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

Liliane Manny[a,b,*], Mario Angst[c], Jörg Rieckermann[b], Manuel Fischer[b,d]

[a] Institute of Civil, Environmental and Geomatic Engineering, ETH Zürich, Stefano-Franscini-Platz 5, 8093, Zürich, Switzerland
[b] Eawag, Swiss Federal Institute of Aquatic Science and Technology, Überlandstrasse 133, 8600, Dübendorf, Switzerland
[c] Digital Society Initiative, Universität Zürich, Rämistrasse 69, 8001, Zürich, Switzerland
[d] Institute of Political Science, University of Bern, Fabrikstrasse 8, 3012, Bern, Switzerland

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ABSTRACT

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

## 1. Introduction

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

However, given entrenched and path-dependent systems, both technical and social transitions towards these potential solutions are not easy to achieve (Bolton and Foxon, 2015; Hodson and Marvin, 2010; Wihlborg et al., 2019). Any actions, strategies, processes, or policies aiming at addressing challenges, overcoming deficits, and developing

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*Abbreviations:* STN, socio-technical network; UWS, urban wastewater system.

* Corresponding author. Eawag, Swiss Federal Institute of Aquatic Science and Technology, Überlandstrasse 133, 8600, Dübendorf, Switzerland.

*E-mail address:* liliane.manny@eawag.ch (L. Manny).

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solutions require an understanding of both social and technical dimensions of infrastructures. Accordingly, infrastructure systems have been studied from a socio-technical perspective, including social, technical, and intertwined socio-technical elements (Finger et al., 2005; Ottens et al., 2006). It has been argued that such a holistic analysis of the socio-technical nature of infrastructure systems is required in order to improve economic and environmental outcomes (Markolf et al., 2018). The respective literatures have relied on socio-technical system theories (Bolton and Foxon, 2015; de Haan et al., 2013; Fuenfschilling and Truffer, 2016; Guy et al., 2011; Ottens et al., 2006; Jensen et al., 2015), system dynamics approaches (Prouty et al., 2020; Whyte et al., 2020) or agent-based modeling (Berglund, 2015; Dam et al., 2013; Panebianco and Pahl-Wostl, 2006).

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

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

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

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

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

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

## 2. Infrastructures as socio-technical systems

### 2.1. Analyzing relations between social and technical systems

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

### 2.2. Digitalization, decentralization, and integrated management of infrastructure systems

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

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

#### 2.2.1. Digitalization

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

#### 2.2.2. Decentralization

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

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

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

#### 2.2.3. Integrated management

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

### 2.3. The idea of networks in socio-technical systems

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

## 3. Socio-technical networks of infrastructure management

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

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

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

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

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

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

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

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

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

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

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

### *3.2. Socio-technical network (STN) concepts*

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

The STN concepts are divided into three categories. First, we make use of certain commonly used basic concepts in network analysis and apply these to STNs. Second, we illustrate the potential of studying meaningful sub-structures in a STN. Third, based on the first two categories, we suggest how the STN of infrastructure management can be analyzed in terms of digitalization, decentralization, and integrated management.

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

Table A.1 in Supplementary Materials A presents a comparison of three descriptive concepts, namely density,[2] reciprocity,[3] and (degree) centrality,[4] for social networks and adapted to a STN. We consider all four networks in the STN (s. Table A1) and describe density individually for each of them ($d_S$, $d_T$, $d_{ST}$, $d_{TS}$). The densities of the social and technical networks in the STN can be determined, similarly to the social network density, by calculating the ratio of actually present, observed network edges to the number of all possible edges, given the network nodes. For the cross-level social-technical and technical-social networks ($G_{ST}$ and $G_{TS}$), we need to include both technical nodes $|V_T|$ as well as social nodes $|V_S|$ in the denominator to calculate the number of all possible edges between technical elements and social actors (s. Table A1).

For the concept of reciprocity, we specify two equations. The first

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

[2] Density refers to the ratio of edges that are actually present in a network to the maximum number of edges that are possible given the number of nodes (Wasserman and Faust, 1994) (s. also Table A1).

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

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

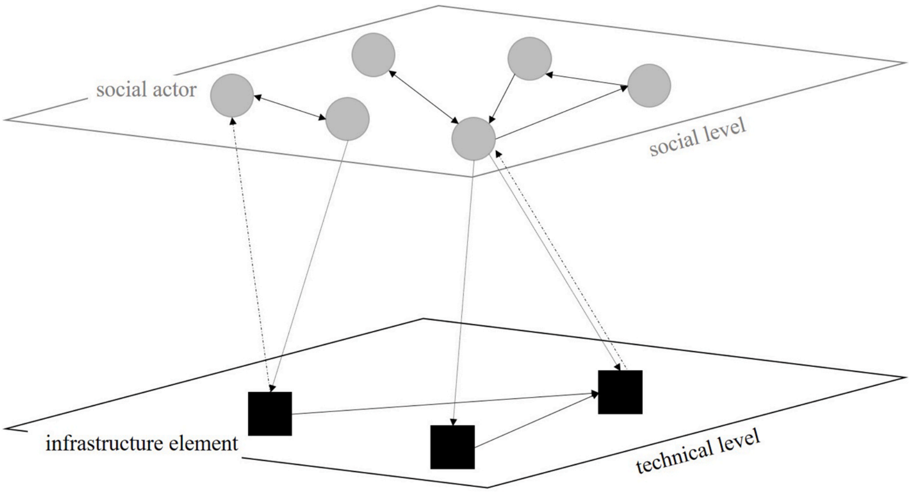


**Fig. 1.** Socio-technical network consisting of social actors at the social level and technical infrastructure elements at the technical level and multiple relations in between.

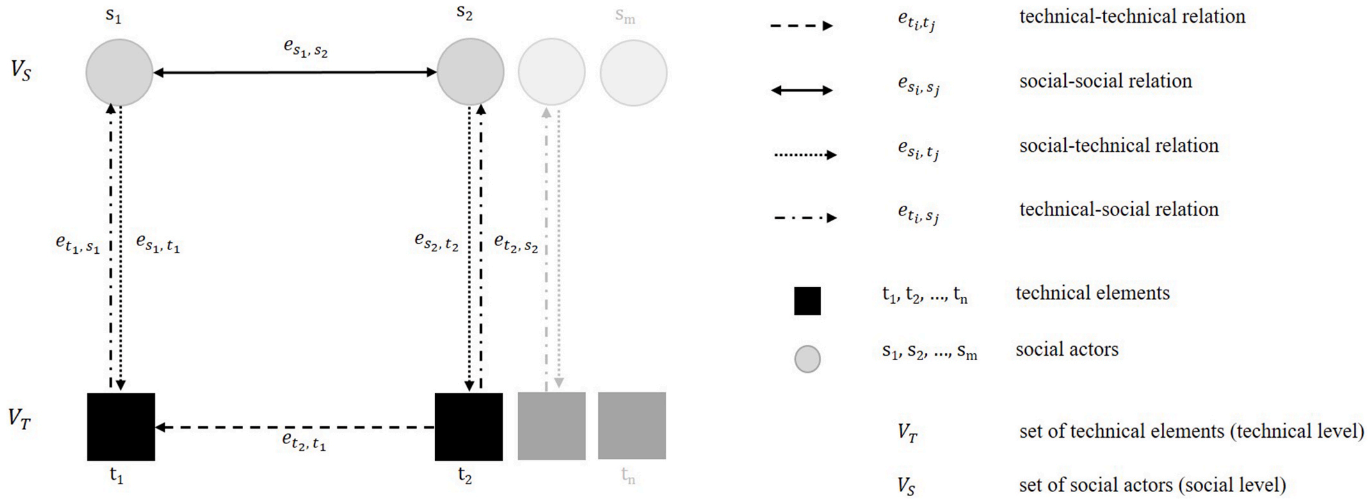


**Fig. 2.** Representation of a socio-technical network (STN) as a multi-level network.

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

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

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

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

Taking the social-technical network ($G_{ST}$) as an example, the concept of degree centrality can help determine whether a social actor is related to many technical elements (social-technical out-degree centrality $C^{ST}_{D+}(s_i)$). Considering the opposing direction of edges in the technical-social network ($G_{TS}$), we can find out similar circumstances, i.e., a technical element being related to either a single, to few or to many social actors (technical-social out-degree centrality $C^{TS}_{D+}(t_i)$).

The equations for degree centrality as presented in the respective column in Table A1 allow for the identification of central social actors and central technical elements in a STN.

### *3.2.2. Socio-technical motifs*

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

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

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

### *3.2.3. STNs and digitalization, decentralization, and integrated management of infrastructures*

Based on the descriptive concepts in Table A1 and the socio-technical motifs in Table 2, we provide interpretations of entire STN structures related to the trends of digitalization, decentralization, and integrated management in Table C1 in Supplementary Materials C.

In Table C1, we illustrate exemplary STN configurations and suggest mathematical equations to determine the degrees of digitalization, decentralization, and integrated management from a STN perspective. For example, an infrastructure system can be either socio-technical digital or not socio-technical digital or somewhere in-between. In the same way, an infrastructure system can be rather centralized or more decentralized. By considering social-social relations as well as social-technical relations, we can further determine whether an infrastructure system is managed in a fragmented or integrated way. Overall, the proposed equations may prove useful for comparing different STNs of infrastructure management in an analytical and formal way.

## 4. Application to the management of urban wastewater systems

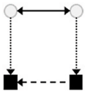
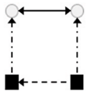
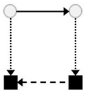
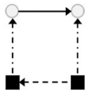
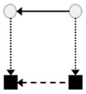
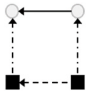
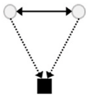
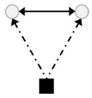
We take urban wastewater systems (UWS) as our case study to demonstrate the applicability of the STN approach. We do so by outlining the social and technical characteristics of UWS and describing how they can be studied from a STN perspective. We then provide a concrete operationalization of nodes and edges that is guided by a visualization. Based on our operationalization choices, we designed an empirical case study of a regional unit of an UWS in Switzerland and collected STN data through a context interview, document analysis, and a survey. Using the obtained case study data, we apply selected STN concepts from Tables A1, 2 and C.1, and conduct a preliminary analysis and interpretation of respective descriptive results. Our empirical application of STN is guided by the general research question: "What is the structure of a STN in urban wastewater systems and how can knowledge about this structure inform researchers and practitioners about governance and infrastructure challenges?"

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

Centralized UWS consist of multiple technical elements that are

**Table 2**

Selected socio-technical motifs within socio-technical networks.

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

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

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

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

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

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

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

### 4.2. STN operationalization and data collection

Drawing on the context interview and complementary document analysis, we identified all relevant technical elements, the technical-technical relations, and all social actors who are involved in the management of the UWS. We used a technical infrastructure map of the UWS given to us by the context interviewee to identify technical elements and technical connections (i.e., technical-technical relations). The context interviewee also provided us with information on all municipalities, engineers, and authority representatives involved in managing the UWS. Additional social actors relevant to the management of technical elements in the catchment area were added based on a check of all websites from municipalities active within the catchment area as well as available planning documents. The resulting list of social actors was then again validated by the context interviewee and can be found together with the list of all technical elements included in the analysis in Supplementary Materials E. With respect to the system boundaries, we represent technical elements of a WWTP and its main trunk sewer. For the latter, we consider the following technical elements: combined sewer overflows (CSO), and CSO tanks (CSO T), as well as pumping stations (P). The representation excludes the rest of the collection system and minor elements such as manholes. The technical elements are chosen based on their relevance to the investigated infrastructure trends and three considerations. First, they are equitable with digital technologies, which potentially transfer data to social actors. Second, they are important elements in terms of urban wastewater management and water protection. Third, they need to be actively operated, planned, and monitored by social actors. The correct representation of the technical network $G_T$ consisting of the technical elements and the technical-technical relations was validated by the key stakeholder with whom we conducted the context interview and a representative of the authority.

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

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

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[5] A wastewater association is an organizational form of inter-municipal cooperation where several municipalities join forces to operate technical elements of the UWS.

[6] We refrain from presenting the actual location to protect the anonymity of social actors.

[7] We provide a complete version of the survey questionnaire in Supplementary Materials D.

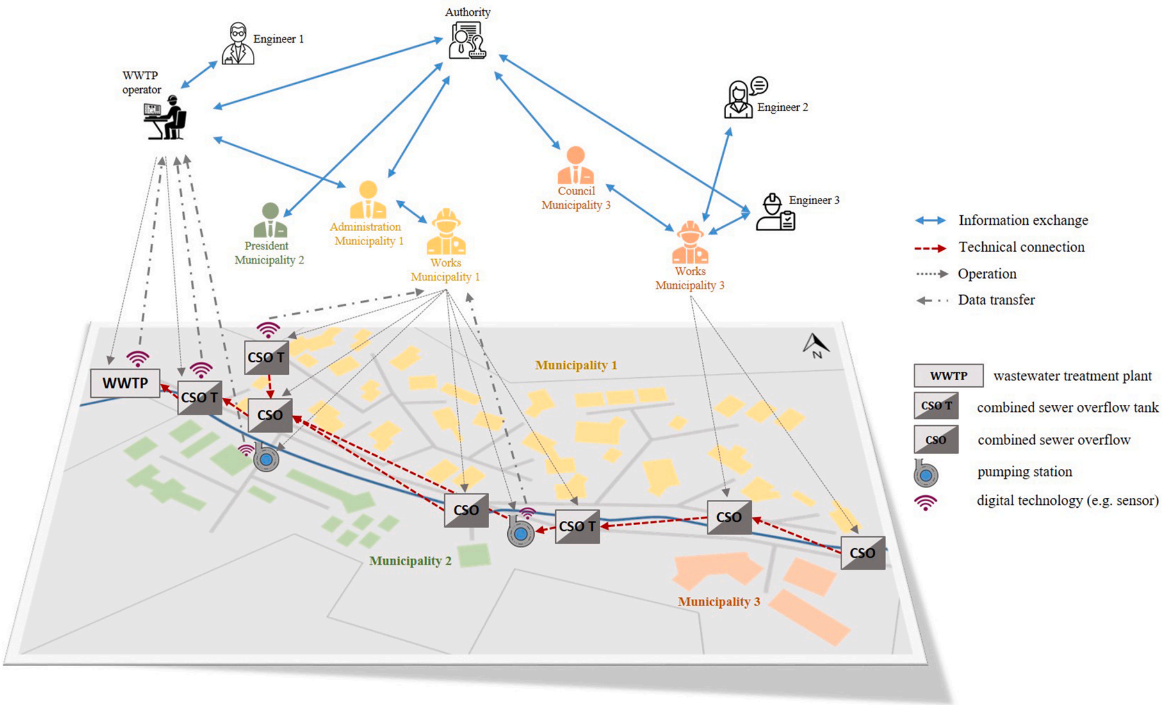

**Fig. 3.** Operationalization of a simple example of a socio-technical network (STN) of an urban wastewater system (UWS).

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

### 4.3. *Descriptive results from the STN analysis*

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

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

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

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[8] Data on social and technical nodes can be found in Supplementary Materials E. The analysis of the STN was performed in R studio using, for example, the packages graphlayouts (Schoch, 2020) and motifr (Angst and Seppelt, 2020).

[9] While Fig. 3 illustrates a simple example not based on any empirical data of our representation of the nodes and edges of a STN (i.e. including a technical infrastructure map and respective symbols of technical elements and social actors), Fig. 4 is based on empirically validated information and visualizes the empirical STN of a real-world UWS.

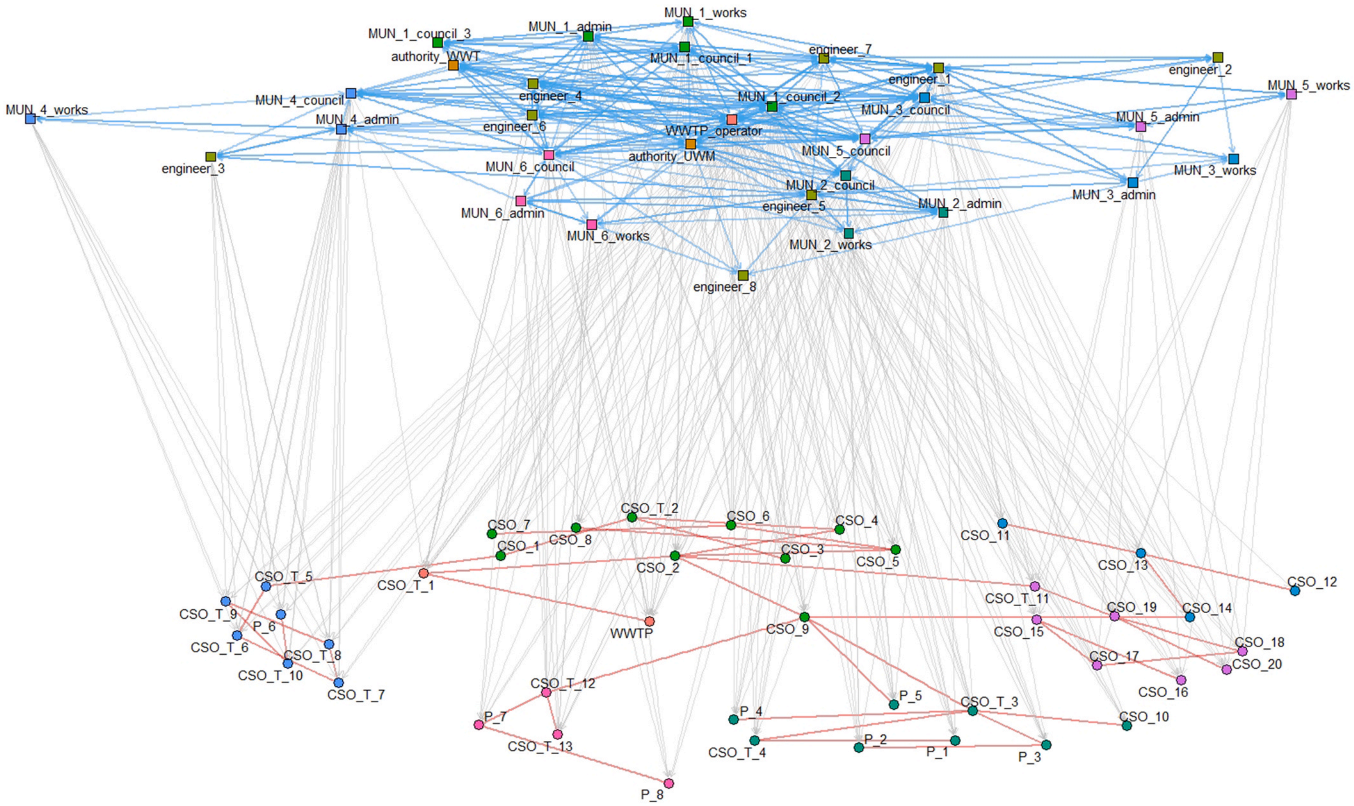

**Fig. 4.** Socio-technical network (STN) of an urban wastewater system (UWS) in Switzerland. Social actors are at the top, technical elements are at the lower level and colored based on their affiliation to a municipality. Information exchange edges are blue, technical connection edges are red, operation and data transfer edges are both colored grey. This STN was visualized using graphlayouts (Schoch, 2020) in R studio. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Based on the determination of degree centrality[10], the empirical STN study reveals that the municipal council representative 2 of municipality 1 who also has the role of the president of the wastewater association is most degree central[11] in the information exchange network, i.e., exchanges information with most other social actors (degree centrality: 39 edges). We further identify two degree central social actors[12] in terms of operation: the WWTP operator as well as the municipal council representative 2 of municipality 1 (i.e., the president of the wastewater association). These two social actors are degree central in the sense that they are involved in the operation of the highest number of technical elements (in total 38 out of 42 technical elements). This implies that they are critical social actors for the entire operation of the case study UWS. In terms of data transfer, CSO tank 1 is the most degree central technical element, as data is transferred to the maximum number of four social actors.

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

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

With respect to the social-technical motifs D (socio-technical triads)

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[10] Besides degree centrality, several different centrality parameters can be applied to evaluate the importance of a network node, for example, betweenness, closeness or eigenvector centrality (Freeman, 1978). Here, we base our interpretation on degree centrality. However, we provide additional results for betweenness, closeness, and eigenvector centrality in the social network in Supplementary Materials G along with information on in- and out-degree centrality.

[11] Here, degree central social actors in the information exchange network are those social actors that show the highest count of in-coming and out-going information exchange edges (social-social relations). Degree central social actors are those who exchange information with most other social actors and many social actors indicated that they exchange information with them (s. also Table A1 for the differentiation between in-degree (in-coming edges for a node) and out-degree (out-going edges from a node) centralities. Degree centrality is the sum of in- and out-degree centralities for a node.

[12] We base our interpretation of central social actors for the operation of the UWS on degree centrality, while other centrality parameters could be relevant as well (s. also footnote 10 and Supplementary Materials G).

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

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

in the operation network, we identified information exchange gaps between the municipal council representative 1 of municipality 1 and the WWTP operator as well as the municipal works representative of municipality 1. Further, by exchanging information with the WWTP operator as well as the municipal council representative of municipality 2, engineer 5 could bridge important information exchange gaps.

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

## 5. Discussion

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

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

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

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

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

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

First, researchers working with a STN approach could ask questions about central social actors or central technical elements. This could be important for understanding which technical elements are most crucial for integrated management (as they, e.g., connect different parts of the STN), or which social actors could play an important role in pushing towards decentralization or digitalization (Hoolohan et al., 2021; Mergel et al., 2019). A question allowing for a more detailed analytical insight into infrastructure systems would ask whether the STN is highly fragmented, or whether it is well integrated (s. Table C1). This information again could provide hints on where more efforts towards integrated infrastructure management might be needed.

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

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

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

## 6. Conclusions

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

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

## Credit author

**Liliane Manny:** Conceptualization; Data curation; Formal analysis; Methodology; Software; Visualization; Writing - original draft; Writing -

review & editing. **Mario Angst:** Writing - review & editing. **Jörg Rieckermann:** Funding acquisition; Project administration; Supervision; Writing - review & editing. **Manuel Fischer:** Conceptualization; Supervision; Writing - original draft; Writing - review & editing.

## Declaration of competing interest

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

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## Supplementary Materials. Supplementary Materials

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