An integrated system approach to characterise a drinking water infrastructure system

Kloosterman, Ritsche Anne ; van der Hoek, Jan Peter

DOI
10.1504/IJCIS.2020.105403

Publication date
2020

Document Version
Final published version

Published in
International Journal of Critical Infrastructures

Citation (APA)
Kloosterman, R. A., & van der Hoek, J. P. (2020). An integrated system approach to characterise a drinking water infrastructure system. *International Journal of Critical Infrastructures*, *16*(1), 1-22. https://doi.org/10.1504/IJCIS.2020.105403

An integrated system approach to characterise a drinking water infrastructure system

Ritsche Anne Kloosterman*

Vitens N.V.,
Oude Veerweg 1, Zwolle,
Postbus 1205, 8001 BE Zwolle, The Netherlands
Email: rian.kloosterman@vitens.nl
*Corresponding author

Jan Peter van der Hoek

Department of Water Management,
Faculty of Civil Engineering and Geosciences,
Delft University of Technology,
Stevinweg 1, 2628 CN Delft, The Netherlands
Email: J.P.vanderHoek@tudelft.nl

Abstract: The object of this article is the drinking water infrastructure (DWI), a critical societal infrastructure. To make effective decisions it is important to characterise and understand the complexity of DWI systems. DWI systems can be seen as a system of systems, consisting of the social-ecological system and the social-technical system. The social-ecological system determines the location and seize of the water resources, while the social-technical system is about the technical infrastructure. The two systems with different characteristics must align to work effective together in the DWI system. The tension between different lifecycles of the assets and dynamic changes in both systems, the time of change, is important to take into account. The SoPhyTech infra framework was developed based on the two systems and time of change. The advantages of applying the SoPhyTech infra framework is studied in a case comparing two very different DWI systems: Indonesia (Semarang) and the Netherlands (Vitens). The SoPhyTech infra framework was shown to be effective for characterising a DWI system with different interacting lifecycles in different systems and it is expected that it also can be used to characterise other infrastructure systems.

Keywords: system of systems; SoS; decision-making; complexity; drinking water; critical infrastructure; water resources; social-ecological system; technical infrastructure; social-technical system; long-term decisions making; long life time assets; Semarang; Vitens.

Reference to this paper should be made as follows: Kloosterman, R.A. and van der Hoek, J.P. (2020) 'An integrated system approach to characterise a drinking water infrastructure system', *Int. J. Critical Infrastructures*, Vol. 16, No. 1, pp.1–22.

Biographical notes: Ritsche Anne Kloosterman is a Senior Strategic Advisor from Vitens, the largest drinking water company of the Netherlands and researcher from the Technological University of Delft. He is a Senior Advisor for strategic planning of the infrastructure, asset management, water resources and R&D on asset management. He is member of the program commission and a technical commission of next generation infrastructures, a collaboration of large infrastructure organisations in the Netherlands.

Jan Peter van der Hoek is a Professor of Drinking Water Engineering from the Technical University of Delft. He is also the Head of the Strategic Centre of Waternet, the water cycle company of Amsterdam and surroundings. In this position he is responsible for the innovation strategy and the research agenda of Waternet. He is a member of Standard Commission 1 of EurEau, the European Union of National Associations of Water Suppliers and Waste Water Services. Standard Commission 1 deals with drinking water affairs. He is the Chair of the program committee of the Joint Research Program of the Dutch drinking water companies, and chairs the Program Council of the TKI Watertechnologie, part of the Dutch Topsector Water.

1 Introduction

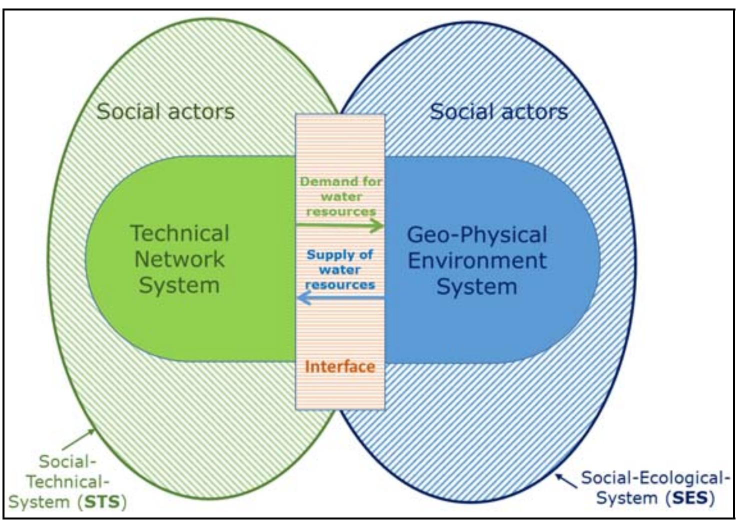
The object of this article is the drinking water infrastructure (DWI), a critical infrastructure that maintains the essential function of collective drinking water supply. Worldwide the drinking water demand served by DWI systems has increased enormously in the last 100 years. Important reasons for this are the increased coverage rate of houses connected to the DWI systems, the population growth and increasing welfare. DWI systems have to be able to supply enough and reliable drinking water at all times, which is critical due to different kind of complexities and uncertainties. These are related to the long life time of the assets of DWI systems, the (changes in) availability and quality of water resources for DWI systems, new water treatment techniques and new techniques for monitoring the water quality, the length and connections of pipes needed to distribute the drinking water, physical barriers like rivers and mountains and changes in the demand of drinking water. Beside this, organisational responsibilities, capabilities and ideas of stakeholders, interconnectivities and the system approach are important points of interests (Hatton et al., 2018; Bauer and Herder, 2009).

The aim of this article is to support the decision-making in DWI systems for the long-term. To reduce the likelihood that the DWI system does not function over a given period the DWI manager has to make decisions that are effective now but also in the future. For the effectiveness of decision-making it is important to characterise and understand the complexity of DWI systems.

DWI systems consist of complex interactions of assets and social actors in the technical network (socio-technical system) and the water resources in the geo-physical environment (social-ecological system) making DWI systems a system of systems (SoS). Small changes in a sub-system may lead to (unexpected) system changes (Herder et al., 2008). To analyse the vulnerability, stability, and resilience of different infrastructures these (inter)dependencies must be known. The understanding of such multiple interdependencies is at an early stage and is one of the major challenges in the design of infrastructures (Vespignani, 2010; Johansson and Hassel, 2010; Hatton et al., 2018; Ed-daoui et al., 2018). Studying infrastructure systems in isolation without taking into account the systems with which they interact does not capture secondary or higher effects, which are difficult to understand. Therefore, a comprehensive and holistic SoS approach is needed (Johansson and Hassel, 2010; Bauer and Herder, 2009). An SoS approach attempts to characterise the complexity of infrastructures by taking a view that extends beyond technical design and considers aspects embedded at a multitude of levels (Ackoff, 1971; Agusdinata and DeLaurentis, 2008; Walker, 2000; Bruijn and Herder, 2009; Bauer and Herder, 2009; Herder et al., 2008). When studying interdependencies, finding a balance between complexity and simplicity is challenging (Utne et al., 2011).

Interfaces are critical areas of concern for SoS, because interdependencies are created and the different systems impact the integration (Figure 1). An important interface for DWI systems is the interface between the technical network (social-technical system) and the geo-physical environment (social-technical system). The technical network is the primarily responsible of the drinking water (DW) company, while the geo-physical environment consists of common pool resources (CPRs) managed by the government. For DWI systems it is crucial that the water resources – an ecological service – interact with and adapt to their geo-physical surroundings (Vespignani, 2010; Eusgeld et al., 2011) but it is also crucial that technical network and water resources adapt and interact to each other (Figure 1). Changes in the availability or quality of the water resources can have a big impact on the water supply, forcing to interventions in the layout and management of DWI systems. Even small changes in a sub-system may lead to (unexpected) system changes (Herder et al., 2008).

Figure 1 Drinking water infrastructure (see online version for colours)



Bauer and Herder (2009) developed a framework for socio-technical systems that can be used for DWI systems. However, as DWI systems include the social-technical system and the social-ecological system, it is better to add the geo-physical environment as this is an important characteristic of the DWI and the geo-physical environment interacts – in the interface – in a complex way with the technical network. There are many situations showing the importance of geo-physical systems for DWI systems. The availability of water resources determines the architecture of the technical system, a declining availability of existing water resources may cause complex transportation challenges, may force the introduction of new laws and regulations, or may force infrastructure companies to use resources of lower quality with more complex water treatment processes. Calamities in the geo-physical environment may also have a direct impact on operational activities. These elements of the geo-physical environment can change in time, as seen in the socio-technical framework.

For example, the opinion in the Netherlands on drought changed in time. Before 1984 it was a minor attention point (Ministerie van Verkeer en Waterstaat, 1968) and after awareness on the impact of drought was risen, drought caused by groundwater extractions of DWI systems was a big issue (Ministerie van Verkeer en Waterstaat, 1984, 1989). In combination with the expected growth in the drinking water demand governments obliged DWI managers to change (partly) from groundwater to surface water. After some years, the knowledge on the causes and impact of drought had grown and policy makers realised that DWI systems were only one part of the causes of drought and only eliminating groundwater extractions of DWI systems did not help to solve the problem. All parties involved in the drought had to participate. Climate change and the low vulnerability of groundwater for climate change, but also terrorist attacks (11 September 2001) changed the ideas and groundwater became the first preferred water resource for DWI systems of the responsible governments (provinces and national government) (Ministerie van Verkeer en Waterstaat, 2009).

The extension of the socio-technical framework with the geo-physical environment is called SoPhyTech infra framework. The objective of this article is to develop the SoPhyTech infra framework and to subsequently describe the advantages of applying the SoPhyTech infra framework to DWI systems for long-term decisions.

2 Methods

Bauer and Herder (2009) developed a framework for socio-technical systems. The geo-physical system is integrated into this socio-technical framework. To describe the advantages of applying the SoPhyTech infra framework, the framework is examined in comparing DWI systems in different social, technical, and geo-physical environments. For comparing and describing different situations two case studies were used (Yin, 2013): Semarang (Indonesia) and Vitens (Netherlands). Indonesia and the Netherlands differ in their geo-physical systems (tropical climate versus sea climate, geohydrologic situation, etc.), the social situation (welfare, institutional arrangements, etc.) and their technical systems (the engineering principles and techniques that are used, etc.).

The definitions of Morse (2015) and Maxwell and Chmiel (2014) are used to evaluate the reliability, validity, and generalisability of the SoPhyTech infra framework:

- *Reliability:* The ability to obtain the same results if the study were to be repeated.
- *Validity:* The logic of the description and whether it can be recognised by others.
- *Generalisation:* The possibility to extend the results to other individuals, settings, times, or institutions.

3 Developing the SoPhyTech infra framework

In this research, a DWI system is defined according to the SoS perspective as the combination and interaction between:

1. The technical network (system) with links and nodes. The links are pipes of different seize and materials for the transport and distribution of drinking water. The nodes are technical installations to extract water from water resources, pumping installations, treatment plants and different forms of water storage.
2. The geo-physical environment (system) consisting the common pool water resources needed for DWI systems
3. The social actor network (system) or all actors who are involved. The two main distinctions are the actors involved with the technical network (socio-technical system) and the actors involved with the geo-physical environment (socio-ecological system).

Bauer and Herder (2009) developed their framework for socio-technical systems based on the concept of different timescales of change developed by Williamson (1998) and the concept of social-technical systems (Table 1) (Trist, 1980; Geels, 2004). Williamson made a distinction between four layers, each with a different timescale of change: embeddedness, institutional environment, governance, and operation and maintenance. This framework was extended to the social and technical environment by Bauer and Herder (2009). As analytically precise definitions are difficult to formulate, Bauer and Herder (2009) operationalised the socio-technical system as arrangements of multiple purposive actors and material artefacts interacting in ways that make it necessary to analyse the total system and not just the underlying subsystems. Hereafter, we describe the building of the integrated SoPhyTech infra framework by extending the social-technical framework with the geo-physical environment.

Table 1 Socio-technical framework of Bauer and Herder

Timescale		*Social environment (after Bauer and Herder, 2009)*	*Technical environment (after Bauer and Herder, 2009)*
Layer 1	*Embeddedness* Often non-calculative, Changes 100 to 1,000 years.	Informal institutions, customs, traditions, norms, religion.	Informal conventions embedded in the technical artefacts or existing infrastructure.
Layer 2	*Institutional environment* Changes 10 to 100 years, institutional setting.	Formal rules of the game (property, policy, judiciary, etc.).	Technical standards, design conventions, technological paradigms.
Layer 3	*Governance* Changes 1 to 10 years, design of efficient government regime.	Play of the game (contracts, governance of transactions).	Protocols and routines governing operational decisions and the (best available) technology.
Layer 4	*Operation and maintenance* Continuous adjustments.	Prices, quantities, incentives.	Operational decisions.

3.1 Time framework of Williamson in the geo-physical system

The geo-physical system is that part of the environment that includes entirely geo-physical factors such as soil, climate and meteorology, water, and minerals. The way that actors of the physical system precondition, enable, or disturb the infrastructure and its function and use of resources are shown in the social geo-physical environment column in the SoPhyTech infra framework (Table 2).

Table 2 The SoPhyTech infra model

Timescale		*Social geo-physical environment*	*Social-technical environment*
Layer 1	*Embeddedness* Often non-calculative, changes 100 to 1,000 years.	Informal ideas about the potencies of the geo-physical environment.	Informal conventions embedded in the technical artefacts or existing infrastructure.
Layer 2	*Institutional environment* Changes 10 to 100 years, institutional setting.	Regulation of the use of resources.	Technical standards, design conventions, technological paradigms.
Layer 3	*Governance* Changes 1 to 10 years, design of efficient government regime.	Governance of (water) resources.	Protocols and routines governing operational decisions and the (best available) technology.
Layer 4	*Operation and maintenance* Continuous adjustments.	Operational decisions in the day-to-day use of (water) resources.	Operational decisions.

Layer 1: embeddedness

Geo-physical factors (soil, minerals, water, etc.) can be used in different ways. Layer 1 includes informal ideas and knowledge about the potential uses of the geo-physical environment such as exploration for minerals, settlement areas, transportation lines, disposing of waste, and drinking water resources.

Layer 2: institutional environment

The regulation of water resources – the formally approved availability and rules on the quality of resources – have an important impact on the layout of the DWI and on spatial planning.

Layer 3: governance

At the interface, between different water resources, governance problems can emerge through conflicting claims and interests. DWI makes direct use of space; drinking water resources also impact others through restrictions in environmental protection zones and changes in the (ground) water level. Decisions in the governance of the water resources affect the availability and quality of the resources that are used in the infrastructure system.

Layer 4: operation and maintenance

This is related to operational decisions regarding the day-to-day use of (water) resources; the protection (maintenance) of these water resources; and the management of unexpected geo-physical calamities and accidents such as earthquakes, storms and floods, and pollution such as pollution caused by leaking oil tanks or chemical freight spillages.

3.2 Integration of the geo-physical system into the framework

In the framework the four layers are interconnected, but for the purpose of analysis – using a shorter time horizon – Williamson (1998) and Altamirana (2010) opt to disregard the feedback between layers. The first layer is spontaneous, while the other layers have the following purposes: to get the institutional environment right (layer 2); to get the governance structure right (layer 3); and to get the marginal conditions right (layer 4).

A first exercise of the framework was done to identify long-term trends for long-term vision of a DWI company, Vitens. Vitens made this long-term vision with the objective of being more resilient to uncertain future events. To be able to define resilience measures, the possible trends must be known and described. Vitens used the SoPhyTech infra framework to identify the trends of the DWI systems. These trends were used to define scenarios, which subsequently were used to describe resilience measures (Vitens, 2016). It turned out to be important to define the different key (powerful) stakeholders and fill in the table for each key stakeholder.

4 Application of SoPhyTech infra framework to compare different social-technical and social geo-physical environments

In this case two countries with different DWI systems are compared: Indonesia and the Netherlands. The Netherlands has many regulations, a mild sea climate and a long history of a systematically technical approach in a high welfare environment. Indonesia, at this moment the largest economy of Southeast Asia, is a former plantation colony of the Netherlands and a diverse archipelago nation of more than 300 ethnic groups (World Bank, 2018). In an overview of Indonesia, the World Bank (2018) indicates that Indonesia is the fourth most populous nation, the world ten largest economy and an emerging middle-income country. Infrastructure development and reduction of poverty are important objectives of the government.

To examine the applicability of the SoPhyTech infra framework, both DWI systems are described for each of the four layers and the two systems of the framework. As indicated in the previous section it is necessary to define the stakeholder for whom the analysis is done. In this case the perspectives of the (national) government are used. In Table 3 the SoPhyTech model is operationalised by questions to analyse the differences.

4.1 Layer 1: embeddedness

4.1.1 General description

Econometric analyses suggest that political stability and the control of corruption are important factors for access to safe water in rural areas in developing countries (Davalos, 2016). Cultural assumptions (paradigms) are dominant in perceived causes, explanations, and possible remedies. Cultural theory claims that these biases are unavoidable, making paradigms at odds with integrated holistic solutions (Pahl-Wostl et al., 2008; Hoekstra, 1998). In cultural theory, the group-grid typology has been developed – four combinations of high and low grid and group, which are called ways of life: hierarchist, egalitarian, individualist, and fatalist (Table 4). The group axis describes the incorporation of individuals into groups, while the grid axis describes how external rules determine the behaviour of individuals.

Table 3 Stakeholders and questions for comparing two different DWI systems

Timescale	*Social geo-physical environment*	*Social-technical environment*
	Focus on the water resources.	*Focus on the technical part of the infrastructure.*
Layer 1: embeddedness	What are the (informal, cultural) ideas about the potencies and use of the geo-physical environment? The ideas are embedded in the existing use of water resources.	What are the (informal, cultural) ideas about the drinking water supply? The ideas are embedded in the technical artefacts or existing infrastructure.
Layer 2: institutional environment	How is the use of water resources regulated?	What are the technical standards, design conventions, technological paradigms imposed by the DWI company and the government?
Layer 3: governance	How is the governance of (water) resources organised? What are the protocols and routines governing operational decisions and (best available) technology?	How is the governance of the technical part of the infrastructure organised? What are the protocols and routines governing operational decisions and (best available) technology?
Layer 4: operation and maintenance	What are the incentives in the use of resources?	What are the incentives for operational decisions?

Table 4 Group-grid topology

	Low grid	*High grid*
Low group	Individualist	Fatalist
High group	Egalitarian	Hierarchist

Table 5 Views on water

	Hierarchist	*Egalitarian*	*Individualist*	*Fatalist*
Water demand	A given need	A manageable desire	Price-driven	An unmanageable desire
Public water supply	Incremental improvements	Basic supply to everyone	Driven by economic growth	Given to the rich
Groundwater use	Inevitable	Below sustainable level	Desirable if cost effective	Profitable to a few
Water scarcity	Supply problem	Demand problem	Market problem	Problem of individuals

Hoekstra (1998) described the characteristics of views on water according to the four ways of life (Table 5). The water culture – the shared core beliefs and views of stakeholders – changes as the beliefs of individuals change (Valkering et al., 2009; Jorgensen et al., 2009).

Netherlands (Vitens)

The Netherlands has characteristics of the egalitarian way of life (Maleki and Hendriks, 2015). Over the period of more than a century, the social interest in water resources for the drinking water supply changed from the domination of public responsibility as a basic supply to everyone, to prevent disease, to a decentralised optimisation of one of different equal interests (Ministerie van Verkeer en Waterstaat, 2009). The water supply must be provided in the most efficient and sustainable way, with attention for responsible use by the customers (water scarcity as a demand problem) (Ministerie van Verkeer en Waterstaat, 2009).

Indonesia (Semarang)

Semarang is a predominantly Islamic society. Although fatalism scores high in the Muslim society, Indonesia has compared to other Islamic societies a relative low score on fatalistic attitudes, probably because the society is influenced by China, western colonisation and other religious minorities (Acevedo, 2008). In Semarang fatalistic elements are found in the drinking water supply. Semarang is served by a relative big DWI company (Perusahaan Daerah Air Minum – PDAM) and several relative small public and private DW companies and a lot of customers have their own water supply system. Kooy (2008) investigated the genealogy of Jakarta's water supply and described the unequal patterns of water access as a product of (post) colonial governmentalies. The concept of governmentalies is taken from Foucoult and used by Kooy (2008) as a framework to analyse how power works (material and discursive) and what it does (on nature, space and subjects).

In Jakarta very complex power relations makes it difficult to change the architecture and government of the water supply system (Kooy, 2008) and it is to be expected this is also the case in Semarang. An important reason for this is the basic western, colonial idea of a central piped water supply system versus the eastern idea of more decentralised water supply systems (Kooy, 2008). Kooy (2008) states that the decentralised system makes distinctions for economical productive urban spaces and for different categories of populations (European, native, modern, undeveloped, politically obedient, economically mobile and illegal groups) leading to a socio-economical fragmented network. The contra dictionary and inherently conflicting nature of government and the uncooperative population contributed to this splintering of the network (Kooy, 2008).

4.1.2 Layer 1: social geo-physical environment

What are the (informal, cultural) ideas about the potencies and use of the geo-physical environment? The ideas are embedded in the existing use of water resources.

Netherlands (Vitens)

The Netherlands is a delta area with large rivers and sand layers (aquifers). In most of the northern, eastern, and southern areas of the Netherlands, these aquifers contain fresh groundwater, which is relative easy to access and well protected by semi-confined clay layers (65% of the drinking water is produced from groundwater). Precipitation supplements the groundwater. Because the groundwater in the western part of the Netherlands is brackish, two different concepts are used: drinking water is produced from surface water (19%) in combination with reservoirs for monitoring, storage, and quality improvement; or indirectly by managed aquifer recharge (16%) (VEWIN, 2017; de Moel et al., 2004). Approximately 1% of the total water balance in the Netherlands is used for drinking water (Dufour, 2000).

Indonesia (Semarang)

Semarang capital of Central Java Province, with approximately 1.5 million inhabitants, is located on the northern part of Java. Semarang has a tropical climate with a rainy and a dry season and is geologically composed of alluvial deposits of clay and sand. The bearing capacity of the soft sandy clay layers is very low and causes soil subsidence (Widada et al., 2017), which is increased by groundwater extractions, in 2000 about 38 million m^3/year (Lubis et al., 2011; Rockefeller Foundation, 2016). Lubis et al. (2011) measured that the soil subsidence is approximately 8 cm/year.

The city Semarang is divided into thirds by two rivers. The annual rainfall is about 2,065–2,460 mm (Lubis et al., 2011).

DW companies are called PDAM in Indonesian. The municipality of Semarang is facing severe water resource challenges that directly affect the performance of the PDAM in Semarang and the service levels it provides to its customers (Laksmiwati et al., 2017):

1 Uncontrolled and unregulated extractions by domestic and commercial/industrial consumers are inducing dramatically falling groundwater levels, causing
   - a soil subsidence, especially in the coastal belt and Kota Lama (Old Town)
   - b saline intrusion.

2 Many customers are not satisfied with PDAMs service levels and have constructed private wells, further depleting the scarce groundwater resources. PDAM needs to double its production capacity to meet future demand.

4.1.3 Layer 1: social-technical environment

What are the (informal, cultural) ideas about the drinking water supply? The ideas are embedded in the technical artefacts or existing infrastructure.

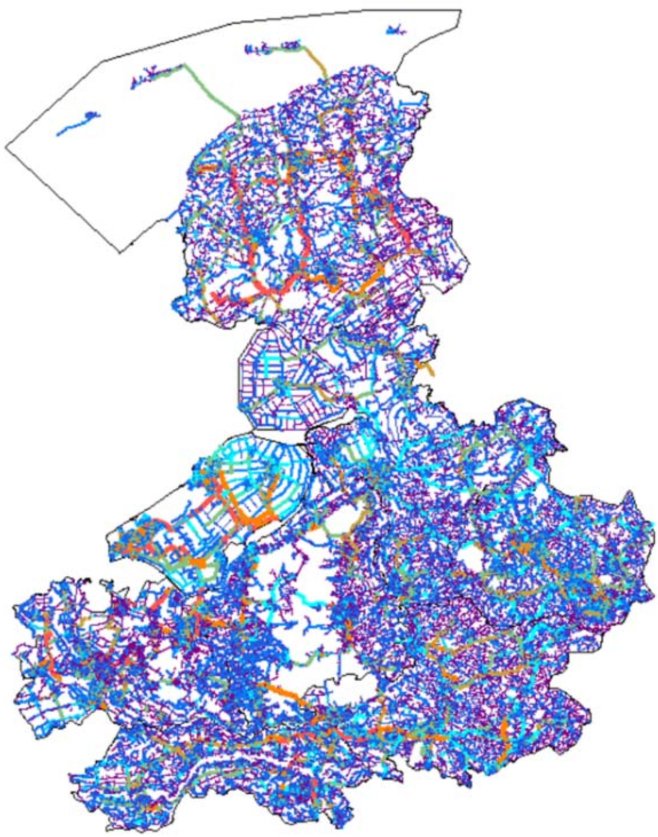
Netherlands (Vitens)

Since the 1980s, an important paradigm shift in making reliable drinking water in the Netherlands is the abandoning of chlorine as the main disinfectant (de Moel et al., 2004).

To illustrate the complexity of the layout of a DWI, the DWI of Vitens is highlighted. Vitens is a drinking water company in the northern, middle, and eastern part of the Netherlands. It originated from a merger of dozens of smaller drinking water companies, each with their own technical layout. As a result, the Vitens technical system is an aggregation of assets such as pipes and pumps using different materials and in different sizes. Although the merging of the first companies began more than 30 years ago, the inheritance of the different companies is still visible in the assets and the layout of the drinking water system.

In Figure 2, the Ijsselmeer Polders are clearly visible in the central left part of the figure. These polders were designed, developed and occupied at the same time. Therefore, in that area, the technical part of the DWI is very systematically constructed. In the eastern part, the different communities developed their own DWI systems, which were coupled over a period of decades (after mergers for example) – an organic growth.

Figure 2 Layout of Vitens infrastructure with different colours for different pipe diameters (see online version for colours)

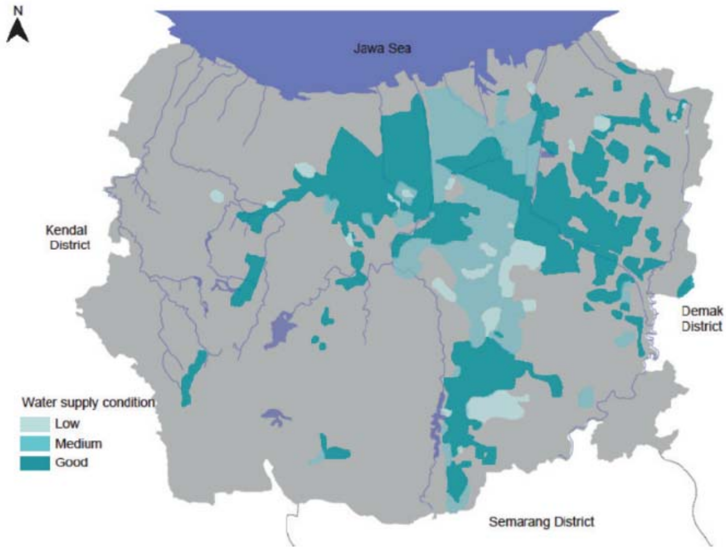


Indonesia (Semarang)

The description of the situation in Semarang is taken from the assessment made by Laksmiwati et al. (2017).

In 1911, the Dutch government started with the drinking water supply for the European inhabitants of Semarang with an artesian well. Nowadays PDAM has a splintered network and only covers 60% of the customers (Figure 3 and Figure 4). As mentioned before in this article Kooy (2008) analysed and explained the background of this situation.

Figure 3 Pipeline network coverage in 2012 (see online version for colours)



Source: Laksmiwati et al. (2017)

Figure 4 Houses connected to PDAM (black houses are connected) (see online version for colours)

Water losses due to non-revenue water (NRW) are also an important issue for PDAM. Currently the NRW is 40% and PDAM ambition is to reduce it to 30%. Losses are found in the commercial, distribution and metering processes. Compared to other DWI systems the energy consumption at PDAM is very high (1.67 kwh/m^3).

Maintenance of the technical infrastructure can be characterised as breakdown or curative maintenance. PDAM wants to change this in preventive maintenance (Laksmiwati et al., 2017).

4.2 Layer 2: institutional environment

4.2.1 Layer 2: social geo-physical environment

How is the use of water resources regulated?

Netherlands (Vitens)

All the water resources used for drinking water are renewable. However, the extraction of drinking water can limit other groundwater users or can have an undesirable impact – for example, to nearby wet nature areas. In 1853, the increased use of groundwater made it necessary to secure the use of groundwater for public health in the Civil Code, and in 1954 the most urgent issue, the extraction of drinking water, was regulated in law through the Groundwater Law for Drinking Water Companies (Ministerie van Sociale Zaken en Volksgezondheid, 1954). Until today, all licenses for groundwater extractions are permanent (Ministerie van Verkeer en Waterstaat, 2009). In the following decades, growing insights and knowledge regarding the importance of protecting water quantity and later water quality led to an increase in the number of related regulations such as the Law on Pollution of Surface Water (1969) and the Law on Soil Protection (1986).

The European Water Framework Directive (European Parliament and Council, 2000) requires countries to designate waterbodies for drinking water extraction with specific water quality requirements. Countries have an obligation to prevent quality deterioration. This is implemented in Dutch regulation, which will be explained for one source: groundwater. Based on the environmental law (Ministerie van VROM, 1979), regional authorities (provinces) are obliged to install groundwater protection zones and corresponding regulations. There are different protection zones based on the geo-physical characteristics of the DWI – for example, the Dutch province of Gelderland distinguishes between the following zones: the one-year protection zone, limited to drinking water production; the 25-year protection zone, with restrictions on land use; a drill-free zone, where drilling through protective soil layers is prohibited; and a 1,000-year zone, the recharge area, with restrictions on the recovery of fossil fuels such as shale gas. Through these regulations, the risks of groundwater pollution are reduced, making extra treatment steps unnecessary.

Indonesia (Semarang)

The institutional framework for the regulation of groundwater use in Indonesia is complex. In the constitution of the republic of Indonesia (1945) it is defined that water is owned by the state. In 1974 a law (Undung-Undang) regulates that the surface water is organised by the Ministry of Public Works and the Ministry of Mining and Energy regulates the groundwater (Syaukat and Fox, 2004). The surface water resource management is a shared responsibility among various ministries and agencies.

Since early 1980's a regulatory framework for groundwater management exists in Indonesia, based on the instruments: water quotas and water tariffs (Braadbaart and Braadbaart, 1997).

The department of mines has formal jurisdiction over groundwater and the operational department the Environmental Geology Directorate (EGD) monitors the groundwater resources and gives technical advice but shares its groundwater management tasks with the province (Syaukat and Fox, 2004). The province operates in two agencies: the Water Management Office, responsible for the registration and issuing of permits and the Revenue Agency, responsible for the collection of water retributions (Braadbaart and Braadbaart, 1997).

4.2.2 Layer 2: social-technical environment

What are the technical standards, design conventions, technological paradigms imposed by the DWI Company and the government?

Netherlands (Vitens)

In the Netherlands, the drinking water law stipulates that drinking water companies must have public shareholders and have the task to deliver reliable drinking water in a sustainable and efficient way in a determined distribution area. The drinking water company must take care of the water resources (monitoring and research, stimulate to prevent pollution, and education), must take special care for small users, and must have tariffs that are cost-effective, transparent, and non-discriminatory (Ministerie van Infrastructuur en Milieu, 2009).

Within the Netherlands, the scale of the drinking water companies has changed from municipal to interprovincial.

Different paradigms under the responsibility of one DWI Company and in the same DWI system are often found. In the Vitens infrastructure, different visions of the storage of water can be found. Storage is necessary as the water demand fluctuates during the day. Water storage in reservoirs is possible close to centres of water demand, close to production stations, or in between, which enables the mixing of water from different productions stations. The storage capacity in the Vitens distribution area also varies over periods ranging from several hours to a week.

In the Dutch drinking water sector, cast iron was the main material used for pipes until approximately 1955. This changed due to the introduction of asbestos cement pipes. The health risks of these materials urged the drinking water sector to develop a new type of pipes: PVC. For Vitens (2016) this has been the dominant material used for new pipes from 1960 until the present day.

Indonesia (Semarang)

The provision of water supply services in Indonesian urban areas is the responsibility of PDAMs, local government owned water utilities. Currently there are approximately 400 PDAMs in Indonesia. PDAM Tirta Moedal Kota Semarang (http://www.pdamkotasmg.co.id/) is the drinking water utility in Semarang and was established in

1911. The Municipalities (Kota) are tasked with sanitation (solid and liquid waste collection). There are a few exceptions where PDAMs are also tasked to provide sanitation services, however, not in Semarang. There is no regulatory authority. The performance of the PDAMs is assessed and supervised by the municipality (Kota) they serve, BPKP (national auditor, under the Ministry of Finance) and BPP-SPAM (Ministry of Public Works).

The PDAMs are free to publish information about their performance on their individual websites. Two national benchmarking systems exist, both report annually:

- performance and financial benchmark by BPKP (the national auditor under Ministry of Finance)
- technical performance benchmark by BBP-SPAM (Ministry of Public Works).

Perpamsi is the national association of PDAMs. It maintains regional offices, organises training, exchange and partner visits and publishes a bi-monthly magazine.

The Ministry of Public Works and Public Housing (PUPR, the former PU) has a natural interest in well performing and resilient PDAMs that ensure provision of adequate water supply services to the public. They initiated a program with the aim for an effective implementation of the '100-0-100 program' aiming at 100% water supply coverage, 0% living in slums and 100% sanitation coverage by 2019.

PDAM is obliged by law to serve for free water towers (warung air), fire connections, public water, Islam boarding school, orphans or to serve water by a truck if people do not have water caused by not functioning of the water supply (Laksmiwati et al., 2017).

As there is no legislation of drinking water quality, the World Health Organization (WHO, 2017) standards are used.

4.3 Layer 3: governance

4.3.1 Layer 3: social geo-physical environment

How is the governance of water resources organised?

Netherlands (Vitens)

The governance of water projects in the Netherlands is changing from a technocratic top-down process to a more network oriented approach (Buuren et al., 2012). This is mainly caused by the complexity of water projects, decentralisation, and the professionalisation of interest groups (Meerkerk et al., 2015). The literature considers network management to be an important factor in realising high network performance (Koppenjan and Klijn, 2004). To develop new water resources in areas with many stakeholders with complex interrelations, Vitens works with *area processes*. In an *area process* all stakeholders who are involved participate, bringing in their ideas and performance wishes. The objective of this *area process* is to define a desired collective network performance, including the financial division between the stakeholders, and to realise this (Vitens, 2016). Vitens also uses covenants and agreements with other stakeholders, especially governments, to make appointments about taking measures to reduce water quality risks and to improve the future performance of the DWI (Vitens, 2016).

Indonesia (Semarang)

Despite a regulatory framework, the pumping of groundwater in urban areas has increased dramatically (Syaukat and Fox, 2004; Braadbaart and Braadbaart, 1997). Braadbaart and Braadbaart (1997) showed that the reason for this grow is weak enforcement. The division in execution between EGD and province was a reason for failure in groundwater quota enforcement. Water pumpers with water-metres mostly paid a negotiable amount of money at the Revenue Agency, not related to the actual withdrawal and pumpers from unreported abstractions did not pay at all. The core priority for the Revenue Agency was to raise the provincial revenues and this stimulates the groundwater consumption what clashes with sustainable groundwater conservation. Another aspect was that the cost of groundwater (investment costs, execution costs and tariffs) was too low to influence the decisions of firms to manage their own water supply. This division in execution was the cause for failure in groundwater quota enforcement.

4.3.2 Layer 3: social-technical system

How is the governance organised? What are the protocols and routines governing operational decisions and (best available) technology?

Netherlands (Vitens)

Designates of public shareholders are responsible for setting the tariffs for drinking water based on a substantiated proposal of the executive directors of a drinking water company. As the designates of the public shareholders are controlled by elected representatives, the tariffs and underlying plans and strategies are indirectly controlled by elected representatives. Total drinking water expenses are based on the amount of water used, which is mostly measured by means of water metres.

The asset management standard for DWI systems in the Netherlands that is increasingly being used is ISO 55001. ISO 55001 describes the establishment, implementation, maintenance, and improvement of the management of assets. It also emphasises the transparency and alignment between objectives at different organisational levels (Arthur et al., 2015) and the way opportunities and risks are managed to realise the desired balance of performance, risk, and cost (Chattopadhyay, 2016).

Several performance indicators have been developed to guarantee the water quality and water supply during both normal situations and extreme events. For example, in all situations 75% of delivery must be guaranteed within 24 hours in settlements of 2,000 people or more (Ministerie van Infrastructuur en Milieu, 2009). If this condition was chosen for settlements of 500 rather than 2,000 people, a much more detailed distribution network would have been realised.

Indonesia (Semarang)

Semarang Municipality, represented by its Mayor (Walikota, selected for five years) ‘owns’ the PDAM. Its performance is supervised by a supervisory board (Dewan Pengawas) that consists of five members – municipal secretary (chair), municipal treasurer (secretary), and three professional representatives representing customer interest (2×) and commercial interest (1×). The chair and treasurer can sit as long as they please; the mayor selects the three professional members. The Mayor and board decide on budgets, investments, tariffs and appoints new managerial staff. PDAM pays dividend (55% of net profit) to the municipality and in return, the municipality may provide funds for investments, but the amount of this funding is unpredictable for PDAM staff (Laksmiwati et al., 2017).

A president director (Direktur Utama) and several directors manage PDAM Semarang. The president director is appointed by the mayor for a period of four years and can be extended. The mayor also appoints the director operations and director general affairs, for an indefinite period. PDAM Semarang currently (2017) employs 494 staff (Laksmiwati et al., 2017).

4.4 Layer 4: operations and maintenance

4.4.1 Layer 4: social geo-physical environment

What are the incentives for the use of resources?

Introduction

The idea of competitive exclusion – the belief that complete competition cannot exist – took more than a century to emerge (Hardin, 1968). This principle was applied to CPRs to predict the suboptimal or destructive use of a resource. CPR shares with private goods the ability to remove resource units and with public goods the difficulty of excluding individuals from using them. Ostrom (1990) and Ostrom et al. (2006) was challenged by the principle of competitive exclusion in combination with the prisoner's dilemma, illustrating the conflict between individual and group rationality in the use of CPRs. Ostrom et al. (2006) showed that in many instances, the communication of agreed rules and strategies (layer 3) improved the outcomes of individuals who jointly used CPRs.

Netherlands and Indonesia

Daily practices in both countries are different as there are differences in culture, regulations, and governance. This, in combination with competitive exclusion, makes the interactions in layer 4 very divers and complex. Additionally, in both countries, a great deal of different and unexpected geo-physical activities can be found.

4.4.2 Layer 4: social-technical environment

What are the incentives for customers and other stakeholders?

Introduction

There are a number of important and sometimes contradictory theories about public policies. These are based on different ideas about the dynamics of policy – the same data may thus be perceived in quite different ways. Differences in focus (accounts of coordination mechanisms and what is taken into account) and research questions makes this more problematic (Peters and Zittoun, 2016). Ideas about rationality in public policy and economics have also changed over time. Rationality as thought in classical economics changed, as rationality is bounded by limited human abilities (Williamson, 1975; Simon, 2000; Williamson, 1998). People are limited in their knowledge of what is relevant and what the consequences will be, in handling uncertainty, and in adjudicating among their competing wants. So, in addition to rationality, decisions are also determined by the 'inner environment' of people's minds – both processes and memory – and the 'outer environment' – their interactions with the world on which they act (Simon, 2000).

Netherlands (Vitens) and Indonesia (Semarang)

Daily practices in both countries are different as there are differences in culture (layer 1), regulations (layer 2), and governance (layer 3). In combination with local professionalism, bounded rationality, these different behaviours and information lacks on different organisational levels makes the interactions in layer 4 very complex (Altamirana, 2010; Hazeu, 2007).

5 Discussion

In this study, the SoPhyTech infra framework was developed and applied to a case study – focusing on the usefulness of the SoPhyTech infra framework for comparing different DWI systems. In this section, the SoPhyTech infra framework will be evaluated using the concepts of reliability, validity, and generalisability. Beside these concepts the SoPhyTech infra framework is discussed on relationships to other systems (interdependencies).

5.1 Reliability

The SoPhyTech infra framework was used to develop questions for the layers and two systems that are related to the purposes examined. It is important to distinguish, in the questions, which are used to operationalise the framework, the relevant themes and different stakeholders.

The starting point of the SoPhyTech infra framework is to disregard feedback loops between the different layers (Altamirana, 2010). This is line with the power concept used by Kooy (2008) that showed feedback loops in layer 3 (and layer 4), but no feedback loops between layers.

Although the formulation of the questions used depends on the researcher we do not expect this to lead to different results, because the subject of each cell is relatively well marked and independent of the other cells. Important differences in results can occur due to the way that the questions are answered. Possible reasons for this are variations in preferences, knowledge, theories, techniques, and models used to describe the differences.

The operationalisation of the SoPhyTech infra framework to the purpose of the application of the frameworks – for example, by formulating questions, as in the two cases – is important for improving the reliability.

5.2 Validity

The case showed that the SoPhyTech infra framework helped to compare DWI systems. The framework organised the work in a very systematic way. Adding the geo-physical environment to the socio-technological approach helps to describe an important factor of the DWI system explicitly. The case showed that the geo-physical system contains leading factors for the layout of the infrastructure as it determines the location and quality of resources. We conclude that adding the geo-physical system is important for a better understanding of a DWI system. The result is a more integrated and full description of the complexity of the system because it shows the many interactions between the three systems and between the time layers.

5.3 Generalisation

The assessment showed that it is possible to use the framework to look at both a drinking water supply company level and a national level. We believe it can also be used in more specific situations such as drinking water extraction from groundwater.

The DWI System has been used for the assessment of the SoPhyTech infra framework. Based on the results of this assessment we expect that it is also possible to use the framework to describe other water infrastructure systems as they also deal with different time layers and social-technical, and social-ecological systems.

5.4 Interdependencies

In the article, the SoPhyTech infra framework was applied to a DWI system. It would be interesting to extend this research to other not water related infrastructure systems with interdependencies with the DWI system, such as energy, ICT and traffic systems. What is the impact of interdependent systems on the architecture of DWI systems? In addition how important are these interdependencies for a correct characterisation when using the SoPhyTech infra framework?

6 Conclusions and recommendations

To characterise the architecture of DWI systems using the SoS and the time of change perspectives, we expanded the socio-technical system concept with the geo-physical system and developed the SoPhyTech infra framework.

Adding the geo-physical system and the four different layers to describe the time of change helps to develop a better understanding and characterisation of the layout and choices in a DWI system. The reliability of the results increases by smart defining the relevant themes and powerful stakeholders. When studying the interactions in the governance (layer 3) and daily interactions (layer 4) it is advisable to use the concept power to increase the validity and reliability of the results. To describe the complexity in a correct way it is necessary to be aware of possible interdependencies with other systems and it is recommended to study interdependencies of DWI systems with other systems. The SoPhyTech infra framework is useful to structure the complexity of DWI systems. It is expected that the SoPhyTech infra framework can also be used to characterise other infrastructure systems with different interacting lifecycles in the geo-physical, technical, and social environment. It is recommended to apply the SoPhyTech infra framework for other infrastructures to verify this assumption.

References

Acevedo, G. (2008) 'Islamic fatalism and the clash of civilizations: an appraisal of a contentious and Dubious theory', *Social Forces*, Vol. 86, No. 4, pp.1711–1752.

Ackoff, R. (1971) 'Towards a system of systems concepts', *Management Science*, Vol. 17, No. 11, pp.661–671.

Agusdinata, D. and DeLaurentis, D. (2008) 'Specification of system-of-systems for policymaking in the energy sector', *The Integrated Assessment Journal Bridging Sciences & Policy*, Vol. 8, No. 2, pp.1–24.

Altamirana, M. (2010) *Innovative Contracting Practices in the Road Sector; Cross-national Lessons in Dealing with Opprtunistic Behanviour*, Next Generation Infrastructures Foundation, Delft.

Arthur, D., Schoenmaker, R., Hodkiewicz, M. and Muruvan, S. (2015) 'Asset planning performance management', Koskinen, K. et al. (Eds.): *Proceedings of the 10th World Congress on Engineering Asset Management (WCEAM 2015)*, Lecture notes in Mechanical Engineering, Springer, Cham.

Bauer, J. and Herder, P. (2009) 'Designing socio-technical systems', *Handbook of the Philosophy of Science*, Philosophy of Technology and Engineering Sciences, Vol. 9.

Braadbaart, O. and Braadbaart, F. (1997) 'Policing the urban pumpung race: industrial groundwater overexploitation in Indonesia', *World Development*, Vol. 25, No. 2, pp.199–210.

Bruijn, H. d. and Herder, P. (2009) 'System and actor perspectives on sociotechnical systems', *IEEE Transactions on Systems, Man and Cybernetics – Part A: Systems and Humans*, Vol. 39, No. 5, pp.981–992.

Buuren, M.v., Klijn, E. and Edelenbos, J. (2012) 'Democratic legitimacy and new forms of water management', *International Journal of Water Resources Development*, Vol. 28, No. 4, pp.629–645.

Chattopadhyay, G. (2016) 'Issues and challanges of balancing cost, performance and risk in heavy-haul rail asset management', *IEEE International Conference on Industrial Engineering and Engineering Management (IEEM) Bali*, Indonesia [online] http://www.IEEM.org (accessed 1 September 2018).

Davalos, M. (2016) Socioeconomic Indicators as Determinants for Water Access in Rural Areas of Developing Countries: A Panel Data Approach, Univesitat Autonoma de Barcelona, Barcelona.

de Moel, P., Verberk, J. and van Dijk, J. (2004) *Drinkwater-principes en praktijk*, Sdu uitgevers b.v., Den Haag.

Dufour, F.C. (2000) *Groundwater in the Netherlands*, Netherlands Institute of applied Geoscience TNO, Delft/Utrecht.

Ed-daoui, I., Itmi, M., El Hami, A., Hmina, N. and Mazri, T. (2018) 'A deterministic approach for system-of-systems resilience quantification', *International Journal of Critical Infrastructures*, Vol. 14, No. 1, pp.80–99.

European Parliament and Council (2000) *Directive 2000/60/EC (EU Water Framework Directive)*, European Parliament and Council, Brussel.

Eusgeld, I., Nan, C. and Dietz, S. (2011) ''System-of-systems'' approach for interdependent critical infrastructures', *Reliability Engineering & System Safety*, Vol. 96, No. 6, pp.679–686, ESREL 2009 special issue.

Geels, F. (2004) 'From sectoral systems of innovation to socio-technical systems; insights about dynamics and change form sociology and institutional theory', *Research Policy*, Vol. 33, Nos. 6–7, pp.897–920.

Hardin, G. (1968) 'The tragedy of the commons', *Science*, Vol. 162, No. 3859, pp.1243–1248.

Hatton, T., Brown, C., Kipp, R., Seville, E., Brouggy, P. and Loveday, M. (2018) 'Developing a model and instrument to measure the resilience of critical infrastructure sector organisations', *International Journal of Critical Infrastructures*, Vol. 14, No. 1, pp.59–79.

Hazeu, C. (2007) *Institutionele economie; een optiek op organisatie en sturingsvraagstukken*, coutinho, Bussum.

Herder, P.M., Bouwmans, I., Dijkema, G.P., Stikkelman, R.M. and Weijnen, M.P. (2008) 'Designing infrastructures using a complex systems perspective', *Journal of Design Research*, Vol. 7, No. 1,pp.17–34.

Hoekstra, A. (1998) 'Appreciation of water: four perspectives', *Water Policy*, Vol. 1, No. 6, pp.605–622.

Johansson, J. and Hassel, H. (2010) 'An approach for modelling interdependent infrastructures in the context of vulnerability analysis', *Reliability Engineering & System Safety*, Vol. 95, No. 12, pp.1335–1344.

Jorgensen, B., Graymore, M. and Toole, K.O. (2009) 'Household water use behavior: an integrated model', *Journal of Environmental Management*, Vol. 91, No. 1, pp.227–236.

Kooy, M. (2008) *Relations of Power, Networks of Water: Governing Urban Water, Spaces and Populations in (Post) Colonial Jakarta*, Doctor thesis of the University of Vancouver, Vancouver.

Koppenjan, J. and Klijn, E-H. (2004) *Managing Uncertainties in Networks*, Routledge, London.

Laksmiwati, E., Cahyani, R., Kloosterman, R., Lips, M. and Jager, F.d. (2017) *Moving Together Towards Resilient Water Supply for Semarang. Semarang*, WaterWorX, Interception Phase II: Project Plan, Indonesia.

Lubis, A., Sato, T., Tomiyama, N., Isezaki, N. and Yamanokuchi, T. (2011) 'Ground subsidence in Semarang-Indonesia investigated by ALOS-PALSAR satellite SAR interferometry', *Journal of Asian Earth Sciences*, Vol. 40, No. 5, pp.1079–1088.

Maleki, A. and Hendriks, F. (2015) 'Grid, group, and grade: challenges in operationalizing cultural theory for cross-national research', *Cross-Cultural Research*, Vol. 49, No. 3, pp.250–280.

Maxwell, J. and Chmiel, M. (2014) 'Generalization in and from qualitative analysis', in Flick, U. (Ed.): *The SAGE Handbook of Qualitative Data Analysis*, Sage, Thousand Oaks, CA.

Meerkerk, I.v., Edelenbos, J. and Klijn, E-H. (2015) 'Connective management and governance network performance: the mediating role of throughput legitimacy. Findings form survey research on complex water projects in the Netherlands', *Environment and Planning C: Government and Policy*, Vol. 33, No. 4, pp.746–764.

Ministerie van Infrastructuur en Milieu (2009) *Drinkwaterwet*, Wet van 18 juli 2009, houdende nieuwe bepalingen met betrekking tot de productie en distributie van drinkwater en de organisatie van de openbare drinkwatervoorziening (Drinkwaterwet), 18 July, Staats uitgeverij, Den Haag.

Ministerie van Sociale Zaken en Volksgezondheid (1954) *Grondwaterwet Waterleidingbedrijven 1952–1954*, Ministerie van Sociale Zaken en Volksgezondheid, Netherlands.

Ministerie van Verkeer en Waterstaat (1968) *De waterhuishouding van Nederland (eerste nota waterhuishouding)*, Staatsuitgeverij, Den Haag.

Ministerie van Verkeer en Waterstaat (1984) *De Waterhuishouding van Nederland; tweede nota waterhuishouding*, Staatsuitgeverij, Den Haag.

Ministerie van Verkeer en Waterstaat (1989) *Derde nota Waterhuishouding*, Staatsuitgeverij, Den Haag.

Ministerie van Verkeer en Waterstaat (2009) *Nationaal Waterplan 2009–2015*, Staatsuitgeverij, Den Haag.

Ministerie van VROM (1979) *wet milieubeheer*, 13 June, Staatsuitgeverij, Den Haag, the Netherlands.

Morse, J. (2015) 'Critical analysis of strategies for determining rigor in qualitative inquiry', *Qualitative Health Research*, Vol. 25, No. 9, pp.1212–1222.

Ostrom, E. (1990) *Governing the Commons; The Evolution of Institutions for Collective Action*, Cambridge University Press, New York.

Ostrom, E., Gardner, R. and Walker, J. (2006) *Rules, Games and Common-Pool Resources*, The University of Michigan Press, Michigan.

Pahl-Wostl, C., Tabara, D., Bouwen, R., Craps, M., Dewulf, A., Mostert, E., …, Taillieu, T. (2008) 'The importance of social learning and culture for sustainable water management', *Ecological Economics*, Vol. 64, No. 3, pp.484–495.

Peters, B. and Zittoun, P. (2016) *Contemporary Approaches to Public Policy; Theories, Controversies and Perspectives*, Palgrave Macmillan, London.

Rockefeller Foundation (2016) *Resilient Semarang; Moving Together Towards a Resilient Semarang*, Semarang City Government, Semarang.

Simon, H. (2000) 'Bounded rationality in social science: today and tomorrow', *Mind & Society*, Vol. 1, No. 1, pp.25–39.

Syaukat, Y. and Fox, G. (2004) 'Conjunctive surface and ground water management in the Jakarta region, Indonesia', *Journal of the American Water Resources Association*, Vol. 40, No. 1, pp.241–250.

Trist, E. (1980) 'The evolution of socio-technical systems; a conceptual and an action research program', *Conference on Organizational Design and Performance*, Pennsylvania.

Utne, I., Hokstad, P. and Vatn, J. (2011) 'A method for risk modeling of interdepencies in critical infrastructures', *Reliability Engineering and Safety System*, Vol. 96, No. 6, pp.671–678.

Valkering, P., Tabara, D., Wallman, P. and Offermans, A. (2009) 'Modelling cultural and behavioural change in water management: an integrated, agent based, gaming approach', *The Integrated Assessment Journal Bridging Sciences and Policy*, Vol. 9, No. 1, pp.19–46.

Vespignani, A. (2010) 'Complex networks: the fragility of interdependency', *Nature*, Vol. 464, pp.984–985.

VEWIN (2017) Sector in Beeld, 10 February [online] http://www.vewin.nl (accessed 1 September 2018).

Vitens (2016) *Veerkrachtig vooruit*, Zwolle.

Walker, W. (2000) 'Policy analysis: a systematic approach to supporting policymaking in the public sector', *Journal of Multi-Criteria Decision Analysis*, Special Edition: Decision Support in the Public Sector, Vol. 9, No. 3, pp.11–27.

Widada, S., Saputra, S. and Hariadi (2017) 'Determination of soft lithology causes the land subsidence in coastal Semarang city by resistivity methods', *3rd International Conference on Tropical and Coastal Region Eco Development, Earth and Environmental Science*, IOP Publishing, Vol. 116, No. 2018, p.012092.

Williamson, O. (1975) *Markets and Hierarchies; Analysis and Antitrust Implications*, Free Press, New York.

Williamson, O. (1998) 'Transaction cost economics: how it works; where it is headed', *De Economist*, Vol. 146, No. 1, pp.23–58.

World Bank (2018) 1 June [online] http://www.worldbank.org/en/country/indonesia/overview (accessed 1 August 2018).

World Health Organization (WHO) (2017) *Guidelines for Drinking-Water Quality*, 15 March, ISBN 978-92-4-154995-0 [online] http://www.who.int/water_sanitation_health/publications/ (accessed 1 September 2018).

Yin, R. (2013) *Case Study Research: Design and Methods*, Sage, Thousand Oaks, CA.