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Enhancing the resilience of drinking water infrastructures

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Abstract: Long term uncertainties in combination with long lifetime of assets of drinking water infrastructures (DWIs) and changing expectations of stakeholders make strategic decisions in drinking water infrastructures (DWIs) complex. A framework with building blocks and design spaces was developed to support these decisions. Building blocks, divided in governance and system properties, were generic resilience enhancing design principles found in literature. The design spaces were defined by characteristics (water quantity, water quality and environmental impact), and the scale dimension. The DWI design principles framework was operationalised in a case study. The case showed that the DWI design principles framework was useful for strategic issues and the results were recognised and accepted by a diverse group of stakeholders. It may also be possible to apply the framework for other water infrastructures with comparable characteristics and dimensions.

Keywords: drinking water; infrastructure; resilience; complex systems; design principles; water quantity; water quality; environmental impact; long term planning; Vitens.

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1 Introduction

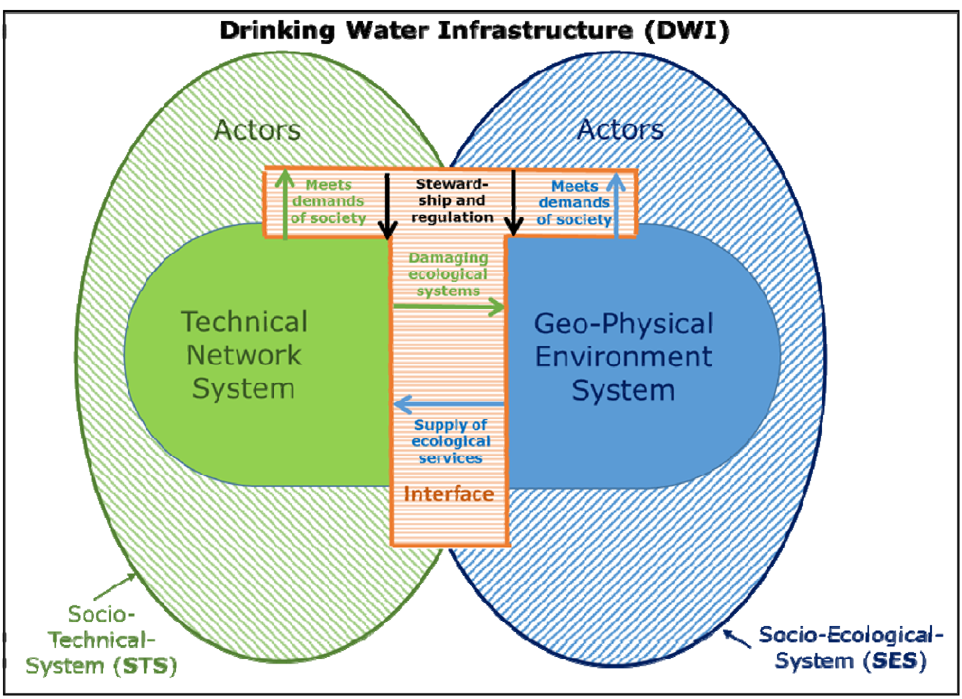
Societal infrastructures, like the drinking water infrastructure (DWI), are very important for societies as they provide the essential functions for wellbeing and welfare of societies (Doorn et al., 2018). The purpose of the manager of DWIs is to deliver all customers reliable and safe drinking water all times of the day, seven days per week. This is complex because not all locations are suitable and acceptable to extract water from the environment and the extracted water with different kind of (sometimes unknown) substances has to be purified and distributed to a changing number of customers who are spread in a sometimes wide area. The fact that the drinking water demand of customers fluctuates over the day (diurnal pattern), and also over the week and season (weekly and seasonal pattern), makes this challenge even more complex (Vitens, 2016; de Moel et al., 2004).

The complexity of the DWI is further increased by the long lifetime, high capital value and complex interdependencies of the assets of DWIs in an increasing unpredictable world with changing expectations of stakeholders (Markolf et al., 2018; Vitens, 2013, 2016; Koppenjan et al., 2008).

Comparable with other societal infrastructures, DWIs can be seen as socio-technical systems (STS) (Kloosterman and van der Hoek, 2019; Herder et al., 2008), because DWIs consist of a network with technical objects like wells, pipes and water treatment installations, which are regulated by regulators, and operated and managed by actors, like technicians and managers. However, DWIs are more complex, because the STS is not the only system in which DWIs operate. DWIs extract water from the environment that is not part of the STS, but can be seen as a socio-ecological system (SES) that is used, governed and regulated by different actors and institutions (Kloosterman and van der Hoek, 2019; Biggs et al., 2015; Ostrom, 1990, 2007; Ostrom et al., 2006). The land and water use of an actor in the SES can cause problems for other land users, like drought, flooding, issues in the water quality and space that is not available on the desired location. The result of all this can be that DWIs have to work with a less preferable layout of the technical network. The technical network consists of all kind of technical installations like the piped network, pumping stations and reservoirs. This can cause limitations and fluctuations in the water quality and quantity (Kloosterman and van der Hoek, 2019; Vitens, 2016). Fluctuations in the water quality of water resources is a challenge in the design of water treatment plants and the piped network. A good and constant biological and chemical water quality of the water leaving the treatment plant is needed because the water quality during transport and distribution is difficult to manage as pipes are beneath the ground, not visible and difficult to monitor (Vitens, 2020; de Moel et al., 2004).

All these complex interdependencies between actors, the technical network and the geo-physical environment, make DWIs complex systems. Using the STS and the SES approach, in some articles indicated as the socio ecological technical system (SETS) lens, is helpful to understand and develop strategic decisions in the design and management of societal infrastructures (Markolf et al., 2018; Agusdinata and DeLaurentis, 2008; Walker, 2000; Bauer and Herder, 2009).

Figure 1 DWI and the interactions in the interface between SES and STS (see online version for colours)



Source: Kloosterman and van der Hoek (2019)

In Figure 1 the DWI is presented, with interactions at the interface between the two underlying systems (STS and SES). Technical network systems are designed to meet the needs of society and rely on resources from the SES, which are affected by this use. Ecological systems have to benefit from social stewardship, and ecological and technical systems have to be regulated by actors (Markolf et al., 2018).

The aim of this paper is to develop design principles for strategic decisions in the design and management of DWIs. The design principles must guide the design and management in such a way that DWIs function in the desired way at present and in the future, despite possible threats due to uncertainties changing conditions and all kind of risks. Different approaches can be used to develop these design principles. The different parts of STS are mostly designed independently from each other using concepts as reliability and robustness. However, if systems are becoming more complex the application of these concepts is not straightforward and becomes complex (Uday and Marais, 2015; Jackson and Ferris, 2012). Beside that these concepts are meant for specific risks. Uday and Marais (2015) state that reliability on component level minimise the likelihood of failure, but reliability has not the ability to survive or recover from a failure and robustness does not accept performance losses, for example in the recovery from a disruption. An overarching approach is needed to enhance DWI services to function during and after disruptions. Resilience may be such an overall approach.

Resilience was developed in recent years as a system response to disruptions by either maintaining the functioning of the system or to recover from a disruption to survive (Uday and Marais, 2015; Jackson et al., 2015). Resilience is used in different disciplines and helps to integrate different viewpoints and underlying concepts as an overarching approach (Cimellaro et al., 2016; Marchese et al., 2018). Despite this there is not a consistent and approved definition for resilience that can be used for water infrastructure systems (Shin et al., 2018). A reason for this may be differences between the use and function of water, like drinking water for consumption, wastewater for discharge of pollutants, urban water for discharge of rain water, and the context dependency of resilience (Uday and Marais, 2015; Krumme, 2016; Rodina, 2019; Rodina and Chan, 2019). For water resources of DWIs resilience has been used to develop a framework with design principles by applying generic resilience enhancing design principles (REDPs) of STSs (Kloosterman et al., 2020).

Design principle based on resilience have also been developed for SESs (Folke, 2006, 2016; Biggs et al., 2015; Folke et al., 2010).

Resilience thinking, used in STS and in SES literature, may be used to reach our goal to develop design principles to support strategic decisions for DWIs under changing circumstances. This paper, therefore, answers the research question how resilience can be used effectively to develop design principles for DWIs.

2 Approach

DWIs are operating in the SES and STS and the first step was to study resilience in both systems (Section 3), with the aim to find design principles to enhance resilience. The literature study provided useful, yet generic, design principles. The next step was to integrate these generic design principles in a framework with the aim to develop design principles for DWIs. A water resource design principles framework (Kloosterman et al., 2020), developed by the authors, was used as starting point for our DWI design principles framework. This framework was chosen, because water resources are part of DWIs and the design principles for water resources should also be part of our broad design principles framework for DWIs.

The water resource design principles framework is described in Section 4 and three adjustments are proposed, and discussed in the subsequent sections, to be able to apply the framework on DWIs.

The water resource design principles framework only uses generic design principle from STS and as DWIs are operating in the SES and in the STS, the generic design principles that will be used in our DWI design principles framework had to be extended from STS to both STS and SES and these generic design principles have to be applicable on DWIs and not only on water resources. This was done in three adjustment steps. The first adjustment, elaborated in Section 5, was the development of generic design principles for DWIs using the generic REDPs of SES and the second adjustment was the development of generic design principles for DWIs using the generic REDPs of STS (Section 6).

The third adjustment, elaborated in Section 7, was to extend the characteristics [water quantity, water quality, environmental impacts (EI)] and the two dimensions (system scale and class, the technical and social aspects) of the water resource design principles framework to such a level that they are applicable for DWIs. This extension had to be done, because water resources are just one part of DWIs, while DWIs cover more technical assets, like treatment plants and pipes. Another reason for the extension was the interaction of DWIs with SES, which can be broader than the interaction between water resources and SES.

After the previous steps were combined and the DWI design principles framework was formulated in Section 8, the framework was applied in a case to test and operationalise the framework (Section 9). The case was the development of a long-term vision for the DWI of a drinking water company, Vitens, in the Netherlands. To evaluate the framework the criteria reliability, validity and generalisation were used, as operationalised by Morse (2015) and Maxwell and Chmiel (2014). Finally, the conclusions and recommendations are given in Section 10.

The experience and knowledge of the team that applied and evaluated the framework may influence the results. The first author of this article was one of the team members that developed, applied and evaluated the framework and that may have biased the results. To mitigate this risk the evaluation was done with different teams of experts and managers and the evaluation steps are explicitly addressed.

3 Resilience

In this section resilience as applied in the STS and SES is explored, with the aim to find design principles to enhance resilience.

3.1 REDPs for STSs

REDPs for the STS have been studied for a long time (Hollnagel et al., 2010) and collected and described by Jackson and Ferris (2012) (Table 1). The REDPs for STS are different in abstraction and solutions for different kind of threats can conflict with each other. This makes that they are difficult to compare, but all the REDPs have in common that they contribute to the resilience of the system. The REDPs are divided in four attributes of a system: capacity, flexibility, tolerance and cohesion, which respond in a different way to a threat. Capacity is the ability to survive, flexibility is the ability to adapt, tolerance is the ability to degrade successfully in the face of a threat, and cohesion is the ability to act as a unified whole.

A more detailed description of all the REDPs is given in Jackson and Ferris (2012).

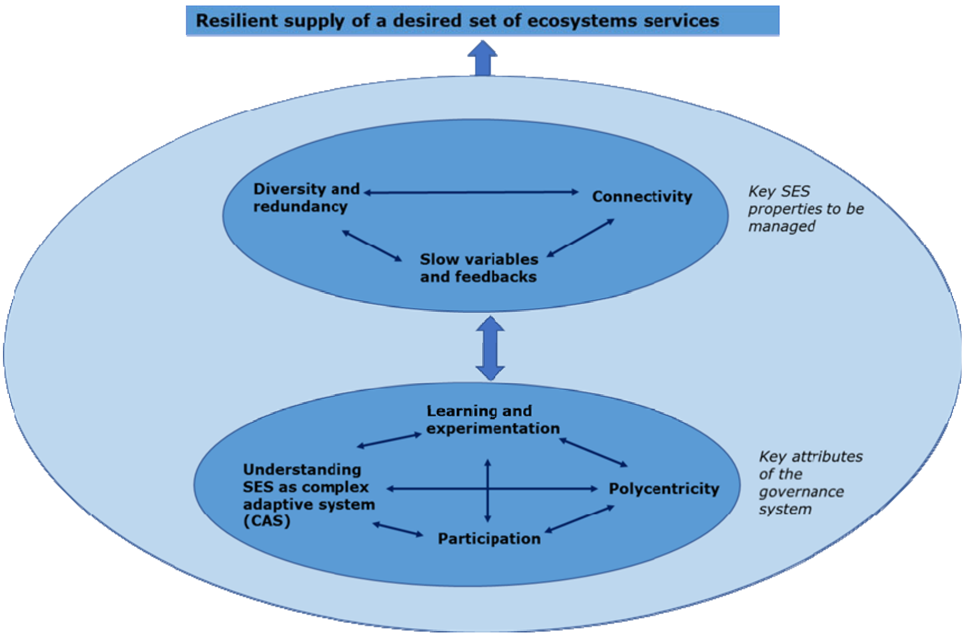
Table 1 REDPs for STS, taken from Jackson and Ferris (2012)

Resilience enhancing design principles for engineered systems			
Capacity	*Flexibility*	*Tolerance*	*Cohesion*
Absorption	Reorganisation	Localised capacity	Inter-node interactions
Physical redundancy	Human-in-the-loop	Drift correction	Reduce hidden interactions
Functional redundancy	Reduce complexity	Neutral state	
Layered defence	Repairability		
	Loose coupling		

3.2 REDPs for SESs

Providing adequate and reliable ecological services in a world with a growing population and economy is a challenge. Ecological services, or ecosystem services, can have different forms, like supply (fresh water for drinking water and crops), regulation (flood protection) and spatial services (space for infrastructures and other activities like e.g., recreation) (Quinlan et al., 2015; Biggs et al., 2015). Enhancing the resilience of ecological services is important to guarantee the reliability of these services despite changes in the environment. Therefore, REDPs for SES were developed by different scholars and summarised by Biggs et al. (2015) in seven generic principles for enhancing resilience in SES to deliver the desired services. These principles are divided in two groups: 'key SES properties to be managed' and 'key attributes of the governance system' (Figure 2). The SES properties that have to be managed are *diversity and redundancy, connectivity* and *slow variables and feed backs*. The key attributes of the governance system are *learning and experimentation, participation, polycentricity* and *understanding SES as a complex adaptive system (CAS).*

Figure 2 Seven design principles for SESs (see online version for colours)

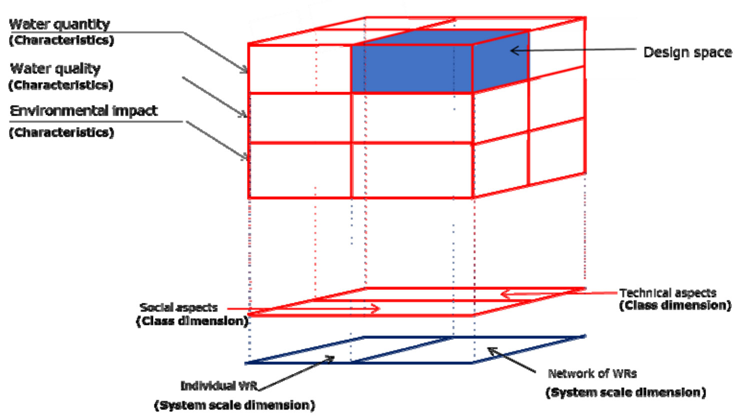


Source: Taken from Biggs et al. (2015)

4 Water resource design principles framework

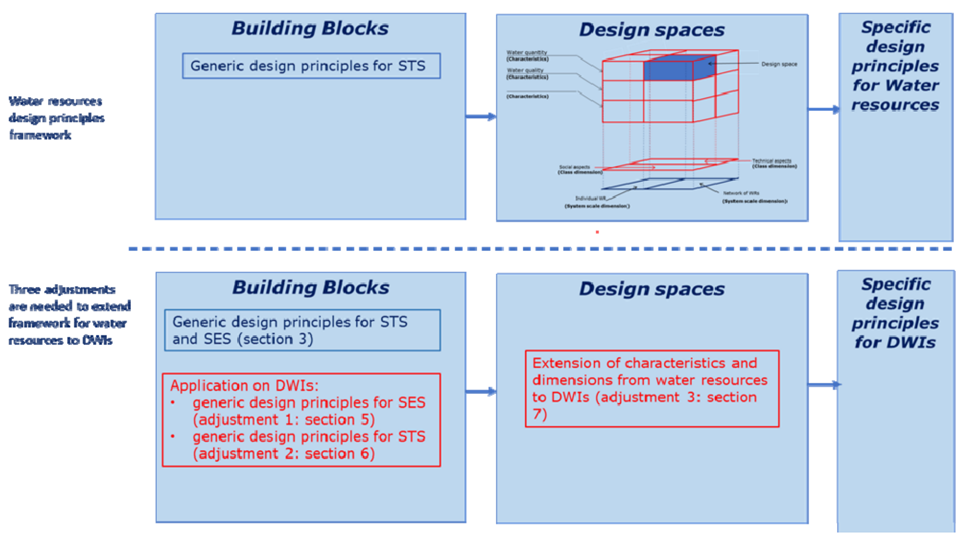
The water resource design principles framework was developed with the aim to design and manage the water resources of DWIs in such a way that they function in the desired way at present and will also function properly in the future (Kloosterman et al., 2020). The situation in which water resources operate can change due to for example climate change and competing and changing use of water and space, but also changes in the drinking water demand have impact on the use of the water resources. The notion of resilience was used to develop building blocks for this framework. The building blocks are existing generic design principles for STSs from literature. From these generic design principles specific design principles for water resources are made, by applying them on design spaces. The water resource design framework consists of twelve design spaces, that originate from three characteristics and four quadrants, created by two dimensions. The three characteristics of water resources are water quantity, water quality and the EI of the water resources. The two dimensions are 'system scale' and 'class'. The system scale dimension makes a distinction between one water resource and a network of water resources and the class dimension makes a distinction between social aspects and technical aspects. The water resource design principles framework with the twelve design spaces is presented in Figure 3.

Figure 3 Characteristics, dimensions and twelve design spaces of the water resource design principles framework (see online version for colours)



Source: Adapted from Kloosterman et al. (2020)

Figure 4 Three adjustments are needed to extend the existing framework for water resources to a framework with design principles for DWIs (see online version for colours)



The water resource design principles framework is at the interface of the STS and SES and covers parts of the STS and the SES of DWIs. By that, the framework is a good starting point to develop design principles for DWIs, but three adjustments are needed, as illustrated in Figure 4.

The first adjustment is to extend the application of resilience for SES from water resources to DWIs (adjustment 1: Section 5) and the second adjustment is to extend the application of resilience for STS from water resources to DWIs (adjustment 2: Section 6).

The third adjustment, worked out in Section 7, is to extend the characteristics and dimensions of the water resource design principles framework to such a level that they are applicable to develop specific design principles for DWIs.

5 Assessing and developing generic design principles for DWIs using the generic REDPs for SESs

In this section the generic REDPs for SES are assessed on applicability for DWIs. The seven REDPs for SES are presented in Figure 2, divided in two groups. The first group contains design principles to manage (social ecological) system properties and the second group design principles for the governance, the process of decision making, of (social ecological) systems.

This distinction in two groups will also be used in our framework. Firstly, a somewhat similar distinction, indicated with social aspects and technical aspects, was already made in the class dimension of the water resource design principles framework. Secondly, a distinction between governance and management of system properties is not only relevant for water resources, but also for DWIs, because DWIs are working in social systems with a lot of stakeholders influencing the DWI, but DWIs also have a technical network, with specific properties and have a relation with the properties of the ecological system (Figure 1).

The assessment, for both groups of REDPs for SES, is done in two steps:

1 explanation of the background of the REDPs for SES

2 application of the REDPs in DWIs and resulting generic design principle(s) for DWIs.

The REDPs related to management of SES properties are discussed in Section 5.1 and after that the REDPs related to governance of SES in Section 5.2.

5.1 REDPs related to management of SES properties

In SES three REDPs are distinguished which are related to management of SES properties: *diversity and redundancy, connectivity* and *slow variables and feedbacks* (Figure 2).

5.1.1 Explanation of the background of the REDPs for SES

Diversity and redundancy

Diversity in SES, with the objective to respond to all kind of threats encompasses different aspects, like differences or variety in elements, the amount of each element and the differences between the elements. Elements can be species, genes, landscapes etc. (Biggs et al., 2015; Folke, 2016).

Redundancy to enhance resilience in SES is related to the capacity of functionally comparable elements to substitute for each other (Biggs et al., 2015).

Connectivity

Connectivity in SES is defined by Biggs et al. (2015) as the capacity of resources, actors and species to interact, migrate and disperse across ecological landscapes. Connectivity is important to enhance resilience because it stimulates the exchange of species and information, and connections can help to accelerate the restoration of disturbed areas. Disturbance of connections, for example the construction of a road dividing a SES habitat, has a strong (negative) effect on the viability of species.

Slow variables and feedbacks

Interactions between variables in SES occur on different timescales. Slow variables determine the underlying structure of SES. Slow variables in SES are for example the hydrologic water system, legal systems and regulations. Fast variables are for example the production of crops and the vegetation in nature areas. The performance of fast variables is determined by the slow variables and changes in slow variables and feedbacks caused by these changes (Biggs et al., 2015).

5.1.2 Application of the REDPs for SES in DWIs and resulting generic design principle(s) for DWIs

The resulting design principles derived in this section, written in italics, are summarised in Table 2.

To describe the possible applications of REDPs of SES, first the interactions between SES and STS in DWIs have to be made clear. In Figure 1 this interaction is visualised with two arrows: *supply of ecological services* and *damaging ecological services*.

To meet the human needs now and in the future, it is critical to enhance the resilience of the supply of ecosystem, or ecological services (Biggs et al., 2015). Water, the input for DWIs, is an essential ecosystem service for DWIs and the continuity of DWI services is problematic if the water availability decreases or the EI reaches an unacceptable level due to environmental changes, like for example climate change. This makes the design principle *enhance resilience of SESs services and minimise damage of SESs* (SP-D, Table 2) critical for the continuity of DWIs now and in the future.

The explanation of the background of the REDPs for SES shows that *redundancy*, *connectivity*, *diversity* and *slow variables and feedbacks* are elaborated with specific characteristics from SES, like species, genes, habitats, and biodiversity, which is not just extensible to the technical part of DWIs in the STS. Although the REDPs for SES are not directly applicable in STS, it is remarkable that comparable design principles are used in the REDPs for STS. To work this out r*edundancy, connectivity* and *diversity* are discussed together, because they have a lot in common and after that *slow variables and feedbacks* are elaborated.

Redundancy, connectivity, diversity

Redundancy is also found as a REDP of STS (Table 1) and *connectivity* can be found in the REDP localised capacity (Table 1), the capacity to distribute the functionality through various nodes of the technical network.

In this section *redundancy* and *connectivity* do not give new design principles as for the SES part of DWIs they are already included in *enhance resilience of SESs* *services and minimise damage of SESs* (SP-D, Table 2) and the STS part is worked out in Section 6 in the analysis of using the generic REDPs for STS.

Diversity is also found in STS. Jackson et al. (2012) state that the designer of technical systems has to find the best combination of different REDPs (Table 1) to respond to different kind of threats (Jackson and Ferris, 2012). Rodina (2019) has conducted a survey to investigate strategies of experts on water management to enhance resilience in water infrastructures and found that there is considerable convergence about the actions that have to be taken to enhance resilience. Diversity in responses was mentioned as option to reduce flood risks and scored high.

Maintain and develop response diversity (SP-A, Table 2) is the thought behind the application of REDPs for STS but has not been explicitly stated and is therefore added as design principle for DWIs.

Folke (2006) has mentioned three methods to maintain and develop response diversity for options in SES: functional redundancy, stimulating innovation and prioritise between conservation and change.

These three methods to maintain *response diversity* in SES can be helpful to develop design principles for DWIs and are discussed in more detail:

- *Functional redundancy* has been discussed above.
- *Innovation* is necessary for DWIs to develop new and better strategies to response to changes (Pieron et al., 2014; Cusumano and Markides, 2001; Markides, 1999). *Innovation* is seen as part of *learning, monitoring and experimentation* that is worked out in Section 5.2.2 (G-1, Table 2).
- *Prioritising between conservation and change* is typically for SES, especially in nature management, but comparable with this is the difficult (asset management) choice for DWIs between maintenance (conservation) and replacement (change) (Smet, 2017; ISO 55001, 2014; Ofwat, 2017). Therefore prioritisation between conservation and change, or in DWI terms *prioritising between maintenance (of existing assets) and renewal of DWIs* (SP-B, Table 2) is added as design principle for DWIs.

Slow variables and feedbacks

Managing slow variable and feedbacks is a principle that can also be found in DWIs (Kloosterman and van der Hoek, 2019). The understanding of (dynamic) interdependencies between societal infrastructures is at an early stage and is one of the major challenges in the design of societal infrastructures (Vespignani, 2010; Johansson and Hassel, 2010; Hatton et al., 2018; Ed-daoui et al., 2018). Kloosterman and van der Hoek (2019) made a SoPhyTech infra framework to characterise and understand the complexity of DWIs. The tension between different lifecycles of the assets and dynamic changes are important aspects to take into account. The SoPhyTech infra framework was developed based on two environments (socio geo-physical environment and socio-technical environment) and four time scales of change (*embeddedness*, *institutional environment*, *governance*, *operation and maintenance*). The SoPhyTech infra framework is effective for characterising DWIs with different interacting lifecycles (Kloosterman and van der Hoek, 2019). *Manage slow variables and feedbacks* of DWIs

(SP-C, Table 2) is important due to the different lifetime in DWIs and is added as design principle.

5.2 REDPs related to the governance of SES

In SES four REDPs related to governance are distinguished: learning and experimentation, polycentricity, participation and understanding SES as a CAS.

5.2.1 Explanation of the background of REDPs for SES

Learning and experimentation

Learning is the process of acquiring new knowledge and modifying existing knowledge and is based on the assumption that knowledge is always incomplete, and that uncertainty and change are inevitable in complex SESs (Biggs et al., 2015).

Polycentricity

Polycentric governance is the governance exercised by multiple governing authorities on different system scales (Biggs et al., 2015). A relevant principle of polycentric governance for ecosystem services is the fit between the scale of the problem and the governance level (Biggs et al., 2015).

Participation

Participation has to do with active engagement of stakeholders with an interest in the SES and increases the resilience, while failing participation can degrade resilience (Biggs et al., 2015). Biggs et al. (2015) give the following reasons to broaden participation in SES:

1. improve legitimacy
2. facilitate monitoring and enforcement
3. promote system understanding
4. improve capacity to detect and interpret shocks and disturbances.

Understanding SES as a CAS

Biggs et al. (2015) states that SES can be seen as CAS, because they are continuously evolving and responding to feedbacks and uncertainty exists at all levels, making it important to understand the complexity and adaptivity of the system.

5.2.2 Application of the REDPs in DWIs and resulting generic design principle(s) for DWIs

The resulting design principles of this section, written in italics, are summarised in Table 2 (Section 8).

Learning and experimentation

DWIs are also complex systems dealing with incomplete knowledge, uncertainties and change, and that makes *encourage learning, monitoring and experimentation* (G-1, Table 2) a design principle that is applicable for all parts of DWIs (Kloosterman and van der Hoek, 2019). Learning, monitoring and experimentation are also promoted in international standards that are widely used to preserve, maintain and improve infrastructures (NEN, 2019; ISO 55000, 2014; ISO 55001, 2014; ISO 55002, 2014).

Polycentricity

Originally, national societal networked infrastructures were centrally organised by the state, but liberalisation in the last decades gives rise to more polycentric national infrastructures (Turner, 2017). The role of the state is not excluded but differs per country and type of the infrastructure, from regulation to direct provision of (parts) of the services (Turner, 2017).

Although DWIs are managed by a DWI manager, the DWI manager relies on water resources from the SES, which are usually governed by other, mainly governmental, organisations and complex interdependencies have to be managed (Guidotti et al., 2016). By this, polycentric governance is common practice for DWIs, but how it is done differs per country and DWI company and it is often complicated to match the governance with the scale of the issue that has to be solved. Scale matching issues are mainly caused by differences in responsibility between government areas (national, regional, local) which often do not match with the scale of the water catchment areas (Vitens, 2016, 2019). If problems are solved on the wrong scale inefficient and ineffective solutions may be chosen (Vitens, 2016, 2019, 2020) and to prevent this the design principle *match problems to the correct governance level* (G-2, Table 2) is included.

Participation

Societal infrastructures are designed to comply with societal needs. In the short-term stakeholder participation can conflict with the planning and other requirements of infrastructure projects because participation has risks for delay and changes in requirements for the infrastructure. However, in the long term, which is important due to the long lifetime of infrastructures, the quality of the infrastructure services is at risks if infrastructures don't comply with societal needs at that time (Sierra et al., 2018). Stakeholder participation reduces the risks of mismatches between the social infrastructure and the public need and is needed for infrastructure sustainability (Sierra et al., 2018). Biggs et al. (2015) mentions the importance of stakeholder participation in infrastructures to manage the uneven distribution of benefits and costs between the different stakeholders.

Active participation of stakeholders, with an interest in the DWI, helps to realise new DWIs and to accept the negative (and positive) changing impact of DWIs (Vitens, 2016, 2019). Ofwat (2017) emphasises also the need to indicate customers as stakeholders of DWIs to increase resilience. Based on this the design principle *stimulate participation of all relevant stakeholders of DWIs in the design and operation phase* (G-3, Table 3) is included.

Understanding SES as a CAS

Oughton et al. (2018) evaluated the use of CAS on socio-technical infrastructure systems, like DWIs, and concluded that the properties of CAS characterise the working of technical infrastructure systems well. Comparable with SES social technical infrastructure systems are continuously evolving and responding to feedbacks because they are driven by all kind of interdependencies, decisions on agent levels and are dependent and adaptive to the environment (Oughton et al., 2018; Bowd et al., 2015; Bollinger and Dijkema, 2012; Choi et al., 2001; Uday and Marais, 2015). Based on this, *foster complex systems understanding of DWIs, for example by using the CAS* lens (G-4, Table 2), is included as design principle because it can be helpful to understand the DWI.

6 Assessing and developing generic design principles for DWIs using the generic REDPs for STSs

First step in the assessment is an explanation of the background of the REDPs for STS. After that, the application of REDPS in DWIs is discussed. The last step is the description of the generic design principles for DWIs.

6.1 Explanation of the background of the REDPs for STS

The REDPs for STS are divided in four groups of attributes of a system (capacity, flexibility, tolerance and cohesion) (Table 1). The REDPs that contribute to an attribute respond in a comparable way to all kind of different threats, by surviving (capacity), adapting (flexibility), degrading (tolerance) or acting as a whole (cohesion) (Jackson and Ferris, 2012). Attributes are properties of a system and not add-ons (Jackson and Ferris, 2012). REDPs of STS therefore belong to design principles for *system properties* and not to *governance*.

6.2 Application of the REDPs in DWIs and resulting generic design principle(s) for DWIs

The design principles that are derived in this section are written in italics followed by a number that refers to a design principle in Table 2.

REDPs for STS are design principles for system properties and developed for STSs, like water resources, water treatment plants and other technical parts of DWIs. They have already been used to develop design principles for water resources (Kloosterman et al., 2020). The application of REDPs for STS in the SES part of DWIs has not yet been discussed and will be examined further in this section. The SES part in DWIs is limited to the supply of eco system services which are needed for DWIs, like water, space, chemicals, energy and the damage to the ecological system through this use (Figure 1), so the REDPs for the STS are assessed on application to these two issues:

1 the supply of eco system services

2 the damage on the environment caused by the supply of these eco services.

The assessment is done on attribute level, because all REDPs of an attribute contribute in a comparable way to different kind of threats. If one or more REDPs of an attribute are applicable as design principle it is assumed that the attribute is applicable for DWIs. Other REDPs of that attribute may be less applicable, but this does not invalidate the usability of the applicable REDPs. For the assessment as much as possible REDPs contributing to that attribute are taken into account. For this the impact on enhancing resilience of the four attributes is analysed. First on the supply of eco system services and after that on the damage on the environment caused by the supply of these eco services.

6.2.1 Supply of ecoservices: impact of the attributes on enhancing the resilience of eco system services

Capacity

The eco system service supply can survive all kind of threats better if the supply is made redundant, by having more independent eco system services or if there are functional alternatives. Threats can also be survived by absorption or a layered defence. An example for DWIs, regarding the eco system service water are water resources that are not planned in an area with vulnerable nature but in an area that is not affected by changes in water extractions. A layered defence helps to guarantee the water quality with layers as preventing, limiting, mitigating and removing contaminations.

Flexibility

The eco system service supply can adapt better to all kind of threats by making the supply not more complex as necessary, having connections between the different eco system services, making possibilities to correct and being able to reorganise the organisation or the supply.

Tolerance

The eco system service supply can be continued if in a case of a known or unknown threat, the supply has enough local capacity and storage, measures can be taken to avoid the threat or corrective actions can be taken to diminish the threat.

Cohesion

The eco system service supply can be improved if negative interactions between different supplies are minimised and information of the different supply location are available and can be used to react on risks.

6.2.2 the damage on the environment caused by the supply of eco services: Impact of the attributes on enhancing the resilience in managing the damage on the environment

Capacity

The environment can be damaged due to the supply of eco services for DWIs. The damage is affected by how the supply of eco services is organised. If the supply is made redundant with two independent services, the damage occurs at two places. At the other side the damage for the environment caused by an eco-services, like the extraction of water for DWIs, can be decreased if the water resources are planned in an area which can absorb the causes. An example is groundwater extraction in an area that can be supplied with surface water to prevent drought.

Flexibility

Flexibility in the DWI system makes it possible to change the place and volume of the ecosystem service. An example is a DWI with many water resources that are connected in a technical network. The flexibility in the DWI makes it possible to switch between the different water resources to reduce the damage on a vulnerable location.

Tolerance

Tolerance gives time to take measures to avoid or diminish damage.

Cohesion

The resilience in managing the damage is enhanced if interactions that can cause damage are reduced and information of the different interactions and possible damages are monitored and available and can be used to react on risks.

The assessment on the supply of eco system services and on the damage on the environment caused by the supply of these eco services showed that the REDPs for STS are applicable for all parts of DWIs. This gives the design principles *apply the REDPs for capacity* (SP-E, Table 2), *apply the REDPs for flexibility* (SP-F, Table 2), *apply the REDPs for tolerance* (SP-G, Table 2) and *apply the REDPs for cohesion* (SP-H, Table 2).

7 Extending the characteristics and dimensions of Water recources to DWIs

The central part of the water resource design principles framework (Figure 2) is a matrix with the characteristics, 'water quantity', 'water quality' and 'EI', and the dimensions 'system scale' and 'class'. The cells of the matrix are called design spaces.

The question that will be answered in this section is how the matrix of the water resource framework has to be modified to be applied in our framework with design principles for DWIs.

First the extension of characteristics and dimensions from water resources to all STS parts of DWIs is discussed and subsequently the extension to the SES part of DWIs. The SES part in DWIs is limited to the supply of resources and the damage to the ecological system through this use.

For the extension it is necessary to understand the background of the characteristics and dimensions in the water resource design framework. This is described in Section 7.1.

This discussion for both the extensions for the STS part (7.2) and the SES part (7.3) is done in three steps by focusing on missing elements. In the first step the characteristics are discussed, after that the system dimension and finally the class dimension.

The conclusions on how the framework has to be modified are presented in 7.4.

7.1 Background of the characteristic and dimensions in the water resource design framework

Characteristics

The supply of drinking water starts with the extraction from water resources and this input has to be assured in terms of the characteristics water quantity and water quality. Another characteristic that is distinguished is how the extracted water damages ecological systems: the environmental impact (EI).

Dimension: system scale

The dimension system scale was introduced in the water resource design principles framework to distinguish a single water resource with multiple water resources that are designed to work together.

Dimension: class

The dimension class was introduced in the water resource design principles framework to distinguish social and technical aspects.

7.2 Extension to all parts of the STS: the technical network

Characteristics

The objective of the technical network of DWIs is to deliver reliable drinking water. In line with water resources, the water quantity and water quality are also characteristics of the technical network. The EI in the water resources design principles framework is limited to the impact of water resources on the environment, but for the technical network the EI is broader than that. Assets of the technical network have an EI during production, operation and removal of the assets, because they use scarce space, raw materials, chemicals, energy and produce waste. By this also aspects related to sustainability and material choices for the network infrastructure, like concrete, PVC or cupper, are included in EI. This all makes EI a characteristic of the technical network of DWIs.

Dimension: system scale

For DWIs the system scale is relevant, not only for water resources, but also for other assets, like for example drinking water production plants. A production plant can be connected to one city, but it is also possible to connect different production plants with multiple cities. Solutions on different scales are possible to guarantee the reliability of the drinking water supply for that city. In the water resource framework only two possibilities are distinguished, one water resource and a network of water resources. Using these two scale options for the whole DWI means that other scale options are missing, like for example administrative borders, watershed borders, smaller areas in the technical network, DWI company scale etc. To include different scale possibilities the dimension scale for DWIs varies along an axe with different scale options, from an asset to interactions between DWIs.

Dimension: class

The adjustments of the class dimension were already discussed at the start of Section 5 and the distinction between social and technical aspects of the water resource framework was replaced by system property and governance.

7.3 Extension to the SES

Characteristics

Water quantity and water quality are important for DWIs because that are key characteristics of drinking water. The characteristic 'EI' of the technical network of DWIs has more aspects then only the extraction of water and corresponds with the possible damage to the ecological system by the use of all kind of resources, scarce space, raw and auxiliary materials, chemicals, energy and the disposal of waste. These affect the ecological system.

Based on this the characteristics for the DWIs are water quantity, water quality and EI.

Dimension: system scale

In the extension to STS parts of the DWI (Section 7.2) the system scale dimension varies from an asset to interactions between DWIs. Comparable with this the system scale for the SES part of DWIs can also vary. DWIs can impact one specie, a group of species, habitats, (parts of) ecological systems or multiple ecological systems (interactions between DWIs scale).

Dimension: class

The distinction between system property and governance comes from SES and is applicable in the SES part of DWIs.

7.4 Conclusions of the assessment to extend characteristics and dimensions of water resources to DWIs

The water resource design principles framework was used as starting point and therefore the conclusions are presented as changes to this framework:

- The characteristics water quantity and water quality are not changed, and the EI has been broadened to the EI of all needed resources for DWIs, like water, raw material, energy etc.
- In the system scale dimension, the two options are replaced by a scale from an individual asset to interactions between DWIs.
- In the class dimension the distinction between social and technical aspects is replaced by the distinction between 'system properties' and 'governance'.

8 The DWI design principles framework

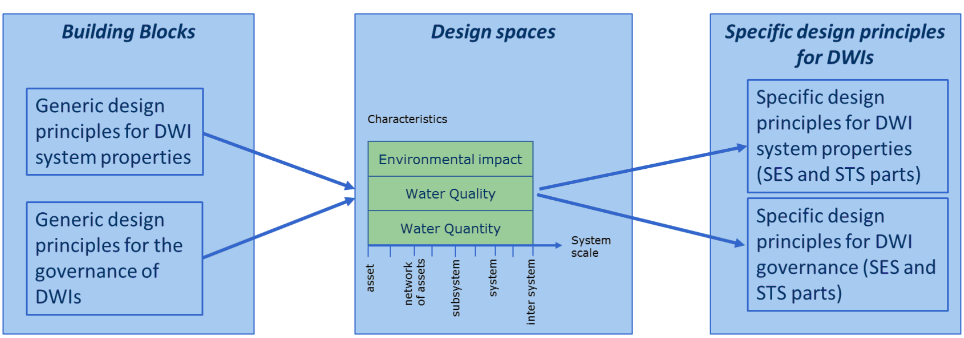
Building blocks for the DWI design principles framework (DWI-DP framework) were discussed the Sections 5 and 6, resulting in the following building blocks with generic design principles for DWIs.

Table 2 Building blocks of the DWI design principles framework

Building blocks: general design principles for DWIs			
Design principles for system properties of DWIs		*Design principles for the governance of DWIs*	
SP-A	Maintain and develop response diversity of DWIs	G-1	Encourage learning, monitoring and experimentation
SP-B	Prioritise between maintenance and renewal of DWIs	G-2	Match problems to the correct governance level
SP-C	Manage slow variables and feedbacks of DWIs	G-3	Stimulate participation of all relevant stakeholders of DWIs in the design and operation phases
SP-D	Enhance resilience of SESs services and minimise damage of SESs	G-4	Foster complex systems understanding of DWIs, for example by using the CAS lens.
SP-E	Apply the REDPs for capacity		
SP-F	Apply the REDPs for flexibility		
SP-G	Apply the REDPs for tolerance		
SP-H	Apply the REDPs for cohesion		

In Section 7 the adjustments to the central block of the water resource design principles framework were discussed and summarised.

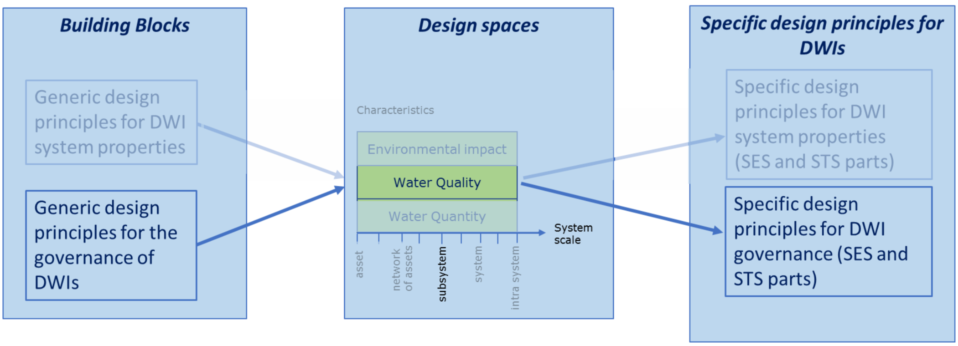
Figure 5 DWI design principles framework (DWI-DP framework) (see online version for colours)



The resulting DWI design principles framework (DWI-DP framework) is presented in Figure 5.

The building blocks for DWIs are applied in the design spaces to develop the specific design principles for DWIs in the design spaces. The application of building blocks on a design space is illustrated for the design space 'governance, water quality, subsystem' (Figure 6). Since all building blocks are worked out in the same way only the first two building blocks are shown (see Table 3).

Figure 6 Development of specific design principles for the governance of DWIs, by using the DWI design principles framework (see online version for colours)



Note: This is worked out Table 3.

Table 3 Illustration of the development of specific design principles for the governance of the water quality in piped networks for the first two building blocks.

Building blocks	*Specific design principles for DWIs*
a Encourage learning and experimentation.	Encourage learning and experimentation *in the governance of the water quality in technical subsystems (for example the piped network) AND in ecological subsystems.*
b Match problems to the correct governance level.	Match problems to the correct governance level *in the governance of the water quality in technical subsystems (for example the piped network) AND in ecological subsystems.*

9 Operationalisation of the design principles framework for DWIs in a case

Vitens, a drinking water company in the Netherlands, developed in 2019 and 2020 a long-term vision on the Vitens DWI. Vitens choose resilience as strategy and used the DWI-DP-Framework to work this strategy out. To understand how the framework is applied it is helpful to have some background information about the Vitens DWI and the context in which it is operated (see text block). The application of the framework is described in Section 9.1 for the governance and the system properties of the Vitens DWI and in Section 9.2 the different parts of the DWI-DP-framework are assessed on the use of the DWI-DP framework in the development of the Vitens strategy.

Case study: background information

The information that is used in this text block is taken from Vitens (2019, 2020) and (Kloosterman and de Gooyert, 2020).

Vitens is a publicly owned, DWI company in the northern, eastern and central part of the Netherlands. The Vitens DWI is spread over a large area, with about 50,000 km pipes and about 100 production plants, mainly groundwater and two bank infiltration plants, extracting more than 90% surface water from the rivers Vecht and IJssel, a branch of the river Rhine.

History of the Vitens DWI; the challenge to change the DWI

The collective supply of drinking water started in the Netherlands around 1880 in the big cities with centralised DWIs on municipality level. These DWIs were made with very robust installations and pipes, and most of them are still in operation. Later the rural areas and after that the remote houses were also connected to the central DWI. Due to problems in the drinking water supply municipalities started to cooperate and these collaborations subsequently merged into the Vitens company. The bigger scale made solutions on different scales possible, nevertheless, mainly local solutions were sought and used for bottlenecks in the drinking water supply. Important reasons for this are the responsibilities of local authorities and the differences in lifetime of the assets. At the end of a lifetime Vitens must choose between maintenance and replacement or a completely new design, a greenfield renewal (Boomen, 2020). In the Vitens practice the most used choice is maintenance and replacement of assets that are at the end of the lifetime, because a greenfield renewal is more expensive, and assets have to be renewed that are not yet at the end of their lifespan which evokes resistance of the decision makers.

Water resources are polluted and impact the environment more and more due to climate change

Especially in the eastern part of the Vitens area, groundwater is extracted from shallow sandy layers, aquifers, which are vulnerable for pollutions and cause drought in nature and agricultural areas, which increases due to climate change. The western groundwater extractions are in deeper thick sand layers, covered by clay layers, but these extractions have sometimes water quality problems caused by sea water intrusion or because they extract water with high salt concentrates from deeper layers deposited by the sea.

Water demand is increasing while the development of new water resources is under pressure

The water demand is growing the last years and this is also expected for the coming years, so new water extraction locations are needed, but the development of new locations is problematic due to the increasing competition on the use of land and the use of the underground. Conflicts on land use are caused by a growing population and economic growth and the use of the underground for the energy transition. Surface water is in the Vitens area available, mainly from the river Rhine system, and some small rivers. Climate change impacts the discharge of the rivers. High peaks in the discharge of the rivers are expected to increase, but the chances of very low discharges are also increasing.

Peaks in the water demand are difficult to handle

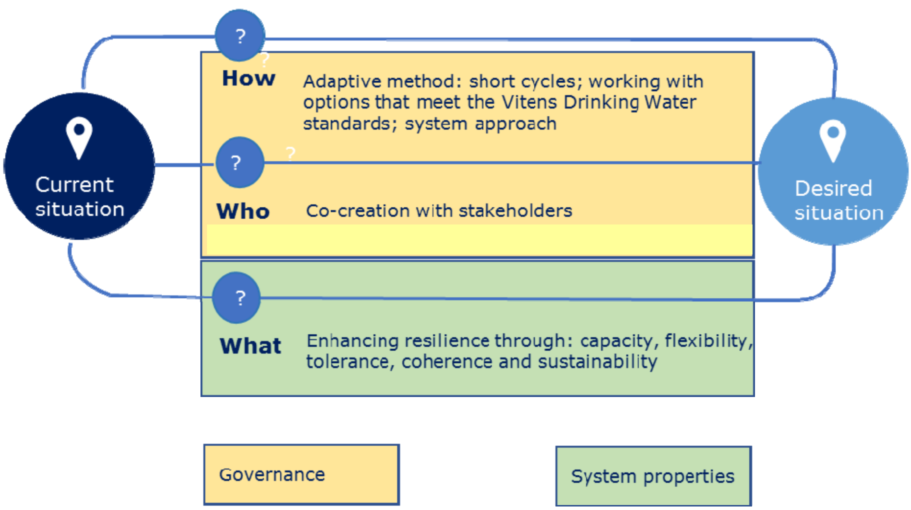
Due to the start and organic growth, the Vitens DWI mainly has production plants that feed one or some surrounding villages or cities with limited connections to other production stations. The production plants are located near the villages or cities, which is not always the best location at this moment, causing that the amount that can be extracted is limited. The consequences of all this is that in longer periods with drought and hot weather, like the summers in 2018, 2019 and 2020, which are expected to increase due to climate change, the Vitens DWI cannot deliver the peak in the water demand. The Vitens DWI is not flexible enough to react on changes.

9.1 Resilience worked out for the governance and the system properties of the Vitens DWI

The Vitens DWI is difficult to change mainly caused by lack of flexibility in the Vitens DWI. Flexibility is needed because water resources are dealing with pollution and impact the environment which will increase due to climate change, the water demand is increasing while the maintenance and development of new water resources are under pressure and peaks in the water demand are difficult to handle, (see text block). The Vitens DWI has to change, but how? Vitens choose resilience as strategy to realise this change.

Resilience was worked out along three lines: *how, who* and *what* (Figure 7). The *How* and *Who* are taken from the governance part of the DWI-design principles framework and the *What* is taken from the system properties. The *How, Who* and *What* are briefly described and then explained in more detail.

Figure 7 Resilience worked out along three lines, by using the DWI design principles framework (see online version for colours)



Source: Vitens (2020)

9.2 Use of the DWI-DP framework in the development of the Vitens strategy

The role of the framework is explained by describing whether and how the building blocks and design spaces are used for the Vitens strategy. Building blocks are the design principles for system properties for DWIs (part a) and the design principles for the governance of DWIs (part b).

The design spaces are limited by the characteristics (part c) and the scale dimension (part d).

a *Assessment for the application of the design principles for system properties of DWIs.*

In the *what* most design principles of the DWI-DP framework (Table 2), related to system properties, were used. To solve the performance problems of Vitens (text block), Vitens analysed the response diversity (SP-A) of the Vitens DWI and it turned out that the Vitens DWI misses flexibility, and for unknown long term the resilience in the Vitens DWI has to be increased. For that, the *REDPs for capacity* (SP-E), *flexibility* (SP-F), *tolerance* (SP-G) and *cohesion* (SP-H) were used (*what* in Figure 7).

The last design principle of the DWI-DP framework (Table 2), related to system properties design principles, that has to be discussed is *prioritise between maintenance and renewal* (SP-B). This design principle is a repetition of a bottleneck encountered by Vitens that has been worked out in the adaptive working method *(How* in figure 7). An important objective of the adaptive working method is to improve the choice between maintenance and a greenfield renewal and to *optimise the management of slow variables* (SP-C), because both stagnate possible and necessary changes of the Vitens DWI. For the adaptive working method, options on different scale levels have to be developed. The most important driver for the development of the adaptive working method were the design principles *foster complex systems understanding of DWIs, for example by using the CAS lens (G-4)* and *match problems to the correct governance level (G-2).* The CAS lens gave insight in how the different parts of the Vitens-DWI adapt in a small or bigger scale to the environment, the impact of slow and faster variables and how all changes take place mostly independently from each other creating the new Vitens DWI and *matching problems to the correct scale* (G-3) was used in the development of options with stakeholders on different scales.

The last not yet mentioned design principle for system properties of DWIs, about *enhancing the resilience of ecosystem services (SP-D),* is part of the sustainability that was added in the *What.*

b *Assessment for the application of the design principles for the governance of DWIs.*

In the *how* and the *who* the different design principles of the DWI-DP framework, related to governance, were used.

Beside the design principles that are already mentioned in a) the design principles Stimulate participation of all relevant stakeholders of DWIs in the design and operation phases (G-3) was the basis for the Who. Encourage learning & experimentation (G-1) was useful to develop new options and change the current static situation and was integrated in the Who and How by inviting stakeholders to develop new and innovative options.

c *Assessment for the application of characteristics of the design spaces.*

The distinguished characteristics water quantity, water quality and EI were used, among other things, to formulate Vitens Drinking Water standards in the *How.* The standards were used to make a selection between different possible options.

Design principles for DWIs were developed by applying the building blocks on the three characteristics (Figure 5). After that a selection was made, by a group of experts and management in the Vitens company, between design principle that are needed to guarantee the reliability of the drinking water supply (Vitens Drinking Water standards) and other design principles to increase the resilience. The standards were also discussed and approved by provinces and regional water authorities in the Vitens area.

d *Assessment for the application of scale dimension of the design spaces*.

Working on different scales is part of the *how*, *who* and *what*.

In the *how* options on different scale levels have to be developed, like different material options for a pipe, different water treatment options, different water supply possibilities on a regional scale, on Vitens scale or on an inter-company scale.

In the *who* collaborations can be done on different scale levels, like improving the quality of the river Rhine, on international level until local collaborations with a neighbour to reduce the EI.

In the *what* system properties can be improved on different scale levels, like improving the flexibility of a pump, improving the tolerance of a water treatment plant or improving the cohesion in the transportation system on Vitens scale.

10 Evaluation of the DWI design principles framework

The DWI design principles framework was developed to support strategic decision making for DWIs under changing circumstances, by using resilience. Central aspects in the evaluation are the use of resilience in the framework, the structure of the central part of the framework and the value of the framework in strategic decision making. These three aspects of the framework are evaluated on reliability, validity and generalisability (Morse, 2015; Maxwell and Chmiel, 2014; Leeuw, 2005):

- *Reliability*: are the same results (same framework) obtained if the study was repeated?
- *Validity*: are the descriptions recognisable by other users?
- *Generalisation*: is the framework usable for other situations?

10.1 Reliability

Use of resilience in the framework

DWIs are active in different systems, STS and SES, and resilience is used in both systems as an overall approach to integrate different viewpoints and underlying concepts to react to all kind of threats. The use in both systems and the integration of different responses to threats makes resilience very powerful to develop a variety of design principles. It is interesting to investigate if other concepts can add new types of design principles.

A literature study was done to find REDPs from the STS and SES and the most recent literature was used. New literature can possibly lead to more design principles.

Structure of the central part of the framework

The structure of the framework consists of characteristics and dimensions. The three characteristics, water quantity, water quality and EI, are important and often used for DWIs, but it is interesting to investigate if any other distinction in characteristics is possible and what the impact of another distinction would be on the design principles for DWIs. The class dimension, that distinguishes *system properties* and *governance* is used in the SES and leads to a clearer distinction in design principles for DWIs. This distinction is not used in the RDPs for STS, and as the REDPs for the STS are a mix of *governance* and *system property* design principles, it is recommended to use this distinction also in the REDPs for STS.

The scale dimension is important to distinguish the scale on which problems occur and the scale on which solutions can be found. This can be on the same scale level, but it can be better to use solutions on another scale level, because that gives a cheaper or a better solution for the society. It is complex to find the best scale for a solution and it is recommended to investigate this further to optimise this process.

Use of the framework in strategic decision making

The case showed that the use of the framework ensured that the current working method at Vitens was questioned and a completely new working method with *How*, *Who* and *What* was chosen. The change at Vitens is probably also caused by a changing context. Hot and dry summers in 2018, 2019 and a hot and dry spring in 2020 caused in the Netherlands a shortage of water for users like nature and agriculture. For DWI companies this created a lot of social pressure to reduce the capacity or remove the drinking water extractions that caused the most drought. The framework gave insight in the current bottle necks in working methods and structured the process for a change. Other frameworks may also be helpful in developing design principles for this change, but the Vitens case showed that the DWI-DP framework fits in very well with this strategic issue.

The team that works with the framework and the context may influence the results, but this does not reduce the reliability of the framework itself, but illustrates the context dependency, which has to be managed if the framework is applied, to increase the reliability of the application results.

10.2 Validity

Use of resilience in the framework

Resilience is also used by some of the regional water authorities and provinces in the Vitens area, so they recognised and accepted the use of resilience. In the Vitens company resilience was chosen as strategy four years ago, so they recognised and accept the use of resilience in the framework (Vitens, 2016).

Structure of the central part of the framework

Vitens (2016) used resilience as a combination of capacity and flexibility but missed a more extensive and coherent elaboration of resilience. The framework met that need.

Use of the framework in strategic decision making

The DWI-DP-framework is used to develop a new long-term vision for the Vitens DWI that is developed and reviewed by experts and management of Vitens. An external review is done by employees of the regional water authorities and provinces in the Vitens area. They all recognised and accepted the results and the board of Vitens adopted the document as the guiding strategic document for the Vitens DWI (Vitens, 2020).

10.3 Generalisation

Use of resilience in the framework

Resilience is a broad concept that is used in different disciplines. However, the use is strongly context dependent and the application of the framework must be within these limits.

Structure of the central part of the framework

The characteristics and dimensions are developed for DWIs. The Vitens DWI, that is used in the case, is an extensive infrastructure where different characteristics and dimensions of the framework can be found. The Vitens DWI-system has about 100 different water production plants, using mainly groundwater while some use surface water. This leads to a considerable variation in possibilities with respect to water quantity, water quality and EI. As result of this variation Vitens has different water treatment plants and a large transport and distribution network with connections on different scale levels. It is expected that the variety of the Vitens DWI include the variety of other DWIs on the characteristics and dimensions of the framework, and that the DWI-DP-framework can be applied for other DWI-systems (de Moel et al., 2004).

Application of the framework can be done for DWIs. Application on other infrastructures, like for example urban water systems, can be possible, but a good review to which extend the characteristics and dimensions may be applied to the other infrastructures is necessary.

Use of the framework in strategic decision making

The framework is developed to support strategic decisions under changing circumstances and can be used for that kind of problems.

11 Conclusions and recommendations

The objective of this paper was to develop design principles for strategic decisions, in the design and management of DWIs, under changing circumstances and therefore a framework was developed, by using resilience. Resilience turned out to be very suitable because it integrates different possible responses to all kind of different threats and is used in both SES and STS, which are part of DWIs. Internal and external stakeholders recognised and accepted the use of resilience in this framework.

The central part of the framework is determined by characteristics and dimensions. The characteristics and dimensions have been taken from an existing water resource design principles framework, which is subsequently evaluated and adapted to make it applicable for DWIs.

The three characteristics water quality, water quantity and EI have been taken over from the water resources framework, with the EI being extended. In the class dimension from the water resource design principles framework a distinction is made between governance and system properties. This distinction is adopted from the SES and provides a clear distinction for design principles for DWIs.

The scale dimension from the water resource design principles framework is extended to integrate different scale possibilities to define and solve problems.

The Vitens case showed that the DWI-DP framework is suitable for the development of a long-term vision. By that, it is important to realise that the context and the team that work with the framework affect the results, which has to be managed, to increase the reliability of the application results.

The framework is suitable for the Vitens DWI and based on the diversity of the Vitens DWI it is expected that it also can be used in other DWIs. It may also be possible to apply the framework for other water infrastructures with comparable characteristics and dimensions. In that case, it is necessary to review to which extend the characteristics and dimensions may be applied.

Resilience is used to develop generic design principles for DWIs, although this turned out to be reliable and valid, it is interesting to investigate if other concepts than resilience or new literature on resilience can add new types of design principles.

It is also interesting to investigate if any other distinction in characteristics is possible and what the impact of another distinction would be on the design principles for DWIs.

Finally, differences in responsibility between government areas (national, regional, local) and the scale of the water catchment areas makes it complex to match problems on the correct scale to find the best solutions and it is recommended to investigate this further to optimise this process.

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