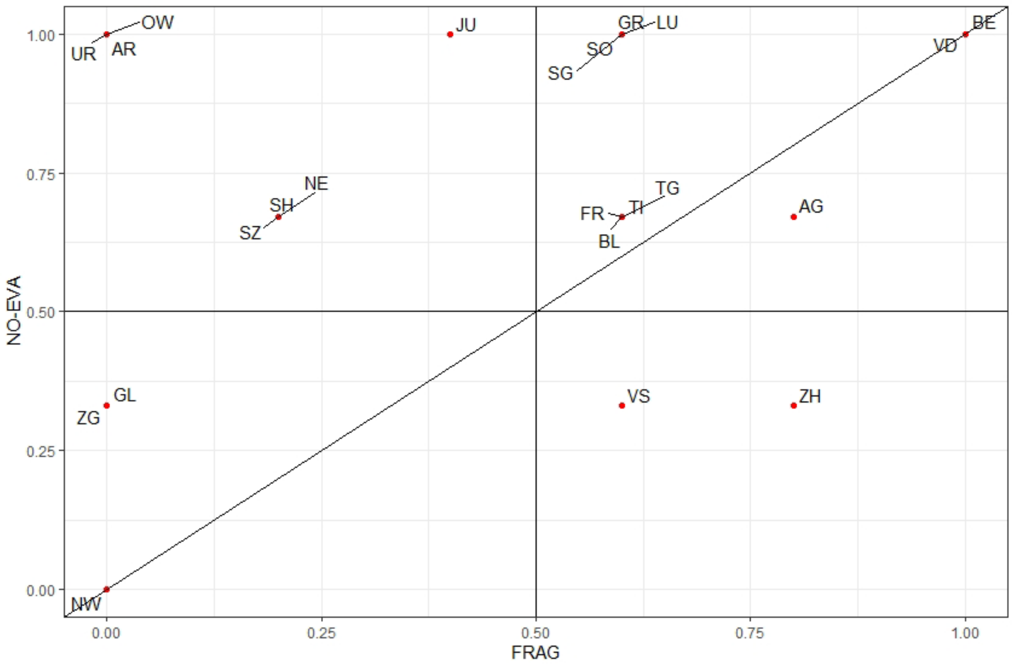


Figure C.4: *Condition FRAG and outcome NO-EVA*



Appendix D: Robustness tests

Robustness tests serve to assess the sensitivity of QCA results. Skaaning (2011) suggests to focus on three aspects: i) calibration of fuzzy-set membership scores from raw data, ii) empirical evidence in terms of frequency of cases linked to the configurations, and iii) choice of raw consistency thresholds. Whereas all of our solution configurations are covered by multiple cases (criteria ii)), we elaborate on raw consistency thresholds and calibration of fuzzy-membership scores below.

First, as shortly discussed in the main text, our solution is sensitive to the choice of the consistency threshold. In the text, we give two explanations for our choice of a 0.9 threshold. First, we define the consistency threshold based on the first major gap in consistency scores, which lies between 0.88 and 0.95 (see Table 2: Truth table). Second, our consistency threshold separates well cases that are strong members in the outcome set NO-EVA (membership scores higher than 0.5) from cases that are only weak members in NO-EVA (membership score lower than 0.5). If we lower the consistency threshold to take into account the next major gap (below 0.86), the solution changes to LACKVIS + LACKRES + LACKDIGI + FRAG (parsimonious and intermediate solution consistency: 0.85, coverage 0.94). We also shortly mention this solution in the main text, but mainly interpret the solution based on the higher threshold.

Second, alternative calibrations of outcome and conditions appear in tables below together with short comments. With respect to alternative calibrations of the outcome NO-EVA, the solution terms LACKVIS and LACKRES (our main solution) appear in all solutions achieved by different calibration alternatives. The other two conditions, LACKDIGI or FRAG, do never appear as individually sufficient conditions in any of the solutions produced through the alternative calibrations. This robustness result holds even for varying consistency thresholds (0.9 and 0.8). We conclude that given different calibrations, LACKVIS and LACKRES are consistently appearing in the solution term and therefore the presented parsimonious solution is robust concerning the calibration of the outcome NO-EVA.

Table D.1: *Robustness of solution concerning calibration of outcome NO-EVA*

	Calibration of NO-EVA			Skewness* of NO-EVA	Consistency threshold	Parsimonious solution
	fs-score	description	raw data			
Original Calibration	0	periodic data evaluation <u>and</u> after relevant incident	3	78.26 %	0.9	LACKVIS + LACKRES → NO-EVA
	0.33	periodic data evaluation	2			
	0.67	incident-based data evaluation	1			
	1	no data evaluation	0			

Calibration Alternative 1	0 0.67 1	periodic data evaluation incident-based data evaluation no data evaluation	2, 3 1 0	78.26 %	0.9	LACKVIS + LACKRES * lackdigi → NO-EVA
					0.8	LACKVIS + LACKRES → NO-EVA
Calibration Alternative 2	0 0.33 1	periodic data evaluation incident-based data evaluation no data evaluation	2, 3 1 0	43.48 %	0.9	M1: LACKVIS*LACKRES*LACKDIGI + (LACKVIS*lackres*lackdigi) → NO-EVA M2: LACKVIS*LACKRES*LACKDIGI + (LACKVIS*lackdigi*frag) →NO-EVA
					0.8	LACKVIS + LACKRES*lackdigi → NO-EVA

**Skewness: Cases > 0.5 / Total number of cases; if skewness equal 50 %, there is "no skewness"*
Consistency threshold: varies

Our solution is robust with respect to different types of calibration of the condition LACKVIS.

***Table D.2:** Robustness of solution concerning calibration of condition LACKVIS*

	Calibration of LACKVIS			Skewness* of LACKVIS	Parsimonious solution
	fs-score	description	raw data		
Original Calibration	0 0.4 1	agreement to vision agreement under preconditions disagreement to vision	1 0.5 0	56.52 %	LACKVIS + LACKRES → NO-EVA
Calibration Alternative 1	0 0.6 1	agreement to vision agreement under preconditions disagreement to vision	1 0.5 0	69.57 %	LACKVIS + LACKRES → NO-EVA

** Skewness: Cases > 0.5 / Total number of cases; if skewness equal 50 %, there is "no skewness"*
*Consistency threshold: **0.9***

Our solution is robust with respect to different types of calibration of the condition LACKRES

Table D.3: *Robustness of solution concerning calibration of condition LACKRES*

	Calibration of LACKVIS		Skewness* of LACKRES	Parsimonious solution
	fs-score	raw data values		
Original Calibration	0 0.33 0.67 1	$OC > 4$ $2 < OC \le 4$ $1 \le OC \le 2$ $OC < 1$	65.22 %	LACKVIS + LACKRES → NO-EVA
Calibration Alternative 1	0 0.33 0.67 1	$OC > 5$ $2.5 < OC \le 5$ $1 \le OC \le 2.5$ $OC < 1$	73.91 %	LACKVIS + LACKRES → NO-EVA
Calibration Alternative 2	0 0.33 0.67 1	$OC > 4$ $2.5 < OC \le 4$ $1 \le OC \le 2.5$ $OC < 1$	73.91 %	LACKVIS + LACKRES → NO-EVA
Calibration Alternative 3	0 0.33 0.67 1	$OC > 2.8$ $1.8 < OC \le 2.8$ $0.8 \le OC \le 1.8$ $OC < 0.8$	65.22 %	LACKVIS + LACKRES → NO-EVA

** Skewness: Cases > 0.5 / Total number of cases; if skewness equal 50 %, there is "no skewness"*
Consistency threshold: ***0.9***

Our solution is most sensitive to different types of calibration of the condition LACKDIGI (Table D.4 below). This can be explained by a change of the cross-over point (here: from 0 to -0.2) which implies that three cases lie above the cross-over point (GL, JU, SH) with calibration alternatives 3 and 4. For calibration alternatives 3 and 4, more conditions are part of the solution: LACKDIGI (alternative 3) and LACKDIGI and FRAG (alternative 4), respectively. Nevertheless, LACKVIS and LACKRES, i.e., our main solution, is still part of both solutions. Given that our calibration of LACKDIGI is based on a simple index (D_index), we propose to stick to numeric calibration anchors, such as the mean of D_index (here: -0.04) and median (-0.1). Both values suggest following the original calibration or calibration alternatives 1 and 2, which also show a more even distribution in terms of skewness (52.17 %).

Table D.4: *Robustness of solution concerning calibration of condition LACKDIGI*

	Calibration of LACKDIGI		Skewness* of LACKDIGI	Parsimonious solution
	fs-score	raw data values		
Original Calibration	*0* *0.33* *0.67* *1*	$D_{index} > 1$ $0 < D_{index} \leq 1$ $-1 < D_{index} \leq 0$ $D_{index} \leq -1$	52.17 %	LACKVIS + LACKRES → NO-EVA
Calibration Alternative 1	*0* *0.33* *0.67* *1*	$D_{index} > 1$ $-0.1 < D_{index} \leq 1$ $-1 < D_{index} \leq -0.1$ $D_{index} \leq -1$	52.17 %	LACKVIS + LACKRES → NO-EVA
Calibration Alternative 2	*0* *0.33* *0.67* *1*	$D_{index} > 0.8$ $-0.1 < D_{index} \leq 0.8$ $-1 < D_{index} \leq -0.1$ $D_{index} \leq -1$	52.17 %	LACKVIS + LACKRES → NO-EVA
Calibration Alternative 3	*0* *0.33* *0.67* *1*	$D_{index} > 0.8$ $-0.2 < D_{index} \leq 0.8$ $-1 < D_{index} \leq -0.2$ $D_{index} \leq -1$	39.13 %	LACKVIS + LACKRES + LACKDIGI → NO-EVA
Calibration Alternative 4	*0* *0.33* *0.67* *1*	$D_{index} > 0.8$ $-0.2 < D_{index} \leq 0.8$ $-1.2 < D_{index} \leq -0.2$ $D_{index} \leq -1.2$	39.13 %	LACKVIS + LACKRES + LACKDIGI + FRAG → NO-EVA

** Skewness: Cases > 0.5 / Total number of cases; if skewness equal 50 %, there is "no skewness"*
Consistency threshold: ***0.9***
D_{index}*mean: -0.04 and* D_{index} *median: -0.1*

Our solution is robust with respect to different types of calibration of the condition FRAG.

Table D.5: *Robustness of solution concerning calibration of condition FRAG*

	Calibration of FRAG		Skewness* of FRAG	Parsimonious solution
	fs-score	raw data values		
Original Calibration	0 0.2 0.4 0.6 0.8 1	$N_{mun} \leq 25$ $25 < N_{mun} \leq 50$ $50 < N_{mun} \leq 75$ $75 < N_{mun} \leq 150$ $150 < N_{mun} \leq 250$ $N_{mun} > 250$	56.52 %	LACKVIS + LACKRES → NO-EVA
Calibration Alternative 1	0 0.2 0.4 0.6 0.8 1	$N_{mun} \leq 25$ $25 < N_{mun} \leq 50$ $50 < N_{mun} \leq 75$ $75 < N_{mun} \leq 100$ $100 < N_{mun} \leq 200$ $N_{mun} > 200$	56.52 %	LACKVIS + LACKRES → NO-EVA
Calibration Alternative 2	0 0.2 0.4 0.6 0.8 1	$N_{mun} \leq 25$ $25 < N_{mun} \leq 55$ $55 < N_{mun} \leq 80$ $80 < N_{mun} \leq 150$ $150 < N_{mun} \leq 250$ $N_{mun} > 250$	47.83 %	LACKVIS + LACKRES → NO-EVA

Calibration Alternative 3	0 0.2 0.4 0.6 0.8 1	$N_{mun} \leq 25$ $25 < N_{mun} \leq 60$ $60 < N_{mun} \leq 90$ $90 < N_{mun} \leq 150$ $150 < N_{mun} \leq 250$ $N_{mun} > 250$	39.13 %	LACKVIS + LACKRES → NO-EVA
Calibration Alternative 4	0 0.2 0.4 0.6 0.8 1	$N_{mun} \leq 30$ $30 < N_{mun} \leq 60$ $60 < N_{mun} \leq 90$ $90 < N_{mun} \leq 150$ $150 < N_{mun} \leq 250$ $N_{mun} > 250$	39.13 %	LACKVIS + LACKRES → NO-EVA
Calibration Alternative 5	0 0.2 0.4 0.6 0.8 1	$N_{mun} \leq 25$ $25 < N_{mun} \leq 65$ $65 < N_{mun} \leq 100$ $100 < N_{mun} \leq 150$ $150 < N_{mun} \leq 250$ $N_{mun} > 250$	39.13 %	LACKVIS + LACKRES → NO-EVA
Calibration Alternative 6	0 0.2 0.4 0.6 0.8 1	$N_{mun} \leq 20$ $20 < N_{mun} \leq 60$ $60 < N_{mun} \leq 120$ $120 < N_{mun} \leq 180$ $180 < N_{mun} \leq 240$ $N_{mun} > 240$	26.09 %	LACKVIS + LACKRES + FRAG → NO-EVA
Calibration Alternative 7	0 0.2 0.4 0.6 0.8 1	$N_{mun} \leq 15$ $15 < N_{mun} \leq 30$ $30 < N_{mun} \leq 50$ $50 < N_{mun} \leq 100$ $100 < N_{mun} \leq 200$ $N_{mun} > 200$	60.87 %	LACKVIS + LACKRES → NO-EVA

** Skewness: Cases > 0.5 / Total number of cases; if skewness equal 50 %, there is "no skewness"*
Consistency threshold: ***0.9***

3. Publication 2

Socio-technical networks of infrastructure management: network concepts and motifs for studying digitalization, decentralization, and integrated management

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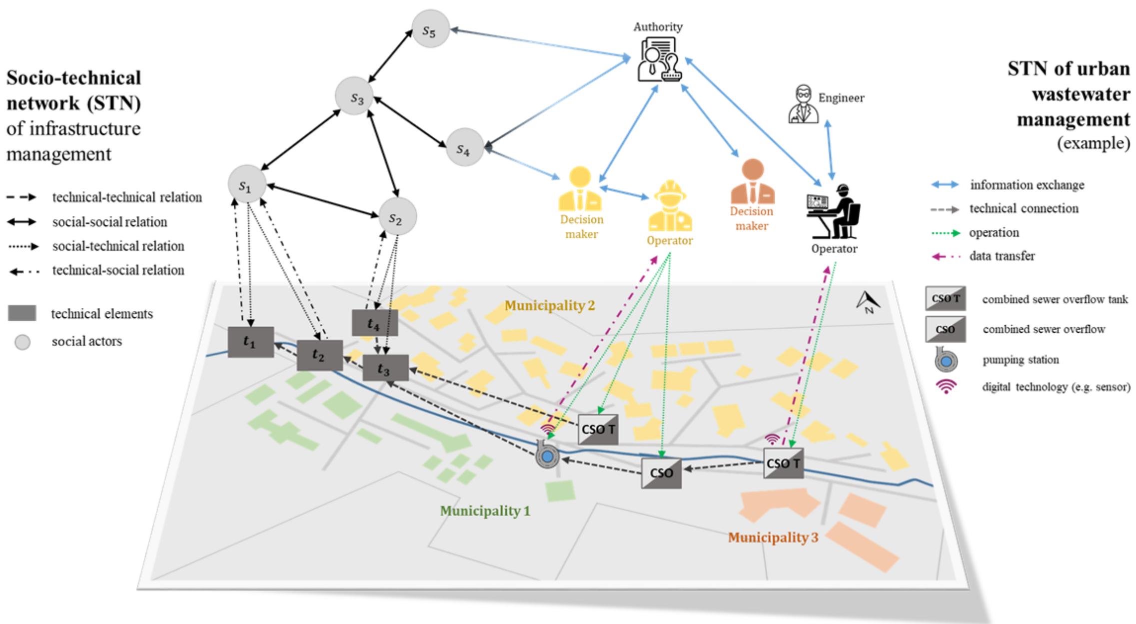
Jörg Rieckermann: Writing - review & editing; Supervision; Project administration; Funding acquisition

Manuel Fischer: Conceptualization; Writing - original draft; Writing - review & editing; Supervision

Graphical abstract



Abstract

Networked infrastructure systems — including energy, transportation, water, and wastewater systems — provide essential services to society. Globally, these services are undergoing major transformative processes such as digitalization, decentralization, or integrated management. Such processes not only depend on technical changes in infrastructure systems but also include important social and socio-technical dimensions. In this article, we propose a socio-technical network perspective to study the ensemble of social actors and technical elements involved in an infrastructure system, and their complex relations. We conceptualize structurally explicit socio-technical networks of networked infrastructure systems based on methodological considerations from network analysis and draw on concepts from socio-technical system theories and social-ecological network studies. Based on these considerations, we suggest analytical methods to study basic network concepts such as density, reciprocity, and centrality in a socio-technical network. We illustrate socio-technical motifs, i.e., meaningful sub-structures in socio-technical networks of infrastructure management. Drawing on these, we describe how infrastructure systems can be analyzed in terms of digitalization, decentralization, and integrated management from a socio-technical network perspective. Using the example of urban wastewater systems, we illustrate an empirical application of our approach. The results of an empirical case study in Switzerland demonstrate the potential of socio-technical networks to promote a deeper understanding of complex socio-technical relations in networked infrastructure systems. We contend that such a deeper understanding could improve management practices of infrastructure systems and is becoming even more important for enabling future data-driven, decentralized, and more integrated infrastructure management.

Keywords: Socio-technical networks, multilevel networks, socio-technical relations, infrastructure management, urban wastewater management

1. Introduction

Globally, infrastructure systems are facing multiple challenges. Demographic change, rapidly growing urban areas, and climate change affect technical infrastructure systems and their performance in many ways (Wilbanks and Fernandez 2012; Zimmerman and Faris 2010). In this context, infrastructure systems show several deficits, for example, inefficient operation and management (Roelich et al. 2015), ineffectively implemented regulations (Bolognesi and Pflieger 2019; Sherman et al. 2020), or insufficient evidence of system performance (Benedetti et al. 2008; Mugisha 2007; Oswald et al. 2011). In order to address these challenges and deficits, solutions such as digitalized infrastructures (Barns et al. 2017; Zimmerman and Horan 2004), decentralization of infrastructure systems (R. Bird 1994; Levaggi et al. 2018; Libralato et al. 2012), or integrated infrastructure management (Halfawy 2008; Roelich et al. 2015; Saidi et al. 2018) have been proposed in the academic and grey literature.

However, given entrenched and path-dependent systems, both technical and social transitions towards these potential solutions are not easy to achieve (Bolton and Foxon 2015; Hodson and Marvin 2010; Wihlborg et al. 2019). Any actions, strategies, processes, or policies aiming at addressing challenges, overcoming deficits, and developing solutions require an understanding of both social and technical dimensions of infrastructures. Accordingly, infrastructure systems have been studied from a socio-technical perspective, including social, technical, and intertwined socio-technical elements (Finger et al. 2005; Ottens et al. 2006). It has been argued that such a holistic analysis of the socio-technical nature of infrastructure systems is required in order to improve economic and environmental outcomes (Markolf et al. 2018). The respective literatures have relied on socio-technical system theories (Bolton and Foxon 2015; de Haan et al. 2013; Fuenfschilling and Truffer 2016; Guy et al. 2011; Ottens et al. 2006; Jensen et al. 2015), system dynamics approaches (Prouty et al. 2020; Whyte et al. 2020) or agent-based modeling (Berglund 2015; Dam et al. 2013; Panebianco and Pahl-Wostl 2006).

Socio-technical systems have further been studied using the concept of socio-technical networks (STNs) (Elzen et al. 1996; Hu et al. 2010), related to a variety of conceptual considerations and different types of network operationalizations (C. Bird et al. 2009; Kling et al. 2003; Schweber and Harty 2010). For example, C. Bird et al. (2009) represent software component networks as a STN in order to predict software failures. Schweber and Harty (2010) draw on a STN operationalization to explore the adoption of an innovative technology in the construction sector. In the context of networked infrastructure systems, STNs have often been represented in a structurally implicit or qualitative form (Elzen et al. 1996; Guy et al. 2011; Lamb et al. 2000). Only three recent studies provide a more structurally explicit approach but lack a generic terminology based on network analysis to describe respective STNs' operationalizations (Eisenberg et al. 2017; Gonzalez et al. 2021; Weerasinghe et al. 2021).

This article presents a structurally explicit description and application of the STN approach to study interrelated social actors and technical elements of managing networked infrastructure systems, such as energy, transportation, water, or wastewater systems. To do so, we draw on concepts from the literature on social-ecological networks (Bodin 2017; Bodin et al. 2019; Sayles et al. 2019) that we combine with theories of socio-technical systems (Ottens et al. 2006) and related literature. We conceptualize STNs of infrastructure systems as an empirically grounded, quantitative network representation that includes social actors (i.e. stakeholders) and technical infrastructure elements as network nodes, and multiple relations in-between these nodes as network edges (social, technical, social-technical, and technical-social relations). We apply our framing of analyzing socio-technical aspects of infrastructure management as a STN to the example of urban wastewater systems. Urban wastewater management is a good application case as it is a strongly engineering-dominated field that shows slow transformations despite a large number of technical innovations over the last decades (Kiparsky et al. 2013). Urban wastewater systems have been studied using socio-technical system perspectives before (de Haan et al. 2013; Jensen et al. 2015; Panebianco and Pahl-Wostl 2006), but not with a structurally explicit STN approach.

The approach, as discussed in this article, makes several contributions to the literature and addresses related industrial and research gaps. First, analyzing the STN of infrastructure systems can help identify socio-technical barriers, for example toward digitalization. Barriers can be technical (e.g., insufficient data quality (Langeveld et al. 2013) or absent data standards (Eggimann et al. 2017)) or social (e.g., lack of vision or resources of relevant actors (Manny et al. 2021)), but also socio-technical (Mao et al. 2020), e.g., if data transfer between technical infrastructure elements and social actors is hindered by ill-defined responsibilities. In this case, STN can provide information about whether social actors who operate technical elements do also receive data from these elements.

Second, the analysis of STN can help to assess how social actors exchange information related to a technical infrastructure system. For example, a STN analysis can uncover whether the trends of decentralization or integrated management of a technical infrastructure network are reflected in the form of a more decentralized or more integrated corresponding social information exchange network. This is especially relevant if we consider that the performance outcome of an infrastructure system is dependent on how social and technical subsystems are aligned (i.e., socio-technical fit (Guerrero et al. 2015)).

Third, applying STN to networked infrastructure systems favors systematic analysis, comparability, replicability, and knowledge accumulation between cases of socio-technical systems. It can further serve as a tool for science-policy exchanges, as barriers or potential gaps in the STN may be illustrated and discussed with relevant stakeholders. As a result, infrastructure management practices and related information exchange among actors could be improved.

This article proceeds with a theoretical discussion of socio-technical systems, related infrastructure trends, and the idea of networks in socio-technical systems. In the third section, the STN approach is formally introduced, and different analytical concepts are proposed. In section four, conceptual considerations are applied to the case of urban wastewater systems. Section five discusses how infrastructure management and relevant research questions can benefit from the STN approach. The final section concludes that the STN approach is of theoretical, conceptual, empirical, and practical relevance to the scientific community as well as to practice.

2. Infrastructures as socio-technical systems

2.1 Analyzing relations between social and technical systems

While technological developments can improve infrastructure systems, their implementation within social structures is often challenging. A socio-technical perspective on infrastructure systems comprises two subsystems, a social subsystem and a technical subsystem, and emphasizes the interdependencies between both subsystems. Socio-technical system theories provide generic conceptualizations of socio-technical systems that have also been applied in the context of infrastructure systems. For example, Ottens et al. (2006) point to the importance of including rule-like social elements such as regulations, laws, standards, or culture, into the conceptualization of infrastructures as socio-technical systems by exploring intelligent transport systems in the Netherlands. Focusing on the transformation of Australia's urban water sector, Fuenfschilling and Truffer (2016) adopt a socio-technical systems perspective by developing the concept of institutional work in the empirical context of seawater desalination technology. Socio-technical system studies tend to be mostly interested in more macro-level societal processes around radical technical change or transitions and seldom specify and operationalize the interfaces between technical and social systems at the micro-level.

2.2 Digitalization, decentralization, and integrated management of infrastructure systems

Among the different types of infrastructure systems, our focus lies on technical infrastructure networks such as energy, transportation, water, or wastewater systems. Compared to social infrastructures, such as health or education systems, or green infrastructures, technical infrastructure networks are characterized by capital-intensive fixed physical assets, which often have a lifespan of several decades and are functionally interlinked. Examples of such technical infrastructure networks are power plants, transportation terminals, or (waste) water treatment plants, which are physically connected through power lines, streets, railway lines, and drinking water or sewer pipes.

Among the most important trends related to these technical infrastructure systems are digitalization, decentralization, and integrated management which have been previously studied from a social (Barns et al. 2017; Goldthau 2014), a technical (Eggimann et al. 2017; Libralato et al. 2012), or a socio-technical (Carvalho 2015; de Haan et al. 2013) perspective. In the following, we briefly describe how a conceptualization of infrastructure systems as a STN can help to disentangle and assess socio-technical complexities underlying all three trends.

2.2.1 Digitalization

The ongoing trend of digitalization and digital transformation reflects an embedding of digital technologies and evidence-based utilization of data and information for managing infrastructure systems (de Reuver et al. 2016; Kerkez et al. 2016; Zimmerman and Horan 2004). Digital technologies may offer new opportunities due to lower transaction costs, and thus impacting modes of organization among social actors (Künneke et al. 2010). However, the successful implementation of digital technologies within infrastructure systems requires both their actual technical installation and respective social adaptations of the surrounding social system (Ghaffari et al. 2019). A socio-technical perspective on digital transformation compromises a relational perspective on both social and technical levels at the same time. For example, technical elements may be equipped with digital technologies, but relevant social actors need to have access to data obtained with these digital technologies in order to make use of it. Recognizing the socio-technical nature of infrastructure systems makes it possible to evaluate the progress of digital transformation in a socio-technical way.

2.2.2 Decentralization

At the technical level, decentralization is an important trend and potential future solution to address ageing infrastructure, improving sustainability, or the fast and flexible adaptation to demand fluctuations, e.g., related to growing cities or renewable energy. For example, electricity supply is complemented by an increasing multiplicity of distributed generation units that locally feed into the existing distribution network, thereby enhancing the technical complexity of the electricity system (Goldthau 2014). In a similar way, traditional centralized urban wastewater systems are more and more challenged by decentralized technological solutions such as stormwater harvesting or greywater recycling (Larsen et al. 2016; Moglia et al. 2011). The literature implies that mixed systems, which are partly (de)centralized, are even more complex than either fully centralized or fully decentralized infrastructures.

The increasing complexity of infrastructure systems in their technical dimensions goes hand in hand with an increasing number of social actors that participate, challenge, and transform how infrastructure systems are managed (Elmqvist et al. 2021; Goldthau 2014). Over the recent decades, infrastructure systems that were historically vertically integrated monopolies have been increasingly separated into different entities in order to allow for competition (Künneke et al. 2010). Accordingly, liberalization processes have also multiplied the number and diversity of public and private actors with regulating and decision-making competencies.

Exploiting economies of scale, infrastructure systems are expanding and have to be coordinated across a large geographic area involving different technologies and standards, as well as numerous actors with different resources and interests (Finger et al. 2005). Additionally, in order to coordinate and regulate liberalized infrastructure sectors, regulatory agencies have been introduced as new actors in the course of liberalization processes (Fischer et al. 2012; Gilardi 2002, 2009; Thatcher 2002). With respect to decentralization, new actors on the demand-side have also been joining the traditional supply-side oriented actor-network. For example, local communities may now autonomously produce and distribute electricity through their own microgrids (Warneryd et al. 2020).

2.2.3 Integrated management

The management of infrastructure systems is often fragmented into different geographical or sectoral systems. The multiplicity of involved actors and organizations requires coordination, collaboration, or information exchange. Yet, since the components of infrastructures are in one way or another connected through a physical network, there are potentially strong dependencies and interactions among technical elements. Therefore, the technical elements cannot be operated independently from another (Künneke et al. 2010). There has been a trend in both discourse and practice toward an integrated management of infrastructure systems (Hansman et al. 2006; Roelich et al. 2015; Saidi et al. 2018). This trend goes beyond single infrastructure systems. Recognizing dependencies between different infrastructure systems (e.g., water and energy systems) has resulted in more integrated perspectives such as the water-energy-nexus (Hamiche et al. 2016). Overcoming fragmented organizations would benefit from a better understanding of potential relations or even relational barriers that hinder a more effective, integrated management of infrastructure systems. Such an integrated management would incorporate geographical aspects through spatial integration as well as separated sectors through horizontal integration.

2.3 The idea of networks in socio-technical systems

According to the widespread recognition that technical and social systems are interdependent, network approaches and concepts have been previously used for the analyses of infrastructure systems. For example, techno-economic networks (Callon 1990) consider the combined dynamics of social and technical change, but focus on a set of heterogeneous actors only as network elements, without considering the technical system as a network. Elzen et al. (1996) introduce the term socio-technical network (STN) to study problems that emerge in the course of technical change using the example of the development of the European Fighter Aircraft. While they consider structurally explicit actors as nodes of a social network, technical elements are seen rather as technical artifacts that can move between actors (Elzen et al. 1996). Lamb et al. (2000) define STNs as heterogeneous arrangements that consist of interactions between social units (e.g., individuals, organizations, and institutions) and technical units (i.e., technologies). However, they do not explicitly operationalize the concept through network analysis. More applied research was conducted by Eisenberg et al. (2017) who investigated the resilience of power grids in South Korea by analyzing a STN consisting of the power grid as a technical network, as well as the social network of power companies and emergency management headquarters. Their results suggest that response in case of blackouts improves if owners and operators of associated power plants are connected to other important stakeholders, e.g., emergency management organizations. Cassidy and Nehorai (2014) use a social network-based model to analyze smart grid adoption, i.e., a user's decision to switch from a conventional energy grid to a smart grid. They determine important influencing factors, e.g., pricing, knowledge, and density of communities, on the probability of smart grid adoption. Chopra and Khanna (2014) study industrial symbiosis networks and their resilience. They use centrality measures, which capture the importance of a node (e.g., water resources or industries) to an overall network, to analyze how vulnerable given nodes in the network are. Their case addresses a water synergy system (across resources, i.e., across water resources, power plants, and aquatic environment). Most of these examples rather rely on structurally implicit network concepts — without explicitly assessing the entire diversity of relevant nodes and edges — to study socio-technical systems (Scott and Ulibarri 2019). In the following, by contrast, we propose structurally explicit network methods in order to systematically connect the social and technical systems and analyze them jointly.

3. Socio-technical networks of infrastructure management

The approach to operationalizing socio-technical networks is borrowed from the literature on social-ecological networks. The concept of social-ecological networks was introduced in order to conceptualize, operationalize and analyze complex interdependencies in social-ecological systems (Bodin and Tengö 2012; Bodin et al. 2019). Similar to socio-technical systems, the social-ecological systems concept posits that understanding the dynamics and outcomes of ecological systems needs to take into account the social system linked to the ecological system, and vice versa (Berkes et al. 2000; Ostrom 2010). The advantage of the network approach is that both the ecological system and the social system are assessed through the same lens. The common denominator of network approaches is that they consist of different components (nodes) that interact in different ways (edges) (Wasserman and Faust 1994). Furthermore, the network approach provides a shared terminology and a common conceptualization of complex systems such as social-ecological or socio-technical systems.

3.1 Formal representation of a socio-technical network (STN)

The proposed STN conceptualization frames social actors as nodes of a social network and includes technical nodes of an infrastructure system. We conceptualize relations between social actors and technical elements at multiple levels: relations among social actors (social-social relations), relations among technical elements (technical-technical relations), and relations among social actors and technical elements and vice versa (social-technical and technical-social relations, respectively).

The STN representation (s. Figure 1) considers social-social relations among social actors, e.g., private and public actors responsible for given infrastructure elements, as well as physical dependencies between relevant technical infrastructure elements, e.g., power stations, (waste)water treatment plants or transportation terminals. Crucially, the approach further considers social-technical relations such as competencies for operation or ownership, or technical-social relations such as data transfer. Other social-technical or technical-social relations are possible, depending on the infrastructure system under study.

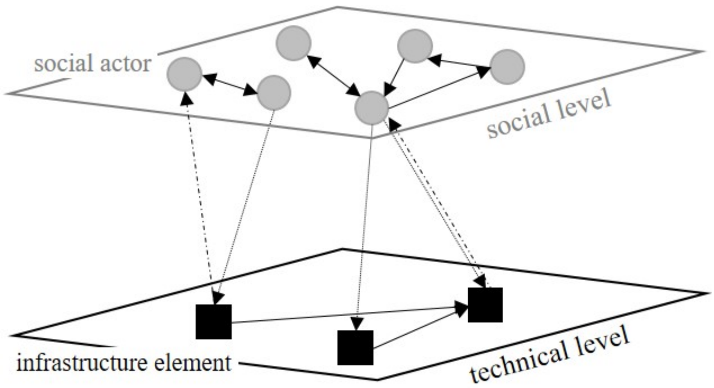


Figure 1: *Socio-technical network consisting of social actors at the social level and technical infrastructure elements at the technical level and multiple relations in between*

The proposed STN represents a multi-level network connecting social and technical levels. It is, however, not a multi-level network in the sense of hierarchically nested social structure (as in multi-level social networks; see Lomi et al. (2016)). Instead, our usage of multi-level terminology in networks that extend beyond social networks uses the term levels to describe different systems, i.e., the social and the technical systems.

In the following, we present a formal description of our conceptualization of a STN in the context of networked infrastructure systems (s. Figure 2). We define two sets of nodes (also known as 'vertices') V_T and V_S. V_T contains technical elements t of an infrastructure system, thus $V_T = \{t_1, t_2, \dots, t_n\}$. Each social actor s, who is involved in managing the infrastructure system, belongs to the second set $V_S = \{s_1, s_2, \dots, s_m\}$.

To fully describe the STN, we additionally define four edge sets. Two of these edge sets, E_T and E_S, are homogenous as edges occur only with nodes of the same set, i.e., V_T or V_S. The two other edge sets, E_{ST} and E_{TS}, are heterogeneous sets, as they comprise cross-level edges between nodes from different sets, e.g. edges between nodes of V_T and nodes of V_S.

E_T contains all technically given connections between technical elements t, i.e., it forms a technical network. Thus, E_T represents the set of edges between pairs of nodes of V_T. In the same way, E_S contains relations between social actors s, i.e., between pairs of nodes of V_S. Here, it is assumed that technical-technical relations (E_T) are directed, i.e. go from one technical element to the other. Infrastructure systems often transport a medium (e.g., water, wastewater, energy) into one direction, that is, from one technical node to the next. However, E_T can also be conceived of as undirected, e.g., in the case of transportation systems where technical edges would describe traffic between two nodes, independently of the direction of the traffic. Social-social relations (E_S) can take either directed (for example measuring the exchange of information between actors) or undirected (such as collaboration between actors) forms.

E_{ST} contains directed relations between social actors s and technical elements t. Note that for set E_{ST} the direction is defined from s to t ($s \xrightarrow{E_{ST}} t$). Opposite to the set of social-technical relations (E_{ST}), the set of technical-social relations E_{TS} contains directed relations from technical elements t to social actors s, thereby $t \xrightarrow{E_{TS}} s$. We differentiate between E_{ST} and E_{TS} because these cross-level relations have two conceptually different meanings. E_{ST} describes directed relations from social actors to technical elements and, therefore, accredits agency to social actors. By contrast, for E_{TS} we assume that technical elements can provide a certain medium (e.g., data) to social actors. Consequently, the socio-technical edge sets are divided into social-technical and technical-social edges allowing for different conceptual representations of respective cross-level relations.

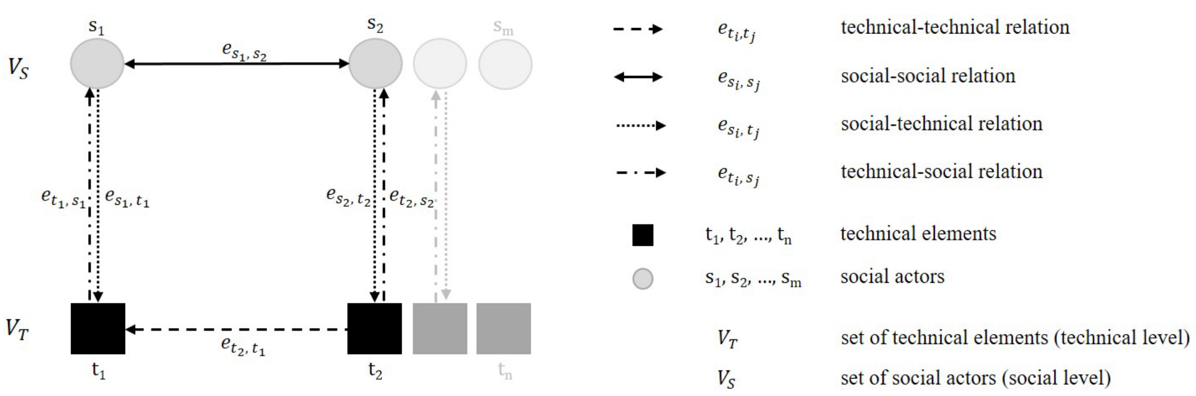


***Figure 2**: Representation of a socio-technical network (STN) as a multi-level network*

If we partition the entire multi-level network based on its edge sets, we obtain four sub-networks. These represent a unipartite technical (G_T), a unipartite social (G_S), a bipartite social-technical (G_{ST}), and a bipartite technical-social (G_{TS}) network within the entire STN.

We can alternatively describe these networks in a sociometric form if we consider their adjacency matrices[1]. For example, in the adjacency matrix of G_S, the entries e_{s_i,s_j} either take the value 1 (if an edge is present between nodes s_i and s_j) or 0 (if an edge is absent). The adjacency matrix entries e_{t_i,t_j}, e_{s_i,t_j} and e_{t_i,s_j} are defined analogously for G_T, G_{ST}, and G_{TS}. In Table 1, we provide an overview of these four networks and link them individually to previous studies or suggested examples in the context of infrastructure systems.

***Table 1**: Four networks (G_T, G_S, G_{ST}, G_{TS}) within the socio-technical network (STN)*

Networks within the STN		Previous studies and suggested examples for infrastructure systems
$G_T = (V_T, E_T)$	Technical network	- Electrical infrastructure networks *(Aksoy et al. 2018)* - Water distribution systems *(Dunn and Wilkinson 2013)* - Infrastructure systems in general *(Dunn et al. 2013)*
$G_S = (V_S, \mathrm{E_S})$	Social network	- Information exchange *(Haythornthwaite 1996; Leifeld and Schneider 2012)* - Collaboration *(Angst et al. 2018; Lienert et al. 2013)* - Financial transactions *(Pan et al. 2020)*
$G_{ST} = (V_S, V_T, E_{ST})$	Social-technical network	- Ownership - Operation - Financial responsibility
$G_{TS} = (V_T, V_S, E_{TS})$	Technical-social network	- Data transfer

3.2 Socio-technical network (STN) concepts

Using the formalized description of a STN, we suggest methods to analyze the STN of infrastructure management. We label these methods as STN concepts. Drawing on descriptive concepts often used in network analysis, we provide adapted concepts that fit the properties of the STN structure of infrastructure systems.

The STN concepts are divided into three categories. First, we make use of certain commonly used basic concepts in network analysis and apply these to STNs. Second, we illustrate the potential of studying meaningful sub-structures in a STN. Third, based on the first two

[1] An adjacency matrix of a network is a square matrix where the matrix entries indicate whether two nodes are adjacent (i.e., connected) or not (Wasserman and Faust 1994).

categories, we suggest how the STN of infrastructure management can be analyzed in terms of digitalization, decentralization, and integrated management.

3.2.1 Density, reciprocity, and (degree) centrality in a STN

Table A.1 in Supplementary Materials A presents a comparison of three descriptive concepts, namely density[2], reciprocity[3], and (degree) centrality[4], for social networks and adapted to a STN. We consider all four networks in the STN (s. Table A.1) and describe density individually for each of them (d_S, d_T, d_{ST}, d_{TS}). The densities of the social and technical networks in the STN can be determined, similarly to the social network density, by calculating the ratio of actually present, observed network edges to the number of all possible edges, given the network nodes. For the cross-level social-technical and technical-social networks (G_{ST} and G_{TS}), we need to include both technical nodes $|V_T|$ as well as social nodes $|V_S|$ in the denominator to calculate the number of all possible edges between technical elements and social actors (s. Table A.1).

For the concept of reciprocity, we specify two equations. The first equation concerns reciprocity in the social network G_S, i.e., social-social relations that are reciprocated between two social actors. The second equation reflects our conceptual understanding of reciprocity from a socio-technical perspective. With the term socio-technical reciprocity we refer to a social-technical edge e_{s_i,t_j} between two nodes s_i and t_j that is also present in the technical-social network (e_{t_j,s_i}). Reciprocity can be assessed for a pair of nodes or for the entire network. For the latter, we summarize all observed reciprocated socio-technical relations ($|E_{ST} \leftrightarrow E_{TS}|$) and divide by the sum of social-technical ($|E_{ST}|$) and technical-social edges ($|E_{TS}|$) to determine the socio-technical reciprocity r_{st}.

(Degree) centrality is an important concept that serves for the identification of central nodes (Wasserman and Faust 1994). In a STN, central nodes can be central technical elements or central social actors. If central nodes have a high number of edges, they are considered to be degree central. Degree centrality can be either defined by looking at social or technical edges or at cross-level social-technical or technical-social edges. Further, the degree centrality can be calculated for in-coming edges, i.e., edges directed towards a node (in-degree centrality c_{D-}), or for out-going edges, i.e., edges directed away from a node (out-degree centrality c_{D+}), or both (degree centrality c_D).

Taking the social-technical network (G_{ST}) as an example, the concept of degree centrality can help determine whether a social actor is related to many technical elements (social-technical out-degree centrality $C_{D+}^{ST}(s_i)$). Considering the opposing direction of edges in the technical-

[2] Density refers to the ratio of edges that are actually present in a network to the maximum number of edges that are possible given the number of nodes (Wasserman and Faust 1994) (s. also Table A.1).

[3] Reciprocity describes that a directed edge from node A to node B is reciprocated, so there is a directed edge from node B to node A as well.

[4] Centrality is best described for an individual node that is central in the network. In the case of degree centrality, a (degree) central node has a high number of (in-coming and out-going) edges.

social network (G_{TS}), we can find out similar circumstances, i.e., a technical element being related to either a single, to few or to many social actors (technical-social out-degree centrality $C_{D+}^{TS}(t_i)$).

The equations for degree centrality as presented in the respective column in Table A.1 allow for the identification of central social actors and central technical elements in a STN.

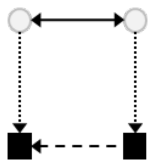
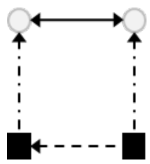
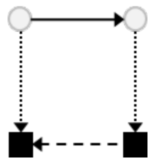
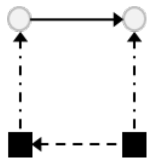
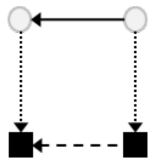
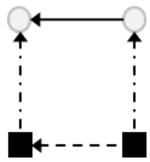
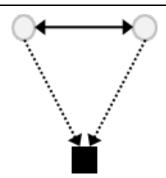
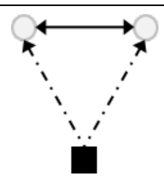
3.2.2 Socio-technical motifs

Besides studying individual nodes or pairs of nodes (i.e., so-called dyads), we illustrate the potential of studying meaningful sub-structures with three nodes (i.e., triads) and with four nodes (i.e., cycles) in Table 2. Adapting terminology from social-ecological network theory (Bodin et al. 2019), we label these sub-structures "socio-technical motifs" and provide respective socio-technical interpretations (s. Table 2). These socio-technical motifs include one technical element and two social actors in the case of socio-technical triads or two technical elements and two social actors for socio-technical cycles. The illustrations of socio-technical motifs in Table 2 demonstrate that multiple relations are taken into account as well.

For example, motif A or "socio-technical alignment with reciprocated social-social relation" represents a sub-structure where social actors interact with reciprocating social actors who are related to technical elements (or vice versa) which are connected at the technical level. This socio-technical cycle takes into account three types of edges: the technical, the social, and either the social-technical or the technical-social. Motifs B and C differ from motif A in the form of social edges, as motif A includes reciprocated social-social relations between social actors, and motifs B and C do not feature this reciprocity. Motif D represents a socio-technical triad, where two social actors are related to the same technical element. Table 2 shows four selected simple socio-technical motifs out of a number of potential further examples as presented in Supplementary Materials B.

The conceptual objective of socio-technical motifs is to analyze them descriptively, i.e., by counting the number of observed motifs in a STN. Socio-technical motifs can also be interpreted in a normative way, e.g., by assuming that the presence of numerous motifs A, B and C in a STN implies a well-functioning infrastructure management from a STN perspective.

__Table 2__: Selected socio-technical motifs within socio-technical networks

Motif	Motif description	Motif representations		Socio-technical interpretation
		Cross-level edges represent **social-technical relations** (e.g., operation/ownership)	Cross-level edges represent **technical-social relations** (e.g., data transfer)	
A	Socio-technical alignment with reciprocated social-social relation *(socio-technical cycle)*			Tendency of social actors to interact with reciprocating social actors who are related to technical elements (or vice versa) which are connected at the technical level
B	Socio-technical alignment with same direction of social-social and technical-technical relations *(socio-technical cycle)*			Tendency of social actors to interact with social actors who are related to technical elements (or vice versa) which are connected at the technical level *(social-social relation has same direction as technical-technical relation)*
C	Socio-technical alignment with opposing direction of social-social and technical-technical relations *(socio-technical cycle)*			Tendency of social actors to interact with social actors who are related to technical elements (or vice versa) which are connected at the technical level *(social-social relation has opposite direction as technical-technical relation)*
D	Socio-technical transitive closure *(socio-technical triad)*			Tendency of social actors to interact with reciprocating social actors who are related to the same technical element

Note: Circles denote social actors and squares denote technical elements. Lines denote social-social relations, technical-technical relations, social-technical relations and technical-social relations.

3.2.3 STN and digitalization, decentralization, and integrated management of infrastructures

Based on the descriptive concepts in Table A.1 and the socio-technical motifs in Table 2, we provide interpretations of entire STN structures related to the trends of digitalization, decentralization, and integrated management in Table C.1 in Supplementary Materials C.

In Table C.1, we illustrate exemplary STN configurations and suggest mathematical equations to determine the degrees of digitalization, decentralization, and integrated management from a STN perspective. For example, an infrastructure system can be either socio-technical digital or not socio-technical digital or somewhere in-between. In the same way, an infrastructure system can be rather centralized or more decentralized. By considering social-social relations as well as social-technical relations, we can further determine whether an infrastructure system is managed in a fragmented or integrated way. Overall, the proposed equations may prove useful for comparing different STNs of infrastructure management in an analytical and formal way.

4. Application to the management of urban wastewater systems

We take urban wastewater systems (UWS) as our case study to demonstrate the applicability of the STN approach. We do so by outlining the social and technical characteristics of UWS and describing how they can be studied from a STN perspective. We then provide a concrete operationalization of nodes and edges that is guided by a visualization. Based on our operationalization choices, we designed an empirical case study of a regional unit of an UWS in Switzerland and collected STN data through a context interview, document analysis, and a survey. Using the obtained case study data, we apply selected STN concepts from Tables A.1, 2 and C.1, and conduct a preliminary analysis and interpretation of respective descriptive results. Our empirical application of STN is guided by the general research question: "What is the structure of STN in urban wastewater systems and how can knowledge about this structure inform researchers and practitioners about governance and infrastructure challenges?"

4.1 Empirical case study: technical elements and social actors in Swiss UWS management

Centralized UWS consist of multiple technical elements that are arranged in a way that stormwater is drained from impervious city areas, and wastewater from individual households is directed to a wastewater treatment plant (WWTP). The WWTP discharges the treated water into nearby surface waters, e.g., creeks, rivers, or lakes.

At the social level, many different actors and organizations are involved in the management of UWS, e.g., operators, planners, and authorities (Lienert et al. 2013). Yet, organizational fragmentation may result in inefficient operation and management (Roelich et al. 2015; Worthington 2014), absence of system-wide performance assessment (Benedetti et al. 2008; Fu et al. 2008), slow innovation (Kiparsky et al. 2013), or even negative environmental impacts in the long run (Kim et al. 2015).

The example of UWS illustrates the importance of socio-technical dependencies, as socio-technical configurations can influence the technical performance of an infrastructure system. Such dependencies become especially relevant when it comes to changes at the technical or socio-technical level. Examples are the integration of digital technologies (e.g., sensors) within existing infrastructure systems (i.e., digitalization), transitions towards more decentralized infrastructure systems (i.e., decentralization), or more system-wide management of regional system units (i.e., integrated management).

In Switzerland, UWS are managed by public entities such as municipalities or wastewater associations[5]. Most of the regulative and executive competencies are situated at the sub-state level and provided by public administrations (Luís-Manso 2005). While the trends of decentralization and integrated management are currently on the agenda of the national Swiss wastewater association, they are only sporadically addressed and implemented in practice (Lienert et al. 2006). In terms of digitalization, the 26 sub-states are in different stages, with the sub-state Zurich being rather advanced, for example (Manny et al. 2021).

Our case study UWS is located in the sub-state Zurich[6], thereby representing one out of 62 UWS in the entire sub-state area. The case study UWS was chosen based on two considerations. First, the catchment area of the case study UWS includes six municipalities with their respective technical elements, which are connected to the central WWTP. Based on a survey conducted in 2017 (Manny et al. 2018), we identified a median of 6 municipalities per wastewater association in Switzerland. Therefore, the selected case study UWS is comparative to many other UWS in terms of its size. Second, the region where the case study UWS is located reflects a typical Swiss peri-urban region. In total, around 28’000 inhabitants are connected to the WWTP of the catchment area. A first impression of the area, the systems’ technical elements, and social actors was achieved by conducting a context interview with a key stakeholder that had a broad knowledge of the case in June 2020. Based on the context interview, we classify the empirical case study UWS as rather not advanced in terms of digitalization, decentralization, and integrated management.

4.2 STN operationalization and data collection

Drawing on the context interview and complementary document analysis, we identified all relevant technical elements, the technical-technical relations, and all social actors who are involved in the management of the UWS. We used a technical infrastructure map of the UWS given to us by the context interviewee to identify technical elements and technical connections (i.e., technical-technical relations). The context interviewee also provided us with information on all municipalities, engineers, and authority representatives involved in managing the UWS. Additional social actors relevant to the management of technical elements in the catchment area were added based on a check of all websites from municipalities active within the catchment area as well as available planning documents. The resulting list of social actors was then again validated by the context interviewee and can be found together with the list of all technical elements included in the analysis in Supplementary Materials E. With respect to the system boundaries, we represent technical elements of a WWTP and its main trunk sewer. For the latter, we consider the following technical elements: combined sewer overflows (CSO), and

[5] A wastewater association is an organizational form of inter-municipal cooperation where several municipalities join forces to operate technical elements of the UWS.
[6] We refrain from presenting the actual location to protect the anonymity of social actors.

CSO tanks (CSO T), as well as pumping stations (P). The representation excludes the rest of the collection system and minor elements such as manholes. The technical elements are chosen based on their relevance to the investigated infrastructure trends and three considerations. First, they are equitable with digital technologies, which potentially transfer data to social actors. Second, they are important elements in terms of urban wastewater management and water protection. Third, they need to be actively operated, planned, and monitored by social actors. The correct representation of the technical network G_T consisting of the technical elements and the technical-technical relations was validated by the key stakeholder with whom we conducted the context interview and a representative of the authority.

When it comes to the system boundaries for the social network, we focus on the organizational level. Our case study UWS is owned and operated by public entities, i.e., by six municipalities. Social actors have one of the following roles: WWTP operator, wastewater association president, municipal president, municipal council, municipal administration, municipal works, engineer, or authority. In other cases, social actors should be selected based on their relevance to managing technical elements of an infrastructure system. There are different ways to operationalize social-social edges in a STN, depending on the aspects of infrastructure management that researchers decide to analyze, such as collaboration (Angst et al. 2018; Lienert et al. 2013) or financial transactions (Pan et al. 2020) (s. also Table 1). In our case study UWS, we rely on an explicit operationalization of relations in the STN. All four types of relations are deduced based on their representativeness related to the three trends of digitalization, decentralization, and integrated management. We define social-social relations between social actors as information exchange (Haythornthwaite 1996; Leifeld and Schneider 2012) and technical-technical relations as technical connections in the form of physical dependencies (Aksoy et al. 2018; Dunn and Wilkinson 2013). Social-technical relations are represented as operation, i.e., the competence to operate technical elements. This operationalization allows us to study the trends of decentralization and integrated management. Technical-social relations describe data transfer from a technical element to a social actor, thus providing socio-technical information on the trend of digitalization. In order to illustrate our STN operationalization, we provide a visualization in the form of a simple example — not based on any empirical data — in Figure 3.

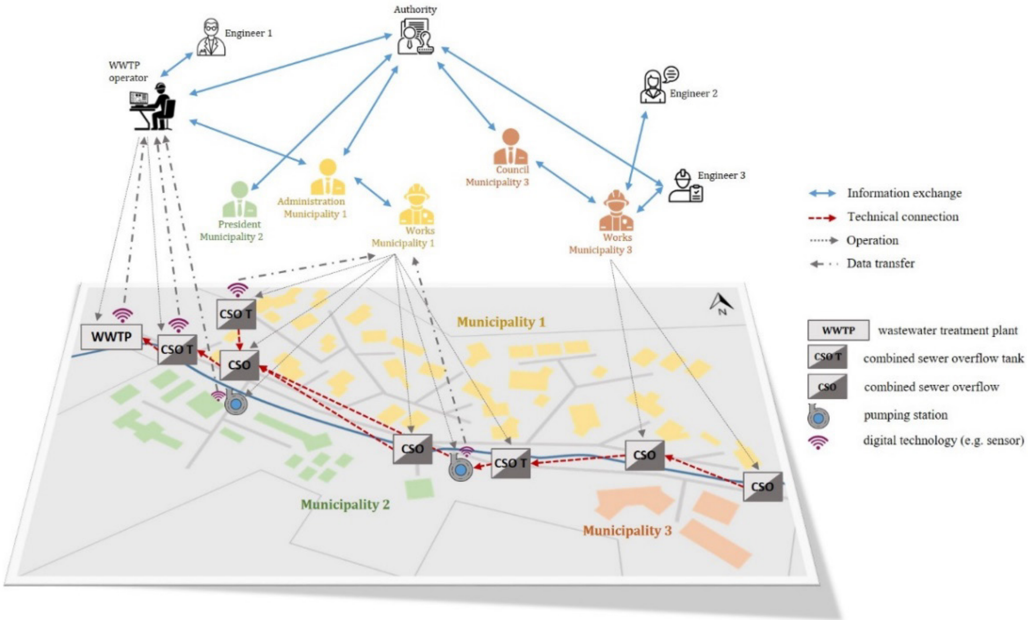


***Figure 3**: Operationalization of a simple example of a STN of an UWS*

Using an online survey, we gathered STN data from March to May 2021 with a response rate of 97 percent (31 out of 32 social actors represented). The obtained STN dataset contains data on technical elements and social actors as well as relational data on information exchange, operation, and data transfer. For example, we provided survey participants with a list of social actors who are active in the case study area and asked them with whom they were exchanging information on urban water management issues during the past two years.[7] Survey participants were allowed to identify up to ten additional actors with whom they exchange information. However, only at most two additional social actors were added by survey participants. Therefore, we decided to exclude these additionally stated actors as each name was only mentioned once. We assume that additionally stated actors are rather personal contacts and not relevant for all social actors in the catchment area in terms of information exchange.

All relational data was converted to matrix format in order to apply network analysis tools.[8] For the purpose of reproducibility, we give a more detailed description on STN data collection and data analysis in Supplementary Materials F. Based on the network matrices, we visualize the empirical STN of the case study UWS in Figure 4[9]. The figure reflects an empirical observation in network format, assessed based on empirical information from a context interview, document analysis, and a survey. The empirical STN consists of 31 social actors and 42 technical elements. In total, there are 285 information exchange edges, 41 technical connection edges, 249 operation edges, and 7 data transfer edges (s. Table 3).

[7] We provide a complete version of the survey questionnaire in Supplementary Materials D.
[8] Data on social and technical nodes can be found in Supplementary Materials E. The analysis of the STN was performed in R studio using, for example, the packages graphlayouts (Schoch 2020) and motifr (Angst and Seppelt 2020)
[9] While Figure 3 illustrates a simple example not based on any empirical data of our representation of the nodes and edges of a STN (i.e. including a technical infrastructure map and respective symbols of technical elements and social actors), Figure 4 is based on empirically validated information and visualizes the empirical STN of a real-world UWS.

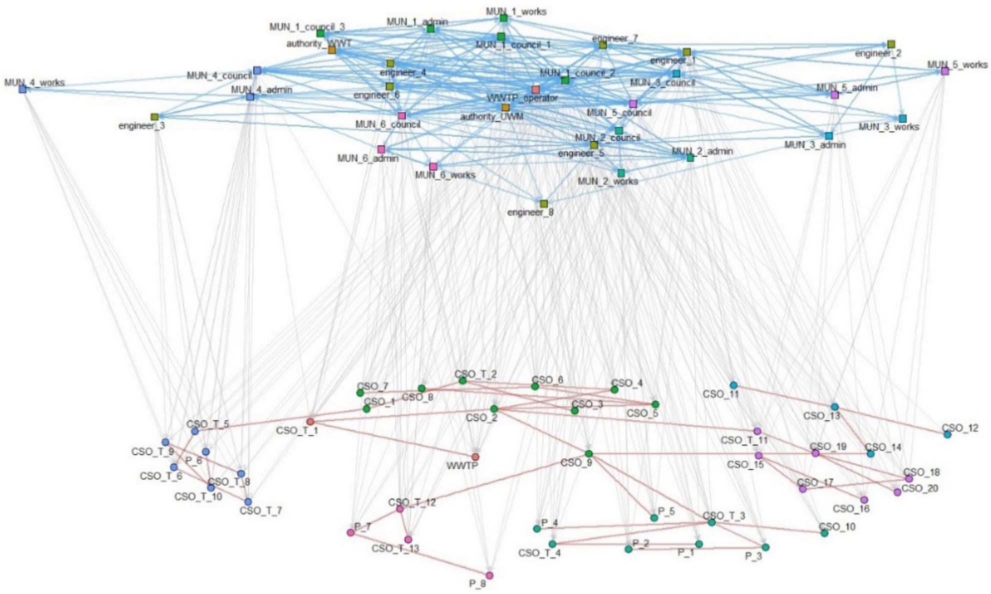


***Figure 4**: STN of an urban wastewater system in Switzerland. Social actors are at the top, technical elements are at the lower level and colored based on their affiliation to a municipality. Information exchange edges are yellow, technical connection edges are red, operation and data transfer edges are both colored grey. This STN was visualized using graphlayouts (Schoch 2020) in R studio.*

***Table 3**: Socio-technical network analysis of the empirical STN as visualized in Figure 4*

Concept	**Description**	**Result**
$\|V_S\|$	Number of social actors	*31*
$\|V_T\|$	Number of technical elements	*42*
$\|E_S\|$	Number of social-social relations *(here: information exchange)*	*285*
$\|E_T\|$	Number of technical-technical relations *(here: technical connection)*	*41*
$\|E_{ST}\|$	Number of social-technical relations *(here: operation)*	*249*
$\|E_{TS}\|$	Number of technical-social relations *(here: data transfer)*	*7*
d_S	Social network density (directed)	0.31
d_T	Technical network density (undirected)	0.05
d_{ST}	Social-technical network density *(operation network density)*	0.19
d_{TS}	Technical-social network density *(data transfer network density)*	0.005
r_S	Social network reciprocity	0.6
$\mathrm{r_{st}}$	Socio-technical reciprocity	0.005
$\max(C_{D+}^{ST})$	Most central social actor(s) based on social-technical network *(central in terms of operation of technical elements)*	WWTP operator; municipal council 2 of municipality 1 (i.e., wastewater association president)
$\max(C_{D+}^{ST})$	Most central technical element based on technical-social network *(central in terms of data transfer to social actors)*	CSO tank 1
motif A	Count of socio-technical motif A *(socio-technical cycle)*	754
	Count of socio-technical motif A without social-social relations	453
motif D	Count of socio-technical motif D *(socio-technical triad)*	366
$d_{digital}$	Socio-technical degree of digitalization	0.41
$d_{decentral}$	Socio-technical degree of decentralization	0.1
$d_{integrated}$	Socio-technical degree of integrated management	0.24

4.3 Descriptive results from the STN analysis

In the following, we present results that reflect a selection of our suggested descriptive STN concepts in section 3.2. Based on the number of social actors and technical elements as well as the number of different edges, we determine the densities of the four networks G_S, G_T, G_{ST}, and G_{TS} (s. Table 3). The density of the social information exchange network is 0.31. This value is in line with what we observe in similar networks. For example, the densities of collaboration networks among actors being involved in 11 policy processes on the Swiss national level range from 0.27 to 0.43, with most values being right above or below 0.30 (Fischer and Sciarini 2016). In information exchange networks on hydraulic fracturing politics in Swiss sub-states, information exchange network densities range between 0.11 and 0.20 (Ingold and Fischer 2016). Indeed, we would expect to see lower density values for networks dealing with hydraulic fracturing — a new issue on the political agenda — as compared to higher densities in networks related to an established issue such as urban wastewater management. These exemplary comparisons with published network studies validate the structure of our social network in terms of one of the most basic and important network indicators, i.e., network density.

At the socio-technical level, the densities of the operation and data transfer networks are generally dependent on the number of social actors and technical elements. The social-technical network of operation shows a higher density ($d_{ST} = 0.19$) than the technical-social network of data transfer ($d_{TS} = 0.005$). We assume that theoretically, it is more likely that a single social actor operates many technical elements and that data transfer rather occurs from one technical element to a few specific social actors than to all. This likely explains the observation in the empirical STN that the density of the operation network is higher than the density of the data transfer network.

With respect to reciprocity, we determine both the reciprocity within the social network $r_S = 0.6$ and the socio-technical reciprocity $r_{st} = 0.005$. The latter is very low due to the minor presence of only seven data transfer edges, i.e., only a few social actors who operate technical elements receive data from them. More advancement in digitalization could result in higher socio-technical reciprocity, where ideally, data from technical elements would be available to those social actors operating them. Further, the social reciprocity $r_S = 0.6$ indicates that some information exchange edges are reciprocated while others remain one-way forms of information "forwarding". This is interesting as social actors have different roles (e.g., municipal administration, engineer, authority) that include organizational hierarchies and, therefore, may also compromise forms of one-way reporting instead of reciprocal information exchange.

Based on the determination of degree centrality[10], the empirical STN study reveals that the municipal council representative 2 of municipality 1 who also has the role of the president of

[10] Besides degree centrality, several different centrality parameters can be applied to evaluate the importance of a network node, for example, betweenness, closeness or eigenvector centrality (Freeman 1978). Here, we base our interpretation on degree

the wastewater association is most degree central[11] in the information exchange network, i.e., exchanges information with most other social actors (degree centrality: 39 edges). We further identify two degree central social actors[12] in terms of operation: the WWTP operator as well as the municipal council representative 2 of municipality 1 (i.e., the president of the wastewater association). These two social actors are degree central in the sense that they are involved in the operation of the highest number of technical elements (in total 38 out of 42 technical elements). This implies that they are critical social actors for the entire operation of the case study UWS. In terms of data transfer, CSO tank 1 is the most degree central technical element, as data is transferred to the maximum number of four social actors.

For the operation network, we counted 754 socio-technical motifs A (socio-technical cycle) and 366 socio-technical motifs D (socio-technical triad). The quantitative assessment is more informative if multiple different empirical STNs are compared, which is out of the scope of this article. However, looking at particular socio-technical motifs within the STN allows for a more qualitative identification of social actors or technical elements that are in fact part of such motifs. For example, most of the appearances of socio-technical motif A in the operation network include the municipal council representative 2 of municipality 1 (i.e., the president of the wastewater association) (part of 150 socio-technical motifs A) and the WWTP operator (part of 125 socio-technical motifs A) (s. Table H.1 in Supplementary Materials H).

By contrast, social actors and technical elements that are not part of such motifs can be determined, which would be useful to detect certain governance gaps or misfits (Angst and Seppelt 2020). Relating to socio-technical motif A in the operation network for example, we identified 453 configurations, where two social actors who operate two connected technical elements do not exchange information. In Table H.1, we determine a ratio of socio-technical motifs A where social actors do not exchange information (i.e., "open socio-technical cycles") to socio-technical motifs where social actors do exchange information (i.e., "closed socio-technical cycles") in the operation network. Based on the ratio values for each social actor, we found that particularly two engineers and three municipal works representatives should exchange information with more social actors. For example, in order to close the socio-technical cycle, the municipal works representative of municipality 4 should exchange information with engineer 3.

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centrality. However, we provide additional results for betweenness, closeness, and eigenvector centrality in the social network in Supplementary Materials G along with information on in- and out-degree centrality.

[11] Here, degree central social actors in the information exchange network are those social actors that show the highest count of in-coming and out-going information exchange edges (social-social relations). Degree central social actors are those who exchange information with most other social actors and many social actors indicated that they exchange information with them (s. also Table A.1 for the differentiation between in-degree (in-coming edges for a node) and out-degree (out-going edges from a node) centralities. Degree centrality is the sum of in- and out-degree centralities for a node.

[12] We base our interpretation of central social actors for the operation of the UWS on degree centrality, while other centrality parameters could be relevant as well (s. also footnote 9 and Supplementary Materials G).

With respect to the social-technical motifs D (socio-technical triads) in the operation network, we identified information exchange gaps between the municipal council representative 1 of municipality 1 and the WWTP operator as well as the municipal works representative of municipality 1. Further, by exchanging information with the WWTP operator as well as the municipal council representative of municipality 2, engineer 5 could bridge important information exchange gaps.

Finally, the determined degrees of digitalization, decentralization, and integrated management demonstrate that the case study UWS can be seen as rather not-socio-technical digital ($d_{digital} = 0.41$), socio-technical centralized ($d_{decentral} = 0.1$), and managed in a fragmented way ($d_{integrated} = 0.24$). The value interval for all three degrees is between 0 and 1, where values close to 1 imply socio-technical digital, socio-technical decentralized, or integrated management (s. also Supplementary Materials C).

5. Discussion

The analysis of the case study UWS demonstrates the applicability of the STN approach to empirical cases and illustrates the use of network concepts such as density, reciprocity, and (degree) centrality. STNs are a useful approach if the findings are valid and accurate. Regarding validity, we have discussed that a STN should be validated depending on the operationalization of network nodes and edges, most easily based on separate validation approaches for different parts of the STN. In this article, two experts confirmed the correct representation of the technical network. The structure of the social information network was validated by comparing the density value to observations in similar studies. Social and technical nodes of the social-technical and technical-social networks were validated as they are part of the social and technical networks. In order to validate edges in the social-technical operation network, we checked whether operation edges between social actors from different municipalities and technical elements associated with these municipalities were present. For example, we tested whether technical elements owned by municipality 1 showed social-technical edges to social actors affiliated with municipality 1. Analogously, we examined all municipalities and found that each municipality was represented and operation edges were present for all technical elements owned by the respective municipality. The technical-social data transfer edges were validated based on information about technical elements that are equipped with a sensor (in total 3 technical elements) and that, therefore, can potentially transfer data. We observed that those technical elements that are equipped with a sensor (i.e., the WWTP, CSO tank 1, and CSO tank 13) transfer data to at least one social actor, validating the technical-social edges.

A further issue related to validation is missing data. Indeed, missing data is an extremely common problem with surveys and can have an influence on the correct representation of the network (Berardo et al. 2020). Yet, in our case, we have an exceptionally high survey response rate of 97 percent, i.e., only one actor did not respond to our survey (a second WWTP operator for the same WWTP).

Two additional strategies could contribute both to the validation of the STN as well as to more in-depth analytical insights. First, the analysis could benefit from quantitative results being combined with more qualitative insights, deriving, namely, from context interviews. For example, the interviewee stated that "most infrastructure elements are not equipped with sensors" and consequently cannot transfer data to social actors. In addition, the interviewee tried to bring social actors together to "sensitize them to an integrated management of the entire urban wastewater system", which suggests that the system is still managed in a fragmented way. A quantitative analysis based on the STN concepts might inform stakeholders about where such fragmentation still exists, and how it might be addressed.

Second, comparing the case study UWS to other empirical STNs could provide benefits in terms of validation as well as additional insights. In terms of validation, we were only able to compare the structure of our networks to other networks from other sectors, but not to UWS networks in other cases. As for additional insights, for example, different network densities in different cases, or different actors that take central roles, might enable us to better grasp why different systems differ in their performance or adaptation capacity.

Our STN analysis has provided accurate findings on the challenges in existing UWS. For example, we identified municipal council representative 2 of municipality 1 (i.e., the president of the wastewater association) and the WWTP operator as central social actors either in terms of information exchange or operation. This finding emphasizes that different social actors play important roles depending on their social and socio-technical relations. Such a finding accurately represents the functioning of Swiss local governance, where public, semi-private, and private actors collaborate and jointly fulfill functions related to the management, development, implementation, and innovation within infrastructure systems. Systematic knowledge about these roles can be crucial to understanding the functioning of an UWS and its capacity for transformation in light of trends such as digitalization, decentralization, or integrated management. Also, in our empirical illustration, we counted 754 configurations of the socio-technical motif A where reciprocal information exchange is present compared to 453 of the same configuration with absent information exchange edges. The latter configuration describes a form of governance gap or socio-technical misfit that could be resolved by supporting the formation of information exchange edges between identified social actors. Again, this finding accurately represents the empirical reality where some actors have long-established and trustful relations, while others lack these relations due to different system understandings (Herzog and Ingold 2019), different policy preferences and values (Metz et al. 2019), or sectoral or administrative boundaries (Fischer and Ingold 2020; Fischer and Sciarini 2016).

Even though UWS have been previously studied from socio-technical system perspectives (de Haan et al. 2013; Jensen et al. 2015; Panebianco and Pahl-Wostl 2006), we have demonstrated that a STN approach reveals relevant insights as interrelated technical elements and social actors are jointly analyzed based on detailed empirical information on each social and technical node, and different edges between these nodes. Compared to system dynamics (Prouty et al. 2020; Whyte et al. 2020) or agent-based modeling (Berglund 2015; Dam et al. 2013; Panebianco and Pahl-Wostl 2006; Williams 2018) approaches, STNs do not capture dynamic changes, but create a conceptual and methodological basis to achieve a deeper understanding of socio-technical infrastructure systems.

First, researchers working with a STN approach could ask questions about central social actors or central technical elements. This could be important for understanding which technical elements are most crucial for integrated management (as they, e.g., connect different parts of the STN), or which social actors could play an important role in pushing towards decentralization or digitalization (Hoolohan et al. 2021; Mergel et al. 2019). A question allowing for a more detailed analytical insight into infrastructure systems would ask whether the STN is highly fragmented, or whether it is well integrated (s. Table C.1). This information again could provide hints on where more efforts towards integrated infrastructure management might be needed.

Second, a STN approach could help to identify social or socio-technical barriers toward digitalization, decentralization, or integrated management of infrastructure systems (Manny et al. 2021). For example, related to digitalization, even though digital technologies are already available, barriers may hinder their adoption if the social system is lagging behind in developing and implementing fitting forms of coordination, cooperation, or collaboration (Guy et al. 2011; Marchant et al. 2013). By coupling social and technical systems, data and information flows between technical elements and social actors can be studied in combination.

Third, in terms of the entire infrastructure performance, the literature has emphasized critical transactions essential for the functioning of infrastructures (Künneke et al. 2010). The successful restructuring of infrastructures requires the capacity to align technical functions and modes of organization. Identifying critical transactions, such as relevant information exchange relations between social actors, could be supported by the idea of socio-technical fit. This would be achieved if important connections at the technical level are aligned with respective connections at the social level, as illustrated with the example of two social actors, who are responsible for two technically connected technical elements and exchange information (s. socio-technical motif A in Table 2).

Finally, infrastructure trends such as digitalization, decentralization, or integrated management require the implementation of policy instruments (Soutar 2021). However, identifying the right policy instruments involves complex decisions. Understanding the relations among social and technical levels at the micro-level of their individual elements, potential opportunities for action may become transparent (Prager and Pfeifer 2015). A STN approach might thus help to identify fitting policy instruments by specifying how these act on different related technical and social elements, such as e.g., actor coordination, in infrastructure systems. These policy instruments are also needed to address challenges affecting infrastructure systems such as demographic change, rapidly growing urban areas, and climate change mitigation.

6. Conclusions

Socio-technical networks of networked infrastructure systems, as presented in this article, are of theoretical, conceptual, empirical, and practical relevance. First, STNs combine insights from several theoretical strands within social sciences as well as interdisciplinary literature on infrastructure management and beyond. More specifically, studies on digitalization (Barns et al. 2017; Zimmerman and Horan 2004), decentralization (R. Bird 1994; Levaggi et al. 2018; Libralato et al. 2012), integrated management (Halfawy 2008; Roelich et al. 2015; Saidi et al. 2018), among others, will benefit from this approach as it provides them with a systematic and formalized tool for analysis. Based on this tool, answers to important questions about socio-technical fit within infrastructure systems, or around central social actors or technical elements, as discussed above, can be explored. Second, STNs are of conceptual relevance as we propose a structurally explicit operationalization of the concept of STN in the context of infrastructure systems. The concept is not new to the literature (Elzen et al. 1996), but the actual network has mostly been dealt with implicitly, without operationalizing each network node and edge (Kluger et al. 2020; Scott and Ulibarri 2019). Third, STNs are of empirical relevance as they allow for a detailed analysis of the functioning of specific infrastructure systems, as well as propositions on how to adapt those systems and induce transformations in order to adapt to challenging and dynamic contexts, for example, related to digitalization, decentralization, or integrated management. Fourth, STNs have a high potential for practical relevance. Not only does stakeholder knowledge provide crucial information for assessing the different nodes and edges, but the resulting networks could be used as a tool for discussion with stakeholders. For example, discussions could focus on whether they perceive the interdependencies similar to those represented in the STN, or whether STNs allow stakeholders to identify potential governance gaps or misfits (Angst and Seppelt 2020). A STN of infrastructure systems is thus also a potential tool to be used in stakeholder interactions and could be beneficial in instances of science-policy exchange (Cvitanovic et al. 2016).

The STN approach as presented in this article relies on a few assumptions that, if modified, would change the structure of the network as well as findings. First, we assume that any ecological and natural elements of the environment are not part of the STN. Indeed, including these elements would increase the network complexity. However, in future studies, the environment could be included within an even more holistic "social-ecological-technological network", as infrastructures have been considered as social, ecological, and technological systems (Markolf et al. 2018). Such an extended approach could be useful for explicitly addressing innovative concepts such as blue-green infrastructure (Dai et al. 2021; Donati et al. 2022; Thorne et al. 2018) and nature-based solutions (Cohen-Shacham et al. 2016). Second, we assume that only social actors are part of the social side of the social-technical systems, but we disregard important other social elements such as institutions or forums (Fischer and Leifeld 2015) that could support the coordination among actors, or ideas and discursive elements (Heiberg et al. 2022). In addition, our operationalization relies on a single representation of social-social relations in the form of information exchange, however, other types of relations, such as collaboration (Angst et al. 2018) or financial transactions (Pan et al. 2020) could be included as well. Taking these elements and relations into account could provide additional insights into how coordination within a STN works, and provide different results with respect to central actors. Third, we assume that our conceptualization of a STN as a "snapshot" view of data gathered at one point in time indicates a realistic representation of a socio-technical system that in reality is dynamic, with different elements of the network dynamically changing and adapting over time. Such a dynamic network evolution can be studied by comparing consecutive STN at different points in time, but data gathering and analysis would again add complexity to such an endeavor.

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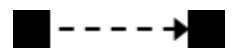
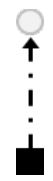
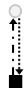
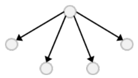
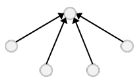
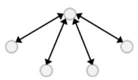
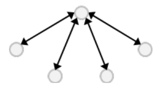
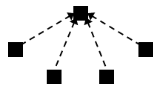
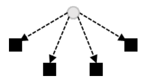
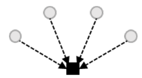
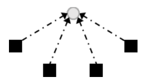
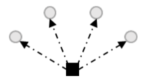
Supplementary Materials

A Density, reciprocity, and centrality in STNs of infrastructure systems

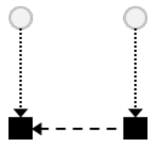
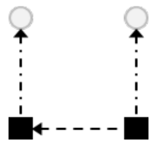
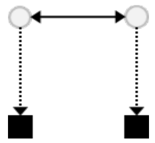
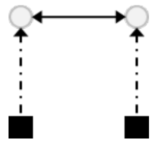
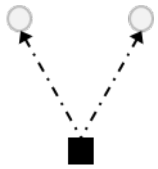
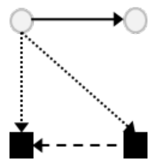
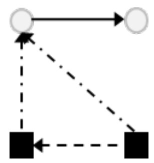
***Table A.1**: Comparison of density, reciprocity, and centrality concepts and proposed extension of these concepts to socio-technical network analysis*

Network analysis			**Socio-technical network analysis**		
Concept	**Representation**	**Equation**	**Concept**	**Representation**	**Equation**
Density	 	Directed network: $d = \frac{\lvert E\rvert}{\lvert V\rvert\cdot(\lvert V\rvert-1)}$ Undirected network: $d = \frac{\lvert E\rvert}{\frac{1}{2}\lvert V\rvert\cdot(\lvert V\rvert-1)}$	Social network density		Directed network: $d_S = \frac{\lvert E_S\rvert}{\lvert V_S\rvert\cdot(\lvert V_S\rvert-1)}$
			Technical network density		Directed network, but only one-way directions: $d_T = \frac{\lvert E_T\rvert}{\frac{1}{2}\lvert V_T\rvert\cdot(\lvert V_T\rvert-1)}$
			Social-technical network density		$d_{ST} = \frac{\lvert E_{ST}\rvert}{\lvert V_S\rvert\cdot\lvert V_T\rvert}$
			Technical-social network density		$d_{TS} = \frac{\lvert E_{TS}\rvert}{\lvert V_T\rvert\cdot\lvert V_S\rvert}$
Reciprocity		$r = \frac{\lvert E \leftrightarrow\rvert}{\lvert E\rvert}$	Social network reciprocity		$r_S = \frac{\lvert E_S \leftrightarrow\rvert}{\lvert E_S\rvert}$
			Socio-technical reciprocity		$r_{st} = \frac{\lvert E_{ST} \leftrightarrow E_{TS}\rvert}{\lvert E_{ST}\rvert + \lvert E_{TS}\rvert}$
Degree centrality	 Out-degree centrality  In-degree centrality  Degree centrality	$C^S_{D+}(s_i) = \sum_{s_j \in V_S} e_{s_i,s_j}$ $C^S_{D-}(s_i) = \sum_{s_j \in V_S} e_{s_j,s_i}$ $C^S_D(s_i) = C^S_{D+}(s_i) + C^S_{D-}(s_i) = \sum_{s_j \in V_S} e_{s_i,s_j} + e_{s_j,s_i}$	Degree centrality in social network • Central social actor		$C^S_D(s_i) = C^S_{D+}(s_i) + C^S_{D-}(s_i) = \sum_{s_j \in V_S} e_{s_i,s_j} + e_{s_j,s_i}$
			Degree centrality in technical network • Central technical element		$C^T_D(t_j) = C^T_{D-}(t_j) = \sum_{t_j \in V_T} e_{t_i,t_j}$
			Degree centrality in social-technical network • Central social actor • Central technical element	 	$C^{ST}_{D+}(s_i) = \sum_{t_j \in V_T} e_{s_i,t_j}$ $C^{ST}_{D-}(t_i) = \sum_{s_j \in V_T} e_{s_j,t_i}$
			Degree centrality in technical-social network • Central social actor • Central technical element	 	$C^{TS}_{D-}(s_i) = \sum_{t_j \in V_T} e_{t_j,s_i}$ $C^{TS}_{D+}(t_i) = \sum_{s_j \in V_T} e_{t_i,s_j}$

Note: Circles denote social actors and squares denote technical elements. Lines denote social-social relations, technical-technical relations, social-technical relations and technical-social relations.
$|V_S|$ refers to the cardinality of a set, here the set of social actors, and defines the number of elements in the respective set, i.e., here the number of social actors within the socio-technical network.
e_{s_i,s_j} refers to the adjacency matrix entries of the network G_S which can either be 1 (if an edge is present between s_i and s_j) or 0 (if an edge is absent). The adjacency matrix entries e_{t_i,t_j}, e_{s_i,t_j} and e_{t_i,s_j} are defined analogously.

B Socio-technical motifs

***Table B.1**: Further examples of socio-technical motifs within socio-technical networks*

Motif	Motif description	Motif representations		Socio-technical interpretation
		Cross-level edges represent **social-technical relations** (e.g., operation/ownership)	Cross-level edges represent **technical-social relations** (e.g., data transfer)	
E	Socio-technical based affiliation			Tendency of social actors to be related to technical elements which are connected at the technical level
F	Affiliation based reciprocal exchange at the social level			Tendency of social actors to interact with reciprocating social actors who are related to technical elements (which are **not** connected at the technical level)
G	Affiliation based 2-paths			Tendency of social actors to be related to the same technical element
H	Socio-technical affiliation based out-degree assortativity at the social level			Tendency of social actors to be related to two or more technical elements which are connected at the technical level and to additionally interact with social actors at the social level

Note: Circles denote social actors and squares denote technical elements. Lines denote social-social relations, technical-technical relations, social-technical relations and technical-social relations.

C Socio-technical degrees of digitalization, decentralization, and integrated management

In the following, the concepts of socio-technical degree of digitalization, decentralization, and integrated management of infrastructure systems as presented in Table C.1 are described using more detailed explanations.

Socio-technical degree of digitalization

From the node set of technical elements V_T, we define a subset V_{TS} that contains those technical elements which transfer data to social actors, i.e., technical elements that have an out-going data transfer edge (in E_{TS}). The definition of V_{TS} is based on the out-degree centrality of technical nodes in the technical-social network (s. Table C.1). If a technical element has a data transfer edge toward a social actor, its out-degree centrality is larger than 0. Therefore, the set V_{TS} is defined as:

$$V_{TS} = \left\{t_i \in V_T \mid C_{D+}^{TS}(t_i) > 0\right\} \subset V_T \tag{1}$$

Considering V_{TS}, we define the **socio-technical degree of digitalization**:

$$d_{digital} = \frac{|V_{TS}|}{|V_T^*|} \tag{2}$$

$d_{digital}$ is normalized to the number of technical elements in the STN that potentially can transfer data, i.e., are equipable with a sensor for example. This subset of all technical elements is expressed as V_T^*. The normalization allows for a comparison of larger and smaller infrastructure systems.

The socio-technical degree of digitalization reflects how many technical elements transfer data to social actors. The number of data transfer edges ($|E_{TS}|$) is not considered. Further, the degree does not determine if technical elements transfer the data to one single social actor or to many different social actors. However, these two aspects could be incorporated into equation (2) by including the technical-social (degree) centrality of each technical element ($C_{D+}^{TS}(t_i)$) and by weighting certain data transfer edges (in E_{TS}) more than others.

$d_{digital}$ takes values between 0 and 1, where 0 is *not socio-technical digitalized* and 1 is *socio-technical digitalized*. If $d_{digital} = 1$, all technical elements transfer data to social actors.

Socio-technical degree of decentralization

Analogous to the node subset V_{TS}, we define a subset V_{ST} that contains those social actors who are responsible for technical elements, i.e., social actors that have an out-going social-technical edge (in E_{ST}). The definition of V_{ST} is based on the (degree) centrality of social nodes in the social-technical network (s. Table C.1). If a social actor has a social-technical edge to a technical element, its (degree) centrality is larger than 0. Therefore, the set V_{ST} is defined as:

$$V_{ST} = \left\{s_j \in V_S \mid C_{D+}^{ST}(s_j) > 0\right\} \subset V_S \tag{3}$$

Considering V_{TS}, we define the **socio-technical degree of decentralization:**

$$d_{decentral} = \frac{|V_{ST}|}{|E_{ST}|} \tag{4}$$

$d_{decentral}$ is normalized to the number of social-technical edges ($|E_{ST}|$), so larger and smaller infrastructure systems are comparable.

The socio-technical degree of decentralization reflects whether social-technical edges distribute over one or few social actors (centralized) or over many social actors (decentralized). $d_{decentral}$ takes values between 0 and 1. For $|E_{ST}| \gg |V_{ST}|$, $d_{decentral} \approx 0$ or close to 0 is *socio-technical centralized* and $d_{decentral} \approx 1$ or close to 1 is *socio-technical decentralized*.

Socio-technical degree of integrated management

While $d_{digital}$ and $d_{decentral}$ rely on the number of either nodes or edges, the socio-technical degree of integrated management considers a combination of multiple nodes and edges that we label "socio-technical motifs" (s. Table 2). We differentiate between two (extreme) situations: first, a STN with integrated management and second, a STN with fragmented management. We assume that in the case of integrated management, reciprocated social-social relations between social actors (e.g., information exchange) is present where social actors are related to technical elements which are connected at the technical level. This corresponds to socio-technical motif A ("socio-technical alignment with reciprocated social relation") which we also refer to as "socio-technical cycle" (s. Table 2). In the STN of fragmented management, the reciprocated social-social relations are absent where social actors are related to interconnected technical elements. Given this differentiation, we define a set M_A that contains all socio-technical motifs A observed in a STN:

$$M_A = \sum_{s,\tilde{s} \in V_S} \sum_{t,\tilde{t} \in V_T} e_{s,t} \cdot e_{t,\tilde{t}} \cdot e_{\tilde{t},\tilde{s}} \cdot e_{\tilde{s},s} \cdot e_{s,\tilde{s}} \tag{5}$$

Taking M_A into account, we define the **socio-technical degree of integrated management** as:

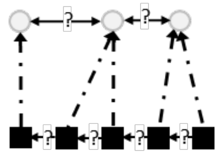
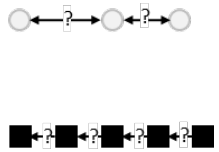
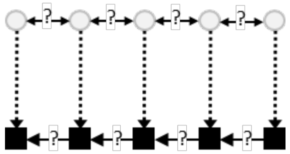
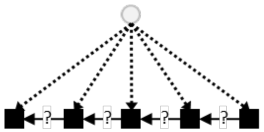
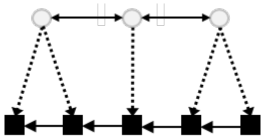
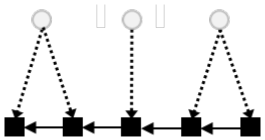
$$d_{integrated} = \frac{M_A}{|E_S^* \leftrightarrow| \cdot |E_T|} \tag{6}$$

$d_{integrated}$ is normalized to the product of two edge sets $|E_S^* \leftrightarrow|$ and $|E_T|$, so larger and smaller infrastructure systems are comparable. $|E_S^* \leftrightarrow|$ represents the number of reciprocated social-social relations for only the nodes in V_{ST}, i.e., social actors that are responsible for the operation of technical elements (s. definition (3)). $|E_T|$ comprises the sum of (undirected) technical-technical relations.

The socio-technical degree of integrated management reflects whether social actors are related, through e.g., information exchange, if they are responsible for technical elements which are connected themselves.

$d_{integrated}$ takes values between 0 and 1, where $d_{integrated} \approx 0$ is *socio-technical fragmented* and $d_{integrated} \approx 1$ is *socio-technical integrated*.

Table C.1: *Socio-technical network configurations related to the trends of digitalization, decentralization, and integrated management*

Trend	Literature	Examplary representation	Socio-technical interpretation	Socio-technical network concept
Digitalization	Barns et al. (2017); Zimmerman and Horan (2004)		**Socio-technical digital** Social actors have access to data from many technical elements which may or may not be connected at the technical level. Social-social relations may be present or absent.	**Socio-technical degree of digitalization** $$d_{digital} = \frac{\lvert V_{TS}\rvert}{\lvert V_T^*\rvert}$$ with $V_{TS} = \{t_i \in V_T \mid C_{D+}^{TS}(t_i) > 0\} \subset V_T$ and V_T^* are technical elements that are able to transfer data (i.e., are potentially equipable with a sensor for example) $d_{digital} \approx 0$, not socio-technical digital, i.e., no data transfer $d_{digital} \approx 1$, socio-technical digital
			**Not socio-technical digital** None or few social actors have access to data from few technical elements which may or may not be connected at the technical level.	
Decentralization	R. Bird (1994); Levaggi et al. (2018); Libralato et al. (2012)		**Socio-technical decentralized** Many social actors operate many technical elements which may or may not be connected at the technical level. Social-social relations may be present or absent.	**Socio-technical degree of decentralization** $$d_{decentral} = \frac{\lvert V_{ST}\rvert}{\lvert E_{ST}\rvert}$$ with $V_{ST} = \{s_j \in V_S \mid C_{D+}^{ST}(s_j) > 0\} \subset V_S$ and V_{ST} are social actors that operate technical elements For $\lvert E_{ST}\rvert \gg \lvert V_{ST}\rvert$: $d_{decentral} \approx 0$, socio-technical centralized $d_{decentral} \approx 1$, socio-technical decentralized
			**Socio-technical centralized** One or few social actors operate many technical elements which may or may not be connected at the technical level.	
Integrated management	Halfawy (2008); Roelich et al. (2015); Saidi et al. (2018)		**Integrated management** Social-social relations are present where social actors are related to technical elements which are connected at the technical level.	**Socio-technical degree of integrated management** $$d_{integrated} = \frac{M_A}{\lvert E_S^* \leftrightarrow\rvert \cdot \lvert E_T\rvert}$$ with $M_A = \sum_{s,\tilde{s} \in V_S} \sum_{t,\tilde{t} \in V_T} e_{s,t} \cdot e_{t,\tilde{t}} \cdot e_{\tilde{t},\tilde{s}} \cdot e_{\tilde{s},s} \cdot e_{s,\tilde{s}}$ M_A: number of observed socio-technical motifs A $\lvert E_S^* \leftrightarrow\rvert$: number of reciprocated social-social relations for nodes in V_{ST} only $d_{integrated} \approx 0$, fragmented management $d_{integrated} \approx 1$, integrated management
			**Fragmented management** Social-social relations are absent where social actors are related to technical elements which are connected at the technical level.	

D Survey questionnaire

Table D.1*: Excerpt of the survey questionnaire that includes questions and answers which provide the STN data (s. Supplementary Materials E).*

	Name	Question	Answers
V_S	Type of responsibility	To which area of responsibility can your current job be assigned?	- Municipal council - Municipal administration - Municipal works - WWTP operator - Commission (e.g., operational, (civil) engineering, planning) - Inter-municipal/regional association - Engineering office/planning office - Other
V_S	Organization	Please assign your area of responsibility to the respective municipality in the catchment area.	- List of names of municipalities
E_S	Information exchange	With whom have you exchanged information in the past 2 years that relates to wastewater treatment, urban drainage, and/or water pollution control in the catchment area? *Examples of how and where information exchange can happen: You receive an email or phone call about the WWTP (e.g. operations or planning) or the sewer system (e.g. operations or planning). You are informed at a meeting where decisions are being made about the WWTP or drainage system in the catchment area. You attend an event or symposium. You receive or send an annual operational report.*	- List of names of all social actors involved in managing the UWS
V_S	Active in operation	Are you involved in the operation of technical elements of the urban wastewater system in the catchment area?	- Yes - No
E_{ST}	Operation	Which technical elements of the urban wastewater system do you operate? (Diagram of the urban wastewater system, such as a flow chart, for example) *By operation we mean a wide range of tasks, such as strategic decisions on operation, but also very practical activities such as visual or functional inspections, cleaning, and maintenance of technical elements or analysis of operational data.*	- List of all technical elements (here: WWTP, CSO tanks, CSOs, pumping stations – as shown in the diagram)
V_T	Sensors	Which technical elements of the urban wastewater system are equipped with sensors/digital technologies?	- List of all technical elements
E_{TS}	Data transfer	From which of the following technical elements of the urban wastewater system do you receive or can you access (monitoring) data?	- List of all technical elements

Note: We do not show the flowchart of the UWS or provide the list of technical elements and social actors here in order to maintain confidentiality.

E Socio-technical network data of the empirical case study UWS

***Table E.1**: Data on the technical and social nodes of the case study STN*

	Technical element V_T	Organization (in terms of ownership)	V_T^*
1	WWTP	Wastewater association	1
2	CSO_T_1	Wastewater association	1
3	CSO_T_2	Municipality 1	1
4	CSO_1	Municipality 1	0
5	CSO_2	Municipality 1	0
6	CSO_3	Municipality 1	0
7	CSO_4	Municipality 1	0
8	CSO_5	Municipality 1	0
9	CSO_6	Municipality 1	0
10	CSO_7	Municipality 1	0
11	CSO_8	Municipality 1	0
12	CSO_9	Municipality 1	0
13	CSO_T_3	Municipality 2	1
14	CSO_T_4	Municipality 2	1
15	CSO_10	Municipality 2	0
16	P_1	Municipality 2	1
17	P_2	Municipality 2	1
18	P_3	Municipality 2	1
19	P_4	Municipality 2	1
20	P_5	Municipality 2	1
21	CSO_11	Municipality 3	0
22	CSO_12	Municipality 3	0
23	CSO_13	Municipality 3	0
24	CSO_14	Municipality 3	0
25	CSO_T_5	Municipality 4	1
26	CSO_T_6	Municipality 4	1
27	CSO_T_7	Municipality 4	1
28	CSO_T_8	Municipality 4	1
29	CSO_T_9	Municipality 4	1
30	CSO_T_10	Municipality 4	1
31	P_6	Municipality 4	1
32	CSO_T_11	Municipality 5	1
33	CSO_15	Municipality 5	0
34	CSO_16	Municipality 5	0
35	CSO_17	Municipality 5	0
36	CSO_18	Municipality 5	0
37	CSO_19	Municipality 5	0
38	CSO_20	Municipality 5	0
39	CSO_T_12	Municipality 6	1
40	CSO_T_13	Municipality 6	1
41	P_7	Municipality 6	1
42	P_8	Municipality 6	1
			22

	Social actor V_S	Organization	V_{ST}
1	engineer_1	Engineering office	1
2	engineer_2	Engineering office	0
3	MUN_1_council_1	Municipality 1	1
4	engineer_3	Engineering office	1
5	MUN_2_admin	Municipality 2	1
6	MUN_6_works	Municipality 6	1
7	engineer_4	Engineering office	1
8	engineer_5	Engineering office	1
9	MUN_1_council_2$^+$	Municipality 1	1
10	MUN_5_admin	Municipality 5	1
11	MUN_2_works	Municipality 2	1
12	MUN_1_admin	Municipality 1	1
13	MUN_3_admin	Municipality 3	0
14	MUN_4_admin	Municipality 4	1
15	MUN_4_works	Municipality 4	1
16	engineer_6	Engineering office	1
17	MUN_3_council	Municipality 3	1
18	MUN_1_council_3	Municipality 1	0
19	MUN_1_works	Municipality 1	1
20	engineer_7	Engineering office	1
21	MUN_5_council	Municipality 5	1
22	MUN_5_works	Municipality 5	1
23	MUN_2_council	Municipality 2	1
24	MUN_6_council	Municipality 6	1
25	WWTP_operator	Wastewater association	1
26	MUN_6_admin	Municipality 6	1
27	MUN_4_council	Municipality 4	1
28	engineer_8	Engineering office	0
29	MUN_3_works	Municipality 3	0
30	authority_WWT	Authority	0
31	authority_UWM	Authority	0
			24

V_T^* represents the technical elements that are equipable with digital technologies and therefore can transfer data (1 in column, in total 22 out of 42 technical elements).

V_{ST} contains social actors that classified themselves as responsible for the operation of technical elements (1 in column, in total 24 out of 31 social actors).

$^+$ MUN_1_council_2 also has the role of the president of the wastewater association.

Data on social-social, technical-technical, social-technical, and technical-social edges of the STN can be obtained from additional files. R scripts and raw data used to produce the results are available here: https://doi.org/10.25678/0006HR.

F Data collection and analysis for STNs of infrastructure systems

Similar to social networks, boundaries need to be defined for the empirical scope of STNs (Wasserman and Faust 1994). Boundaries for STNs can be set based on selecting specific case studies of interest. We suggest to determine network boundaries by restricting the study area to the extent of a closed technical infrastructure system unit, i.e., all technical elements being connected to at least one other technical element. Within the boundaries of the technical infrastructure system unit, all social actors who are directly (e.g., through ownership, operation, data transfer) or indirectly (through the social network) related to the infrastructure need to be identified and included to obtain STN data.

The analysis of STNs requires data at multiple levels if hypotheses span social, technical and socio-technical dimensions. Besides node-level data on technical elements and social actors, data on social-social (e.g., information exchange, collaboration), technical-technical (e.g., technical connection, performance dependency), social-technical (e.g., ownership, operation) and technical-social (e.g., data transfer) relations needs to be obtained. We give concrete examples of potential relations, but these may vary depending on research questions, contexts and infrastructure systems or social actors (e.g., individuals, organizations).

Data collection is best split into several sequential steps. The following four steps can be seen as an exemplary procedure, but should be adjusted to the context of the case. First, a review of available documents and grey literature helps to get an impression of the case study area. Second, semi-structured context interviews with key social actors in the case study area serve for mapping the technical network and for identifying all relevant social actors. Third, it is useful to visualize technical networks of the respective infrastructure system before designing a survey to all relevant social actors. Fourth, the survey needs to include questions on how social actors relate to technical elements and how they interact with other social actors.

STN data can be used for different scientific purposes that range from descriptive to inferential analysis. For network visualization, and particularly for multi-level network visualization, several software tools exist already (e.g., motifr in R (Angst and Seppelt 2020), MuxViz in R (De Domenico et al. 2014), graphlayouts in R (Schoch 2020), or Pymnet in Python (Kivelä et al. 2014)). Some software tools come with programmed commands to run simple descriptive analyses (e.g., density, degree distribution) as well.

Inferential analysis of STNs can be conducted by using statistical network models such as exponential family random graph models (ERGM; Robins et al. (2007)). Combined with a valid causal model, estimating ERGMs allows for statistical inference for STNs, and thus, evaluating influence of node, edge, and network characteristics on the formation of particular edges. Therefore, hypotheses on the network can be tested, such as for example, what influences the formation of particular STN edges.

G In-degree and out-degree centrality as well as additional centrality parameters

In the STN analysis, we use degree centrality (s. also Table A.1) to assess the importance of a node in a network. Table G.1 specifies differences between in-degree and out-degree centrality for each social actor in the social information exchange network within the empirical STN.

Table G.1: *In-degree, out-degree and overall degree centrality for each social actor in the social information exchange network of the empirical STN*

	Social actor V_S	In-degree centrality	Out-degree centrality	Degree centrality
1	engineer_1	15	15	30
2	engineer_2	5	5	10
3	MUN_1_council_1	9	11	20
4	engineer_3	4	4	8
5	MUN_2_admin	7	8	15
6	MUN_6_works	5	3	8
7	engineer_4	14	14	28
8	engineer_5	10	10	20
9	**MUN_1_council_2⁺**	**21**	18	**39**
10	MUN_5_admin	6	6	12
11	MUN_2_works	5	3	8
12	MUN_1_admin	11	10	21
13	MUN_3_admin	4	7	11
14	MUN_4_admin	7	5	12
15	MUN_4_works	2	2	4
16	engineer_6	11	14	25
17	MUN_3_council	14	18	32
18	MUN_1_council_3	10	4	14
19	MUN_1_works	7	6	13
20	engineer_7	15	9	24
21	MUN_5_council	14	17	31
22	MUN_5_works	3	4	7
23	MUN_2_council	11	5	16
24	**MUN_6_council**	10	**21**	31
25	WWTP_operator	18	14	32
26	MUN_6_admin	4	8	12
27	MUN_4_council	11	10	21
28	engineer_8	4	1	5
29	MUN_3_works	4	2	6
30	authority_WWT	10	12	22
31	authority_UWM	14	19	33

Note: Maximum values (most in-degree, out-degree, and degree central nodes) marked bold.

⁺ MUN_1_council_2 also has the role of the president of the wastewater association.

Besides degree centrality, there are further centrality parameters that can be determined additionally, such as betweenness centrality, closeness centrality, or eigenvector centrality (Freeman 1978).

Table G.2 provides an overview of all four centrality parameters for each social actor that is part of the social network within the STN.

We do not calculate betweenness, closeness and eigenvector centrality for the technical network as well as for both the social-technical and technical-social networks, as these centrality parameters are either not meaningful or cannot be easily determined for disconnected graphs (i.e. for the technical network with only very few edges) or bipartite graphs (i.e. for the social-technical and technical-social networks).

Table G.2: *Four centrality parameters (degree, betweenness, closeness and eigenvector centrality) for each social actor of the social information exchange network in the STN*

	Social actor V_S	**Degree centrality**	**Betweenness centrality**	**Closeness centrality**	**Eigenvector centrality**
1	engineer_1	30	69.70	0.022	0.72
2	engineer_2	10	3.33	0.016	0.24
3	MUN_1_council_1	20	5.94	0.020	0.62
4	engineer_3	8	5.79	0.018	0.18
5	MUN_2_admin	15	19.72	0.019	0.32
6	MUN_6_works	8	1.46	0.016	0.16
7	engineer_4	28	22.52	0.022	0.84
8	engineer_5	20	74.85	0.019	0.34
9	**MUN_1_council_2⁺**	**39**	**90.43**	0.024	**1.00**
10	MUN_5_admin	12	2.25	0.016	0.35
11	MUN_2_works	8	2.17	0.015	0.18
12	MUN_1_admin	21	8.96	0.019	0.63
13	MUN_3_admin	11	7.33	0.018	0.23
14	MUN_4_admin	12	15.00	0.016	0.27
15	MUN_4_works	4	0.0	0.013	0.08
16	engineer_6	25	12.77	0.022	0.74
17	MUN_3_council	32	75.95	0.024	0.83
18	MUN_1_council_3	14	1.59	0.016	0.42
19	MUN_1_works	13	1.02	0.016	0.40
20	engineer_7	24	21.43	0.019	0.65
21	MUN_5_council	31	47.81	0.023	0.86
22	MUN_5_works	7	0.0	0.016	0.19
23	MUN_2_council	16	9.26	0.016	0.45
24	**MUN_6_council**	31	71.97	**0.026**	0.77
25	WWTP_operator	32	71.39	0.022	0.87
26	MUN_6_admin	12	12.18	0.019	0.22
27	MUN_4_council	21	35.01	0.020	0.63
28	engineer_8	5	0.14	0.012	0.10
29	MUN_3_works	6	1.57	0.015	0.14
30	authority_WWT	22	3.41	0.021	0.71
31	authority_UWM	33	87.05	0.024	0.76

Note: Maximum centrality values and respective social actors marked bold.

⁺ MUN_1_council_2 also has the role of the president of the wastewater association.

H Open and closed socio-technical cycles related to socio-technical motif A in the operation network

Table H.1: Social actors that are part of closed and open socio-technical cycles and ratio of open to closed socio-technical cycles for each social actor. Closed socio-technical cycles, i.e., socio-technical motifs A show information exchange edges between two social nodes. In open socio-technical cycles, information exchange edges are absent between two social nodes. Here, we refer to the social-technical operation network for representing the cross-level relations in the socio-technical cycles.

	Social actor V_S	**Part of N closed socio-technical cycles**	**Part of M open socio-technical cycles**	**Ratio open/closed socio-technical cycles**
1	engineer_1	92	13	0.14
2	engineer_2	0	0	-
3	**MUN_1_council_1**	**13**	**43**	**3.31**
4	**engineer_3**	**6**	**25**	**4.17**
5	MUN_2_admin	26	16	0.62
6	**MUN_6_works**	**6**	**14**	**2.33**
7	engineer_4	10	0	0
8	**engineer_5**	**15**	**41**	**2.73**
9	MUN_1_council_2+	150	30	0.20
10	MUN_5_admin	23	17	0.74
11	**MUN_2_works**	**10**	**22**	**2.20**
12	MUN_1_admin	42	9	0.21
13	MUN_3_admin	0	0	-
14	**MUN_4_admin**	**12**	**25**	**2.08**
15	**MUN_4_works**	**6**	**31**	**5.17**
16	engineer_6	11	3	0.27
17	MUN_3_council	9	2	0.22
18	MUN_1_council_3	0	0	-
19	MUN_1_works	39	17	0.44
20	engineer_7	22	7	0.32
21	MUN_5_council	50	13	0.26
22	MUN_5_works	19	21	1.11
23	MUN_2_council	22	12	0.55
24	MUN_6_council	14	9	0.64
25	WWTP_operator	125	57	0.46
26	MUN_6_admin	9	14	1.56
27	MUN_4_council	23	12	0.52
28	engineer_8	0	0	-
29	MUN_3_works	0	0	-
30	authority_WWT	0	0	-
31	authority_UWM	0	0	-

Note: High ratio values imply that respective social actors (in bold) do not exchange information where however information exchange would be necessary to close a socio-technical cycle.

+ MUN_1_council_2 also has the role of the president of the wastewater association.

Table H.1 shows that social actors with the highest ratio values of open to closed socio-technical cycles are: municipal works representative of municipality 4 (MUN_4_works), engineer

3, municipal council representative 1 of municipality 1 (MUN_1_council_1), engineer 5, municipal works representative of municipality 6 (MUN_6_works), municipal works representative of municipality 2 (MUN_2_works), municipal administration representative of municipality 4 (MUN_4_admin). These social actors show ratio values above 2, indicating that they are part of more than twice as many open socio-technical cycles compared to closed socio-technical cycles. Looking at the different roles of these social actors, we can conclude that mostly important information exchange edges to and from engineers (identified twice) and municipal works representatives (identified three times) are missing. We can therefore conclude that information exchange to and from these social actors should be established or improved in order to facilitate a more integrated urban wastewater management.

4. Publication 3

Socio-technical challenges towards data-driven and integrated urban water management: a socio-technical network perspective

Sustainable Cities and Society

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Abstract

Climate change and urbanization affect urban water systems, whereby one solution is recognized in data-driven and integrated urban water management. Relying on monitoring data from urban water system elements, a catchment-wide real-time control could help reduce impacts on surface waters. However, data-driven and integrated management also depends on information exchange among many social actors, e.g., operators, engineers, and authorities. In this article, I draw on the approach of socio-technical networks to study social actors and technical elements in urban water systems as well as multiple relations in-between. My hypotheses revolve around the question: How do socio-technical dependencies influence social interactions, such as information exchange among social actors? Further, achieving data-driven and integrated urban water management requires overcoming socio-technical challenges, such as organizational fragmentation, access to data, or diverging perceptions. Based on empirical data from three case study urban water systems in Switzerland, I provide inferential results obtained from fitting exponential random graph models. Findings show that information exchange among social actors is affected by their relation to technical elements. Influences of socio-technical challenges vary among cases, and are potentially contingent upon system size, related socio-technical complexities, forms of organization, or the progress in terms of data-driven and integrated management.

Keywords: Socio-technical networks, urban water management, data-driven, network analysis, ERGM

1. Introduction

Climate change and urbanization affect how urban water systems (UWS) are managed (McDonald et al. 2014; Miller and Hutchins 2017). For example, more frequent and extreme rainfalls challenge existing capacities of UWS, resulting in overflows into surface waters and thus contributing to water pollution (Yazdanfar and Sharma 2015). Such overflow events are further amplified as growing urban areas lead to higher shares in impermeable surface accumulating more rainfall discharges (Salerno et al. 2018).

One potential solution to monitor and reduce overflow events and thus to reduce unnecessary surface water pollution is recognized in data-driven urban water management (UWM), which relies on the utilization of real-time monitoring data on the performance of UWS elements, such as wastewater treatment plants (WWTPs), combined sewer overflows (CSOs), or pumping stations, among others (Yuan et al. 2019; Oberascher et al. 2022). Ultimately, such monitoring data allows for a real-time control of these elements with the objective of exploiting all existing operational capacities to reduce environmental impacts (Blumensaat et al. 2019; Ingildsen and Olsson 2016; Kerkez et al. 2016).

Where centralized UWS prevail, more and more practitioners install sensors in UWS elements as well as technologies enabling data transfer and processing (Kerkez et al. 2016; Sarni et al. 2019). In practice, however, the real-time control and integrated management of UWS is only slowly implemented and where sensor technologies are installed, real-time monitoring data is often not optimally used (Oberascher et al. 2022; Sarni et al. 2019; Manny et al. 2018). To some extent, this observation is grounded on technical reasons, such as a deficiency in monitoring data quality or incompatible data formats (Eggimann et al. 2017; Langeveld et al. 2013).

Real-time control of UWS elements, however, requires not only an integrated management of these elements from a technical point of view but also needs aligning forms of coordination and information exchange between multiple social actors in a catchment area. Simply put: if UWS elements should be technically coordinated across a catchment area to ensure real-time control, social actors operating, planning, or generally, managing these elements need to coordinate in accordance. This idea of a 'socio-technical fit' (Manny et al. 2022; Smith 2020) implies that technical and social systems should align in order to achieve successful, efficient, and sustainable outcomes, in this case for UWS.

However, besides the idea of socio-technical fit, potential socio-technical challenges may play an important and non-negligible role when it comes to establishing data-driven and integrated management of UWS (Fletcher and Deletic 2007; Manny et al. 2021; Yuan et al. 2019). If, for example, social actors from different organizational entities who manage different parts of the UWS (e.g. several operators, engineers, and authorities) do not exchange information within a catchment area, it might be rather difficult to achieve integrated management of UWS elements.

In this article, I adopt a socio-technical perspective on urban water systems and their management to answer the following research question: *How do socio-technical dependencies influence social interactions, such as information exchange among social actors?*

Related hypotheses are divided in two parts, although they uniformly concentrate on *information exchange* as the dependent variable. First, at a theoretical level, I argue that social interactions, such as information exchange between social actors in the context of managing an infrastructure system, not only depend on social factors alone, but are potentially affected by underlying socio-technical dependencies. However, data-driven and integrated UWM, relying on information exchange among social actors, may be impeded by socio-technical challenges, such as organizational fragmentation (Ighodaro et al. 2017; Kim et al. 2015; Lienert et al. 2013), access to data (Fusi 2020; Araya and Vasquez 2022; Reisi et al. 2020), or diverging perceptions (Cousins 2017; Pahl-Wostl 2007; Hommes et al. 2008). Second, this article therefore analyzes three specific hypotheses related to these challenges.

More concretely, the focus lies on social actors, i.e., individual stakeholders and organizations, who are involved in UWM, as well as technical elements of UWS, e.g., WWTPs, CSOs, and pumping stations. In order to analyze both social actors and technical elements as well as multiple relations in-between, I draw on the approach of socio-technical networks (STNs) (Elzen et al. 1996; Eisenberg et al. 2017; Weerasinghe et al. 2021).

This article relies on a case-specific operationalization of a multi-level STN of UWM that includes social actors and technical elements of UWS as well as four different relations (Manny et al. 2022): information exchange between social actors, technical connections between technical elements, operation from social actors to technical elements, and data transfer from technical elements to social actors. These four relations are chosen based on their relevance for analyzing data-driven and integrated UWM in a socio-technical way.

The research, as presented in this article, makes several contributions to the literature addressing both practice-oriented and scientific gaps. First, I study whether social interactions, such as information exchange among social actors in the context of managing an infrastructure system – here an UWS – are influenced by underlying socio-technical dependencies. In this article, socio-technical dependencies refer to how social actors are related to infrastructure elements, for example through operational competencies of social actors for technical elements or data transfer from technical elements to social actors. Second, drawing on the specific STN operationalization, I compare STNs of three case study UWS catchment areas in Switzerland and analyze factors that potentially affect information exchange among social actors. Inferential results are obtained from fitting exponential random graph models (ERGMs)

(Robins et al. 2007). Third, I discuss findings with respect to different case study characteristics, thereby pointing to relevant socio-technical considerations related to data-driven and integrated UWM.

2. Socio-technical dependencies in infrastructure systems

A socio-technical perspective on infrastructure systems takes into consideration that both the technical system and the surrounding social system are inherently interrelated, i.e., form a socio-technical system (Ottens et al. 2006). In the field of UWM, the idea that UWS can be understood as socio-technical systems is not new. For example, de Haan et al. (2013) developed a socio-technical model of UWS to produce different scenarios under various social conditions. Mao et al. (2020) reviewed low-cost water sensor network applications beyond technology, i.e., they discuss important governance factors and conclude that socio-technical issues need to be considered to realize the full potential of sensor technologies in water systems. More universally, socio-technical system theories provide generic conceptualizations, mostly in a qualitative form and often address innovations or transitions at different scales (Fuenfschilling and Truffer 2016; Ottens et al. 2006).

In this article, a socio-technical understanding forms the basis for the analysis of socio-technical dependencies in infrastructure systems from a network perspective including social actors, technical elements and multiple relations in-between. It thereby adopts the idea of coherence between social and technical systems (Finger et al. 2005; Künneke et al. 2010), which is also referred to as 'socio-technical fit' in a network context (Manny et al. 2022). Drawing on this idea of 'socio-technical fit', I expect that social interactions, such as information exchange among social actors, are more likely to be observed if they are influenced by underlying socio-technical dependencies. Here, such a socio-technical dependency refers to two social actors operating two technically connected technical elements of an infrastructure system, thereby forming a 'socio-technical cycle' (s. Figure 1).

> ***Hypothesis 1:*** *Two social actors will more likely exchange information if they are responsible for the operation of two technically connected technical elements.*

Socio-technical fit structures could potentially contribute to better outcomes in terms of technical infrastructure performance (Grabowski et al. 2017; Mohebbi et al. 2020), or environmental impacts (Sayles et al. 2019). However, up to date information on the performance of UWS at catchment level is often not available, and general evidence-based performance metrics are not defined (van Daal et al. 2017). This current state is in fact rooted in the slow development and up-scaling of data-driven and integrated UWM (Oberascher et al. 2022). Consequently, the potential link between socio-technical fit structures and infrastructure performance cannot be investigated. Therefore, in the following, the focus lies on hypotheses related to socio-technical challenges that may play an important role regarding the development towards data-driven and integrated UWM. Social interactions, such as information exchange among social actors, are potentially influenced by factors related to these challenges.

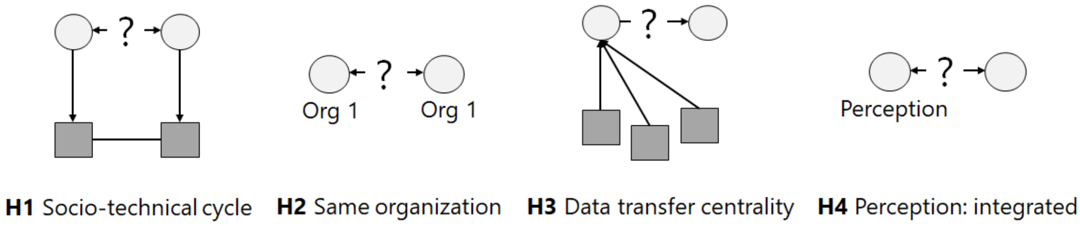

Figure 1*: Illustrations of the four hypotheses.*

3. Benefits and challenges related to data-driven and integrated urban water management

With intensifying impacts from climate change and urbanization, the need for a system-wide or integrated management of UWS is increasing (Oberascher et al. 2022). In the first place, integrated UWM is enabled by tools and technologies related to instrumentation, control, and automation (ICA)[1] (Yuan et al. 2019). The use of ICA in UWS holds several promises and potential benefits. First, real-time monitoring data obtained from sensors installed in UWS elements gives operators access to real-time information on the functioning and performance (Kerkez et al. 2016). This information is key to immediate decision-making, e.g., in case of blockages, and for a better understanding of the system's behavior. Such an evidence-based understanding can help minimize operational efforts and reduce costs as processes within the UWS are constantly supervised. Second, long-term monitoring data series improve infrastructure planning, which in turn could prevent from making unnecessary investments (Korving and Clemens 2002). Third, monitoring data from UWS lays the foundation for assessing their impacts on surface waters. For example, evidence on frequencies and durations of CSO events, could help reduce them by taking appropriate measures.

Despite benefits of data-driven and integrated UWM, the implementation and successful utilization of ICA technologies in UWS is still in its early stages (Oberascher et al. 2022; Yuan et al. 2019). Potential reasons for this slow development have been explored in previous research that has pointed towards the relevance of the 'human factor' – besides technological factors – in establishing data-driven and integrated UWM. For example, in 1998, Olsson and Newell (1998) stated that when it comes to the implementation of ICA in UWS the "management and people possibly create more problems than technology". Besides such technical issues associated with data-driven UWM, social challenges have been identified (Brown et al. 2009;

[1] These technologies are also often labelled as information and communication technologies (ICT).

Kiparsky et al. 2016; Manny et al. 2021; Oberascher et al. 2022; Sherman et al. 2020; Speight 2015; Yuan et al. 2019).

Organizational fragmentation

The fragmented organization of UWM is perceived as a socio-technical challenge, as different parts of the UWS are often managed by different organizational entities (Ighodaro et al. 2017; Kim et al. 2015; Lienert et al. 2013). More concretely, WWTPs and sewer systems are typically operated, planned, and overall managed by various social actors, who are again characterized by different goals, tasks, incentives, and skills. For example, as sewers are exposed to highly dynamic discharges depending on weather conditions, the reduction of CSO events from sewer systems during wet weather is a main goal for sewer operators. However, this goal interferes with the goal of WWTP operators to keep the hydraulic load constant as to improve treatment performance (Yuan et al., 2019).

Social actors managing UWS elements in a catchment area, may further belong to different organizational entities (e.g., several municipalities or an authority) especially in countries where UWS are managed by public sector organizations, as for example, in Germany, Switzerland, or the United States. In these countries, it is not uncommon that several municipalities are responsible for managing their respectively owned parts of the sewer system (Lieberherr and Ingold 2019). Such organizational fragmentation at the municipal level can hinder efficient and integrated management of UWS (Roy et al. 2008). With respect to the implementation of ICA, selective organizational entities could potentially impede achieving data-driven UWM, simply by not taking part and playing along (Sherman et al. 2020). Therefore, overcoming organizational fragmentation to achieve data-driven and integrated UWM would require coordination and information exchange among a multiplicity of organizational entities within a catchment area. Consequently, opposite to the 'challenge logic', hypothesis 2 is concerned with intra- and inter-organizational information exchange, i.e., between social actors of the same organization compared to across organizations (s. Figure 1).

> ***Hypothesis 2:*** *Two social actors will more likely exchange information if they are part of the same organization.*

Data access

Data access is necessary to fully exploit the value of real-time monitoring data, to achieve data-driven management, to control elements in a catchment area, and thus to establish integrated management (Ingildsen and Olsson 2016). Another socio-technical challenge is recognized in the lack of access to real-time monitoring data across a catchment area of an UWS (Fusi 2020; Hoolohan et al. 2021). For example, not every social actor who could potentially utilize such data, may in fact have access to it. On the one hand, this may be due to a lack of social structures that prevent from successful data sharing or because legal barriers prevent from data storage. On the other hand, absent data standards or incompatible data formats or even data systems, e.g. SCADA[2] systems, may hinder the utilization of data by different social actors (Roy et al. 2008). Furthermore, social actors who are not well-connected in the social network within a catchment area, might not be aware of whom to contact to receive access to data or might even not be aware of technical elements that are already equipped with sensors and do transfer data.

Hypothesis 3: *Social actors will more likely forward information if they receive data or have access to data from many technical elements.*

Diverging perceptions

Data-driven and integrated UWM are often perceived differently depending on local preferences (Oberascher et al. 2022). Such perceptions may vary with respect to the roles actors have and could even be related to technical characteristics of the infrastructure system, such as size or location. For example, social actors managing an UWS in a small, rural area may benefit less from the implementation of ICA, whereas large-scale UWS spanning across a city or several municipalities hold a greater need and potential for data-driven and integrated UWM. If social actors do not have the same perceptions on the use of ICA in UWS, the intended outcome might be difficult to achieve (Rieger and Olsson 2012). Perceptions, however, may also be shaped by experiences of individual stakeholders in their respective roles (Cooke et al. 2007; Nieuwenhuis et al. 2022). For example, perceptions by administrative personnel potentially differ from those of operators or actors with regulatory competences, particularly in the case of data-driven and integrated UWM. Within a catchment area, some social actors might be in favor of integrating ICA into UWS, while others rather reject this idea due to various concerns, such as for example, related to unnecessary costs, doubts on usefulness, or cybersecurity issues (Moy de Vitry et al. 2019). Given the various and potentially diverging perceptions of individual social actors within a catchment area, it is important to gain insight into how social actors perceive their catchment's progress in terms of data-driven and integrated UWM. For example, social actors who perceive their catchment to be already managed in an integrated way, might also be well-connected and exchange information with other social actors. Whereas social actors who perceive the opposite, could rather be isolated in terms of information exchange. Therefore, it is important to understand if the perception of social actors on integrated UWM affects information exchange (s. Figure 1).

Hypothesis 4: *Social actors will more likely exchange information, if they perceive the catchment area as managed in a rather integrated or integrated way.*

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[2] SCADA system: supervisory control and data acquisition system

4. Socio-technical networks

Social network approaches describe systems in terms of nodes and edges between nodes (Wasserman and Faust 1994). The analysis of networks aims to provide descriptive statistics on meaningful network properties and structures as well as inferential results using specific models to test network-related hypotheses (Borgatti et al. 2009; Wasserman and Faust 1994). Social network analysis has been extended to bipartite or multi-level networks, for example to investigate social-ecological systems or socio-technical systems. Social-ecological network analysis allows for jointly studying social actors and ecological elements as well as interactions in-between (Bodin 2017; Bodin et al. 2019).

In the context of socio-technical systems, STNs have proven useful (Elzen et al. 1996; Lamb et al. 2000; Bird et al. 2009; Hu et al. 2010; Gonzalez et al. 2021; Manny et al. 2022). The conceptual understanding of STNs depends on the research context and varies from discipline to discipline. Elzen et al. (1996) introduced the idea of STNs to study social aspects during technical system changes. In the field of social informatics, Lamb et al. (2000) conceptualized STNs in a general way as interactions between social units and technical units. More applied research related to infrastructure systems was conducted by Eisenberg et al. (2017), who analyzed a STN consisting of the power grid as a technical network and the social network of power companies and emergency management headquarters to understand which connections contribute to a fast response during blackouts. Investigating the uptake of renewable energy systems in the building industry, Weerasinghe et al. (2021) performed a meta network analysis of STNs to identify critical stakeholders, technical artefacts, and drivers. Similar to these previous studies, this article provides a context-specific STN operationalization of UWS and their management related to the specific socio-technical challenges.

4.1 Socio-technical networks of urban water management

With the objective to analyze UWS from a STN perspective, I present an operationalization of a multi-level STN of UWM (Manny et al. 2022). This specific operationalization includes social actors involved in managing an UWS, technical elements of the UWS, and multiple relations in-between (s. Figure 2). In this article, the STN of UWM is spatially limited to a catchment area of a WWTP, thus representing a regional unit of an UWS. Social nodes in the STN represent individual social actors, such as operators, administrative personnel, engineers, or authority representatives. These social actors are relevant for managing technical elements of the UWS in the catchment area (Manny et al. 2022). Technical nodes in the STN describe technical elements of the UWS, such as WWTPs, CSO tanks, CSOs, or pumping stations. Although there are many more technical UWS elements, e.g., manholes or shafts, I select only technical elements that can potentially be equipped with sensors, and are therefore relevant for data-driven and integrated UWM. Importantly, both social actors and technical elements can be assigned to different organizations, such as for example a local municipality or an authority relevant for the catchment area.

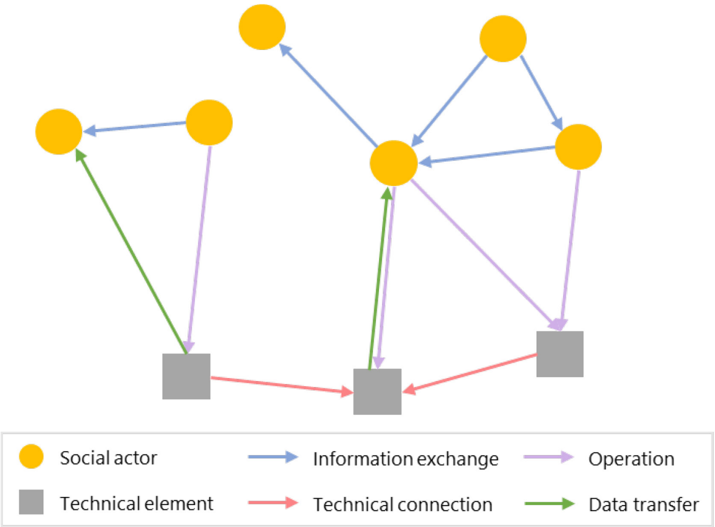

Figure 2*: Socio-technical network where nodes represent social actors and technical elements. Four different relations link these nodes: information exchange, technical connection, operation, and data transfer.*

Besides social and technical nodes, the operationalized STN consist of four different types of edges: 1) information exchange between social actors, 2) technical (physical) connections between technical elements, 3) operation between social actors and technical elements, and 4) data transfer between technical elements and social actors. These edge representations are chosen based on their relevance to assess UWS in terms of data-driven and integrated management. For example, the edge type of data transfer allows for directly assessing which social actors have access to data from which technical elements.

At the social level, information exchange between social entities has been previously studied from a social network perspective (Haythornthwaite 1996; Leifeld and Schneider 2012). In this article, *information exchange* was chosen as it is a necessary relation that is needed for data-driven and integrated UWM: relevant social actors need to exchange information among themselves to make use of obtained data, to control technical elements, and to manage the UWS in an integrated way. Considering the technical level, previous studies have represented UWS as technical networks (Dunn and Wilkinson 2013; Dunn et al. 2013). This approach is adopted here to transfer the technical UWS, including its technical elements and technical connections, into a network. The two types of edges connecting social and technical nodes are operation and data transfer, which have not been extensively studied from a network perspective before. Yet, these types of cross-level edges are included in order to test the hypotheses on socio-technical dependencies and related challenges towards data-driven and integrated UWM.

5. Cases, Data, and Methods

5.1 Cases

Based on the specific STN operationalization, empirical cases were selected to collect and analyze STN data. These empirical cases refer to three separate catchment areas of UWS, which are all located in the sub-state of Zurich in Switzerland. This case limitation to a single sub-state explicitly allows for keeping general legal and institutional settings constant, such as recommendations or procedures, which normally differ from sub-state to sub-state (Ingold and Fischer 2016; Linder and Vatter 2001). Within the federalist structure of Switzerland, sub-states have the regulative and executive competencies, and thus have the responsibility to evaluate if water protection targets are met as defined by national legislation (e.g., the Water Protection Act) and the Swiss Constitution. Competencies for operating UWS are generally delegated to municipalities (Luís-Manso 2005) that often enter forms of inter-municipal cooperation (Silvestre et al. 2018; Ladner and Steiner 2003; Ladner et al. 2013), such as wastewater associations or connection contracts (Lieberherr and Ingold 2022).

When it comes to data-driven and integrated UWM in Switzerland, no national or sub-state regulation currently requires the implementation of ICA technologies or the utilization of data to control UWS elements. Consequently, those catchment areas that already rely on monitoring data or are developing towards integrated management, do so in a fully self-motivated and not legally enforced way. Further, many catchment areas are making progress by partially implementing ICA technologies in selected important locations or specific UWS elements. Such progress is also supported by the professional association of wastewater and water protection experts in Switzerland that provides respective technical guidelines and recommendations (Oppliger and Hasler 2019).

The three selected case studies are examples of catchment areas that are developing towards data-driven and integrated UWM. In Table 4, general information on the three case studies is presented, showing the number of inhabitants connected to the WWTP, the number of municipalities active in the respective catchment area, and the organizational form of inter-municipal cooperation. In this article, the number of inhabitants connected to the WWTP is used as a proxy to describe the size of the catchment area, which goes in hand with a higher technical complexity due to more technical UWS elements.

Table 4: *Information on the three case study catchment areas in the sub-state of Zurich in Switzerland (data from 2020)*

	Case Study 1	Case Study 2	Case Study 3
Number of inhabitants connected to the WWTP	10'821	18'932	28'442
Number of municipalities in catchment area	2	5	7
Form of organization	Wastewater association	Connection contracts	Wastewater association

All three case studies are located in typical peri-urban regions in Switzerland, thus representing the nation-wide majority of UWS catchment areas (Manny et al. 2022). The case studies show differences in terms of connected inhabitants (i.e., size), involved municipalities, and their form of organization. For example, case study 1 is smaller and includes only two municipalities, compared to case studies 2 and 3 with five and seven municipalities, respectively. In terms of the form of organization, wastewater associations are present in case study 1 and case study 3, while municipalities in case study 2 rely on connection contracts with the main municipality that is responsible for operating the WWTP.

Such differences between the case studies are relevant as they potentially affect how social actors are exchanging information within the catchment area. The differences are also important to consider as developments towards data-driven and integrated management may unfold differently depending on the local context. For example, smaller catchment areas with less municipalities might face less efforts in coordinating and exchanging information with fewer municipalities, while social actors in larger catchment areas are subject to higher transaction costs when engaging with other social actors (Leifeld and Schneider 2012; Lubell et al. 2017). Further, organizational fragmentation could be more relevant in larger catchment areas with many municipalities (e.g., case studies 2 and 3), than in smaller ones (e.g., case study 1). These different characteristics are taken up again in the discussion for the interpretation of the results.

5.2 Data

In each of the three case studies, STN data was collected in 2020 and 2021 in three consecutive steps: 1) semi-structured context interviews, 2) document analysis, and 3) case-specific online-surveys. First, general information was obtained during semi-structured context interviews with one to three key representatives in each case study in June 2020. These context interviews lasted approximately one to two hours, and included semi-structured questions on relevant technical elements and social actors involved in managing the UWS in the respective case (s. Appendix A for the semi-structured interview guideline). Second, based on documents (e.g., infrastructure maps, planning documents) provided by a sub-state authority representative as well as the context interviewees, the technical elements of the UWS as well as the technical connection edges were mapped into a technical network. These technical network representations were validated by the sub-state authority representative. Subsequently, all social actors relevant for managing the technical elements, either directly (e.g., municipal works, WWTP operator), or indirectly (e.g., sub-state authority, engineer), were identified. This identification was achieved by checking all websites of municipalities active within the catchment area as well as the provided documents. The list of all identified social actors (s. Appendix B) as well as the technical network representation were validated by the sub-state authority representative and the context interviewee. Third, based on the obtained information, I designed case-specific online-surveys for all social actors in each case study (s. Appendix C for the online-survey questionnaire). Online-survey data was collected between March and May 2021 with response rates ranging between 88 percent (case study 2) and 94 percent (case studies 1 and 3). Survey questions incorporated the logics of each hypothesis as presented in chapters 2 and 3. Related to the dependent variable of *information exchange*, survey participants were given a list of social actors and were asked to indicate with whom they were exchanging information on UWM topics during the previous two years.

Table D.1 in Appendix D shows the number of social actors and technical elements as well as the number of all four edge types obtained from the online-survey. The numbers of social actors and technical elements depend on the different steps in the data collection process, i.e., before and during the survey, and those included in the analysis. For example, in the survey, participants were able to individually add up to ten social actors with whom they exchange information. However, only those social actors were included in the analysis who were added by at least two survey participants in a case study. This choice was based on the assumption, that social actors stated only once are probably rather individual contacts and can be neglected when it comes to information exchange among all social actors in the catchment areas.

Overall, no missing data on the technical networks including technical elements and technical connection edges was reported. The non-participation of social actors in the survey, however, led to missing data on the three types of edges, i.e., information exchange, operation, and data transfer. Information on how I dealt with this missing data is provided in Appendix D.

Additional to the numbers on STN nodes and edges (s. Table D.1), data specific to the social actors was used in the analysis and for hypotheses testing. For example, we asked social actors from which technical elements they receive data, or whether they perceive their catchment area to be managed in an integrated way already. Missing data in the social actor dataset, i.e., when an actor did not participate in the survey, was imputed using the mice package in R (van Buuren and Groothuis-Oudshoorn 2011). In order to make the data imputation as precise as possible, the entire social actor dataset was used including all survey variables as stated in Appendix C.

5.3 Methods

In Appendix E, I provide methodological information on the descriptive analysis of the STNs. The inferential analysis[3] draws on a specific family of statistical network models, named exponential family random graph models (ERGMs) (Robins et al. 2007). In combination with a causal model, the estimation of ERGMs allows for statistical inference, and thus enables evaluating effects of node, edge, or entire network characteristics on the formation of selected edges, i.e., here the information exchange edges in the STNs.

Compared to standard regression models, ERGMs are able to consider dependencies in network data. Such dependencies refer to a given network edge between a pair of nodes that cannot only be explained by attributes of these two nodes, but also depends on the characteristics of the surrounding network. ERGMs capture that observations of network edges are not independent from each other by giving explanatory power to the endogenous network structure in addition to specific actor attributes and further exogenous factors (Cranmer and Desmarais 2011).

Using ERGMs, I analyze what factors most likely explain the structure of the observed STNs, and particularly what affects information exchange among social actors following the logics of the hypotheses. These factors are described as either node or edge covariates (Statnet Development Team 2003-2022). For example, the socio-technical dependencies in hypothesis 1 are operationalized as socio-technical cycles, which are translated into an edge covariate through matrix multiplication. For hypothesis 2, I include a covariate at node level that involves the idea of homophily, i.e., two social actors sharing a similarity. In order to test if being part of the same organization affects information exchange, a nodematch term is included in the ERGMs. Hypothesis 3 refers to degree centrality in the data transfer network. Social actors that receive data from many technical elements are expected to more likely forward information. Therefore, the models include a node covariate that considers only out-going information exchange edges. Hypothesis 4 includes a nodefactor term for the perceptions of individual social actors on integrated UWM[4].

6. Results

Descriptive STN results are described in Appendix F. Results from the inferential STN analysis are presented in the following. Figure 3 visualizes all three case study STNs and illustrates how socio-technical network complexities increase with rising numbers of technical elements and social actors involved in managing the respective UWS.

[3] The code (in R studio) and data to replicate the analysis are available at: https://doi.org/10.25678/0007AC.
[4] The initial four categories of integrated, rather integrated, rather not integrated, and not integrated were aggregated to the two categories: integrated and not integrated.

ERGM results from the inferential analysis are presented in Table 2. Bold values indicate significant effects at the level of $p \leq 0.05$. Statistics and visualizations of the model goodness-of-fit appear in Appendix E, showing a good model fit. Four main findings can be derived from the model results in line with the hypotheses.

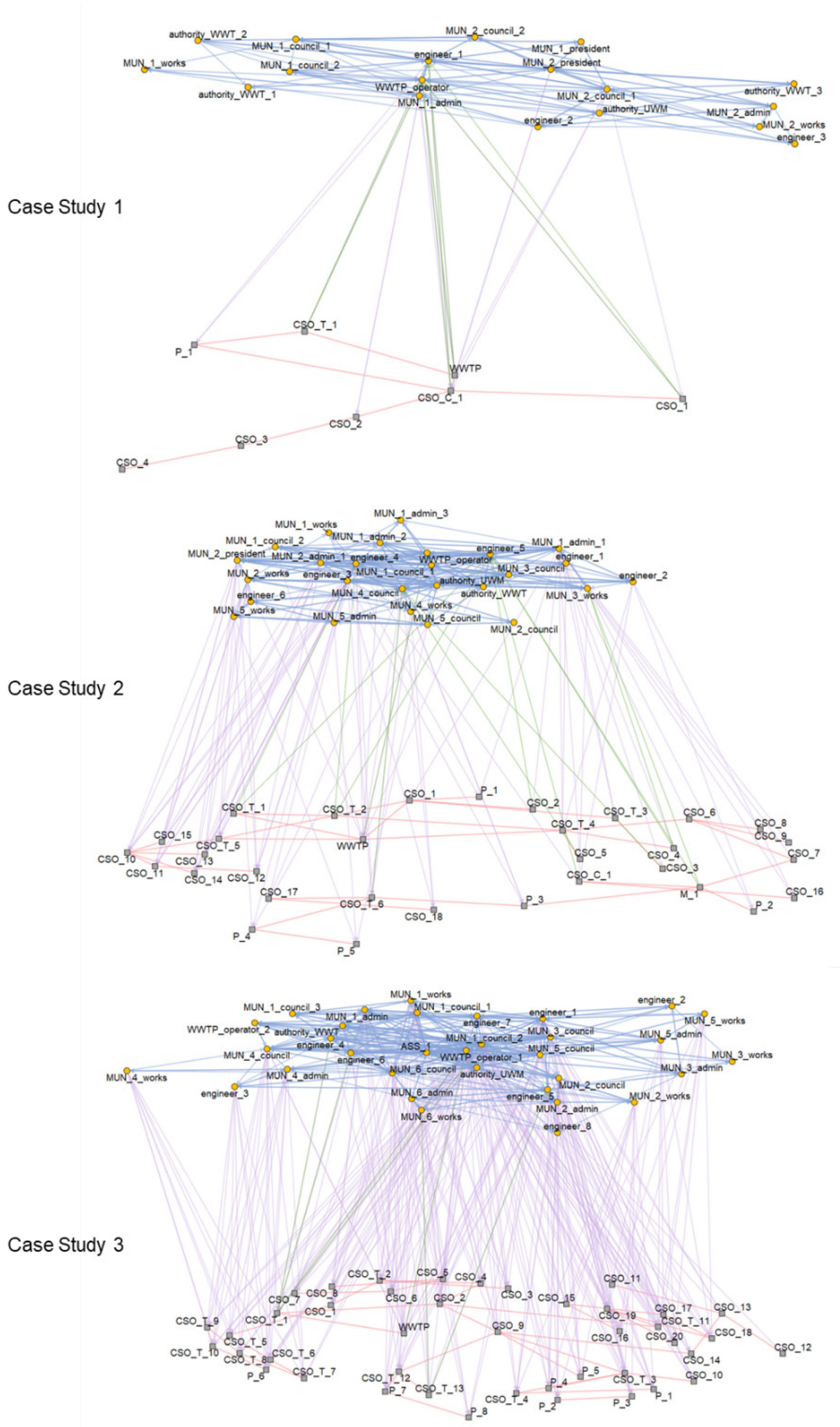

***Figure 3**: Visualization of the three case study STNs using graphlayouts (Schoch 2020) in R studio. Colors have the same meanings as in Figure 2.*

***Table 2**: Inferential results obtained from ERGMs*

	Dependent variable: ***Information exchange***		
	Case Study 1	**Case Study 2**	**Case Study 3**
H1: Socio-technical dependencies in the form of socio-technical cycles	0.86 (0.53)	**1.14** **(0.24)**	**1.42** **(0.18)**
H2: Same organization (municipalities, engineer, authority)	**0.66** **(0.27)**	**0.89** **(0.21)**	**0.92** **(0.20)**
H3: Degree central in terms of data transfer	-0.07 (0.15)	**0.16** **(0.07)**	-0.25 (0.18)
H4: Perception on integrated management: integrated	**0.62** **(0.21)**	0.17 (0.14)	0.00 (0.13)
Controls			
Edges	***-3.85*** ***(0.80)***	***-2.90*** ***(0.62)***	***-2.27*** ***(0.52)***
Reciprocity	***2.48*** ***(0.47)***	***3.20*** ***(0.36)***	***3.23*** ***(0.26)***
GWESP (0.1)	*0.55* *(0.64)*	*0.39* *(0.47)*	*0.08* *(0.32)*
Organization	*see Table G.1 in Appendix G*		
Akaike Inf. Crit.	301.38	619.57	942.68
Bayesian Inf. Crit.	340.76	667.61	1'016.97

Note: Bold values indicate significant effects at the level of p-values of 0.05 or lower.

First, and related to hypothesis 1, in case studies 2 and 3 the presence of socio-technical cycles has a positive influence on information exchange, i.e., if two social actors operate two technically connected technical elements, it is more likely that they exchange information. This finding implies that socio-technical dependencies affect social interactions such as information exchange among social actors, and consequently, social interactions are dependent on underlying socio-technical dependencies, i.e., how social actors are related to technical elements matters. In case study 1, the effect is also positive, although not significant. The size of this effect varies depending on the case study. For example, for case study 2, the model coefficient is 1.14, indicating that two actors operating two technically connected elements are more likely to exchange information by factor 2 ($e^{1.14} - 1 = 2.13$). For case study 3, the odds for the same effect are more than 3 times as high ($e^{1.42} - 1 = 3.14$).

The latter result is in line with the descriptive finding that case study 3 shows many more operation edges, and thus comprises more social actors who are involved in the management of the same technical element, which leads to the presence of more socio-technical cycles in the observed STN (s. also Table F.1). The non-significant effect in case study 1 may result from fewer operation edges and socio-technical cycles in the STN, and potentially also due to a smaller, less complex STN with fewer social actors and technical elements.

Second, there is another significant effect for social actors that are part of the same organization to more likely exchange information. This effect is observable in all three case studies. Odds vary between 93 percent (case study 1; $e^{0.66} - 1 = 0.93$), 144 percent (case study 2; $e^{0.89} - 1 = 1.44$), and 151 percent (case study 3; $e^{0.92} - 1 = 1.51$). Obviously, information exchange is more likely to occur within organizations rather than across organizations, whereby organizations are categorized as individual municipality (municipality 1 as organization 1, municipality 2 as organization 2, etc.), engineers (includes all individual engineers, i.e. engineer 1, engineer 2, etc.), and the authority (includes all authority representatives). This second finding implies that data-driven, and particularly, integrated management is presumably difficult to achieve if inter-organizational information exchange is less established, thus acting as a socio-technical challenge.

Third, in case study 2, social actors who receive data from many technical elements are slightly more likely to give information. The odds are 17 percent ($e^{0.16} - 1 = 0.17$), which is relatively low compared to the previous two effects related to hypotheses 1 and 2. Even though probabilities are lower, it is interesting to find that social actors with access to data are better embedded in the information exchange network. These results suggest that those social actors are potentially also more likely to share their data with their information exchange partners, thus improving the development towards data-driven and integrated UWM. In case studies 1 and 3, the effect is found to be negative, but not significant, which may be related to very few data transfer edges present in the respective STNs (s. also Table F.1).

Forth, in case study 1, the presence of information exchange edges in the STNs is influenced by whether social actors perceive their UWS to be managed in an integrated or not integrated way. The effect is positive and significant, i.e., the odds of information exchange are 86 percent ($e^{0.62} - 1 = 0.86$) higher if social actors perceive an integrated management to be already in place. In case studies 2 and 3, this effect is not significant, and the effect sizes are rather small.

The four remaining effects are controls. First, an "edges" parameter controls for the number of edges in a network. Its negative values, as observed in all three case studies, correspond to information exchange network densities lower than 0.5 (s. also Table F.1), and express that the chances of observing an edge are below 50 percent. The second control "reciprocity" is positive in all three case studies, indicating that actors tend to reciprocate information exchange edges. For example, in case study 1, the probability of an information exchange edge between two actors (A exchanges information with B and B exchanges information with A) is about 11 times higher ($e^{2.48} - 1 = 10.94$). Third, the control "GWESP (0.1)" refers to an endogenous network effect of triangular structures observable in many social networks. GWESP (geometrically weighted edgewise shared partners) is a measure that describes how actors connected through a particular edge are further indirectly connected through a third actor (i.e., a shared partner). The value of 0.1 indicates how strongly the endogenous network effect GWESP is weighted as a control. In all three catchment areas, the effect is positive (i.e., meaning that two actors tend to have shared partners), but not significant. Finally, I control for the type of organization (i.e., each municipality in the catchment, engineers, and authority representatives) as the nodematch covariate on the same organization is biased if many social actors are part of one organizational type. The control coefficients are determined for each type of organization individually, and as these vary between case studies, they are provided additionally in Appendix G.

The presented ERGM results stem from trade-off choices in terms of model fit, inclusion of the same model covariates in all three case studies, and comparative interpretability. Therefore, in Appendix F, I additionally provide case-specific models, which do not allow for cross-case comparisons, but show an improved model fit due to different covariates included in the respective case. These case-specific models further include covariates that are related to factors that potentially enhance information exchange between social actors. For example, in order to overcome the challenge of organizational fragmentation, it might be useful for social actors to be a member in the wastewater association, as such an association might facilitate information exchange in a similar way as forums (Fischer and Leifeld 2015). Another example refers to the participation of social actors in local or regional planning meetings on UWS, which similarly might enact opportunities for information exchange. These two network covariates are included in order to assess their effect on information exchange. Indeed, findings show that, in case study 3, information exchange is more likely among social actors, who are members of the wastewater association or who join the local or regional planning meetings (s. Appendix F).

7. Discussion

Arguing that information exchange among social actors involved in managing technical elements of an UWS in a catchment area is crucial to achieving data-driven and integrated UWM, I expected that socio-technical dependencies and derived hypotheses related to socio-technical challenges influence information exchange. Results from an inferential analysis provided detailed results on the STN structure of UWM in three case studies in Switzerland.

Inferential STN results obtained from ERGMs concern the formulated hypotheses on socio-technical dependencies and socio-technical challenges. Hypothesis 1 is confirmed for case studies 2 and 3, which shows that in these two catchment areas, information exchange is affected by underlying socio-technical dependencies (i.e., socio-technical cycles). This finding supports the argument that social interactions related to a technical infrastructure system, or more generally socio-technical systems, are depended on how social actors are connected to technical elements (Finger et al. 2005; Künneke et al. 2021). Yet, in case study 1 the effect on information exchange is not significant, thus raising the question if such socio-technical dependencies are potentially more relevant in larger UWS (or generally, infrastructure systems). Although controlling for the number of information exchange edges (control "edges"), infrastructure system size and associated socio-technical complexities might be important to consider when it comes to socio-technical challenges. Case study 1 is relatively small, comprising only two municipalities, fewer social actors and technical elements compared to the two larger case studies 2 and 3. Consequently, social interactions in smaller and socio-technical less complex infrastructure systems might be influenced by other factors than socio-technical dependencies. With increasing system size, however, socio-technical dependencies could have more relevance regarding information exchange among social actors.

In accordance with hypothesis 2, the ERGM results confirm the positive effect of two social actors being part of the same organization in all three case studies, which consequently implies that two social actors of different organizations are less likely to exchange information. As information exchange within a municipality, among engineers or among authority representatives outweighs information exchange across municipalities, between engineers and other organizations, or between authority representatives and other organizations, an integrated management of UWS could be difficult to achieve. However, to a certain degree the dominance of intra-organizational information exchange compared to inter-organizational information exchange is also not surprising, as social actors of the same organization require less efforts to exchange information among themselves (Yang and Maxwell 2011) and are potentially closely related spatially (e.g., same building). Therefore, I also control for the type of organization (s. Appendix G). More inter-organization information exchange could help to overcome organizational fragmentation and support the development towards integrated UWM (Lieberherr and Ingold 2019; Kim et al. 2015). As the case-specific ERGM results in Appendix F show, being a member in the catchment area's wastewater association (in case studies 1 and 3, s. also Table 4) or attending local planning meetings can have a positive effect on information exchange. For example, in case study 3, being a member of the wastewater association increases the odds of an information exchange between two social actors approximately by factor 1.4 ($e^{0.87} - 1 = 1.39$), and attending local or regional planning meetings leads to an increase of 46 percent ($e^{0.38} - 1 = 0.46$). Therefore, the development towards integrated UWM could also be supported by integrating more social actors into respective wastewater associations, or by inviting more social actors to planning meetings, not only to incorporate their perspectives, but also to provide more opportunities for information exchange (Haythornthwaite 1996). In this sense, particular forms of organization related to inter-municipal cooperation, could also contribute to different outcomes in terms of information exchange.

For hypothesis 3, the ERGM results demonstrate positive and significant effects for degree centrality of social actors in terms of data transfer in case study 2. There, social actors who have access to data on many technical elements are also more likely to exchange information. From the perspective of data-driven UWM, this finding is crucial, as social actors with access to data of many technical elements potentially can achieve a higher impact by sharing this data and derived information with many other social actors in the catchment area (Fusi 2020; Hoolohan et al. 2021; Yang and Maxwell 2011). In case studies 1 and 3, the same effect is not significant, which is probably due to very few data transfer edges being overall present (s. Appendix F). Two important aspects need to be considered when evaluating these findings. First, data-driven UWM might not only require social actors, who are also well embedded in the information exchange network, to access data but particularly would need to consider social actors who are not well embedded, as for those it might need more efforts in accessing data. Consequently, to provide multiple social actors with data that they can use for their respective purposes, isolated social actors need particular attention from a catchment-wide point of view (Hoolohan et al. 2021). Second, where access to data is given, social actors may further require skills and education to handle such data and enact data-driven UWM (Klievink et al. 2016). The type of education needed may however also depend on the various roles social actors have in managing UWS. For example, operators would benefit from specific hands-on training on sensor installation, maintenance, data interpretation, or real-time decision-making, whereas for administrative personnel cost-benefit assessments, awareness rising on the need for ICA, or evident examples ("business cases") of positive economic and environmental outcomes, might be beneficial (Lundberg et al. 2021).

Finally, the ERGM results confirm hypothesis 4 for case study 1, but not for case studies 2 and 3. This finding can be interpreted in multiple ways. First, in larger UWS, perceptions on whether the current UWS is already managed in an integrated way might be less relevant than other factors. Second, fewer social actors could rather share one common perception of the UWS, whereas with an increasing number of social actors involved, perceptions could become more divergent as social actors may only have a limited view of their respective part of the system (Cooke et al. 2007; Fraser and Zhu 2008). Third, case study 1 shows the highest percentage of technical elements that already transfer data (86 percent) compared to case studies 2 and 3 (56 percent and 27 percent, respectively), and therefore may already be managed in a rather integrated way. This progress in terms of data-driven and integrated UWM could also be reflected in the perceptions of individual social actors.

Overall results from the STN analysis need to be assessed in terms of validity. Several validation strategies were implemented, and assumptions related to missing data (s. also Table D.1) were presented (Huisman 2009; Kossinets 2006).

8. Conclusion

Researchers and practitioners in the field of UWM can benefit from a STN perspective to understand socio-technical dependencies and to learn about socio-technical challenges towards data-driven and integrated management of UWS (Fletcher and Deletic 2007; Yuan et al. 2019). More generally, I showed how social interactions, such as information exchange among social actors, are not only influenced by social factors, but also depend on underlying socio-technical dependencies (Manny et al. 2022; Finger et al. 2005; Künneke et al. 2021). For example, two social actors who operate two technically connected elements are more likely to exchange information in larger, socio-technically complex STN. Where ICA technologies are in use and data transfer from technical elements to social actors is present, social actors who receive data from many technical elements tend to exchange information with many other social actors. This finding is relevant for the development towards data-driven UWM, as it shows the importance and eventually also the responsibility of social actors with access to data, to data to share this data with social actors who do not have access to it (Fusi 2020), but would need it for purposes, such as continuous supervision, real-time control, or monitoring of environmental impacts, in the case of UWS. From a technical point of view, data platforms or SCADA systems, might be a technical solution to more evenly distribute data among relevant social actors (Roy et al. 2008). Here, a STN perspective could help identify which social actors exactly do require access to a data platform or SCADA system.

Achieving an integrated perspective on UWS through the utilization of data, however, requires information exchange across organizational, or more specifically, municipal boundaries in cases where UWS are managed by such entities. Following this argument, social actors need to actively exchange information with social actors who are responsible for managing other parts and elements of the UWS in the catchment area. For example, social actors of municipality A (operating UWS part A in the catchment area) would need to exchange information with social actors of municipality B (operating part B), and vice versa, in order to overcome organizational fragmentation (Kim et al. 2015; Lienert et al. 2013) and to foster the development of an integrated perspective on the catchment area. Further, perceptions of social actors on the state of integrated UWM matter (Cousins 2017; Pahl-Wostl 2007), particularly if the system is managed in a (rather) integrated way already. However, perceptions of social actors on integrated management can also diverge, even if they address a single technical system only.

In this article, the application of the STN approach proved useful to understand UWS and the development towards data-driven and integrated UWM form a socio-technical perspective. Using network concepts, the three empirical case studies shed light on entangled relations between social actors and technical elements and illustrated the heterogeneity in actor-infrastructure constellations for three different UWS.

However, the STN approach bears limitations. First, only four specifically chosen types of edges were operationalized. Besides information exchange, technical connection, operation, and data transfer, other relations could be relevant (Pan et al. 2020; Scott and Ulibarri 2019). Other attributes of social actors, such as years or type of experience might further play a role in terms of information exchange in a catchment area, but are not specific to data-driven and integrated UWM.

Second, the STN approach could be used in interactions and discussions with stakeholders to demonstrate gaps in the information exchange network (Fried et al. 2022; Bergsten et al. 2019), but also to show which technical elements might need to be equipped with sensors, or which social actors would need to have access to data from which technical element. However, transferring such results from the STN analysis into practice (Bixler et al. 2019), might evoke challenges. For example, stakeholders could disagree with top-down suggestions given by informed researchers. To overcome these potential conflicts, stakeholders could be included in the research process at an earlier stage in order to co-create the STNs, based on which opportunities for improvement could be identified by themselves. In this more transdisciplinary sense, researchers could rather act as tool providers and guide stakeholders through workshops.

Third, the operationalized STN in the context of data-driven and integrated UWM includes social actors and their social (network) structure, but neglects other important aspects of social systems, such as institutions (e.g., rules, norms, practices). For example, no differentiation between formal and institutionalized information exchange edges (e.g., operators reporting to the authority) and informal personal relations was made. Such differences, if included in the analysis, however, may affect the ERGM results.

Forth, this article draws only on three selected case studies and respective STN representations. To gain more insights into the relevance of socio-technical dependencies and socio-technical challenges, a larger number of analyzed cases could provide further evidence. Ideally, the selection of such cases would consider varying characteristics, such as system size, forms of organization, or progress in terms of data-driven and integrated UWM, among others.

Future research on STNs of UWM could deal with questions around the technical performance or environmental impacts (Ulibarri 2015; Grabowski et al. 2017; Sayles et al. 2019), which might depend on the STN structure. For example, are centralized forms of organization (e.g., a wastewater association) leading to a better technical performance than decentralized forms (e.g., individual municipalities)? Are environmental impacts lower if more socio-technical cycles are present in the STN or if all relevant social actors have access to required data?

Finally, STNs incorporate a variety of social actors in their respective roles. Including such a multi-actor perspective in the design and implementation of policies aiming to achieve changes in socio-technical infrastructure systems (Sayles et al. 2019), could allow for specifically targeting those affected, those responsible, and those benefitting from such changes.

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Appendix

A Semi-structured interview guideline for context interviews

Table A.1: *Semi-structured interview guideline for context interviews.*

	Topic	Questions
1	Description of the catchment area	• Size and total number of inhabitants in the catchment area • Number and names of involved municipalities • Details on the WWTP (year of construction, historical connections, size) • Year of local drainage plan - is it currently updated? • Length or percentages of combined vs. separated sewer system [km or %] • Number of combined sewer overflow tanks • Number of combined sewer overflows • Number of pumping stations • Existence of monitoring technology (ICA)? If yes, since when? • Which technology? What is monitored? How is the data handled?
2	Description of experiences, (past)/current challenges and successes	• Are there special conditions in the catchment area? For example, bathing waters, lakes? • Are you satisfied with the current management in the catchment area? If yes, why? If no, why? What works well, what works not well? • Are there any current/planned organizational activities? (e.g., merger of WWTP). Have there been any recently? • Are there any current/planned construction activities? • Have there been any particular successes in the catchment area in the past 10 years? • Have there been any notable challenges in the catchment area over the past 10 years? • Are there any challenge(s) in the catchment area currently or in the foreseeable future?
3	Key stakeholders and organizations in the catchment area	• What is your role in the catchment area? • Which stakeholders and organizations are involved in urban water management in the catchment area? Can you give me specific names of contact persons? • Which municipalities are involved? Is there a wastewater association? • Which engineering and planning offices are involved in the area? • Who is the contact person at the sub-state authority? • Are there private companies to which certain tasks have been delegated? If so, which companies? • Which other stakeholders are important? Are there overlaps with other sectors (e.g., water supply)? • With which stakeholders do you have particularly frequent professional exchanges (e.g., once a month), and about what?
4	Information about socio-technical contexts in the catchment area	• Are you involved in the operation of technical elements of the urban wastewater system in the catchment area? • Do you receive or have access to any monitoring data obtained within the catchment area?

B List of all identified social actors and technical elements in the respective case studies

Table B.1: *STN data on technical and social nodes in case study 1.*

	Technical element	Organization
1	WWTP	Wastewater association
2	CSO_T_1	Wastewater association
3	P_1	Wastewater association
4	CSO_C_1	Wastewater association
5	CSO_1	Wastewater association
6	CSO_2	Wastewater association
7	CSO_3	Municipality 1
8	CSO_4	Municipality 1

	Social actor	Organization
1	engineer_1	Engineering office
2	WWTP_operator	Wastewater association
3	MUN_1_council_1	Municipality 1
4	MUN_2_council_1	Municipality 2
5	MUN_1_admin	Municipality 1
6	MUN_1_works	Municipality 1
7	MUN_2_works	Municipality 2
8	engineer_2	Engineering office
9	MUN_2_admin	Municipality 2
10	MUN_2_president	Municipality 2
11	MUN_1_council_2	Municipality 1
12	engineer_3	Engineering office
13	authority_WWT_1	Authority
14	authority_WWT_2	Authority
15	authority_UWM	Authority
16	MUN_1_president	Municipality 1
17	MUN_2_council_2	Municipality 2
18	authority_WWT_3	Authority

Table B.2: *STN data on technical and social nodes in case study 2.*

	Technical element	Organization
1	WWTP	Municipality 1
2	CSO_T_1	Municipality 1
3	CSO_T_2	Municipality 1
4	CSO_T_3	Municipality 1
5	CSO_T_4	Municipality 1
6	CSO_1	Municipality 1
7	CSO_2	Municipality 1
8	CSO_3	Municipality 1
9	CSO_4	Municipality 1
10	CSO_5	Municipality 1
11	CSO_6	Municipality 1
12	CSO_7	Municipality 1
13	CSO_8	Municipality 1
14	CSO_9	Municipality 1
15	P_1	Municipality 1
16	CSO_T_5	Municipality 2
17	CSO_10	Municipality 2
18	CSO_11	Municipality 2
19	CSO_12	Municipality 2
20	CSO_13	Municipality 2
21	CSO_14	Municipality 2
22	CSO_15	Municipality 2
23	CSO_C_1	Municipality 3
24	CSO_16	Municipality 3
25	P_2	Municipality 3
26	CSO_T_6	Municipality 4
27	CSO_17	Municipality 4
28	CSO_18	Municipality 4
29	P_3	Municipality 4
30	P_4	Municipality 5
31	P_5	Municipality 5
32	M_1	Municipality 3

	Social actor	Organization
1	engineer_1	Engineering office
2	MUN_3_works	Municipality 3
3	engineer_2	Engineering office
4	engineer_3	Engineering office
5	MUN_1_council_1	Municipality 1
6	engineer_4	Engineering office
7	MUN_4_council	Municipality 4
8	MUN_1_works	Municipality 1
9	MUN_2_president	Municipality 2
10	MUN_1_admin_1	Municipality 1
11	MUN_4_works	Municipality 4
12	MUN_1_admin_2	Municipality 1
13	MUN_1_admin_3	Municipality 1
14	MUN_5_admin	Municipality 5
15	MUN_2_admin_1	Municipality 2
16	MUN_5_council	Municipality 5
17	MUN_1_council_2	Municipality 1
18	MUN_2_works	Municipality 2
19	engineer_5	Engineering office
20	engineer_6	Engineering office
21	MUN_5_works	Municipality 5
22	authority_WWT	Authority
23	authority_UWM	Authority
24	WWTP_operator	Municipality 1
25	MUN_2_council	Municipality 2
26	MUN_3_council	Municipality 3

***Table B.3**: STN data on technical and social nodes in case study 3.*

	Technical element	Organization		Social actor	Organization
1	WWTP	Wastewater association	1	engineer_1	Engineering office
2	CSO_T_1	Wastewater association	2	engineer_2	Engineering office
3	CSO_T_2	Municipality 1	3	MUN_1_council_1	Municipality 1
4	CSO_1	Municipality 1	4	engineer_3	Engineering office
5	CSO_2	Municipality 1	5	MUN_2_admin	Municipality 2
6	CSO_3	Municipality 1	6	MUN_6_works	Municipality 6
7	CSO_4	Municipality 1	7	engineer_4	Engineering office
8	CSO_5	Municipality 1	8	engineer_5	Engineering office
9	CSO_6	Municipality 1	9	MUN_1_council_2	Municipality 1
10	CSO_7	Municipality 1	10	MUN_5_admin	Municipality 5
11	CSO_8	Municipality 1	11	MUN_2_works	Municipality 2
12	CSO_9	Municipality 1	12	MUN_1_admin	Municipality 1
13	CSO_T_3	Municipality 2	13	MUN_3_admin	Municipality 3
14	CSO_T_4	Municipality 2	14	MUN_4_admin	Municipality 4
15	CSO_10	Municipality 2	15	MUN_4_works	Municipality 4
16	P_1	Municipality 2	16	engineer_6	Engineering office
17	P_2	Municipality 2	17	MUN_3_council	Municipality 3
18	P_3	Municipality 2	18	MUN_1_council_3	Municipality 1
19	P_4	Municipality 2	19	MUN_1_works	Municipality 1
20	P_5	Municipality 2	20	engineer_7	Engineering office
21	CSO_11	Municipality 3	21	MUN_5_council	Municipality 5
22	CSO_12	Municipality 3	22	MUN_5_works	Municipality 5
23	CSO_13	Municipality 3	23	MUN_2_council	Municipality 2
24	CSO_14	Municipality 3	24	MUN_6_council	Municipality 6
25	CSO_T_5	Municipality 4	25	WWTP_operator	Wastewater association
26	CSO_T_6	Municipality 4	26	MUN_6_admin	Municipality 6
27	CSO_T_7	Municipality 4	27	MUN_4_council	Municipality 4
28	CSO_T_8	Municipality 4	28	engineer_8	Engineering office
29	CSO_T_9	Municipality 4	29	MUN_3_works	Municipality 3
30	CSO_T_10	Municipality 4	30	authority_WWT	Authority
31	P_6	Municipality 4	31	authority_UWM	Authority
32	CSO_T_11	Municipality 5			
33	CSO_15	Municipality 5			
34	CSO_16	Municipality 5			
35	CSO_17	Municipality 5			
36	CSO_18	Municipality 5			
37	CSO_19	Municipality 5			
38	CSO_20	Municipality 5			
39	CSO_T_12	Municipality 6			
40	CSO_T_13	Municipality 6			
41	P_7	Municipality 6			
42	P_8	Municipality 6			

C Online-survey questionnaire

***Table C.1**: Excerpt of the survey questionnaire that includes questions and answers that were used to obtain the STN data in the three case studies.*

	Variable	**Question**	**Answers**
1*	Type of responsibility	To which area of responsibility can your current job be assigned?	- Municipal council - Municipal administration - Municipal works - WWTP operator - Commission (e.g., operational, (civil) engineering, planning) - Inter-municipal/regional association - Engineering office/planning office - Other
2*	Organization	Please assign your area of responsibility to the respective municipality in the catchment area.	- List of names of municipalities
3*	Information exchange	With whom have you exchanged information in the past 2 years that relates to wastewater treatment, urban drainage, and/or water pollution control in the catchment area? *Examples of how and where information exchange can happen: You receive an email or phone call about the WWTP (e.g. operations or planning) or the sewer system (e.g. operations or planning). You are informed at a meeting where decisions are being made about the WWTP or drainage system in the catchment area. You attend an event or symposium. You receive or send an annual operational report.*	- List of names of all social actors involved in managing the urban water system *(s. Appendix B)*
4	Active in operation	Are you involved in the operation of technical elements of the urban wastewater system in the catchment area?	- Yes - No
5*	Operation	Which technical elements of the urban wastewater system do you operate? (Diagram of the urban wastewater system, such as a flow chart, for example) *By operation we mean a wide range of tasks, such as strategic decisions on operation, but also very practical activities such as visual or functional inspections, cleaning, and maintenance of technical elements or analysis of operational data.*	- List of all technical elements (here: WWTP, CSO tanks, CSOs, pumping stations – as shown in the diagram) *(s. Appendix B)*
6	Sensors	Which technical elements of the urban wastewater system are equipped with sensors/digital technologies?	- List of all technical elements *(s. Appendix B)*
8*	Data transfer	From which of the following technical elements of the urban wastewater system do you receive or can you access monitoring data?	- List of all technical elements *(s. Appendix B)*
9*	Perceived integrated management	By the term integrated management we mean the joint, technically coordinated management of the system and WWTP. In your opinion, how integrated do you think your catchment area is currently managed?	- integrated - rather integrated - rather not integrated - not integrated

10	Local/regional planning meetings	Are there local or regional planning meetings in your catchment area?	- yes - no - I don't know
11*	Attendance of local/regional planning meetings	Do you participate in local or regional planning meetings?	- yes - no - sometimes
11	Years active	How many years have you been doing your job in the selected organization? *If you have only recently started working, please enter the number 1.*	- Number of years
12	Relevance Work	How many days per week do you approximately deal with tasks related to wastewater treatment, urban drainage and/or water protection?	- None - Less than 1 day / week (<20%) - 1 day / week (20%) - 2 days / week (40%) - 3 days / week (60 %) - 4 days / week (80 %) - 5 days / week (100 %)
13	Importance of monitoring data	How important is integrated urban water management to you?	- important - rather important - rather unimportant - unimportant
14	Importance of integrated urban water management	How important is the use of monitoring technology and data in the catchment area to you?	- important - rather important - rather unimportant - unimportant

*Note: The flowchart of the respective urban water systems are not provided here in order to maintain confidentiality. Variable numbers marked with a * are included in the inferential analysis.*

D Information on missing data in the three case study STNs

The percentage of missing data varies depending on the edge type and the respective case study. In Table D.1, the percentage of missing edges is calculated by dividing the number of missing edges by the number of all possible edges. Missing edges could either refer to a zero or a one in the matrix cell, whereas observed edges always refer to a one in the matrix cell. For example, missing information exchange edges are rather low, while data on several operational edges is missing in all three case studies. In case study 1, data on information exchange edges for two social actors is missing. In case studies 2 and 3, only one or a few matrix cells show missing data in terms of information exchange.

Concerning the operation edges, in case study 1, two out of 18 social actors did not indicate which technical elements they operate. Similarly, no information on potential operation edges is available from seven out of 26 social actors in case study 2, and for six out of 33 social actors in case study 3. In case studies 1 and 3, the information on data transfer from technical elements to social actors is complete, whereas in case study 2, three social actors did not respond to the question on data transfer.

Overall, missing data in the operation network refers to edges that are either present or not present, while the number of observed edges excludes those not present (Kossinets 2006). In many cases, it is very likely that missing operation edges imply that survey participants do not operate respective technical elements. This assumption equally applies to data transfer edges: social actors not answering the respective question, presumably did not receive any data.

Therefore, for the inferential analysis, all matrix cells with missing data were converted to zero, i.e. representing no edge between two particular nodes.

***Table D.1**: Information on STN data for each case study. The number of social actors, technical elements, and all four types of edges is stated including information on missing data.*

Number of	**Case Study 1**	**Case Study 2**	**Case Study 3**
Social actors (nodes)			
identified before survey	17	26	36
identified during survey	29	33	35
included in analysis	**18**	**26**	**33**
Missing actors*	1 (5.6 %)	3 (11.5 %)	2 (6.1 %)
Technical elements (nodes)			
identified before and during survey	8	32	42
included in analysis	**8**	**32**	**42**
Missing elements	0 (0 %)	0 (0%)	0 (0 %)
Information exchange edges	**109**	**237**	**345**
Missing edges**	41 (13.4 %)	8 (1.2 %)	10 (0.9 %)
Technical connection edges	**8**	**34**	**41**
Missing edges	0 (0 %)	0 (0 %)	0 (0 %)
Operation edges	**18**	**83**	**250**
Missing edges***	16 (25 %)	225 (56 %)	251 (37 %)
Data transfer edges	**8**	**14**	**7**
Missing edges	0 (0 %)	95 (24 %)	0 (0 %)

** Percentage of missing actors is calculated by dividing the number of actors who did not participate in the survey by the number of actors who are included in the analysis.*
*** Percentage of missing edges is calculated by dividing the number of missing edges by the number of all possible edges. Missing edges could either refer to a zero or a one in the matrix cell, while the observed edges always refer to a one in the matrix cell.*

E Descriptive STN analysis

The descriptive STN analysis builds on concepts developed to analyze STNs of networked infrastructure systems as proposed by Manny et al. (2022). Here, I present descriptive statistics on network density, reciprocity, and degree centrality[5]. These statistics concern four different sub-networks within the STN, i.e., the technical network, the information exchange network, the operation network, and the data transfer network.

Densities are calculated for each sub-network. Reciprocity values are determined for the directed information exchange network and for the socio-technical operation and data transfer networks. Further, degree central social actors and technical elements in the STN are identified.

Second, network motifs refer to meaningful sub-structures within networks that usually consist of three to four network nodes and respective edges between these nodes. Manny et al. (2022) present various forms of STN motifs, which reveal insights into network sub-structures. One motif example are socio-technical cycles. Socio-technical cycles include two social actors that are related (e.g., through operation) to two technical elements, which are connected at the technical level (s. also hypothesis 1). These socio-technical cycles are "closed" if the two social actors are linked through a social interaction, such as an information exchange edge. As part of the descriptive STN analysis, the ratio of open (information exchange not present) and closed (information exchange present) versions was determined. In addition, I identified those social actors who are part of the most closed socio-technical cycles.

Third, I determine network-wide percentages of technical elements that already transfer data vs technical elements that technically can transfer data, i.e., the sum of the technical elements transferring data already and the technical elements potentially transferring data in the future. This percentage roughly indicates how progressive the respective case study is in terms of data-driven UWM from a technical perspective.

[5] Besides degree centrality, other centrality measures exist, which allow for determining important social actors or technical elements. Examples are betweenness centrality, closeness centrality, or eigenvector centrality (Freeman 1978).

F Results from the descriptive STN analysis

In Table F.1, descriptive results are shown for each case study. The information exchange network density is very similar in all three cases, ranging between 0.33 and 0.36. The size of these values is comparable to those found in literature with similar contexts (Isaac 2012; Ulibarri and Scott 2016). For the small case study 1, a density of 0.36 is not surprising as higher densities are more likely to be observed when fewer social actors are present (Hislop 2005). Similarly, the technical network shows a higher density in case study 1 compared to the other two case studies. Concerning the operation network that includes social actors and technical elements as nodes, the highest density is present in case study 3 ($d_{operation;\,case\ 3} = 0.18$). This finding is surprising but may be due to several actors being part of the operation of the same technical elements. For the data transfer network, case study 1 shows the highest density values followed by case studies 2 and 3. The magnitude of data transfer densities depends on how many technical elements are already equipped with sensors and therefore transfer data (s. also last row in Table F.1). In this sense, case study 1 shows the most progressive state, as already 86 percent of technical elements[6] transfer data compared to 56 percent in case study 2 and 27 percent in case study 3. This observation appears again in the socio-technical reciprocity values indicating the percentage of social actors operating technical elements and receiving data from them. Conformingly, case study 3 has the lowest socio-technical reciprocity values, which is also a result of few data transfer edges being present overall. In the information exchange network, reciprocity is comparatively high, ranging between 0.58 in case study 1, 0.66 in case study 3, and 0.68 in case study 2. This means that more than half or even more than two thirds of the social actors do exchange information in both directions.

The identification of degree central social actors and technical elements in the three STNs reveals varying findings across the case studies. For example, in case study 1 and 3, the most degree central social actor in terms of information exchange is a representative from the council of a municipality (MUN_2_council_1), whereas in case study 2 it is the representative of the authority responsible for UWM (authority_UWM). In the operation network, the WWTP operator is the most degree central social actor in both case studies 1 and 3, i.e., is involved in the operation of the most technical elements. Interestingly, in case study 2, the central position is taken by the representative of the administration of a municipality (MUN_1_admin_1), which is the main municipality with whom the other municipalities have connection contracts with (s. also Table 4). In case study 3, the same social actor (MUN_1_council_2) who is exchanging information with most other social actors, is also the most degree central social actor in terms of operation, i.e., is involved in the operation of most technical elements. This social actor also

[6] This percentage refers to the number of technical elements that (already) transfer data divided by the number of technical elements that technically can transfer data (i.e., the sum of technical elements (already) transferring data and the technical elements potentially transferring data in the future).

has the role of the president of the wastewater association in the catchment area (s. also Table 4). From the point of inter-municipal cooperation, this presidential role potentially allows for more opportunities, but also needs for information exchange. In the technical network, the WWTP takes the most degree central position in all three case studies, which is not surprising as the UWS is centralized, i.e., directs all discharges towards the WWTP as the end-point in the infrastructure network. In case study 1, a CSO canal[7] (CSO_C_1) is equally degree central than the WWTP. This CSO canal in case study 1, is also the most degree central technical element in the data transfer network, as it transfers data to most social actors. In case study 2, CSO tank 4 adopts this position, whereas in case study 3, CSO 2 is most degree central in terms of data transfer.

Table F.1 further indicates the ratio of open (without information exchange) vs closed (with information exchange) socio-technical cycles. This ratio is lowest for case study 1 (23 percent) and highest for case study 2 (78 percent). This finding implies that two social actors operating two technically connected elements are more often exchanging information in case study 1 than not exchanging information. In case studies 2 and 3, this finding is similar, but less distinctive. Additionally, social actors who are part of many socio-technical cycles are listed, who are in case studies 1 and 3 overlapping with degree central social actors in terms of information exchange and operation, but differing from these in case study 2.

Finally, the progress in terms of data-driven management as determined through the percentage of technical elements already transferring data vs those technically being able to do so, reveals that case study 1 is most progressive (86 percent) and case study 3 least progressive (27 percent). Yet, these values also make clear that all three case studies demonstrate potential related to data-driven and integrated management, which points to the need of understanding socio-technical challenges.

[7] A CSO canal has the same function as a CSO tank, but is characterized by retention volumes in the pipes (‘canals’) of the combined sewer system without an additional special structure.

Table F.1: *Descriptive results: network concepts (i.e., density, reciprocity, degree centrality), motifs, and progress in terms of data-driven urban water management*

	Case Study 1	Case Study 2	Case Study 3
Density			
Information exchange network	0.36	0.36	0.33
Technical network	0.14	0.03	0.02
Operation network	0.13	0.1	0.18
Data transfer network	0.06	0.02	0.005
Reciprocity			
Reciprocity in the information exchange network	0.58	0.68	0.66
Socio-technical reciprocity (operation and data transfer)	0.05	0.002	0.005
Degree centrality			
Most central social actor in terms of information exchange	MUN_2_council_1	authority_UWM	MUN_1_council_2
Most central social actor(s) in terms of operation	WWTP_operator	MUN_1_admin_1	MUN_1_council_2 WWTP_operator_1
Most central technical element(s) in terms of operation	WWTP CSO_C_1	WWTP	WWTP
Most central technical element in the technical network	CSO_C_1	CSO_T_4	CSO_2
Motifs			
Ratio of "open" to "closed" socio-technical cycles	23 %	77 %	60 %
Social actors part of many closed socio-technical cycles	WWTP_operator engineer_1 MUN_2_council_1 MUN_1_admin MUN_2_president	MUN_2_admin_1 engineer_3	MUN_1_council_2 WWTP_operator_1
Progress in terms of data-driven urban water management			
Technical elements transferring data	86 %	56 %	27 %

G ERGMs including controls for the type of organization

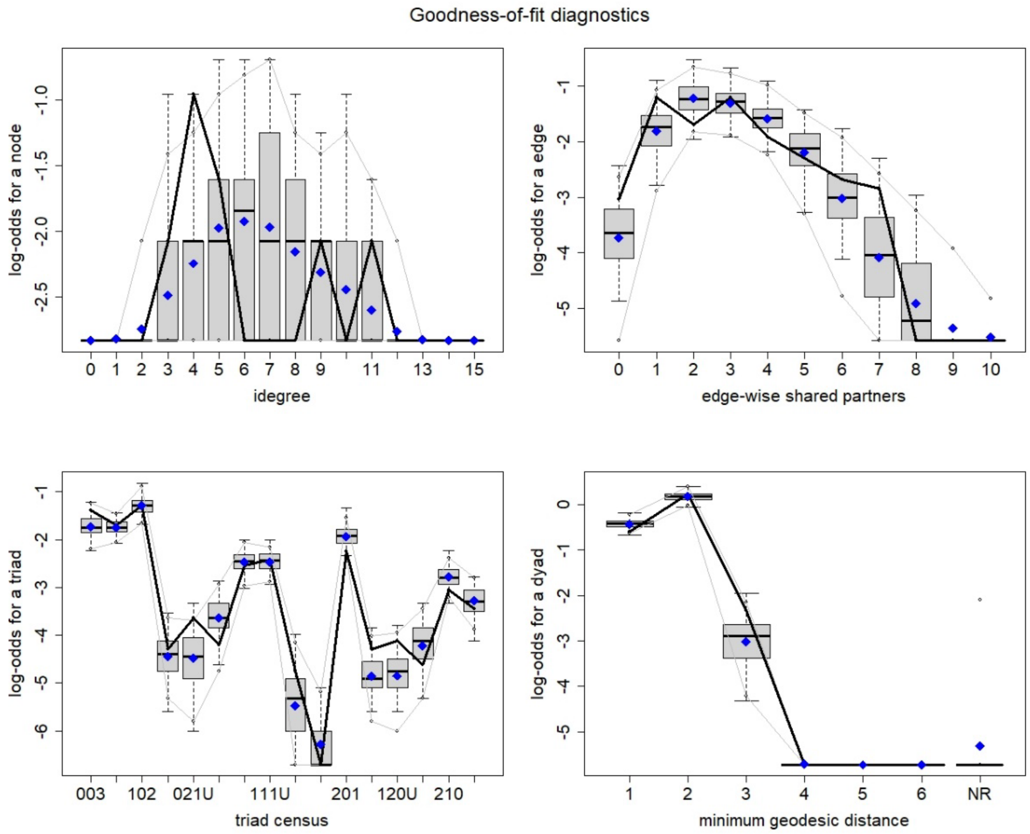
Table G.1: *Inferential results obtained from ERGMs including controls for the type of organization*

	Dependent variable: ***Information exchange***					
	Case Study 1		**Case Study 2**		**Case Study 3**	
H1: Socio-technical dependencies in the form of socio-technical cycles		0.86 (0.53)		**1.14 (0.24)**		**1.42 (0.18)**
H2: Same organization (municipalities, engineer, authority)		**0.66 (0.27)**		**0.89 (0.21)**		**0.92 (0.20)**
H3: Degree central in terms of data transfer		-0.07 (0.15)		**0.16 (0.07)**		-0.25 (0.18)
H4: Perception on integrated management: integrated		**0.62 (0.21)**		0.167 (0.14)		0.00 (0.13)
Controls						
Edges		***-3.85 (0.80)***		***-2.90 (0.62)***		***-2.27 (0.52)***
Reciprocity		***2.48 (0.47)***		***3.20 (0.36)***		***3.23 (0.26)***
GWESP (0.1)		*0.55 (0.64)*		*0.39 (0.47)*		*0.08 (0.32)*
Organization	*MUN 1*	-	*MUN 1*	-	*MUN 1*	***-0.34 (0.19)***
	MUN 2	***0.46 (0.21)***	*MUN 2*	*-0.09 (0.19)*	*MUN 2*	***-0.58 (0.23)***
	Engineers	*0.34 (0.26)*	*MUN 3*	*0.16 (0.23)*	*MUN 3*	-
	Authority	***0.49 (0.25)***	*MUN 4*	*0.32 (0.24)*	*MUN 4*	***-0.66 (0.22)***
	Wastewater association	***0.77 (0.43)***	*MUN 5*	***-0.53 (0.20)***	*MUN 5*	***-0.43 (0.22)***
			Engineers	*-0.24 (0.18)*	*MUN 6*	*-0.25 (0.22)*
			Authority	***1.17 (0.24)***	*Engineers*	***-0.34 (0.19)***
					Authority	***0.76 (0.23)***
					Wastewater association	***0.55 (0.20)***
Akaike Inf. Crit.		301.38		619.57		942.68
Bayesian Inf. Crit.		340.76		667.61		1'016.97

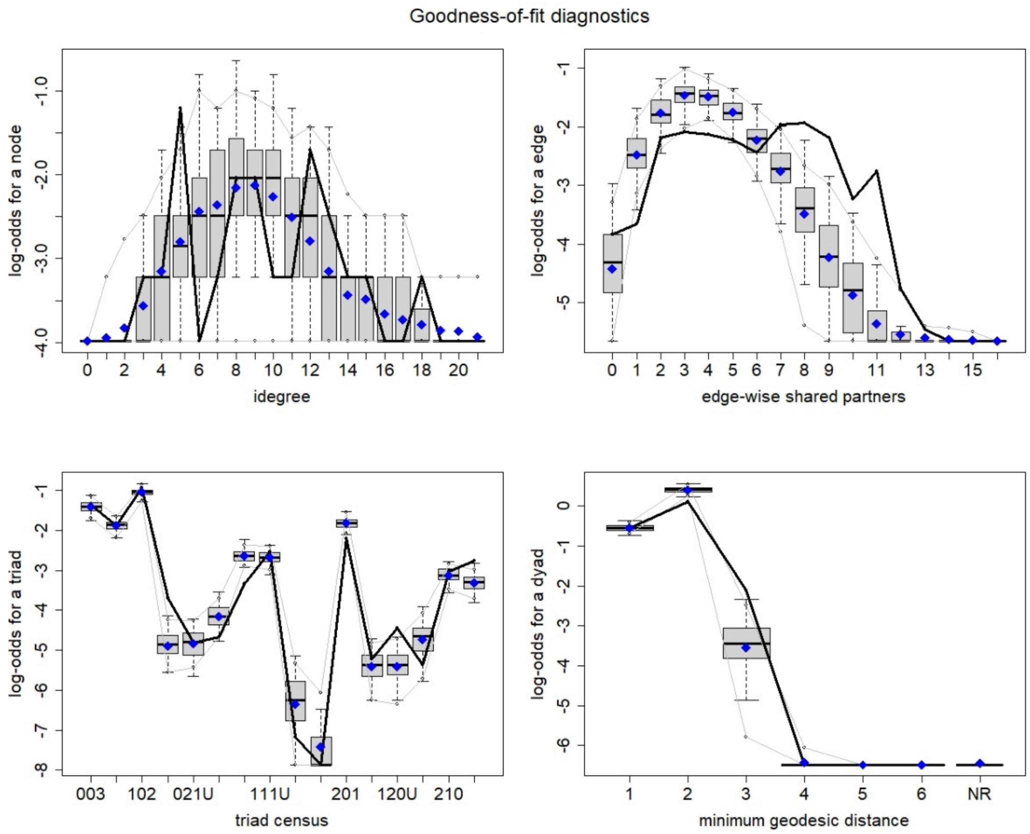
Note: Bold values indicate significant effects at the level of p-values of 0.05 or lower.

H ERGM goodness-of-fit

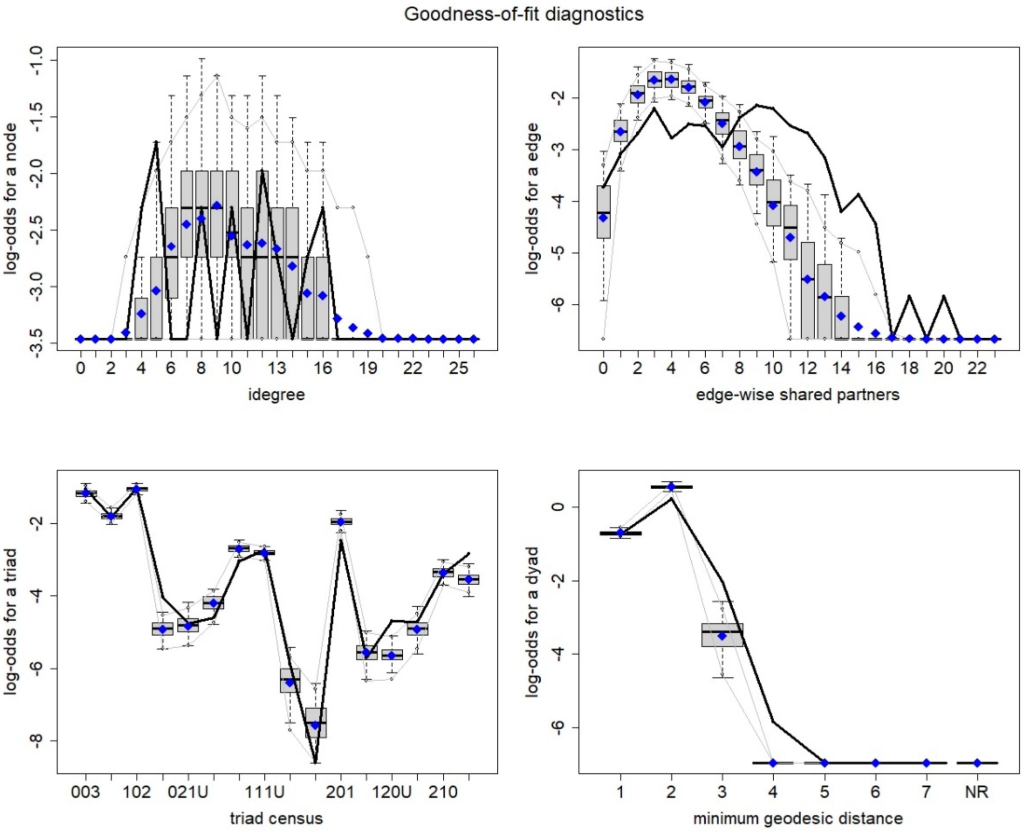
Case Study 1



Case Study 2



Case Study 3


Goodness-of-fit diagnostics
log-odds for a node
idegree
log-odds for a edge
edge-wise shared partners
log-odds for a triad
triad census
003
102
021U
111U
201
120U
210
log-odds for a dyad
minimum geodesic distance
NR

I Case-specific ERGMs and respective goodness-of-fit plots

Table I.1: *Inferential results obtained from extended local ERGM for case study 1*

	Dependent variable: ***Information exchange***	
	Case Study 1	
H1: Socio-technical dependencies in the form of socio-technical cycles	0.75 (0.53)	
H2: Same organization (municipalities, engineer, authority)	**0.74 (0.29)**	
H3: Degree central in terms of data transfer	-0.16 (0.15)	
H4: Perception on integrated management: integrated	**0.36 (0.46)**	
Member in a wastewater association	0.75 (0.54)	
Participation in local/regional planning meeting: -Yes	-0.34 (0.23)	
- Sometimes	-0.59 (0.51)	
Controls		
Edges	***-3.98 (0.92)***	
Reciprocity	***2.44 (0.48)***	
GWESP (0.1)	*0.40 (0.61)*	
Organization	*MUN 1*	-
	MUN 2	***0.42 (0.24)***
	Engineers	***1.06 (0.61)***
	Authority	***0.87 (0.42)***
	Wastewater association	***1.46 (0.74)***
Akaike Inf. Crit.	300.08	
Bayesian Inf. Crit.	350.20	

Note: Bold values indicate significant effects at the level of p-values of 0.05 or lower.

Goodness-of-fit for inferential results obtained from extended local ERGM for case study 1

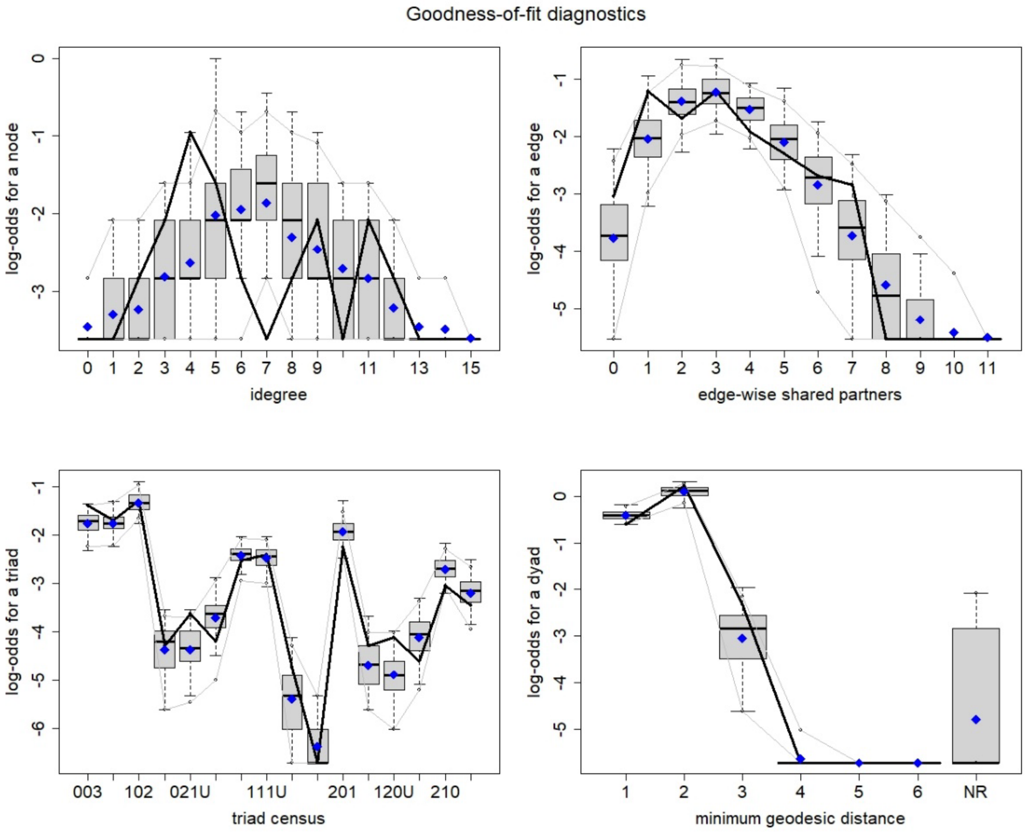


***Table I.2**: Inferential results obtained from extended local ERGM for case study 2*

	Dependent variable: ***Information exchange***	
	Case Study 2	
H1: Socio-technical dependencies in the form of socio-technical cycles	**1.16** **(0.25)**	
H2: Same organization (municipalities, engineer, authority)	**0.92** **(0.21)**	
H3: Degree central in terms of data transfer	**0.21** **(0.08)**	
H4: Perception on integrated management: integrated	0.22 (0.15)	
Participation in local/regional planning meeting: -Yes	0.14 (0.18)	
- Sometimes	-0.16 (0.19)	
Controls		
Edges	***-2.98*** ***(0.64)***	
Reciprocity	***3.21*** ***(0.33)***	
GWESP (0.1)	*0.37* *(0.45)*	
Organization	*MUN 1*	-
	MUN 2	*0.02* *(0.20)*
	MUN 3	*0.14* *(0.24)*
	MUN 4	*0.34* *(0.24)*
	MUN 5	***-0.63*** ***(0.21)***
	Engineers	*-0.30* *(0.19)*
	Authority	***1.09*** ***(0.26)***
Akaike Inf. Crit.	616.94	
Bayesian Inf. Crit.	683.91	

Note: Bold values indicate significant effects at the level of p-values of 0.05 or lower.

Goodness-of-fit for inferential results obtained from extended local ERGM for case study 2

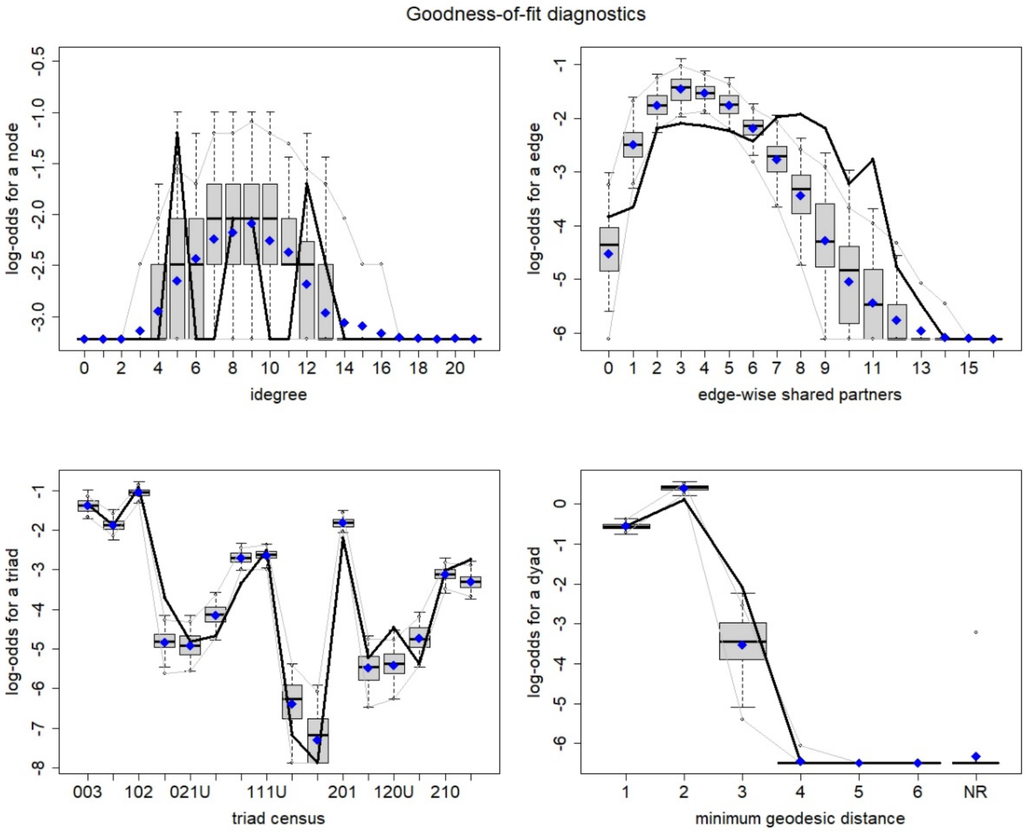
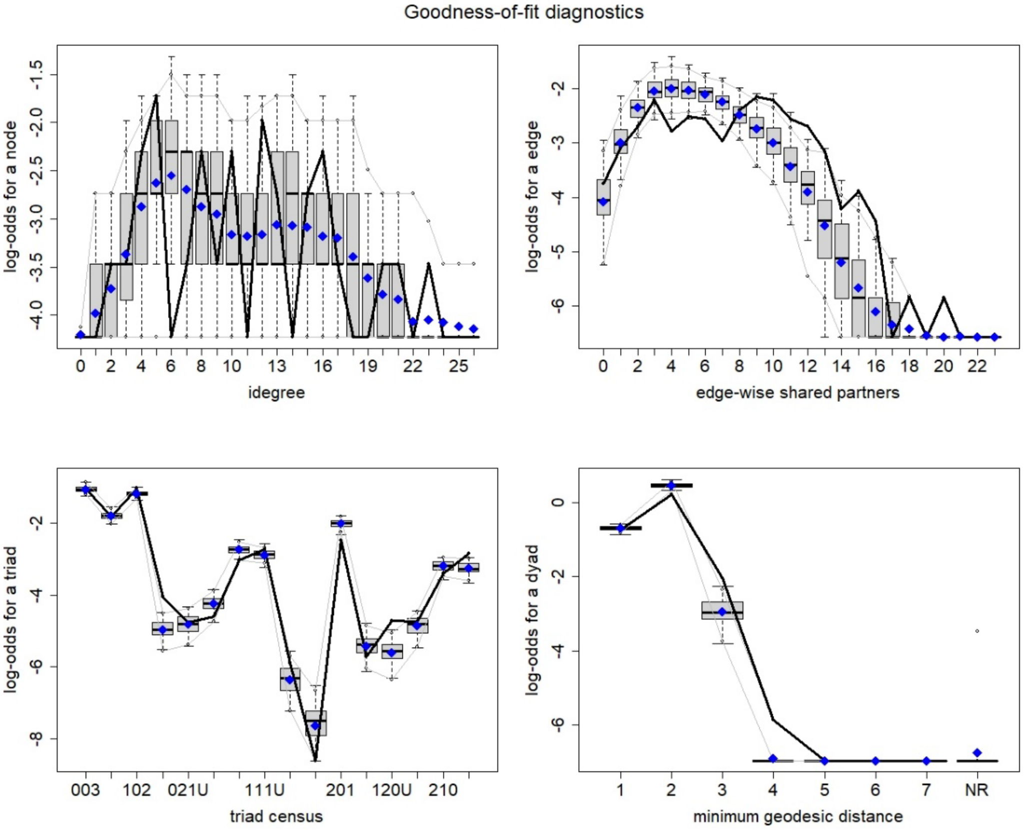


Table I.3: *Inferential results obtained from extended local ERGM for case study 3*

		Dependent variable: ***Information exchange***	
		Case Study 3	
H1: Socio-technical dependencies in the form of socio-technical cycles		**1.12 (0.18)**	
H2: Same organization (municipalities, engineer, authority)		**1.17 (0.22)**	
H3: Degree central in terms of data transfer		**-0.46 (0.20)**	
H4: Perception on integrated management: integrated		-0.17 (0.15)	
Member in a wastewater association		**0.87 (0.13)**	
Participation in local/regional planning meeting: -Yes		**0.38 (0.12)**	
- Sometimes		**-0.46 (0.21)**	
Controls			
Edges		***-2.72 (0.54)***	
Reciprocity		***2.94 (0.27)***	
GWESP (0.1)		*-0.10 (0.29)*	
Organization	*MUN 1*		***-0.50 (0.21)***
	MUN 2		***-0.46 (0.24)***
	MUN 3		-
	MUN 4		**-0.61 (0.26)**
	MUN 5		**-0.62 (0.25)**
	MUN 6		-0.25 (0.25)
	Engineers		*0.24 (0.20)*
	Authority		***0.80 (0.25)***
	Wastewater association		***1.30 (0.26)***
Akaike Inf. Crit.		883.25	
Bayesian Inf. Crit.		972.40	

Note: Bold values indicate significant effects at the level of p-values of 0.05 or lower.

Goodness-of-fit for inferential results obtained from extended local ERGM for case study 3



5. Conclusions

5.1 Summary

This PhD thesis explored the main research question asking about challenges related to the development towards smart urban water systems from a socio-technical perspective. Based on empirical data from Switzerland, challenges were analyzed at multiple levels: from the single-actor perspective of sub-state authorities in publication 1 to a multi-actor perspective in publications 2 and 3. In the following, I present answers to the three research sub-questions and the main research question, and summarize respective contributions.

1) What are barriers to the digital transformation of urban water systems?

Drawing on empirical data from 23 Swiss sub-states, the following two barriers were identified: i) *a lack of vision* or ii) *a lack of resources*. These two barriers did not necessarily occur in combination. Some sub-state authorities were hindered by a lack of vision, whereas others struggled with a lack of resources, and particularly with insufficient personnel for data-related tasks. In general, barriers to the digital transformation may occur at multiple levels: individual, organizational, and institutional levels. Related to the evaluation of monitoring data from sewer systems in Switzerland, barriers were found at the individual level (lack of vision) and the organizational level (lack of resources). Two further barriers were analyzed, the absence of a digitalization culture at the organizational level, and administrative fragmentation at the institutional level, which were both not sufficient for the absence of data evaluation. Beyond the case of urban water systems, these findings suggest that including multiple levels is important to improve the understanding of digital transformation in public organizations.

Contributions

- Investigation of an underexplored topic in studies on digital transformation: most research deals with the implementation of digital innovations, but less with how people utilize data (Maciejewski, 2016; Sun et al., 2016; Surbakti et al., 2019). Instead of analyzing barriers that hinder the adoption of a digital technology, this publication provides evidence on barriers that hinder the effective utilization of obtained data from such technologies.
- Drawing on literature from policy and innovation studies, information technology sciences, and environmental engineering, our model of potential barriers to the digital transformation suggests including individual, organizational, and institutional levels as well as interactions among them. These three levels have previously not been investigated together in studies on digital transformation in public organizations.
- Findings stem from a medium-N comparative setting as compared to many articles that draw on single case studies. With this comparative setting and analysis, important variations among cases are traceable (Chatwin et al. 2019).

2) How can a socio-technical network (STN) perspective of infrastructure systems, such as urban water systems, inform about challenges related to digitalization?

As part of publication 2, the conceptual approach of socio-technical networks (STNs) in the context of networked infrastructure systems was developed, and specifically applied to the case of urban water management. A single empirical case study of an urban water system in Switzerland illustrated how a STN of urban water management can be assessed in a socio-technical way. To analyze such a STN, several analytical concepts were developed drawing on literature from social network analysis and social-ecological networks:

- Descriptive STN concepts on density, reciprocity and (degree) centrality in STNs
- Socio-technical motifs, i.e. sub-structures in STNs consisting of three or four nodes
- Equations to calculate the degree of digitalization, decentralization, and integrated management from a STN perspective

The application of these STN concepts for the empirical case study provided valuable insights on interrelated technical elements and social actors involved in managing an urban water system. For example, urban water systems can be evaluated in terms of digitalization or integrated management from a socio-technical perspective that not only includes whether technical elements are equipped with digital technologies, but also which social actors have access to respective data. The STN operationalization further allows identifying which social actors are currently not exchanging information, but should do so, in order to manage technical elements of an urban water system in a more integrated way. In this sense, publication 2 adopts a relational perspective and considers *potential challenges to smart urban water systems as missing relations* in the STN. Bridging these gaps could overcome respective challenges. This conceptual finding is transferable to other contexts and sectors related to networked infrastructure systems, for example drinking water, transportation, or energy systems.

Contributions

- Novel conceptualization of structurally explicit socio-technical networks (STNs) in the context of networked infrastructure systems and development of descriptive concepts to analyze empirical STNs.
- The analysis of the empirical case study in Switzerland demonstrates how STNs allow for an identification of socio-technical challenges related to digitalization. For example, a STN can inform about social actors who operate specific technical elements but do not have access to (monitoring) data on these elements.
- Studies on socio-technical systems as well as those focusing on digitalization, decentralization, or integrated management, are provided with a systematic and formally explicit tool to analyze infrastructure systems from a STN perspective. This STN tool can also be applied in science-policy exchanges to discuss potential gaps in the network with stakeholders. As a result, infrastructure management practices could be improved.

3) What are socio-technical challenges to managing smart urban water systems?

The following socio-technical challenges were identified in publication 3: i) *organizational fragmentation*, ii) *data access*, and iii) *diverging perceptions*. Drawing on the STN approach as presented in publication 2, an inferential analysis of three case study urban water systems in Switzerland revealed that social interactions, such as information exchange among actors involved in managing an urban water system, are influenced by socio-technical dependencies. For example, two actors who operate two technically connected technical elements are more likely to exchange information. Based on the assumption that such information exchange is necessary to achieve integrated urban water management and to enable real-time control of technical elements in a catchment area, findings showed that the influence of the three socio-technical challenges on information exchange varies between the case studies. Such differences may potentially relate to catchment-specific characteristics, such as catchment size, related socio-technical complexities, forms of organization, or progress in terms of data-driven and integrated urban water management.

Contributions

- From a methodological point: Inferential analysis of socio-technical networks (STNs) using exponential random graph models (ERGMs), which has not been done previously.
- Findings show that social interactions in the context of managing an urban water system (or more generally, an infrastructure system) are influenced by socio-technical dependencies, i.e. how actors are related to technical infrastructure elements.
- Socio-technical challenges (i.e., organizational fragmentation, data access, and diverging perceptions) towards smart urban water systems are studied. The study further sheds light on socio-technical system characteristics (e.g., system size, form of organization), which potentially impede or enable developments towards smart urban water systems.

With respect to the main research question, the following answer can be provided.

> ***What are challenges to the development towards smart urban water systems from a socio-technical perspective?***

Challenges towards smart urban water systems are located at multiple social levels, including individual, organizational, and institutional levels. Moreover, the respective actors representing these levels are intertwined, not only among each other, but also with respect to the technical urban water system. Such social and socio-technical interactions and interdependencies are relevant in terms of smart urban water system developments, and need to be incorporated in policy- and decision-making that aims to support such developments.

5.2 Recommendations for policy and practice

Based on the findings from the three PhD publications as well as additional qualitative insights from interviews and surveys, recommendations that may give orientation and guidance for policy-makers and practitioners are suggested. A variety of stakeholders involved in urban water management and related tasks could benefit from these: representatives from national, sub-state ('cantonal'), or local authorities (i.e., municipalities), from professional associations, but also engineers, planners, operators, or technology companies. The recommendations are applicable to the case of urban water management in Switzerland. However, some recommendations could also be useful for other countries facing challenges related to the development towards smart urban water systems.

The suggested recommendations aim to answer the following question:

> What are potential solutions to overcome identified socio-technical challenges towards smart urban water systems?

This question was formulated as part of the POLAAR project (in which this thesis is embedded) but not addressed in a scientific publication. However, complementary to the main research question of the PhD thesis, the following recommendations concern potential solutions that could help address challenges identified and analyzed in the respective PhD publications.

Potential solutions to overcome respective challenges are:

1) Developing appropriate organizational conditions: the "catchment" perspective

For representatives from national, sub-state ('cantonal'), or local authorities (i.e., municipalities) and professional associations:
Drawing on the results from publications 2 and 3, considering the development towards smart urban water systems at the catchment level of a WWTP is important. Such catchment areas feature different constellations of actors and infrastructure elements and different socio-technical complexities depending on catchment size, form of organization, or progress in terms of data-driven and integrated management, among others. Therefore, respective challenges may vary depending on catchment-specific factors.

Bringing the operation, planning, and management of WWTPs and (combined) sewer systems together at the technical level requires bringing multiple actors from the 'WWTP side' and the 'sewer system side' together (cf. publication 2). In a catchment area with several municipalities, this is to a certain degree already achievable through joint forms of inter-municipal cooperation, e.g., wastewater associations. Ideally, the focus of such wastewater associations, however, would move from "wastewater" to "integrated management", and thus would incorporate the "stormwater" component as well (e.g., "integrated urban water association", "catchment association"). At the operational level, these forms of organization could include the delegation of competencies (for example related to monitoring data), joint financial planning with an own budget and own financial possibilities that concern not only the WWTP, but also elements of the sewer system (e.g., CSOs). Such elements could remain as property of municipalities, but operational competencies (e.g., related to CSOs, for example) could be delegated to the association.

For planners, engineers, and municipalities:
Catchment-wide contracts with consultant engineers and planners would be useful. Until now, it is still very common that each municipality has their own consulting engineer or planner, which potentially hinders integrated urban water management already in the planning phase.

For technology companies, municipalities, and operators:
Similarly, related to smart urban water systems, it seems important to have a certain standard regarding the monitoring technology and the obtained data formats within a catchment area. For example, the dynamic control of urban water system elements is very difficult to achieve if different parts of a single urban water system rely on different digital technologies. It is (still) very difficult to bring data, stemming from different technologies, together. This further prevents certain actors from accessing useful data (cf. publication 3). Therefore, a single digital technology provider per catchment area is considered beneficial.

2) Providing required resources and tools to handle data

For national authorities and professional associations:
Smart urban water systems is not only about installing the digital technologies, but also about equipping relevant actors with the possibilities for handling and utilizing data and increasing their awareness on associated benefits. In publication 1, lack of vision or lack of resources were identified as challenges at the level of sub-state authorities. To address these two challenges, investments in human resources are required. Such human resource investments could be accomplished either by hiring new qualified personnel or by training existing personnel at the municipal and sub-state authority levels. Another option is outsourcing tasks related to monitoring data. Human resource investments can have a positive side effect, if individuals develop a vision towards smart urban water systems. Furthermore, education and training can help building or strengthening such a vision by making the benefits of monitoring data more tangible.

Below are some potentially helpful and more precise suggestions:

- Tools for monitoring data platforms, monitoring data interpretation, automatic report generation. These could be provided nationally with the joint support of companies that have the required expertise.

- Educational measures for raising awareness on integrated urban water management (that for example could be offered as an additional item on the agenda of a 'GEP check event' by invited and skilled representatives).
- Exchange among catchment areas to share knowledge and experience (similar to the 'Regenbecken Nachbarschaften' ('CSO neighborhoods') in Baden-Württemberg (Germany) or the 'Klärwärter Tag' ('WWTP operator day') in Zurich (Switzerland), but including more (diverse) actors from a catchment urban water system).
- Making data publicly available to increase transparency and to engage with the public (one good example is the following website from the UK: https://bit.ly/3yEakFu).

Overall, from a national perspective, sub-state differences in terms of utilizing monitoring data, but also in terms of resources, should be taken into account, particularly when designing regulatory policies or guidelines for handling monitoring data form urban water systems.

3) Aligning policy design with socio-technical characteristics of urban water systems

For national authorities and professional associations:

Data-driven and integrated urban water management are partly difficult to achieve as different actors have different goals, tasks, and perceptions (cf. publication 3). Therefore, adapting regulations that incorporate the idea of integrated urban water management is considered important, i.e., by including all elements of urban water systems, which have an impact on surface waters. In order to bridge the gap and remove the 'organizational silo structure' (cf. publication 3) between representatives responsible for either WWTPs or for sewer systems, integrated management needs to bring actors together at all levels, i.e., at the local and regional operating levels and at the levels of sub-state and national authorities.

Further, when it comes to the design of policies that support the development towards smart urban water systems, the multiplicity of actors involved in integrated urban water management should be considered (cf. publications 2 and 3). For example, if regulatory targets for monitoring data from CSOs will be defined, it must also be made clear who should be responsible for obtaining, handling, and managing this data, and who bears consequences if related targets are not met. Ideally, the design of such a policy would ensure that smart urban water systems and integrated urban water management are approached in a coordinated manner, and not by individual actors themselves.

Incorporating such actor perspectives also emphasizes that urban water systems should not only be assessed from a technical point of view when it comes to the progress in terms of digitalization or integrated management. For example, the installation of monitoring technology in CSOs does not immediately imply that relevant actors have access to obtained data. Drawing on the socio-technical degrees of digitalization and integrated management as developed in publication 2, it is important to evaluate respective progress in a socio-technical way, including both technical and social aspects. This is particularly the case for integrated urban water management, which in fact requires integration at both technical and social levels.

Local or regional planning meetings (as for example the ones related to the 'GEP check') could be used more explicitly to foster exchange within a catchment area and to bring more stakeholders together. For example, in publication 3, results showed that information exchange among actors in a catchment area is more likely if these actors participate in 'GEP check events'. These events could be reframed to include more actors, for example WWTP operators and representatives from municipalities, particularly those from municipal works ('Gemeindewerke'), as they often have a great knowledge on the functioning of the urban water system, but are often not part of 'GEP check' events so far (s. publication 3).

It seems relevant to establish catchment-wide environmental impact assessments, which allows tracing the impact of integrated urban water systems on surface waters. In this sense, each catchment area could also establish a 'catchment taskforce' (similar to the 'V-GEP check' meetings), where stakeholders could more directly approach their commonly defined goals. Ideally, such a taskforce would also include the specific role of a 'catchment coordinator' (similar to the 'V-GEP-Gesamtleiter') to ensure that integrated urban water management happens in a coordinated form. In the long-term, such a taskforce could even open up to include representatives from the drinking water sector (for example, in the context of decentralized technologies, such as greywater recycling or water reuse technologies) or water protection experts. Such a unified 'water taskforce' could ultimately lead to incorporating the entire lifecycle of the resource within an overarching organizational unit for a catchment area (where the boundaries of the catchment area would need to be redefined of course).

All suggested recommendations and measures, if implemented, come at certain costs. The question is if the costs outweigh the benefits, which is often hard to quantify, as there is no monetary value assigned to the (aquatic) environment. For example, there is no clear monetary benefit from reducing CSO events. Yet, an economic perspective could be useful to explore how benefits could be expressed in monetary equivalents. In addition, many open questions need to be addressed by practitioners (and scientists), such as for example related to accountability, responsibility, and potential risks associated with smart urban water systems.

5.3 Limitations and challenges

5.3.1 Research limitations

With the specific research orientation on challenges towards smart urban water systems, this PhD thesis bears several limitations.

1) Policy design, implementation, and effectiveness

Overcoming identified challenges requires developing and implementing appropriate policies at national, sub-state, regional, and local levels. This thesis does not analyze policies that could have a positive impact on the development towards smart urban water systems, although in *chapter 5.2* I suggested recommendations for policy and practice derived from the findings of the publications and qualitative insights from surveys and interviews. However, more research is needed to evaluate potential policies and to measure their effectiveness. To do so, indicators that could capture policy effectiveness, for example in terms of reaching certain defined goals, would need to be developed and tested.

2) Social systems include more aspects than actors

This thesis focuses on actors in urban water management and considers further aspects of social systems as contextual. Consequently, not all aspects of social systems are covered that, however, may have an important effect on the development towards smart urban water systems, such as related to regulative, normative, or cultural-cognitive elements ('social institutions') (Scott 2008). For example, current regulations could be evaluated related to possible extensions to cover particular aspects of smart urban water systems.

3) Research focus on Switzerland

The spatial focus on Switzerland limits the transferability of findings. The identified challenges towards smart urban water systems are valid in the context of Swiss urban water management. Yet, these challenges were derived from overarching theory, which consequently implies that they are potentially relevant in other contexts as well. Therefore, future research could more explicitly focus on comparative research designs, for example to investigate challenges in different countries (Msamadya et al. 2022), or to learn from challenges observed in other sectors. One example for such a cross-sector comparison could apply to smart grid developments in the energy sector.

4) Units of observation

From a methodological perspective, the publications of this thesis draw mostly on in-depth insights from medium-N studies. In publication 1, 23 (out of 26) Swiss sub-states are compared, and in publication 3, the number of social actors surveyed in all three case study catchment areas totals to 77. This methodological focus puts more emphasis on qualitative and relational insights than large N-study results. However, other units of observation could be interesting, such as for example the entire population of Swiss municipalities. Yet, in large N-studies, qualitative or relational insights between individual actors are difficult to obtain.

Qualitative insights, however, may also be important in terms of the progress of smart urban water system developments. Publication 2 suggests how to calculate socio-technical degrees of infrastructure systems in terms of digitalization, decentralization, and integrated management. Besides evaluating such progress in quantitative terms, a qualitative, categorical description that goes beyond a single number could be more beneficial to practitioners. Enhancing the evaluation in a qualitative way could also go in hand with adding specific challenges to each category, thus allowing for addressing these challenges more directly.

5) Analytical approaches

Analytical approaches, such as QCA or network analysis, were specifically chosen to answer respective research sub-questions. Both QCA and network analysis are tools that predefine how and what kind of data is gathered and in which way hypotheses are operationalized. However, other tools and approaches could be relevant; for example, agent-based modeling (Berglund 2015; Panebianco and Pahl-Wostl 2006), or system dynamics (Prouty et al. 2020; Whyte et al. 2020). These approaches could also provide more dynamic perspectives on the development towards smart urban water systems.

6) Speed of smart urban water system developments

The data analyzed as part of publication 1 was already obtained in the year 2017. Given the speed of digital transformation (Green and Daniels 2019), findings from publication 1 might no longer be valid today. It seems realistic that (some of) the identified challenges are not relevant anymore or that new challenges came into place.

In both publications 2 and 3, the STN representation is limited by its one-point-in-time validity. However, developments towards smart urban water system are rather dynamic, and may change quickly, not only at the technical level, but also at the social level, for example, if new social actors become relevant or other social aspects change. The STN approach could be extended to represent such changes, but collecting and analyzing STN data at different points in time would increase scientific efforts and make the research process more complex.

7) Exclusion of ecological or environmental aspects

The approach of STNs in publications 2 and 3 excludes environmental or ecological elements, such as streams, rivers, or lakes, which however could be important. For example, the impact from some technical elements of urban water systems might be more relevant for sensitive surface waters that require more protection. In this sense, the STN only grasps the technical elements and social actors, but neglects potentially important environmental dimensions.

5.3.2 Challenges in an interdisciplinary research context

With my educational background in environmental engineering, a PhD project characterized by its strong social science orientation has brought many challenges to overcome or withstand. Interdisciplinarity, in this chapter, refers to *individual interdisciplinarity* that I experience with my backgrounds in multiple disciplines as compared to *collective interdisciplinarity* where several researchers with different disciplinary backgrounds work together on a project. Compared to collective interdisciplinarity, individual interdisciplinarity and associated challenges and benefits are largely underexplored in scientific research (Locatelli et al. 2021).

While I try to generalize some of my reflections, the three presented examples never leave the thematic proximity of my PhD project: urban water systems. My goal is to show the challenging environment of interdisciplinary research to both engineers and social scientists.

Social sciences and 'engineering sciences' are umbrella terms and include many different sub-disciplines. The following reflections draw on my own experiences but may also apply more generally.

Reflection 1: Different research characteristics

In this thesis, I refer to the case of *(smart) urban water systems and their management in Switzerland*. From a social science perspective, the research therefore revolves around this explicitly defined case study. Engineers, however, would rather recognize (smart) urban water systems as their research object, i.e., it is less common to define 'social' boundaries for studying an urban water system. Most research that engineers conduct focuses on technical aspects, and in the case of urban water systems, these technical aspects are less or not at all influenced by different countries, political systems, or forms of governance. Therefore, results from engineering sciences on urban water systems may be valid globally as long as it concerns the technical level only. For example, insights gained from a single real-world urban water system may be transferrable to many others. This is not the case for social aspects and respective social science research, as social systems vary strongly depending on location and context. Social science research designs generally build on and draw from a wide overarching theoretical sphere. Research questions and hypotheses are often formulated based on extensive literature reviews on relevant theories and often, deductive reasoning, i.e., arguments derived from theory. By contrast, research in engineering sciences is less embedded in a theoretical sphere and rather draws on inductive reasoning, i.e., arguments derived from observations. In terms of goals, roughly speaking, social sciences are concerned with understanding and explaining the social system, from which in some instances potential recommendations on how to improve aspects of the social system are derived. Engineering sciences rather directly address changes in existing technical systems through optimization or improvement approaches. To do so, 'engineering hypotheses' in the context of urban water systems relate directly to certain systems or processes, for example, physical, biological, or chemical processes, among many others. By contrast, social science research draws on a tremendous and manifold availability of frameworks and concepts, which allow for studying specific social hypotheses, for example related to social phenomena, such as collaboration or learning. Finally, whereas social sciences adopt more problem-oriented and/or policy-oriented perspectives, engineering sciences take up solution-oriented or problem-solving perspectives and mostly deal with predictions.

This comparison of social and engineering science characteristics shows several contrasts inherent to the respective discipline. However, in collaborative interdisciplinary settings, such contrasts may often be invisible, neglected, or perceived as causes of conflict. From my own individual interdisciplinary perspective, I encourage accepting and discussing these different perceptions and raisons d'être that each discipline holds for their respective scientific purposes.

Reflection 2: Data validation

(Scientific) validity can be divided into two forms: internal and external validity. Internal validity refers to how trustworthy the studied causal relationships are without being influenced by other factors. External validity describes how the results obtained from a study are applicable or generalizable to other contexts. Generally, both internal validity and external validity in social science research are not easy to achieve (McDermott 2011). Controlling for all other social factors, which potentially affect the data collection process and the studied causal relationship itself, is difficult to achieve. In laboratory experiments, however, one single condition can be generated, thus restricting the effect of other relevant factors. When it comes to external validity, results from laboratory experiments may sometimes not hold in a real-world setting, as other real-world factors may influence the causal relationship. Social science research, although already conducted in a real-world setting, depends on the context. Consequently, findings obtained in one particular context may not be directly transferrable to other contexts.

Social and engineering sciences consider internal and external validation procedures differently. Here, I would like to show an example from the review process of publication 2:

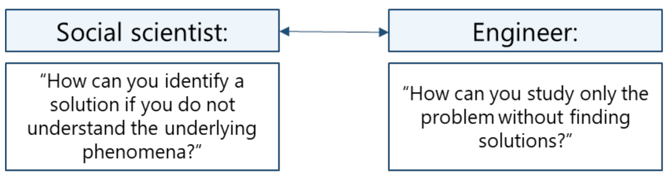
Reviewer: *"Please describe how you mapped a real-world urban water system into a socio-technical network and explain the validation processes"*.

The reviewer, who has most probably an engineering background, points to the need for validation, as for technical systems only 'one' truth may exist. For a technical system, such an assumption may be very valid. However, social scientists studying social systems (which are also more complex than technical systems) do not apply this idea of validation, as they are aware that 'the truth' strongly depends on perspectives and sources of evidence, such as for example surveys or interviews, and data obtained from these. Yet, social scientists normally discuss such perspectives and sources critically.

In the process of revising publication 2, we gave more thought to potential ways of validating socio-technical networks (s. also Narayan et al. (2020), which we explicitly describe in the publication. We provide information on our validation strategies along every step from the research design to data collection and data analysis, and discuss the validity of our results. For example, we validated the technical network, and tried to elaborate on the validity of social and socio-technical parts of the network. However, this is where we also reached our limits. Whereas our validation strategies may satisfy engineering audiences, social scientists will still be aware of the underlying complexities, view 'validation claims' with caution and will not regard them in the same sense and with the same meaning as engineers.

Reflection 3: Research gap and research questions

It is not easy to bring both social scientists and engineers together to share a common idea of a research gap or of the practical relevance of a certain (applied) research topic. This is mainly due to the differences mentioned under Reflection 1. However, other factors play a role as well. As the main research motivation of social scientists differs from engineers – social scientists being interested in explanation, engineers in prediction – a joint formulation of a research gap is not easy to narrow down. For example, social scientists are rather interested in understanding and explaining a certain phenomenon. Findings and learnings then may feed into the development of potential recommendations for practice. Engineers, by contrast, focus on ways to directly solve a certain problem, thus identify a particular solution and develop ways to achieve this solution (i.e., 'fixing the broken machine'). For technical systems, such 'problems' are much more evident and clear. Social scientists, instead would not accept 'a problem' as a research motivation (e.g., who says it is a 'problem'?), as it is difficult to assess and define 'a problem' in itself (i.e., it is not clear when the 'social system machine' is 'broken'). In the context of my PhD research, I collaborated with both social scientists as well as engineers. The following (slightly exaggerated) juxtaposition of two questions shows the opposing views between the two disciplines:



From these two questions, it is easy to do the combination: obviously, in applied interdisciplinary research, it needs both perspectives and disciplines (and even more) to understand a (societal) problem and the underlying phenomena as well as to provide solutions.

5.4 Outlook

This PhD thesis gave answers to the research question asking about challenges towards smart urban water systems from a socio-technical perspective. Drawing on a multiplicity of literatures, the overall research provided i) findings from the application of a general model of barriers towards digitalization in infrastructure sectors, ii) the approach of STNs in the context of networked infrastructure systems, iii) insights on socio-technical challenges towards smart urban water systems based on an inferential STN analysis.

A major part of the PhD publications (2 and 3) revolves around the STN approach, whereby the conceptualization and formal description of such STNs make a relevant contribution to the literature on socio-technical systems, infrastructure management, and urban water governance. In the following, I give two examples of STN operationalizations that could serve to answer further research questions, and thus potentially advance the socio-technical understanding of urban water systems and urban water governance, in particular related to actor constellations. Besides digitalization, another important infrastructure trend that is also touched upon in publication 2 is *decentralization*. Compared to existing centralized urban water systems that consist of a central WWTP and a connected sewer system, the integration of decentralized solutions is on the rise (Fischer et al. 2022; Pakizer et al. 2020; Hoffmann et al. 2020). Among many such solutions, two examples are local or modular technologies that recycle greywater for reuse, or blue-green infrastructures that catch and retain stormwater before it enters combined sewer systems.

In Figure 5.1, I illustrate an example of a STN operationalization in the context of these developments that – if implemented in a research design – could help answer research questions such as:

- How do new actors related to decentralized technologies or blue-green infrastructures interact with traditional actors of centralized systems? How do they collaborate or exchange information? How are such interactions manifested during daily operational practices, planning processes, or specific projects?
- Are new social actor roles created and if so, how are they embedded in the overall social network?
- Who are boundary-spanning actors, i.e., actors that establish connections between traditional actors responsible for centralized systems and new actors associated to decentralized technologies or blue-green infrastructures?
- Who are important actors, and thus potentially relevant to push for or impede developments towards decentralized technologies or blue-green infrastructures?

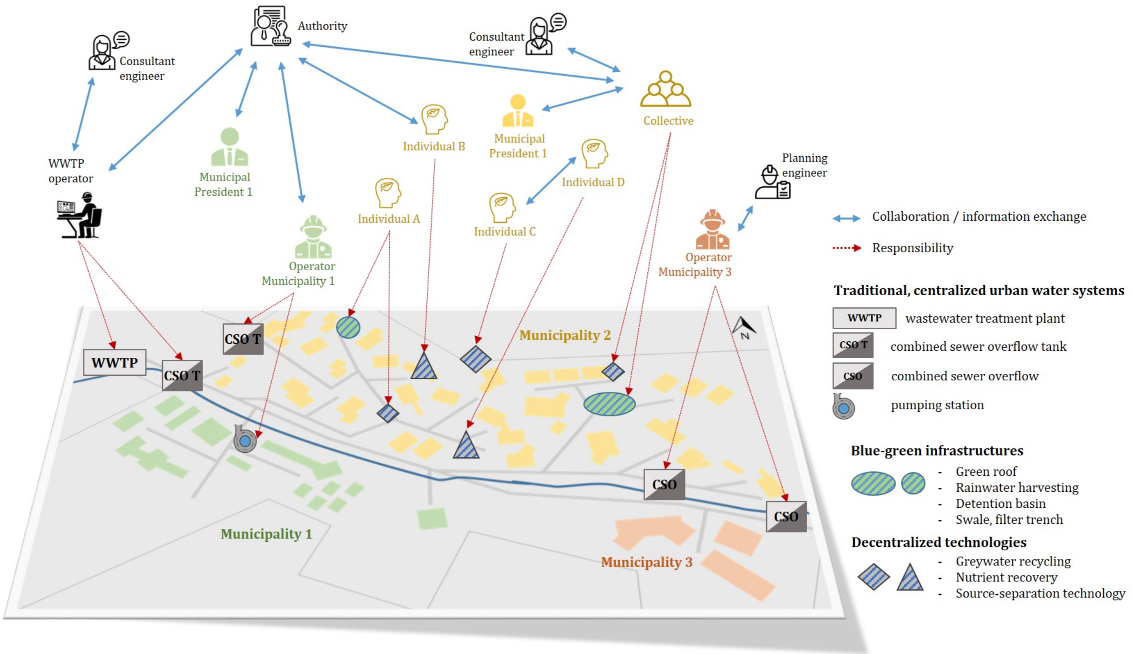


Figure 5.1: An example of a potential STN operationalization, where additional to the centralized urban water system elements, both blue-green infrastructures and decentralized technologies are represented as network nodes. Further, social actors responsible for all types of infrastructure elements are included as well as respective potential edges, such as collaboration or information exchange among social actors.

Finally, in future research, an even more holistic STN representation may further include ecological elements, such as rivers, or more generally aquatic ecosystems, thus forming a 'social-ecological-technical' network, that could draw on theoretical considerations from the literature on social-ecological-technical systems (Markolf et al. 2018; Grabowski et al. 2017; van der Leer et al. 2018).

5.5 Smart urban water systems – the way to go?

The PhD thesis' interest lies in the development of and need for smart urban water systems demanded by both scientific and practice representatives. To close this PhD thesis, this chapter intends to reflect on the necessity of smart urban water systems based on respective literature.

Climate change impacts, urbanization, and aging assets put pressure on existing urban water systems. Making urban water systems smart holds great potential to mitigate such pressures (Lassiter and Leonard 2022), for example by exploiting all operational capacities in sewer systems during heavy rainfalls through real-time control, thereby reducing combined sewer overflow events. Consequently, digital technologies can foster more efficient and environmental friendly urban water systems. Beyond these benefits, smart urban water systems may bring further useful information to light. For example, since the COVID-19 pandemic, continuous qualitative wastewater monitoring has been carried out in several countries, which allows for an early detection of infection hotspots (Fernandez-Cassi et al. 2021) or spread of new virus mutations (Jahn et al. 2022).

Despite the usefulness and benefits associated with smart urban water systems, several risks and potential disadvantages should be mentioned.

First, from a resource point of view, it is unclear if the environmental benefits reached by the utilization of digital technologies in urban water systems in fact outweigh their environmental impacts. For example, rare resources are exploited to produce sensors and transmission technologies. Further, data servers consume non-negligible quantities of electricity. This raises the question if smart urban water systems will truly be more environmental friendly infrastructures as compared to traditional non-smart ones (Santarius et al. 2022). Second, by adding the digital layer to infrastructure systems, such as urban water systems, the dependency on data and digital technologies will increase (Wilson et al. 2017; Habibzadeh et al. 2019). Smart urban water systems, in particular, will become more vulnerable to cyberattacks, for example. Thus, important issues around cybersecurity and privacy deserve further research (Moy de Vitry et al. 2019). Third, obtaining data from urban water systems implies only the means to an end. Making use of data is how the actual benefits can be achieved. Therefore, it is likely that large amounts of data will remain unused and end up as 'data waste' if their value is not recognized (Mergel et al. 2016).

However, given that our society in general, and infrastructure sectors in particular are more and more relying on digital technologies and data to provide infrastructure services, it does not seem conceivable that a particular infrastructure – urban water systems – is left out of the development. Ultimately, with this view on smart urban water systems, this PhD thesis contributes to demonstrating the need to look beyond the technical horizon by drawing on social sciences perspectives and by shifting the focus on socio-technical challenges.

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