

# Socio-technical challenges towards data-driven and integrated urban water management: A socio-technical network approach

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## ABSTRACT

Data-driven and integrated urban water management have been proposed to reduce surface water pollution in light of climate change and urbanization impacts. Besides technological innovation, data-driven and integrated management require information exchange among many actors, e.g., operators, engineers, or authorities. With the aim of achieving a more profound understanding of socio-technical infrastructures, such as urban water systems, I draw on the approach of socio-technical networks to study actors and infrastructure elements as well as multiple relations in-between. In this article, I investigate whether underlying socio-technical dependencies influence social interactions such as information exchange. More specifically related to data-driven and integrated management, I analyze potential challenges, such as organizational fragmentation, data access, and diverging perceptions. Based on empirical data from three case studies in Switzerland, I provide inferential results obtained from fitting exponential random graph models. Findings showed that actors' relatedness to infrastructure elements affects their information exchange. Among the cases, the presence of the three challenges varied and is potentially contingent upon system size, organizational form, or progress in terms of data-driven and integrated management. Thus, incorporating a socio-technical perspective on social actors and infrastructure elements could help to improve policy design and implementation aiming to achieve more sustainable cities.

## 1. Introduction

Climate change and urbanization affect how urban water systems (UWS) are managed in cities (Miller and Hutchins 2017; McDonald et al., 2014). For example, more frequent and extreme rainfalls challenge the 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 surfaces accumulating more rainfall discharges (Salerno et al., 2018).

Potential solutions to these issues have been proposed and studied in several contexts and countries. For example, the “Sponge City Program” in China suggests implementing nature-based solutions rather than relying solely on traditional engineering approaches related to ‘grey’ infrastructure (Chan et al., 2018). In Australia, “Sustainable Urban Drainage Systems” have become popular (Roy et al., 2008), which, similarly to the “Sponge City” concept, refer to more ecological and sustainable solutions to collect and retain stormwater in a catchment

area.

A further solution proposed to address overflow events and thus to reduce surface water pollution from urban settlements is data-driven urban water management (UWM), which relies on the utilization of real-time monitoring data on the performance of UWS elements. Examples of such UWS elements are wastewater treatment plants (WWTPs), combined sewer overflows (CSOs), or pumping stations, among others (Yuan et al., 2019; Oberascher et al., 2022). Ultimately, monitoring data allows for a real-time control of these elements with the objective of exploiting all existing operational capacities to reduce environmental impacts, thereby leading to more sustainable outcomes in urban areas (Blumensaat et al., 2019; Ingildsen and Olsson 2016; Kerkez et al., 2016). Beyond quantitative monitoring data, conducting further qualitative measurements could ideally contribute to evidence-based waterborne disease management or drug control (Castiglioni et al., 2014; Li et al., 2019; Zahedi et al., 2021). One example of qualitative wastewater monitoring is the surveillance of SARS-CoV-2 variants for early detection (Fernandez-Cassi et al., 2021; Jahn et al.,

*Abbreviations:* UWS, urban water system; UWM, urban water management; STN, socio-technical network.

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2022).

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, real-time control and integrated management of UWS are only slowly implemented, and where sensor technologies already exist, real-time monitoring data is often not optimally used (Oberascher et al., 2022; Sarni et al., 2019; Manny et al., 2018). To some extent, technical reasons explain this observation, 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. Bringing these different social actors and their perspectives together, i.e., providing integration at both technical and social levels, could potentially lead to higher economic efficiency through improved technical infrastructure performance (Hällström and Bosch-Sijtsema 2020) and reduced environmental impacts (Biddle and Koontz 2014; Scott 2015). 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 (Finger et al., 2005), in this case, for UWS. Consequently, policy and decision-making supporting the development towards sustainable cities and infrastructures could benefit from evidence on how well technical and social systems align and where important socio-technical dependencies need to be considered when identifying potential ways for improving socio-technical alignment.

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 an UWS (e.g., several operators, engineers, and authorities) do not exchange information within a catchment area, it might be rather difficult to achieve an integrated management of UWS elements.

Therefore, the research, as presented in this article, aims at obtaining a better understanding of socio-technical infrastructure systems, such as UWS. Given the relevance of information exchange among social actors for managing such infrastructures, I investigate how dependencies between social actors and technical infrastructure elements affect information exchange. Further, following the assumption that information exchange is fundamental to achieving data-driven and integrated UWM, the research addresses particular context-specific challenges at the social and socio-technical levels, potentially hindering digitalization and integrated management developments.

To do so, I adopt a socio-technical perspective on UWS and their management to answer the following overarching research question: *How do socio-technical dependencies influence social interactions, such as information exchange among social actors?*

Related hypotheses comprise 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 also 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.

This article makes several contributions to the literature addressing both practice-oriented and scientific gaps. First, with its socio-technical focus, this research connects to the literature on socio-technical systems (Ottens et al., 2006) and infrastructure reforms (Finger et al., 2005; Künneke et al., 2021), particularly related to the alignment of organizational modes and networked infrastructure systems (Künneke et al., 2010). Compared to previous research on these aspects, this article provides a structurally explicit and network-based quantitative analysis of such infrastructure systems, thus allowing for systematic comparability of local or regional empirical cases in various infrastructure contexts (Manny et al., 2022). In this article, I focus on the example of UWS, for which I empirically investigate whether social interactions, such as information exchange among social actors in the context of managing UWS, are influenced by underlying socio-technical dependencies. Here, socio-technical dependencies refer to the social actors' relatedness to technical infrastructure elements, for example, through operational competencies of social actors for technical elements or data transfer from technical elements to social actors. As opposed to dynamic perspectives, the research in this article relies on a one-point-in-time perspective to investigate structural relations between social actors and technical infrastructure elements. Such a perspective is needed to achieve a fundamental understanding of the interplay of actors and infrastructure across heterogeneous cases as well as to derive potential ways for improving the alignment of this interplay, for example, to achieve more sustainable infrastructure outcomes (Fuenfschilling and Truffer 2016; Ghaffari et al., 2019).

Second, drawing on a specific STN operationalization in the context of data-driven and integrated UWM, I compare STNs of three case studies on UWS catchment areas in Switzerland and analyze factors that potentially affect information exchange among social actors. Here, this research addresses gaps more specifically related to data-driven and integrated management of infrastructure systems (Eggimann et al., 2017; Araya and Vasquez 2022; Oberascher et al., 2022), where challenges cannot be understood as either technical or social but rather as interlinked socio-technical challenges (Büscher et al. 2009; Newton 2012). For example, a STN can shed light on whether social actors with access to data from many technical infrastructure elements are also more likely to be well embedded in the information exchange network. Such insights can particularly be useful to the respective social actors themselves, but also to policy and decision-makers as well as to academic scholars studying barriers in infrastructure transition processes (Kiparsky et al., 2016).

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. In this sense, this article contributes to the literature studying the linkages between institutional settings and network structure (Angst et al., 2018; Fischer 2017; Lubell et al., 2014), particularly in a technological context (Burkhardt and Brass 1990). For example, different forms of organization or

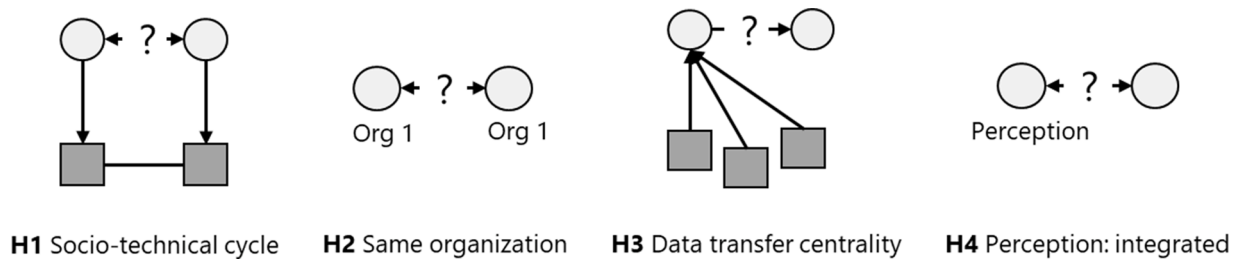


Fig. 1. Visual representations of the four hypotheses. (Illustration by the author).

inter-organizational cooperation, manifested in different STN structures, could potentially have a different influence on the development and the successful establishment of data-driven and integrated UWM.

This article proceeds with a theoretical section on socio-technical dependencies in infrastructure systems, followed by a review of benefits and challenges related to data-driven and integrated UWM. Based on this literature, I derive four hypotheses. In Section 4, I provide a general description of STNs and outline the concrete STN operationalization in the context of UWM. In Section 5, I describe three selected case study areas in Switzerland, the data collection procedure, and the methods used to analyze obtained STN data. Section 6 gives an overview of the descriptive and inferential results, discussed in the subsequent Section 7. The final section concludes that – despite limitations – a STN perspective can help to understand and identify socio-technical challenges towards data-driven and integrated UWM, and beyond.

## 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., forming a socio-technical system (Ottens et al., 2006). In the field of UWM, a socio-technical system understanding of UWS 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 sets 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), 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. Fig. 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, it is not possible to investigate the potential link between socio-technical fit structures and infrastructure performance. 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. Generally, I assume that common infrastructure objectives such as optimal technical performance and environmental excellence do not per se reflect an optimal actor network constellation. Instead, I test alternative hypotheses at the social and socio-technical levels, including social factors, such as different forms of organization or diverging perceptions. Consequently, the STN representation explicitly incorporates the variety of aspirations social actors may have.

## 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 increases (Oberascher et al., 2022). In the first place, integrated UWM is enabled by tools and technologies related to instrumentation, control, and automation (ICA)<sup>1</sup> (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 to minimize operational efforts and reduce costs due to a constant supervision of UWS processes. Second, long-term monitoring data series improve infrastructure planning, which in turn could prevent 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 the 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 studies pointing 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; Kiparsky et al., 2016; Manny

<sup>1</sup> These technologies are also often labelled as information and communication technologies (ICTs).

et al., 2021; Oberascher et al., 2022; Sherman et al., 2020; Speight 2015; Yuan et al., 2019).

### 3.1. 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 experience highly dynamic discharges depending on weather conditions, the reduction of CSO events from sewer systems during wet weather is the main goal for sewer operators. However, this goal interferes with the goal of WWTP operators to keep the hydraulic load constant 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 the 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 entities within a catchment area. Consequently, opposite to the ‘challenge logic’, hypothesis 2 concerns intra and inter-organizational information exchange, i.e., between social actors of the same organization compared to across organizations (s. Fig. 1).

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

### 3.2. 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 successful data sharing or because legal barriers prevent data storage. On the other hand, absent data standards or incompatible data formats or even data systems, e.g., SCADA<sup>2</sup> 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.*

### 3.3. 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 depend on technical characteristics of the infrastructure system, such as size or location. For example, social actors managing a 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 share the same perceptions of the use of ICA in UWS, the intended outcome might be difficult to achieve (Rieger and Olsson 2012). However, experiences of individual stakeholders in their respective roles may also shape perceptions (Cooke et al., 2007; Nieuwenhuis et al., 2022). For example, perceptions by administrative personnel potentially derive from those of operators or actors with regulatory competencies, 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).

Further, in countries where privatized urban water services prevail, profits instead of improved environmental outcomes could motivate social actors. Consequently, such social actors may not support the idea of collectively managing a UWS in an integrated way but rather focus on their own monetary benefits (Tang et al., 2021).

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 as well integrated 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. Fig. 1).

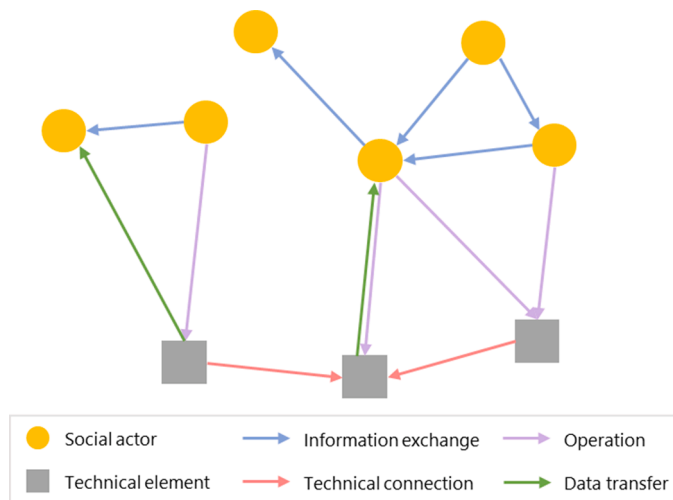
**Hypothesis 4.** *Social actors will more likely exchange information, if they perceive the catchment area as managed in a rather integrated or integrated way.*

## 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 extending to bipartite or multi-level networks, for example, to investigate social-ecological 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

<sup>2</sup> SCADA system: supervisory control and data acquisition system





**Fig. 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. (Illustration by the author).

**Table 1**  
Information on the three case studies in the sub-state of Zurich in Switzerland  
(based on data from 2020 provided by key representative interviewees).

	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

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 artifacts, 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 of analyzing UWS from a STN perspective, in the following, 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. Fig. 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 selected 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 may belong to different organizations, such as, for example, a local municipality or an authority relevant for the catchment area.

Besides social and technical nodes, the operationalized STN consists

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. The choice of edge representations relied on their relevance in assessing 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, I chose *information exchange* as a necessary relation required 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). Here, I adopted this approach 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 so far from a network perspective. Yet, I included these types of cross-level edges 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, I selected empirical cases to collect and analyze STN data. These empirical cases refer to three separate catchment areas of UWS, 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 (Luis-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 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, providing respective technical guidelines and recommendations (Oppliger and Hasler 2019).

The three selected case studies are examples of catchment areas developing towards data-driven and integrated UWM. [Table 1](#) presents general information on the three case studies, 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, I used the number of inhabitants connected to the WWTP 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.

All three case studies are located in typical peri-urban regions in Switzerland, thus representing the nationwide 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 exchange information within the catchment area. The differences are also important to consider as developments towards data-driven and integrated UWM may unfold differently depending on the local context. For example, smaller catchment areas with fewer 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). In the discussion, I take up these different characteristics again for the interpretation of the results.

## 5.2. Data

In each of the three case studies, STN data collection occurred in 2020 and 2021 in three consecutive steps: (1) semi-structured context interviews, (2) document analysis, and (3) case-specific online surveys. First, I obtained general information 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 and the context interviewees, I mapped the technical elements of the UWS, as well as the technical connection edges, into a technical network. The sub-state authority representative validated these technical network representations. Subsequently, I identified 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). This identification was achieved by checking all websites of municipalities active within the catchment area as well as the provided documents. Again, the sub-state authority representative and the context interviewee validated the list of all identified social actors (s. Appendix B) as well as the technical network representation. 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 survey questionnaire) and collected survey data between March and May 2021. Response rates ranged between 88% (case study 2) and 94% (case studies 1 and 3). Survey questions incorporated the logic of each hypothesis as presented in chapters 2 and 3. Related to the dependent variable of *information exchange*, survey participants received a list of social actors 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 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 could individually add up to ten social actors with whom they exchanged information. However, the analysis included

only those social actors added by at least two survey participants in a case study. This choice rested on the assumption that social actors stated only once were probably rather individual contacts and could 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. Appendix D provides information on how I dealt with this missing data.

Additional to the numbers on STN nodes and edges (s. Table D.1), I used data specific to the social actors in the analysis and for hypotheses testing. For example, I asked social actors from which technical elements they received data or whether they perceived their catchment area to be already managed in an integrated way. 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, I included the entire social actor dataset, taking into account all survey variables, as stated in Appendix C.

## 5.3. Methods

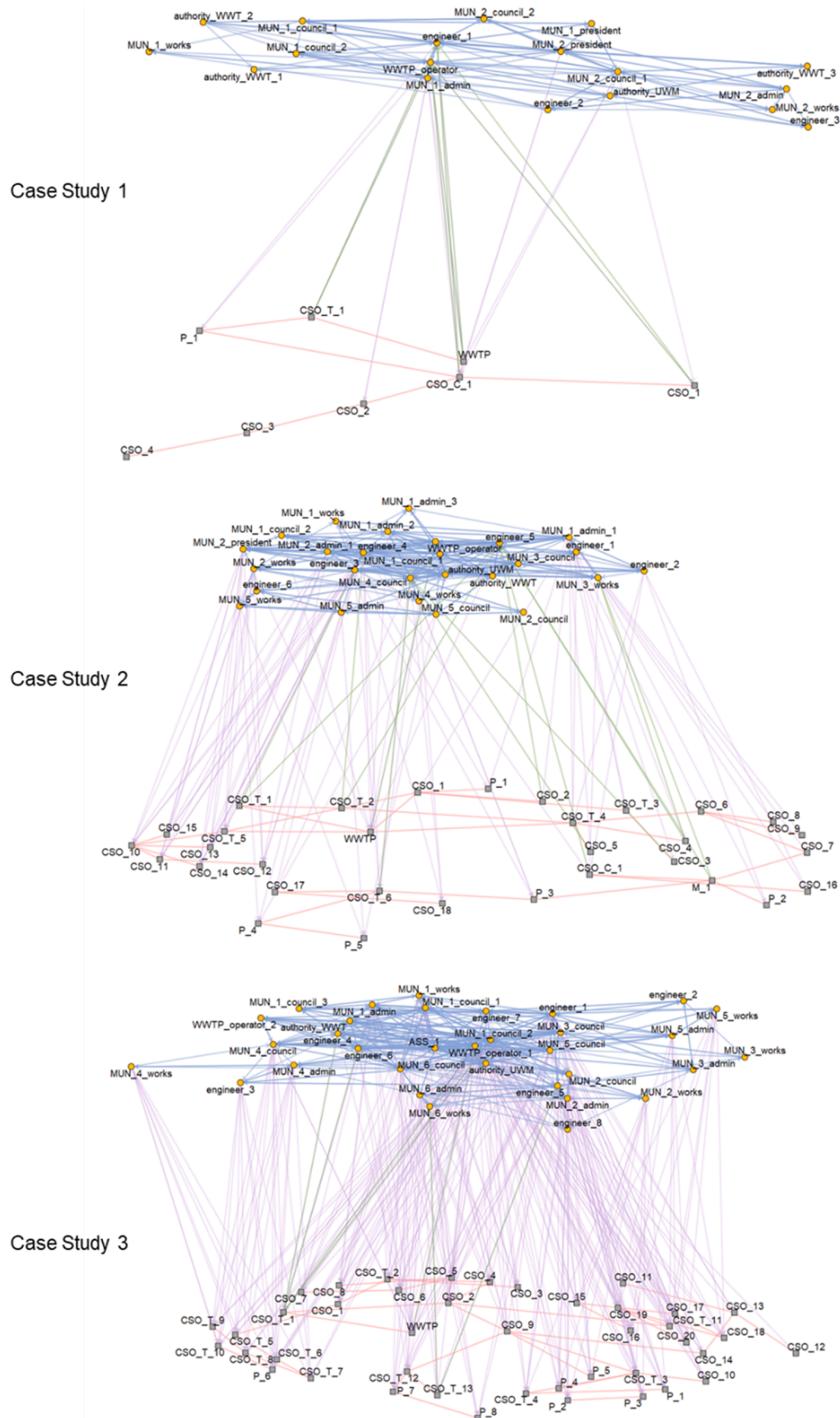
In Appendix E, I provide methodological information on the descriptive analysis of the STNs. The inferential analysis<sup>3</sup> draws on a specific family of statistical network models named exponential family random graph models (ERGMs) (Robins et al., 2007). In combination with a causal model, the 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 can not only be explained by the 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 of 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 analyzed 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 were described as either node or edge covariates (Statnet Development Team 2003–2022). For example, I operationalized the socio-technical dependencies in hypothesis 1 as socio-technical cycles, which I translated into an edge covariate through matrix multiplication. For hypothesis 2, I included a covariate at the 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, I added a nodematch term to 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 forward information more likely. Therefore, I included a node covariate that considers only outgoing information exchange edges. The operationalization of hypothesis 4 incorporated a nodefactor term for the perceptions of individual social actors on integrated UWM<sup>4</sup>.

<sup>3</sup> The code (in R studio) and data to replicate the analysis are available at: <https://doi.org/10.25678/0007AC>.

<sup>4</sup> The initial four categories of integrated, rather integrated, rather not integrated, and not integrated were aggregated to two categories: integrated and not integrated.



**Fig. 3.** Visualization of the three STN case studies using graphlayouts (Schoch 2020) in R studio. Colors have the same meanings as in Fig. 2. (Illustration by the author).



**Table 2**  
Inferential results obtained from ERGMs based on author's analysis.

	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)	<b>1.14</b> (0.24)	<b>1.42</b> (0.18)
H2: Same organization (municipalities, engineer, authority)	<b>0.66</b> (0.27)	<b>0.89</b> (0.21)	<b>0.92</b> (0.20)
H3: Degree central in terms of data transfer	-0.07 (0.15)	<b>0.16</b> (0.07)	-0.25 (0.18)
H4: Perception of integrated management: integrated	<b>0.62</b> (0.21)	0.17 (0.14)	0.00 (0.13)
<i>Controls</i>			
Edges	<b>-3.85</b> (0.80)	<b>-2.90</b> (0.62)	<b>-2.27</b> (0.52)
Reciprocity	<b>2.48</b> (0.47)	<b>3.20</b> (0.36)	<b>3.23</b> (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.

## 6. Results

Appendix F provides an overview on the results from the descriptive STN analysis. In the following, I present results from the inferential STN analysis. Fig. 3 visualizes all three STNs case studies and illustrates how STN complexities increase with rising numbers of technical elements and social actors involved in managing the respective UWS.

Table 2 shows the ERGM results from the inferential analysis. 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 overall. Four main findings can be derived from the model results in line with the hypotheses.

First, and related to hypothesis 1, in case studies 2 and 3, the presence of socio-technical cycles had a positive influence on information exchange, i.e., if two social actors operate two technically connected technical elements, it was 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 was also positive, although not significant. The size of this effect varied 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 were more likely to exchange information by factor 2 ( $e^{1.14} - 1 = 2.13$ ). For case study 3, the odds for the same effect were more than three times as high ( $e^{1.42} - 1 = 3.14$ ).

The latter result is in line with the descriptive finding that case study 3 showed many more operation edges and thus comprises more social actors who were involved in the management of the same technical element, leading 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 due to a smaller, less complex STN with fewer social actors and technical elements.

Second, there was another significant effect for social actors who were part of the same organization to more likely exchange information. This effect was observable in all three case studies. Odds varied between 93% (case study 1;  $e^{0.66} - 1 = 0.93$ ), 144% (case study 2;  $e^{0.89} - 1 = 1.44$ ), and 151% (case study 3;  $e^{0.92} - 1 = 1.51$ ). Obviously, informa-

tion exchange was more likely to occur within organizations rather than across organizations, whereby organizations were categorized as an individual municipality (municipality 1 as organization 1, municipality 2 as organization 2, etc.), engineers (included all individual engineers, i. e., engineer 1, engineer 2, etc.), and the authority (included 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 received data from many technical elements were slightly more likely to give information. The odds were 17% ( $e^{0.16} - 1 = 0.17$ ), which is relatively low compared to the previous two effects related to hypotheses 1 and 2. Even though probabilities were lower, it was interesting to find that social actors with access to data were well embedded in the information exchange network. These results suggest that those social actors were 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 was 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 was influenced by whether social actors perceived their UWS to be managed in an integrated or not integrated way. The effect was positive and significant, i.e., the odds of information exchange were 86% ( $e^{0.62} - 1 = 0.86$ ) higher if social actors perceived an integrated management already in place. In case studies 2 and 3, this effect was not significant, and the effect sizes were rather small.

The four remaining effects were controls. First, an "edges" parameter controlled 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%. The second control, "reciprocity" was positive in all three case studies, indicating that actors tended 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) was 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 was positive (i.e., two actors tended to have shared partners) but not significant. Finally, I controlled for the type of organization (i.e., each municipality, engineers, and authority representatives) as the nodematch covariate on the same organization has a bias if many social actors are part of one organizational type. I determined the control coefficients for each type of organization individually, and as these varied between case studies, I provide them additionally in Appendix G.

The presented ERGM results stem from trade-off choices in terms of model fit, the 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 cases. These case-specific models further include covariates 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 become member of 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. I included these two network covariates in order to assess their effect on information exchange. Indeed, findings showed that in case study 3, information exchange occurred more likely among social actors who were members of the wastewater association or joined the local or regional planning meetings (s. [Appendix F](#)).

## 7. Discussion

Bringing both social and technical levels of infrastructure systems and their management together, the application of STNs shed light on dependencies, whose evidence can point out opportunities for improvement, for example, related to data-driven and integrated management. More generally, uncovering evidence on such dependencies may also be useful for policy and decision-making. For instance, social actors from different organizations, who would greatly benefit from coordination or information exchange, could establish connections based on the information provided in a STN. Closing such gaps in a STN could ultimately lead to improved collaborative governance circumstances, which are needed, for example, with respect to more sustainable infrastructure outcomes within or across cities.

Besides such practice and policy implications, STNs are useful for disentangling socio-technical relations as well as demonstrating particular socio-technical structures when it comes to managing infrastructure systems, such as UWS. In this sense, STNs are of theoretical relevance, as insights gained from their analysis advance the basic understanding of infrastructures from an organizational point of view.

Further, with its network-based framing, the STN approach is also as an interdisciplinary effort in bringing social and technical (sub)systems together through a common language. STNs may include social actors, social interactions, technical elements, technical connections, as well as socio-technical relations, e.g., operation, ownership, or data transfer, among others. Consequently, from a scientific perspective, STN approaches can speak to academic scholars from distinct disciplines, e.g., social sciences and engineering.

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 was confirmed for case studies 2 and 3, indicating that in these two catchment areas, information exchange was 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 was 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, other social factors than socio-technical dependencies might influence social interactions in smaller and socio-technical, less complex infrastructure systems. 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 confirmed the positive effect of two social actors being part of the same organization in

all three case studies, which consequently implied that two social actors of different organizations were less likely to exchange information. As information exchange within a municipality, among engineers, or among authority representatives outweighed 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 fewer efforts to exchange information among themselves ([Yang and Maxwell 2011](#)) and are potentially closely related spatially (e.g., same building). Therefore, I also controlled 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 of the catchment area’s wastewater association (in case studies 1 and 3, s. also [Table 1](#)) 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 increased 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 led to an increase of 46% ( $e^{0.38} - 1 = 0.46$ ). 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 demonstrated positive and significant effects for degree centrality of social actors in terms of data transfer in case study 2. There, social actors with access to data on many technical elements were also more likely to forward 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 was not significant, 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, also well embedded in the information exchange network, to access data but also social actors not well embedded, as, for those, it might need more efforts in accessing data. Consequently, to provide multiple social actors with data valuable for their respective purposes, isolated social actors need particular attention from a catchment-wide point of view ([Hoolohan et al., 2021](#)). Second, when 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 raising on the need for ICA, or evident examples (“business cases”) of positive economic and environmental outcomes, might be beneficial ([Lundberg et al., 2021](#)). Drawing on literature from organizational studies in private sector contexts, successful examples of ICA implementation could further act as a catalytic opportunity to address social innovation related to sustainability ([Vrontis et al., 2021](#)).

Finally, the ERGM results confirmed 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 showed the highest percentage of technical elements that already transferred data (86%) compared to case studies 2 and 3 (56% and 27%, 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, the results from the STN analysis needed validity assessments. I implemented several validation strategies and presented the assumptions related to missing data (s. also Table D.1) (Huisman 2009; Kossinets 2006).

## 8. Conclusion

Researchers and practitioners in the field of UWM and beyond 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). From a theoretical perspective, I showed how social interactions, such as information exchange among social actors, are not only influenced by social factors but are also subject to underlying socio-technical dependencies (Manny et al., 2022; Finger et al., 2005; Künneke et al., 2021). For example, two social actors who operated two technically connected elements were more likely to exchange information in a larger, socio-technically complex STN. Where ICA technologies were in use and data transfer from technical elements to social actors was present, social actors who received data from many technical elements tended to exchange information with many other social actors. This finding is relevant for practitioners concerned with the development towards data-driven UWM, as it shows the importance and, eventually, also the responsibility of social actors with access to data to share it 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, as in the case of UWS. From a technical point of view, data platforms or SCADA systems might serve as a technical solution to more evenly distribute data among relevant social actors (Roy et al., 2008). Here, a STN perspective could help to 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 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, social actors' perceptions of the state of integrated UWM matter (Cousins 2017; Pahl-Wostl 2007), particularly if the system is managed already in a (rather) integrated way. However, perceptions of 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 from a socio-technical perspective.

Using network concepts, the three empirical case studies shed light on the entangled relations between social actors and technical elements and illustrated the heterogeneity in actor-infrastructure constellations for three different UWS in the context of data-driven and integrated UWM.

However, the STN approach bears limitations. First, I operationalized four specifically chosen types of edges. 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 useful for 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 they could identify opportunities for improvement 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 included social actors and their social (network) structure but neglected 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 drew on three selected case studies and their 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.

Fifth, data-driven and integrated UWM, as presented in this article, covered a particular aspect of catchment management related to UWS. A more fundamental attempt to unite various aspects related more broadly to the resource *water*, lies in the principles of Integrated Water Resources Management (IWRM), which are mostly concerned with river basin catchments instead of infrastructure catchments as those associated with urban water infrastructure. Yet, integration plays an important role within catchments independent of the boundaries due to the multiplicity of public and private entities across several sectors involved (Ingold et al., 2016). In this sense, the STN approach followed the general idea of IWRM to include the network of all actors involved in a catchment area as well as their perceptions (e.g., related to the progress in terms of integrated management), their embeddedness within organizations, or their relations to elements of the technical infrastructure system. The STN of UWS analyzed here could be extended to represent an entire river

basin catchment that would include further actors (e.g., drinking water sector, river management organizations), relevant infrastructure elements (e.g., drinking water infrastructure, flood protection infrastructure, hydroelectric power infrastructure), and natural or ecological elements (e.g., rivers, lakes, reservoirs, wetlands).

Future research on STNs of UWM could question whether an actual dependency exists between the structure of a STN and the technical infrastructure performance or environmental impacts (Ulibarri 2015; Grabowski et al., 2017; Sayles et al., 2019). Such a dependency would be of particular interest in the context of sustainable city developments, as certain STN structures of infrastructure management indicating more sustainable infrastructure outcomes could serve as ‘role model’ structures. 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 and cities)? Are environmental impacts lower if more socio-technical cycles are present in the STN or if all relevant social actors have access to the required data?

However, with the article’s focus on data-driven and integrated UWM, tensions between short-term commercial or cost-driven proclivities and long-term environmental protection goals need to be considered (Fryxell and Lo 2001). Even though the analysis included the actors’ perceptions, their information exchange motives might differ. For example, monetary benefits could incentivize some actors not to exchange or to disclose relevant information. In contrast, other actors might aspire long-term objectives aiming at achieving improved environmental protection. Such differing motives could influence the structure of a STN or act as a challenge in terms of data-driven and integrated UWM.

## Appendix

### A. Semi-structured interview guideline for context interviews

Table A1

Table A.1

Semi-structured interview guideline for context interviews.

Topic	Questions
1 Description of the catchment area	<ul style="list-style-type: none"> <li>• Size and total number of inhabitants in the catchment area</li> <li>• Number and names of involved municipalities</li> <li>• Details on the WWTP (year of construction, historical connections, size)</li> <li>• Year of local drainage plan - is it currently updated?</li> <li>• Length or percentages of combined vs. separated sewer system [km or %]</li> <li>• Number of combined sewer overflow tanks</li> <li>• Number of combined sewer overflows</li> <li>• Number of pumping stations</li> <li>• Existence of monitoring technology (ICA)? If yes, since when?</li> <li>• Which technology? What is monitored? How is the data handled?</li> </ul>
2 Description of experiences, (past)/current challenges and successes	<ul style="list-style-type: none"> <li>• Are there special conditions in the catchment area? For example, bathing waters, lakes?</li> <li>• Are you satisfied with the current management in the catchment area? If yes, why? If no, why? What works well, what works not well?</li> <li>• Are there any current/planned organizational activities? (e.g., merger of WWTP). Have there been any recently?</li> <li>• Are there any current/planned construction activities?</li> <li>• Have there been any particular successes in the catchment area in the past 10 years?</li> <li>• Have there been any notable challenges in the catchment area over the past 10 years?</li> <li>• Are there any challenge(s) in the catchment area currently or in the foreseeable future?</li> </ul>
3 Key stakeholders and organizations in the catchment area	<ul style="list-style-type: none"> <li>• What is your role in the catchment area?</li> <li>• Which stakeholders and organizations are involved in urban water management in the catchment area? Can you give me specific names of contact persons?</li> <li>• Which municipalities are involved? Is there a wastewater association?</li> <li>• Which engineering and planning offices are involved in the area?</li> <li>• Who is the contact person at the sub-state authority?</li> <li>• Are there private companies to which certain tasks have been delegated? If so, which companies?</li> <li>• Which other stakeholders are important? Are there overlaps with other sectors (e.g., water supply)?</li> <li>• With which stakeholders do you have frequent professional exchanges (e.g., once a month), and about what?</li> </ul>
4 Information about socio-technical contexts in the catchment area	<ul style="list-style-type: none"> <li>• Are you involved in the operation of technical elements of the urban wastewater system in the catchment area?</li> <li>• Do you receive or have access to any monitoring data obtained within the catchment area?</li> </ul>

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 towards more sustainable socio-technical infrastructure systems (Sayles et al., 2019), could allow for specifically targeting those affected, those responsible, and those benefitting from such changes.

## Declaration of Competing Interest

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

## Data availability

The code and data to replicate the analysis are available at: <https://doi.org/10.25678/0007AC>.

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

## Tables B1, B2, B3

Table B.1

STN data on technical and social nodes in case study 1.

Technical element			Organization		
Technical element			Organization		
1	WWTP	Wastewater association	1	engineer_1	Engineering office
2	CSO_T_1	Wastewater association	2	WWTP_operator	Wastewater association
3	P_1	Wastewater association	3	MUN_1_council_1	Municipality 1
4	CSO_C_1	Wastewater association	4	MUN_2_council_1	Municipality 2
5	CSO_1	Wastewater association	5	MUN_1_admin	Municipality 1
6	CSO_2	Wastewater association	6	MUN_1_works	Municipality 1
7	CSO_3	Municipality 1	7	MUN_2_works	Municipality 2
8	CSO_4	Municipality 1	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		
Technical element			Organization		
1	WWTP	Municipality 1	1	engineer_1	Engineering office
2	CSO_T_1	Municipality 1	2	MUN_3_works	Municipality 3
3	CSO_T_2	Municipality 1	3	engineer_2	Engineering office
4	CSO_T_3	Municipality 1	4	engineer_3	Engineering office
5	CSO_T_4	Municipality 1	5	MUN_1_council_1	Municipality 1
6	CSO_1	Municipality 1	6	engineer_4	Engineering office
7	CSO_2	Municipality 1	7	MUN_4_council	Municipality 4
8	CSO_3	Municipality 1	8	MUN_1_works	Municipality 1
9	CSO_4	Municipality 1	9	MUN_2_president	Municipality 2
10	CSO_5	Municipality 1	10	MUN_1_admin_1	Municipality 1
11	CSO_6	Municipality 1	11	MUN_4_works	Municipality 4
12	CSO_7	Municipality 1	12	MUN_1_admin_2	Municipality 1
13	CSO_8	Municipality 1	13	MUN_1_admin_3	Municipality 1
14	CSO_9	Municipality 1	14	MUN_5_admin	Municipality 5
15	P_1	Municipality 1	15	MUN_2_admin_1	Municipality 2
16	CSO_T_5	Municipality 2	16	MUN_5_council	Municipality 5
17	CSO_10	Municipality 2	17	MUN_1_council_2	Municipality 1
18	CSO_11	Municipality 2	18	MUN_2_works	Municipality 2
19	CSO_12	Municipality 2	19	engineer_5	Engineering office
20	CSO_13	Municipality 2	20	engineer_6	Engineering office
21	CSO_14	Municipality 2	21	MUN_5_works	Municipality 5
22	CSO_15	Municipality 2	22	authority_WWT	Authority
23	CSO_C_1	Municipality 3	23	authority_UWM	Authority
24	CSO_16	Municipality 3	24	WWTP_operator	Municipality 1
25	P_2	Municipality 3	25	MUN_2_council	Municipality 2
26	CSO_T_6	Municipality 4	26	MUN_3_council	Municipality 3
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			



**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 C1

**Table C.1**

Excerpt of the survey questionnaire that includes questions and answers 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?	<ul style="list-style-type: none"> <li>- Municipal council</li> <li>- Municipal administration</li> <li>- Municipal works</li> <li>- WWTP operator</li> <li>- Commission (e.g., operational, (civil) engineering, planning)</li> <li>- Inter-municipal/regional association</li> <li>- Engineering office/planning office</li> <li>- Other</li> </ul>
2*	Organization	>Please assign your area of responsibility to the respective municipality in the catchment area.	- List of names of municipalities
3*	Information exchange	<p>With whom have you exchanged information in the past 2 years relating to wastewater treatment, urban drainage, and/or water pollution control in the catchment area?</p> <p><i>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.</i></p>	- List of names of all social actors involved in managing the urban water system (s. Appendix B)

(continued on next page)

Table C.1 (continued)

Variable	Question	Answers
4	Active in operation	Are you involved in the operation of technical elements of the urban wastewater system in the catchment area?
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) <i>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.</i>
6	Sensors	Which technical elements of the urban wastewater system are equipped with sensors/digital technologies?
8*	Data transfer	From which of the following technical elements of the urban wastewater system do you receive or can you access monitoring data?
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?
10	Local/regional planning meetings	Are there local or regional planning meetings in your catchment area?
11*	Attendance of local/regional planning meetings	Do you participate in local or regional planning meetings?
11	Years active	How many years have you been doing your job in the selected organization? <i>If you have only recently started working, please enter the number 1.</i>
12	Relevance Work	How many days per week do you approximately deal with tasks related to wastewater treatment, urban drainage and/or water protection?
13	Importance of monitoring data	How important is integrated urban water management to you?
14	Importance of integrated urban water management	How important is the use of monitoring technology and data in the catchment area to you?

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. Table D.1 shows percentages of missing edges, calculated by dividing the number of missing edges by the number of all possible edges. Missing edges could refer either to a zero or to 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 whereas 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 very few matrix cells have 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 whereas 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 did 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 D1

**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
<b>Social actors (nodes)</b>			
identified before survey	17	26	36
identified during survey	29	33	35
<b>included in analysis</b>	<b>18</b>	<b>26</b>	<b>33</b>
Missing actors*	1	3	2
	(5.6 %)	(11.5 %)	(6.1 %)
<b>Technical elements (nodes)</b>			
identified before and during survey	8	32	42
<b>included in analysis</b>	<b>8</b>	<b>32</b>	<b>42</b>
Missing elements	0	0	0
	(0 %)	(0%)	(0 %)
<b>Information exchange edges</b>			
Missing edges**	41	8	10
	(13.4 %)	(1.2 %)	(0.9 %)
<b>Technical connection edges</b>			
Missing edges	0	0	0
	(0 %)	(0 %)	(0 %)
<b>Operation edges</b>			
Missing edges	16	225	251
	(25 %)	(56 %)	(37 %)
<b>Data transfer edges</b>			
Missing edges	0	95	0
	(0 %)	(24 %)	(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<sup>5</sup>. 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. 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 versus technical elements that technically can transfer data, i.e., the sum of the technical elements already transferring data 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.

### F. Results from the descriptive STN analysis

In Table F.1, descriptive results are shown for each case study. The density of the information exchange network is similar across 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

<sup>5</sup> 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).

most progressive state, as already 86% of technical elements<sup>6</sup> transfer data compared to 56% in case study 2 and 27% 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 exhibits 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 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 degree central social actor in both case studies 1 and 3, i.e., 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 1). In case study 3, the same social actor (MUN\_1\_council\_2) who is exchanging information with most other social actors, is also the degree central social actor in terms of operation, i.e., is involved in the operation of most technical elements. This social actor also has the role of the president of the wastewater association in the catchment area (s. also Table 1). From the point of inter-municipal cooperation, this presidential role potentially allows for more opportunities but also needs concerning information exchange. In the technical network, the WWTP takes the 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<sup>7</sup> (CSO\_C\_1) is equally degree central than the WWTP. This CSO canal, in case study 1, is also the 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 degree central in terms of data transfer.

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

Finally, progress in terms of data-driven management as determined through the percentage of technical elements already transferring data versus those technically being able to do so, reveals that case study 1 is most progressive (86%) and case study 3 least progressive (27%). Yet, these values also make clear that all three case studies demonstrate potential related to data-driven and integrated management, pointing to the need for understanding socio-technical challenges. Table F1

**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
<b>Density</b>			
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
<b>Reciprocity</b>			
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
<b>Degree centrality</b>			
Central social actor in terms of information exchange	MUN_2_council_1	authority_UWM	MUN_1_council_2
Central social actor(s) in terms of operation	WWTP_operator	MUN_1_admin_1	MUN_1_council_2 WWTP_operator_1
Central technical element(s) in terms of operation	WWTP CSO_C_1	WWTP	WWTP
Central technical element in the technical network	CSO_C_1	CSO_T_4	CSO_2
<b>Motifs</b>			
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
<b>Progress in terms of data-driven urban water management</b>			
Technical elements transferring data	86 %	56 %	27 %

<sup>6</sup> 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).

<sup>7</sup> 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.



## G. ERGMs including controls for the type of organization

Table G1

**Table G.1**

Inferential results obtained from ERGMs including controls for the type of organization.

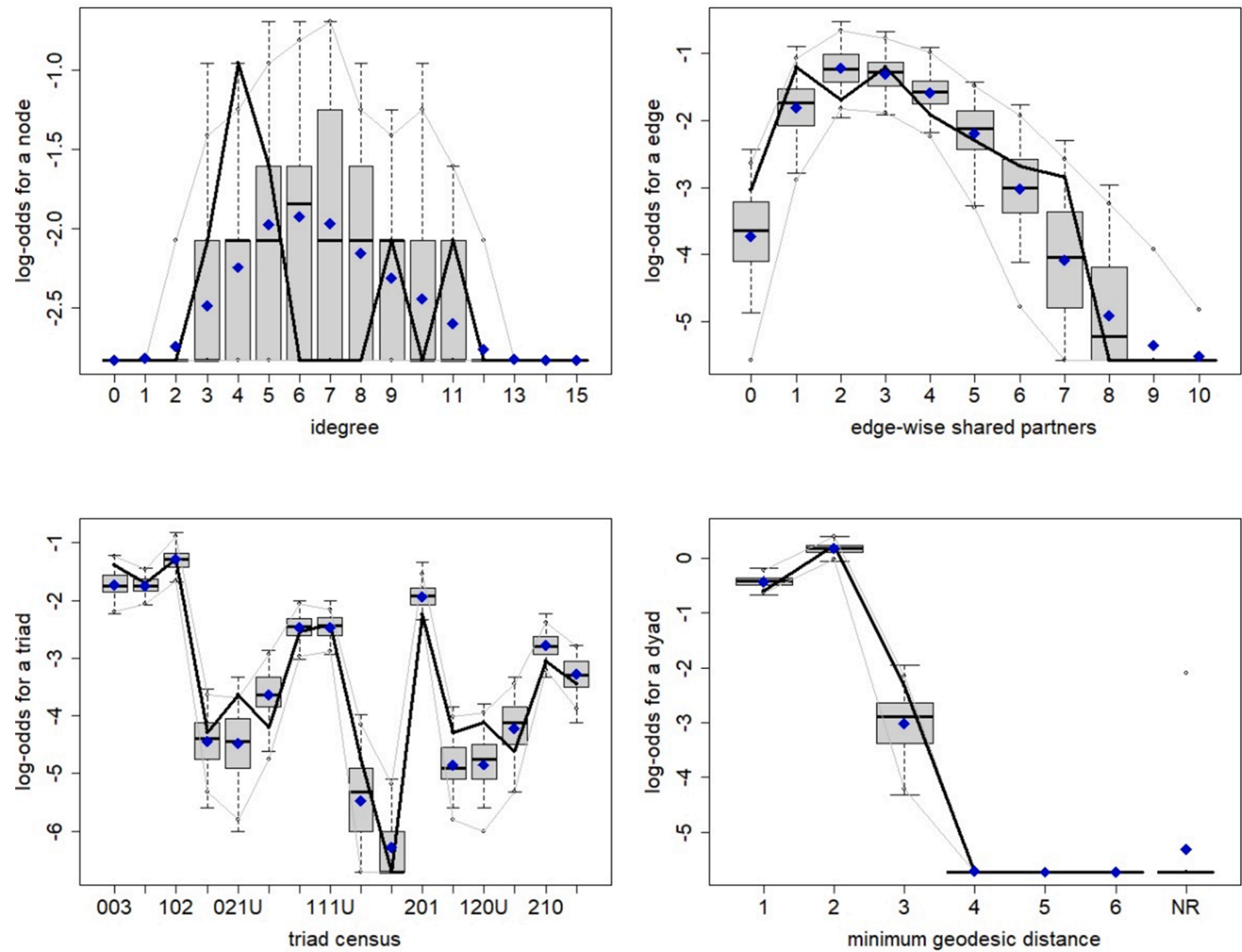
	Dependent variable: Information exchange		
	Case Study 1	Case Study 2	Case Study 3
H1: Socio-technical dependencies in the form of socio-technical cycles	0.86 (0.53)	1.14 (0.241)	1.42 (0.18)
H2: Same organization (municipalities, engineer, authority)	0.66 (0.27)	0.89 (0.21)	0.92 (0.20)
H3: Degree central in terms of data transfer	-0.07 (0.15)	0.16 (0.07)	-0.25 (0.18)
H4: Perception of 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

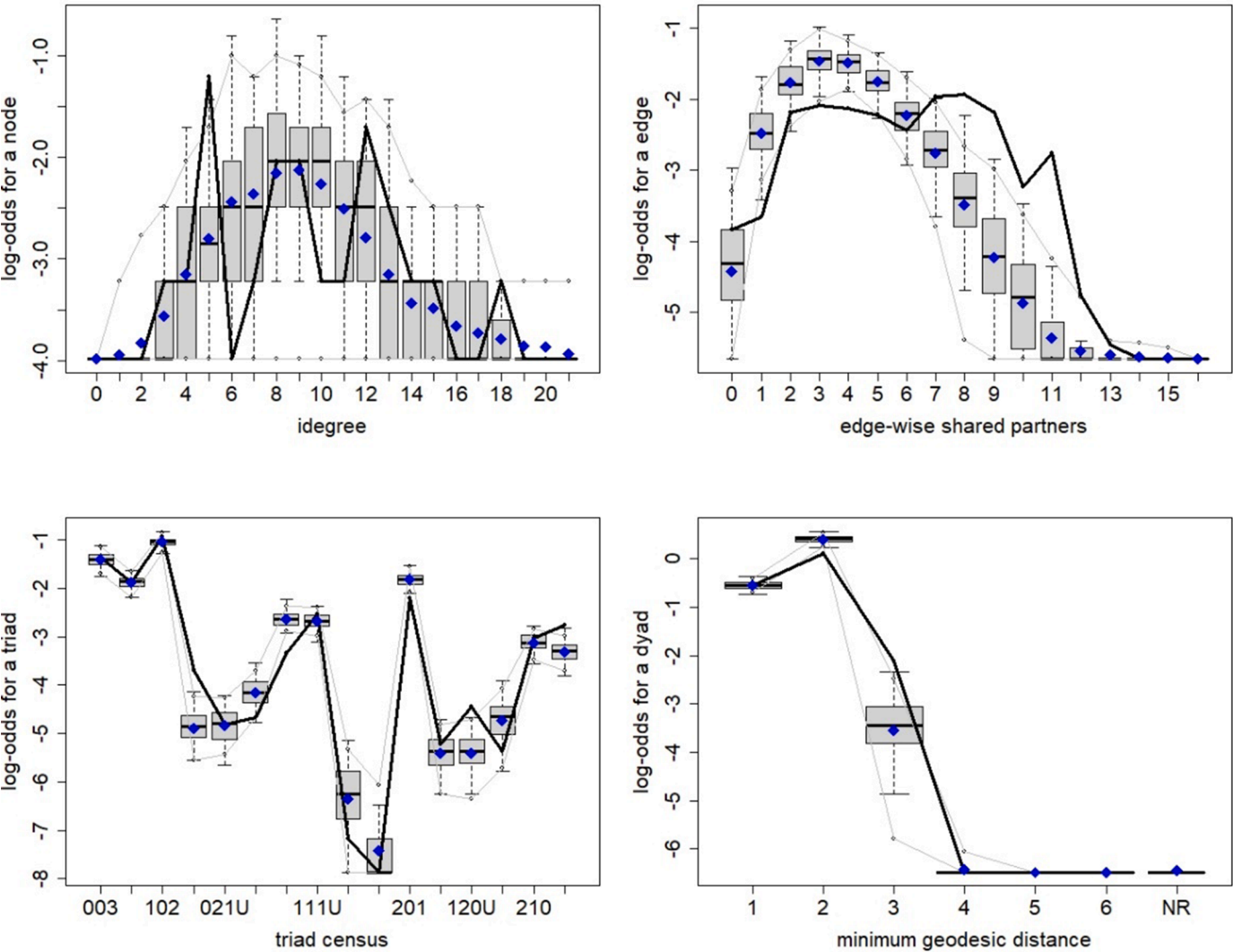
Case Study 1

Goodness-of-fit diagnostics



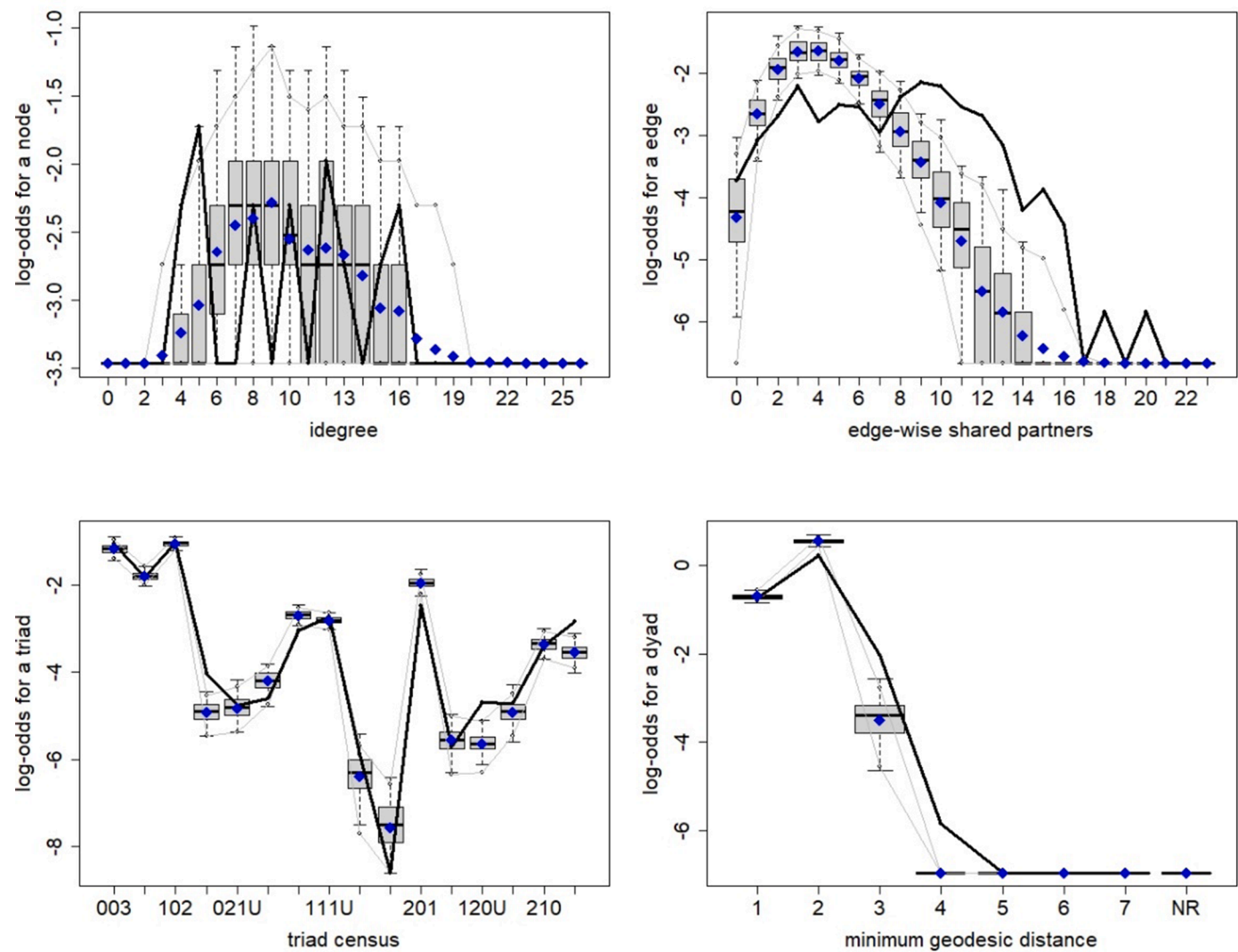
Case Study 2

Goodness-of-fit diagnostics



Case Study 3

Goodness-of-fit diagnostics





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

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

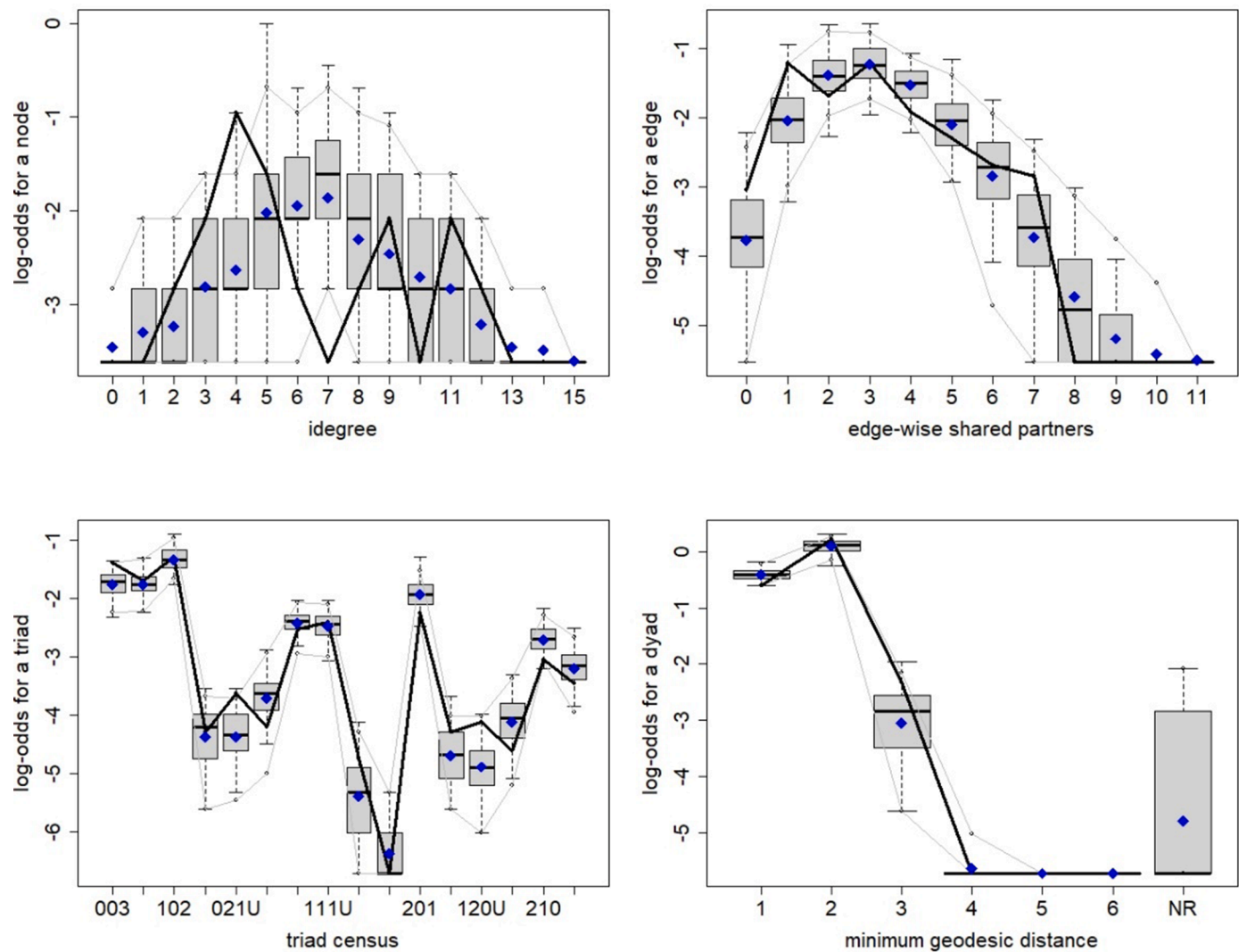
**Table I.1**

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)		<b>0.74</b> <b>(0.29)</b>	
H3: Degree central in terms of data transfer		-0.16 (0.15)	
H4: Perception of integrated management: integrated		<b>0.36</b> <b>(0.46)</b>	
Member of a wastewater association		0.75 (0.54)	
Participation in local/regional planning meeting:		-0.34	
-Yes		(0.23)	
- Sometimes		-0.59 (0.51)	
Controls			
Edges		<b>-3.98</b> <b>(0.92)</b>	
Reciprocity		<b>2.44</b> <b>(0.48)</b>	
GWESP (0.1)		0.40 (0.61)	
Organization	MUN 1		-
	MUN 2		<b>0.42</b> <b>(0.24)</b>
	Engineers		<b>1.06</b> <b>(0.61)</b>
	Authority		<b>0.87</b> <b>(0.42)</b>
	Wastewater association		<b>1.46</b> <b>(0.74)</b>
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 diagnostics



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

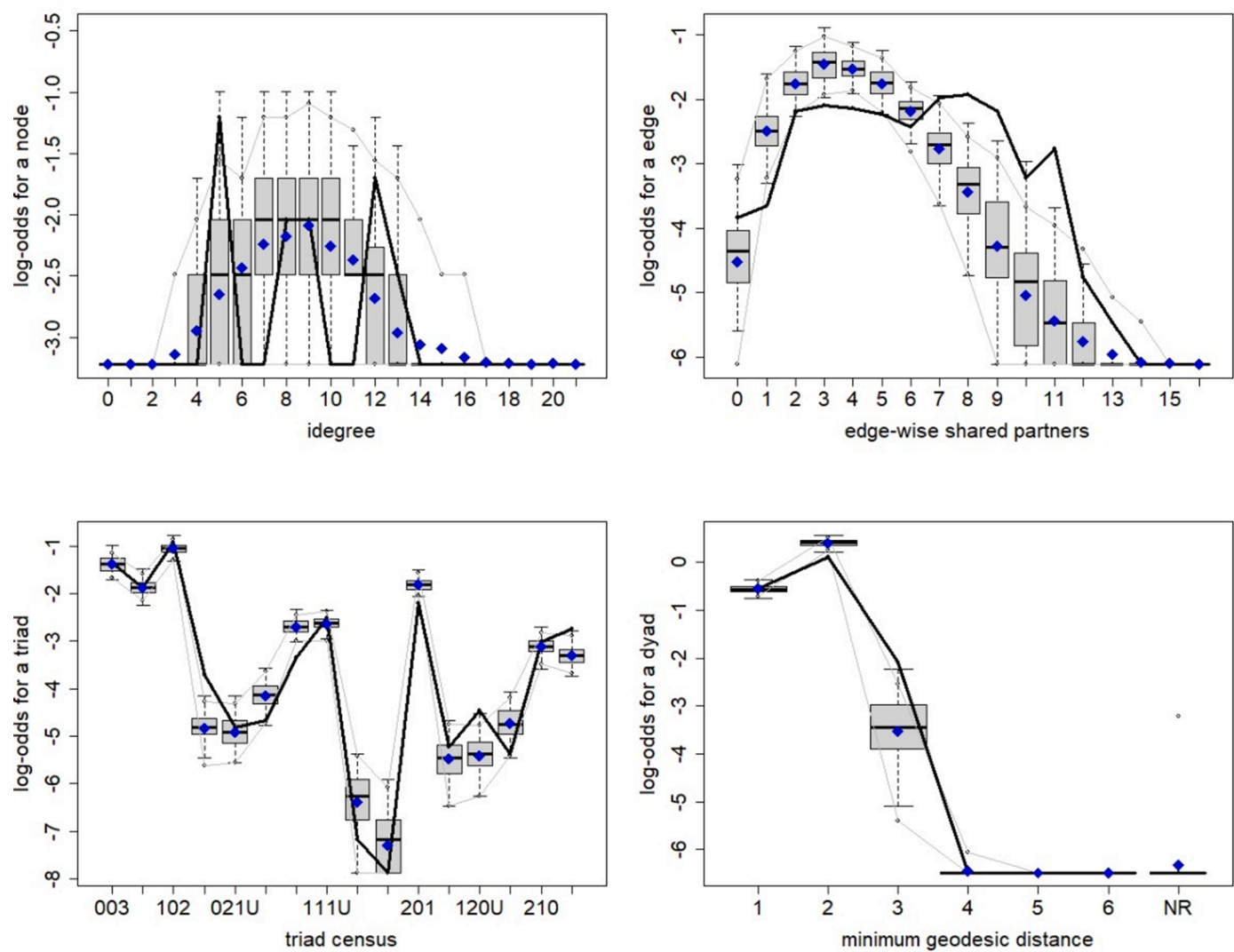
**Table I.2**

Inferential results obtained from extended local ERGM for case study 2.

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



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

**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 of integrated management: integrated		-0.17 (0.15)
Member of a wastewater association		0.87 (0.13)
Participation in local/regional planning meeting:		0.38
-Yes		(0.12)
- Sometimes		-0.46 (0.21)
<i>Controls</i>		
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 diagnostics

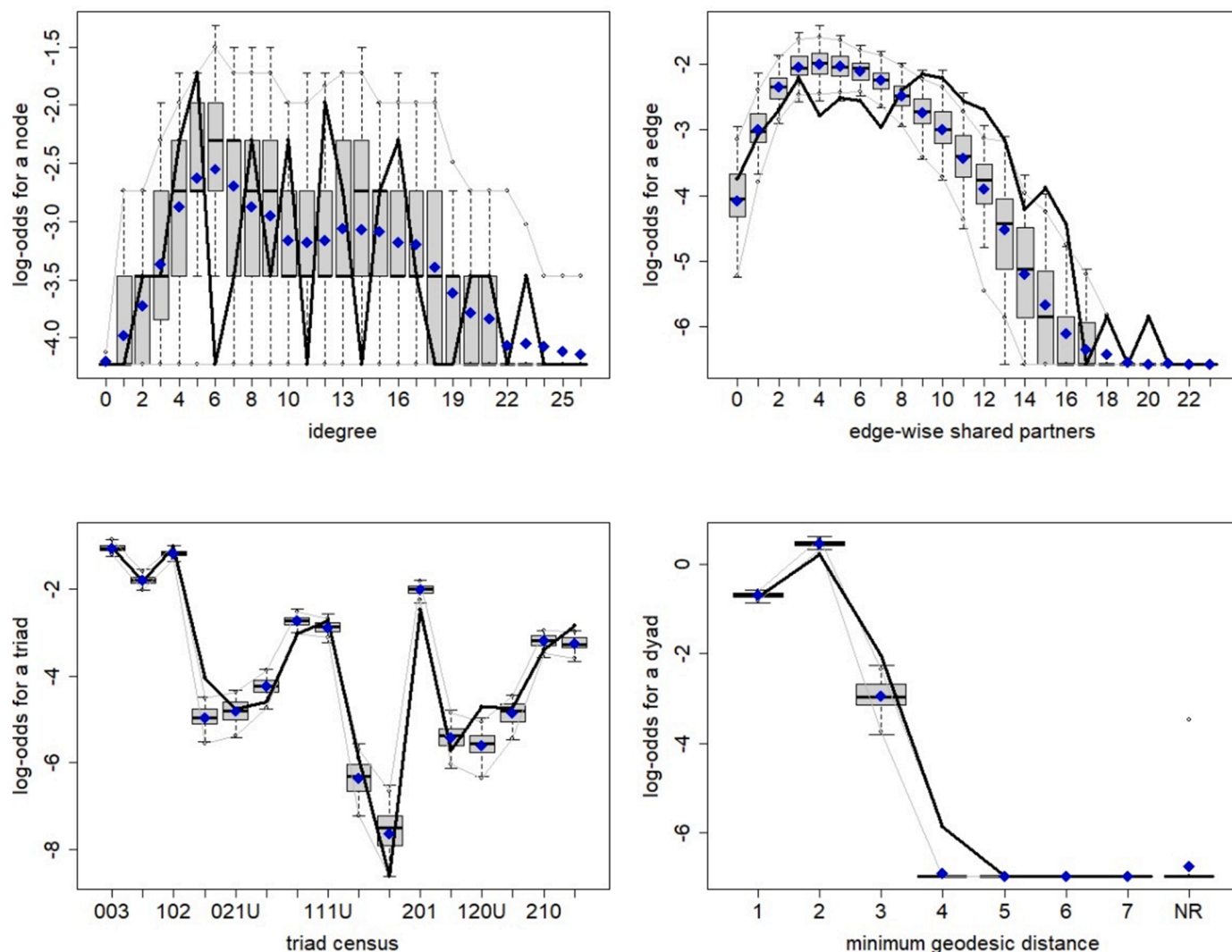


Table 11, 12, 13

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