Towards an Action Perspective for Urban Water Security: Design and Use of Indicators as a Boundary Object

Andrea Vargas-Farías

Civil Engineering and Management, University of Twente, Enschede, 7500 AE, The Netherlands
Deltares, 3584 BK, Utrecht, The Netherlands

* a.vargasfarias@student.utwente.nl

ABSTRACT

Urban water security is a key concern in the context of urbanization and climate change, stressing the need for sound response from local authorities. Indicator-based frameworks are a suitable option to inform the policy decision making processes when aspects about their use are considered. We developed a comprehensive indicator-based framework set to be used by specialists and non-specialists to improve their understanding of integral water-related issues for the purpose of decision making about effective interventions. In order to do that, we identified the key design requisites that need to be considered for an indicator-based framework operationalized as a boundary object in terms of credibility, legitimacy, salience, visualization, context of use and flexibility. These requirements were integrated into a dynamic framework based on the Urban Water Security Dashboard, which characterizes cities based on their overall urban water security score following a systems approach. The resultant framework was applied to Mexico City and tested in an expert's session. This paper reports on the process of developing an insightful indicator-based framework and the object itself, and reflects on the effects caused in its context of use. We found out that aspects such as the actors directing the use of the framework play a big role in its success. Furthermore, we provide recommendations for the continuous development of the tool and for the use of the framework in practice.

Keywords: Urban water security; Systems Thinking; Indicators; Boundary Objects; Urban Water Management, Participatory Decision Making.

1 Introduction

Water security is at the top of the research agenda. It emerged to address the most prominent water-related challenges nowadays (Basco-Carrera, Warren, et al., 2017) and, recently, its study at the urban scale and under an integrative vision has been gaining increased recognition among scholars (see Cook & Bakker, 2012; Hoekstra et al., 2018; Zeitoun et al., 2016). There are two fundamental reasons for this. First, although the scale of water security at the national level facilitates stronger links with national goals and the interconnected sectors, a focus on the urban scale puts a bigger emphasis on highly dynamic environmental and socio-economic conditions (Beek & Arriens, 2014; Srinivasan et al., 2017). This is particularly critical in the context of increasing urbanization, climate change, and a growing demand for better living standards (Bigas, 2013; Bogardi et al., 2012; Koop & van Leeuwen, 2017; Pedrazzini, 2011; Zeitoun et al., 2016). Second, the adoption of an integrative vision aims to guarantee efficient water-related services and use, and manage water-related threats in a way in which welfare, equity, and long-term sustainability are improved (Basco-Carrera, Warren, et al., 2017; Bogardi et al., 2012; Cook & Bakker, 2012; Gerlak et al., 2018; GWP, 2014; Hoekstra et al., 2018; Varady et al., 2016; Zeitoun et al., 2016). This view contrasts with some scholars whose focus lies on more narrow approaches such as water supply and accessibility (Krueger et al., 2019; Padowski et al., 2016; Srinivasan et al., 2017). Despite the stigmatization around the fact that a broad approach is difficult to incorporate into practice (Cook & Bakker, 2012), this study underlines the aspects thereof as part of the many complex and interrelated problems and challenges of the natural and built-in water systems (Basco-Carrera, van Beek, et al., 2017; Bigas, 2013; Biswas & Tortajada, 2016; Hoekstra et al., 2018).

To characterize the inherent complexity surrounding urban water security (UWS), efforts have been directed to the development of appropriate UWS indicator-based frameworks (see Arcadis, 2015; Hoekstra et al., 2018; Jensen & Wu, 2018; Koop & van Leeuwen, 2015; Romero-Lankao & Gnatz, 2016; van Ginkel et al., 2018; Vink, 2019).; and, due to their benefits, their adoption as policy decision making tools has been rising (Wilder, 2016). The use of indicators provides a good starting point towards a water-secure future by offering the possibility of "a new and comprehensive understanding of society's water needs and the water system, with a clear pathway to public and private decision-makers (Grey et al., 2013, p.8)". Water related indicators have the potential to simplify complex real-world phenomena into quantifiable information that is easier to communicate (Molle & Mollinga, 2003). Looking at numbers facilitates evaluation and monitoring (Wilder, 2016) and can reflect differences in water-related matters (Jensen & Wu, 2018). Indicators offer a quick-scan of the situation of the urban water system highlighting its strengths and weaknesses. They appoint what seem to be the most critical issues and contribute to an enhanced problem formulation (Jensen & Wu, 2018) which in turn, gives room to the allocation of better practices (van Leeuwen et al., 2012). Furthermore, when applied to the urban scale, those participating in the policy decision making are given the opportunity to distinguish a direct link between their actions and what the indicators measure (Jensen & Wu, 2018).

In spite of the benefits provided by indicator-based frameworks in the field of UWS, there are some design concerns surrounding their use in the policy decision making processes: the majority of the current tendencies in the design of indicator frameworks on the UWS domain place much attention in the technical and analytical properties, and leave political and practical aspects of their design and use in the background (Howlett & Cuenca, 2017). Furthermore, their contribution to the policy decision making processes is theoretical; little is known on their process of adoption (Howlett & Cuenca, 2017), and an increased rate of use does not translate into satisfaction with the outcomes (Garfin et al., 2016; Hoppe, 2010). Howlett & Cuenca (2017) found that political and practical aspects of the use of UWS indicators are significant to determine their success. The participation of the users has an effect on their success when they are using it (Lehtonen, 2013). Also, the influence the indicators exert is partly subjected to the policy decision making context and settings such as culture, structure and conditions (Howlett & Cuenca, 2017; Lehtonen, 2013). Still, literature regarding UWS is scarce for a comprehensive indicator design that considers characteristics of its use in the policy decision making processes from the beginning. An example of comprehensive design corresponds to a tailored index for UWS developed by Jensen & Wu (2018) that, to our knowledge, bears the closest resemblance to a far-reaching design careful of including aspects beyond the technical and analytical envision.

This study explores the design of an indicator-based framework with a clear link to aspects of its use in the policy decision making processes. Indicators can be used in many different modes in the policy decision making (see Howlett & Cuenca, 2017; Jensen & Wu, 2018; Lehtonen, 2013; Molle & Mollinga, 2003). Our aim is to create a comprehensive indicator-based framework that provides specialists and non-specialists with an improved understanding of integral water-related issues for the purpose of decision making about effective interventions. In order to do that, we focus on the indicators' role in assisting collective learning and joint problem formulation at the science-policy interface. We conceive the science-policy interface as the knowledge intersection between science actors from diverse fields, policy actors, and stakeholders, all interacting in a participatory setting with the purpose of enriched decision making (Gustafsson & Lidskog, 2018; MacDonald et al., 2015; Wiek et al., 2007). In the science-policy interface, actors have different interests which results into a disagreement on what the problem is and what it means (Hegger et al., 2012; Hommes et al., 2009; Lang et al., 2012; Zeitoun et al., 2016). In the context of UWS, indicator-based frameworks can be used to facilitate effective communication among the different actors relevant for the field of water: scientific, bureaucratic and stakeholders (Edelenbos et al., 2011). Consequently, dialogues about UWS-related issues and potential solutions would be enabled (Howlett & Cuenca, 2017; Molle & Mollinga, 2003). We conceptualize the resulting indicator-based framework as a boundary object (see Hegger et al., 2012; Hoppe, 2010; Kimble et al., 2010; Lang et al., 2012; Molle & Mollinga, 2003; Star & Griesemer, 1989; Voinov & Bousquet, 2010; White et al., 2010). We define a boundary object for the UWS domain as an *instrument that functions as a knowledge base and is capable of enabling effective communication across different scientific domains, policy divides and stakeholders found in the science-policy interface. It has the purpose of assisting knowledge co-production to arrive at an integrative definition of the problem, establish a priority agenda, and serve as a solid base for an enriched policy- and decision-making towards effective action perspectives for urban water security.*

The practical implications extend to the use of the resultant design by consultants that work with water related actors relevant for participatory policy decision making. The intervention of actors and organizations that span research and practice surrounding UWS policy decision making are catalogued as an effective approach to co-produce knowledge at the science-policy interface (Varady et al., 2016). Co-producing knowledge in this way often employs strategies to set rigorous interactions among the different actors which results in intensive use of resources (Hegger et al., 2012; Kirchhoff et al., 2015; Lang et al., 2012). We provide a standardized approach that presents a less demanding alternative that is not restricted to the analysis of a consultant oblivious to the policy decision making processes (Jordan et al., 2018). Furthermore, the designed indicator-based framework can be used to prevent institutional fragmentation either from different departments of the same organization or from different organizations.

This research adopts a design-science methodology (Wieringa, 2014). Section 2 presents key insights from the literature on boundary objects and UWS indicators. In Section 3, the theoretical insights retrieved from the last step are integrated with insights retrieved from experts into a conceptual framework. Section 4 provides a research overview and describes the method to incorporate the conceptual framework into a design. Also, the Urban Water Security Dashboard (UWSD) developed by van Ginkel et al. (2018), which constitutes the starting point for the design, and the case study of Mexico City, are introduced. Section 5 presents the resultant design, an approach based on the UWSD to be operationalized as a boundary object in the context of UWS. Section 6 contains the result of the application of the framework to the case study in Mexico City and in an experts' session. Section 7 discusses the main findings of the design and its application, and the trade-offs with similar approaches. Finally, Section 8 summarizes our main conclusions and recommendations.

2 Theoretical Background – UWS Indicator-Based Boundary Object Success Criteria

This section presents the success criteria for an indicator-based framework conceptualized as a boundary object. First, we present the main components of an indicator-based framework. Following, we introduce inherent features that should be considered for the success of a boundary object. These are specifically described for an indicator-based framework and its components.

2.1 UWS Indicator-Based Frameworks: What to Consider for their Composition?

Our understanding of an indicator-based framework distinguishes between four fundamental components, namely *indicators*, *analytical base*, *portrayal, and the process of development*. Indicators refer to the basic unit of analysis; analytical base, to the structure of analysis (e.g. modular approach, system approach); and portrayal, to the way in which the indicators and the analytical base are represented (e.g. graphs, list, dashboard). The fourth one is an underlying component and refers to the process of development of indicators (i.e. definition and/or selection and/or population).

According to the OECD (Linster, 2003), water-related *indicators* should have a balance between the relevance and utility for users, the analytical soundness and the measurability. The *process of development of indicators* should be careful of including the aforementioned aspects and also of considering that the acceptancy of the selected indicators is subjected to a collaborative development with those who are likely to use it (Sullivan, 2002; Wilder, 2016). Furthermore, this process is considered as dynamic where the indicators selected are neither final, nor exhaustive; they keep evolving over time and space (UN-Water, 2006). However, it is important to keep in mind that, even with the right indicators of UWS in place, meaningful results will be elusive until their relative interrelations are identified (Romero-Lankao & Gnatz, 2016). The *analytical base* should provide the opportunity to visualize those interrelations. A defficient understanding of the interaction between environmental, socio-economic and physical aspects in the water system makes it hard to fully grasp the impacts on the functions of the water sector, and those interconnected to it (Biswas & Tortajada, 2016). In terms of *portrayal*, the visual communication of the index must prevent information loss (Hoekstra et al., 2018). Indicators embed large amounts of information in its composition, which can lead to inadequate conclusions derived from an oversimplified reading and presentation (Molle & Mollinga, 2003; Nardo et al., 2005; Sullivan et al., 2006).

2.2 Boundary Objects: How to Achieve Success?

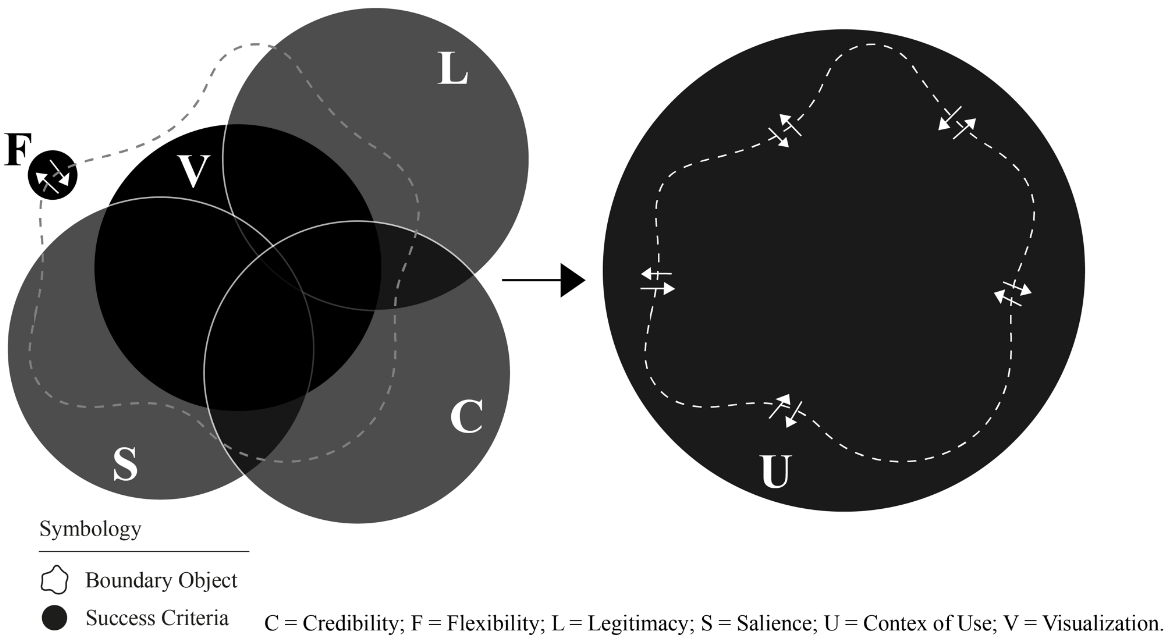

Figure 1. Success criteria for a boundary object. A boundary object is not restricted to a predefined shape and it is flexible to changes that may arise during it use. It is composed by a combination of elements that contemplate an interplay between credibility, legitimacy and salience displayed by means of a set visualization.

Boundary objects are instruments that bridge the gap between science and policy (Hoppe, 2010) by enabling effective communication between different actors found at the science-policy interface (Crona & Parker, 2011; Hegger et al., 2012; Howlett & Cuenca, 2017; Molle & Mollinga, 2003; Voinov & Bousquet, 2010; White et al., 2010). They function as a knowledge base that integrates aspects of the local context and the scientific body of knowledge (Lang et al., 2012). They facilitate a cooperation that takes place in "social processes which encompass relations between scientists and other actors in the policy process, and which allow for exchanges, co-evolution and joint construction of knowledge with the aim of enriching decision-making (Hegger et al., 2012, p.53)". As a result, they can target some of the issues found at the science-policy interface like insufficient problem awareness and framing; deficient integration across knowledge types, communicative styles and/or technical aspects; and an absence of legitimate and transdisciplinary outcomes (Lang et al., 2012).

Boundary objects are not restricted to a specific type of artefact (Hegger et al., 2012; Hoppe, 2010; Molle & Mollinga, 2003; White et al., 2010). Therefore, they can take the form of indicator-based frameworks. However, disregarding the type, we identified certain features that boundary objects have in common that dictate their success based on the function they fulfil, namely *credibility, legitimacy and salience, visualization, context of use* and *flexibility.* Figure 1 illustrates a boundary object and in terms of the success criteria and Table 1summarizes each of the criteria of success of a boundary object and relates it to indicator-based frameworks.

2.2.1 Credibility, Legitimacy and Salience

The production and mobilization of knowledge is more effective when the criteria of salience, legitimacy and credibility are met and the trade-offs among them are balanced for the different users (Hegger et al., 2012). Credibility refers to adequacy of the knowledge integrated into the object in terms of scientific validity and technical evidence. Salience can be defined as the perceived relevance of the boundary object for the policy decision making processes according to the interests and needs of the actors involved in regard of the context. Legitimacy contemplates the extent to which the users perceive the object as fair, balanced, unbiased, respective and inclusive of their perceptions (Edelenbos et al., 2011; Hegger et al., 2012; Kolkman et al., 2005; Lang et al., 2012; Voinov & Bousquet, 2010; White et al., 2010).

Credibility for an indicator framework means that indicators need to be valid and scientifically robust which substantiates their value for the actors involved in the policy decision making process. They need to accurately capture levels and changes in their phenomenon of interest. Their construction must be coherent and transparent built upon data that already exists, and is feasible to collect within time and budget from a trusted source (Jensen & Wu, 2018).

A boundary object needs to be legitimate to be accepted. In an indicator system, this is largely a function of the process of the indicators' development. It concerns the involvement of stakeholders in the definition, selection and population of the indicators. It needs to be contextual and collaborative to include a wide range of perspectives (Jensen & Wu, 2018; Molle & Mollinga, 2003; Sullivan et al., 2003).

Salience will influence the degree to which an indicator is useful for the policy decision making process (Linster, 2003). They should be relevant to the actors involved in regard of the context and the scale of action (Jensen & Wu, 2018).

2.2.2 Visualization

The visual communication of the boundary object influences the compelling and persuasive capacity of the artefact and should not be neglected. Boundary objects help to visualize intricated and large amounts of information. Adequate visualization techniques are required for the exploration and understanding of the resulting large set of information and knowledge. An adequate visualization format with capacity to communicate information, data and knowledge enables an engaging and substantial process (Voinov et al, 2016).

Visualization for an indicator-based framework not only considers the portrayal of the object, but also its analytical base. In first place, in indices, a large amount of information is contained in the composition of the indicators (Molle & Mollinga, 2003; Sullivan et al., 2006). The construction of comprehensive indices and indicators considered of multiple variables can result in information losses (Hoekstra et al., 2018). In addition, to facilitate understanding, the relationships between the phenomenon that single indicators measure must be perceptible (Biswas & Tortajada, 2016; Romero-Lankao & Gnatz, 2016).

2.2.3 *Context of Use*

The role that boundary objects play in the policy decision making process influences them. The actors considered for the development of a boundary object must correspond to the actors who will use it (Hegger et al., 2012; Kolkman et al., 2005; Lang et al., 2012). Also, where and how the boundary object will be used in the process must be clear for the participants (Lang et al., 2012). Furthermore, Kimble et al. (2010) identified that, despite the fact that literature regarding boundary objects stresses that their success relies on the selection of the right object to fit the purpose, their success involves not just the artefact itself but also the role of the 'guide' (i.e. boundary actors). A boundary actor refers here to as the person or organization behind the development of the object. The role of a boundary actor is commonly compared to the one played by facilitators or moderators. They are objective and impartial, and are normally placed outside the formal decision-making processes (Voinov & Bousquet, 2010). They often come from a scientific background (Hegger et al., 2012). Yet, this does not mean that they are restricted to their background; their contribution goes beyond informing and/or consulting and is compared to those of 'issue advocates' and 'honest brokers' (Hegger et al., 2012). They play a key role in the pre-structuration of the problems and in giving direction to the process (Hegger et al., 2012; Hoppe, 2010; Kirchhoff et al., 2015). At the end, a one-directional piece of advice, such as the one provided by an instrument on itself, is not translated into immediate and effective uptake in the policy decision making processes (Hoppe, 2010).

An indicator-based framework that targets the science-policy dialogues interface in the early stages (i.e. collective learning and joint problem identification) (Jensen & Wu, 2018; Lehtonen, 2015), has to consider important aspects regarding its context of use. Actors from the scientific domain, the bureaucratic field and stakeholders will be brought together (Edelenbos et al., 2011). Scientific knowledge may come from scientists or consultants and is based on education and professionalism (Hommes et al., 2009). Bureaucratic refers to that knowledge retrieved from the institutions and stakeholder to that collected from local actors with a direct interest in the problem (Edelenbos et al., 2011). Scientific knowledge cares about the credibility; whilst bureaucratic and stakeholder about the practical relevance (i.e. salience) and legitimacy (Lang et al., 2012). According to Hegger et al. (2012), successful joint knowledge production is reliant on a dynamic interplay between such actors and their discourses, rules and resources. An indicator-based framework under this context should facilitate such interplay in a way in which a stronger link between indicators and the actors involved will allow them to perceive a direct link between their actions and what the indicators measure (Jensen & Wu, 2018). The indicators would perform an instrumental and conceptual function: they can inform specific decisions or projects, and, at the same time, they are a knowledge base for informed decisions (Howlett & Cuenca, 2017; Lehtonen, 2013).

Table 1. Link of success criteria for boundary objects to UWS indicator-based frameworks. References are found in the text.

Success Criteria	**Description**	**Link to indicator-based frameworks**
Credibility	Adequacy of the knowledge in terms of scientific evidence.	Indicators should be scientifically robust and valid.
Legitimacy	Acceptance of the object by the different actors.	Function of the process of development of indicators.
Salience	Relevance and usability for the context in which the object is used.	Degree of relevance of indicators (as single unit and as a set).
Visualization	Visualization of the information.	Analytical base and portrayal of the indicators.
Context of use	Considerations regarding the role of the object and its setting of use.	Link between indicators and decision-makers.
Flexibility	Plasticity to adapt to changes and new information.	Dynamic process for the development of indicators.

2.2.4 *Flexibility*

Boundary objects must be flexible and plastic enough not only for the specific needs of the local context, but also in the face of changes and new information that may arise during their use (Star & Griesemer, 1989; Voinov & Bousquet, 2010; Voinov et al., 2016). Their context of use influences them and vice versa. In response, boundary objects, just as the process in which they are implemented, should be adaptive. This means that they must be ready be redefined and adjusted (Voinov & Bousquet, 2010). To achieve this, boundary objects may be developed as modular, robust and/or hierarchical, which allows a smooth change of components (Voinov & Bousquet, 2010).

In an indicator-based framework, flexibility is attributed to the dynamic process. Indicators are neither final, nor exhaustive. They keep evolving over time and space (UN-Water, 2006). Indicators must remain plastic enough to withstand changes and additions necessary for their usability without compromising their balance and structure.

3 Conceptual Framework – UWS Indicator-Based Boundary Object Requirements

From the past section, we can determine that an UWS indicator-based boundary object must foster a variety of indicators that preserve a balance over *credibility*, *legitimacy* and *salience* (Howlett & Cuenca, 2017; Jensen & Wu, 2018; Molle & Mollinga, 2003). Furthermore, its *visualization* must allow interrelations among indicators to be distinguished (Hoekstra et al., 2018; Krueger et al., 2019; Romero-Lankao & Gnatz, 2016; van Ginkel et al., 2018) in a format that enables effective communication of information, data and knowledge (Hoekstra et al., 2018; Molle & Mollinga, 2003; Nardo et al., 2005). Lastly, its composition ought to consider important characteristics of the *context of use* in which it will be operated (Howlett & Cuenca, 2017; Jensen & Wu, 2018; Molle & Mollinga, 2003) and remain *flexible* to adapt to changes and new information that may arise (Howlett & Cuenca, 2017; Lehtonen, 2013; UN-Water, 2006). **Error! Reference source not found.** summarizes the boundary object success criteria coupled to indicator-based frameworks for the UWS domain. To address the success criteria, 25 design requirements were developed supported by theory and experts' opinion (the insights retrieved by the experts' consultation can be found in Appendix 1). Such requirements are displayed in Table 2. They correspond to the aspects that should be taken into account for the design of a comprehensive indicator-based framework characterized as a boundary object for the UWS domain.

Table 2. Design requirements. A detailed rationalisation of the requirements can be found in Appendix

Success Criteria	Component	Requirement	Key References
Credibility	**Indicators**	Are coherent with UWS and theoretically well founded in technical and specific terms.	(Beek & Arriens, 2014; Dunn & Bakker, 2009; Jensen & Wu, 2018; OECD, 2003; UN-Water, 2006)
		Accurately capture levels and changes in the aspect of interest.	(Jensen & Wu, 2018; Nardo et al., 2005; OECD, 2003)
		Data comes from trusted sources.	(Beek & Arriens, 2014; Dunn & Bakker, 2009; Jensen & Wu, 2018; Nardo et al., 2005; OECD, 2003; UN-Water, 2006; Interviews)
		Data is updated regularly.	(Beek & Arriens, 2014; Dunn & Bakker, 2009; Jensen & Wu, 2018; Nardo et al., 2005; OECD, 2003; UN-Water, 2006)
		Data is easily available.	(Beek & Arriens, 2014; Dunn & Bakker, 2009; Jensen & Wu, 2018; Nardo et al., 2005; OECD, 2003; UN-Water, 2006)
		Its construction is transparent	(Jensen & Wu, 2018; Nardo et al., 2005; Interviews)
		The set of indicators is comprehensive enough to accurately represent UWS with an integrative vision.	(Garfin et al., 2016; Molle & Mollinga, 2003; Nardo et al., 2005)
Legitimacy	**Development of indicators**	There is a representative sample of actors included in the development of the indicators.	(Garfin et al., 2016; Sullivan, 2002; Wilder, 2016)
		The perspective on the situation of the different actors is reflected through the indicators.	(Jensen & Wu, 2018; Molle & Mollinga, 2003; Sullivan et al., 2006; Interviews)
		The different actors agree with the score of the indicators.	(Jensen & Wu, 2018; Nardo et al., 2005; Interviews)
		The different actors agree with the metrics and thresholds set for the indicators.	(Romero-Lankao & Gnatz, 2016; Interviews)

Salience	**Indicators**	The indicators are populated with data according to the spatial scale selected and the specific context.	(Jensen & Wu, 2018; UN-Water, 2006; interviews)
		The indicators are applicable to the local area situation.	(Beek & Arriens, 2014; Dunn & Bakker, 2009; Jensen & Wu, 2018; Interviews)
		The indicators are simple to understand and interpret	(Beek & Arriens, 2014; Dunn & Bakker, 2009; Jensen & Wu, 2018; Nardo et al., 2005; Interviews)
Visualization	**Portrayal**	The framework helps visualize large amounts of information as required.	(Howlett & Cuenca, 2017; Molle & Mollinga, 2003; Sullivan et al., 2003; Voinov & Bousquet, 2010; Wilder, 2016; Interviews)
		The framework presents information in a simple and inspiriting manner (it's not overwhelming).	(Interviews)
		The framework is visually appealing.	(Voinov et al., 2016; Interviews)
	Analytical base	The relationships between indicators are visible, clear, and simple to understand.	(Basco-Carrera, Warren, et al., 2017; Romero-Lankao & Gnatz, 2016; UN-Water, 2006; Indicators)
Context of use	-	The actor(s) that built-up the object (i.e. boundary actor(s)) are neutral, objective, and placed outside the formal policy decision making processes.	(Voinov & Bousquet, 2010)
		The actor(s) that built-up the object (i.e. boundary actor(s)) is(are) present in the context of use.	(Basco-Carrera & Francisco-Mendoza, 2017; Hegger et al., 2012; Hoppe, 2010; Kimble et al., 2010)
		The users (i.e. actors that will interact with the object) are considered for the development of the object.	(Basco-Carrera & Francisco-Mendoza, 2017; Kolkman et al., 2005; Sullivan, 2002)
		It is clear in which part(s) of the context of use the object will be operated.	(Interviews)
		It is clear how will the object be operated.	(Interviews)
		Object considers and complies with the rules of its context of use.	(Hegger et al., 2012, Interviews)
		The output of the object is linked with the rest of the policy decision making process.	(Interviews)
Flexibility	**Various**	The object remains flexible to allow changes and to be responsive when new information arises.	(OECD, 2003; UN-Water, 2006; van Bruggen et al., 2019; Voinov & Bousquet, 2010; Wilder, 2016)

4 Method

This section starts by providing a brief description of the strategy followed to perform this research: design-science. Next, we describe the specific methods followed for the different stages contemplated by the design-science methodology. Following, the UWSD, which is the starting point for our design, is presented and described. It is followed by the introduction to the case study of Mexico City, from which real-life information is collected in the form of qualitative and quantitative data (Yin, 2017) necessary for the design and validation processes.

4.1 Research Strategy: Design-Science Methodology

This study is based on the design-science methodology (Wieringa, 2014). The strategy followed for this research and its specific stages are illustrated in Figure 2. The design is iterative and takes as starting point what we call *Design 0*. The *Design 0* corresponds to an existent UWS indicator-based framework: the Urban Water Security Dashboard (see van Ginkel et al., 2018) (further explained in Section 4.4). *Design 1* corresponds to an upgraded UWSD and corresponds to the design of a UWS indicator-based framework (originated from the UWSD) characterized as a boundary object. The stages and activities of the research displayed in Figure 2 can be translated into the following questions:

(1) According to literature and experts' opinion, what should be considered for the design of an indicator-based framework (design requirements) that aims to operate as a boundary object in the context of UWS?
(2) To what extent are the design requirements present in the original UWSD?
(3) How can the UWSD be upgraded to enhance the incorporation of the design requirements?
(4) How does the design of the upgraded UWSD perform?
(5) What are the theoretical and practical implications derived from the performance of the upgraded UWSD approach?

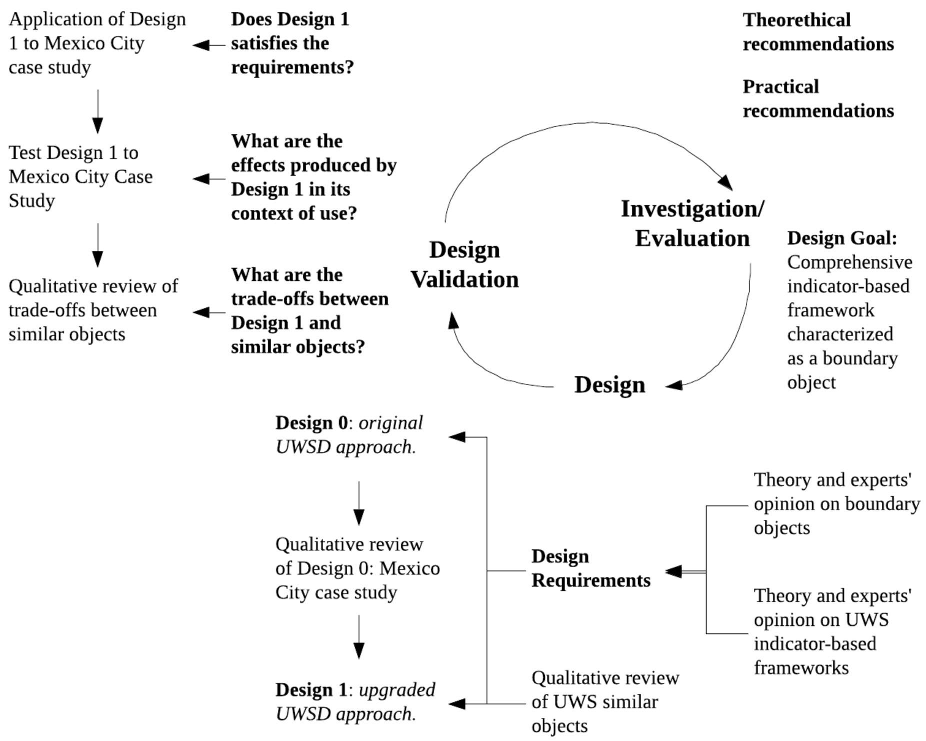

Figure 2. Research strategy based on the design-science methodology. Adapted from (Wieringa, 2014).

4.2 Design

To find the weaknesses and the strengths of the UWSD in terms of the requirements obtained in Section 3, we made use of a learning-by-doing approach and an expert consultation procedure. The premise was that the UWSD in its original form complies with the criteria of success for an indicator-based boundary object only to a certain extent. However, the extent of compliance was unknown. To overcome this issue, we applied the original UWSD methodology to the area of the case study in Mexico City. This exercise allowed us to describe in a qualitative way if and in which form the UWSD was addressing each of the design requirements. Furthermore, we consulted experts (related to the use of boundary objects) about their opinion of the UWSD in relation with the criteria of success of a boundary object. The output of both tasks provided a basis for the upgrade of the UWSD.

Subsequently, we reviewed literature about indicator-based frameworks for the UWS domain to get a grasp on the different alternatives developed by other scholars and practitioners to address the subject. The focus of our investigation at this step revolved around the composition of the frameworks and their underlying methodology.

After the performance of the UWSD in terms of the design requirements was evaluated, and different practices for indicators development were identified, an upgrade on the original UWSD approach took place. Where a requirement was absent or partially met, measures to improve the UWSD were taken. The output of this process corresponded the design of an indicator-based boundary object.

4.3 Design Validation

The upgraded UWSD obtained in the design process was applied to the case study of Mexico City. This allowed us to test the approach to a large extent and to get a real-life example of its application. However, it was not possible to apply the upgraded UWSD to its actual context of use, in this case Mexico City.

To address the aforementioned limitation, an expert session that simulated the science-policy interface of the Mexican context was conducted at Deltares. Deltares is an independent Dutch research institute in the field of water. They work around the world to provide smart solutions, innovations, and applications for people, environment and society. In response to the complexity of the management of socio-ecological systems under the current rapid urbanization, increasing population growth, and climate change, Deltares works along with governments, businesses, and other research institutes and universities, both in the Netherlands and abroad. They have close relationships with Mexican actors and institutes and are familiar with their context. Furthermore, they have experience working at the intersection where different types of knowledge coexist. In this session, the upgraded UWSD approach was tested with a sample of Deltares experts, and we observed and recorded how it performed in terms of the effects produced by the interaction of the boundary object and its 'context of use'. Lastly, we engaged into a discussion on the upgraded UWSD itself and its strengths and opportunities.

The last step of validation consisted of a qualitative review of the upgraded UWSD approach supported by literature against a selection of similar objects and approaches. The purpose of this task was to identify the differences between the effects of different instruments in the same context of use.

4.4 The Urban Water Security Dashboard (UWSD)

The Urban Water Security Dashboard (UWSD) (van Ginkel et al., 2018) has an integrative theoretical base and a system-oriented analytical base, hence making it an adequate starting point for the design of an indicator-based framework characterized as a boundary object. The UWSD is an indicator-based framework that follows an integrative understanding of UWS based on a system approach: pressure – state – impact – response (PSIR). PSIR has been commonly used to represent dynamic environmental systems due to the opportunity it provides for system analysis (Hoekstra, 1998; Hoekstra et al., 2018; Sekovski et al., 2012; van Ginkel et al., 2018) which is why Hoekstra et al (2018), proposed it as an appropriate alternative for understanding the complexity of UWS. From a policy and decision-making point of view, a PSIR approach provides actors involved the opportunity to see environmental, economic and societal issues as interconnected (Hommes, 2008; OECD, 2003).

The conceptual framework of the UWSD is represented and further described in Figure 3. Indicators to fit each of the categories that compose its conceptual framework were developed and measured on a 1-5-point scale. The term water security implies thresholds that set a minimum standard for living beyond which a compromise is unacceptable (Bakker & Morinville, 2013; Grey et al., 2013; van Ginkel et al., 2018). The proposed scale captures such thresholds in a way where *very secure* means a low level of concern in terms of UWS whereas *very insecure* refers to a very high level of concern.

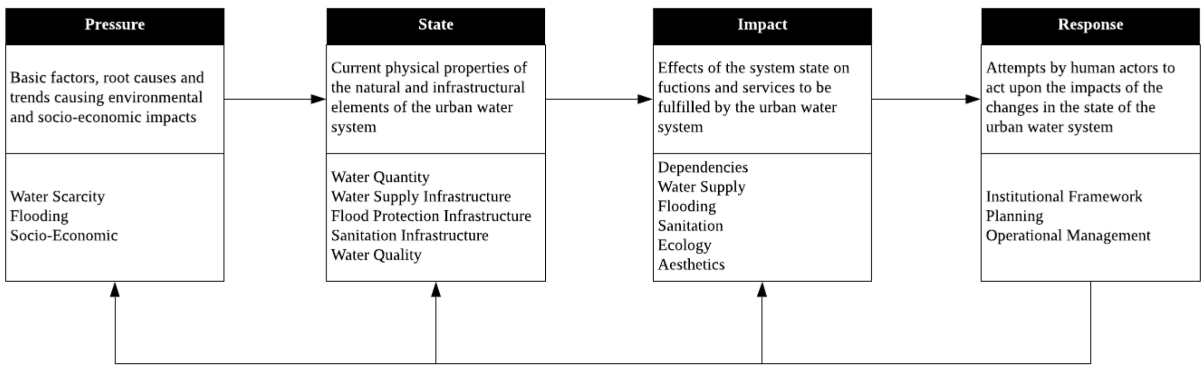

Figure 3. UWSD Conceptual Framework. Adapted from Van Ginkel et al. (2018).

4.5 Case Study: Mexico City

Mexico City is one of the most densely populated cities around the world. The greater area of Mexico City is home to more than 21 million people which has granted it the title of mega city. Mexico City's population faces big challenges in relation to water. Water management impacts different areas that include health, environment, access to basic water services, etc. (De Urbanisten, 2016; Romero-Lankao, 2010; Tellman et al., 2018; Tortajada, 2006a; Tortajada & Castelán, 2003). Although Mexico City is subjected to well-known critical issues such as severe flooding and water shortages, the use of narrow approaches has created a chain of problems in other parts of the system (De Urbanisten, 2016). Depicting the complexity of Mexico City's water system provides a challenging opportunity for an indicator-based boundary object that follows an integrative understanding of UWS. For this reason, Mexico City was chosen as the case study.

The data collection methods employed correspond to document analysis, observation, and a survey. Following, they are briefly described.

(1) Document analysis – Review of official documents, scientific literature, national data bases, and Deltares internal documents and information to investigate the situation regarding UWS in Mexico City.
(2) Observation – Attendance to a participatory modelling process in the area named 'Too Little or Too Much: Addressing Mexico City's Water Issues'. There, policy- and decision-makers were brought together with practitioners and science-related actors to breakdown the water-related problems and create a map of the topic. This session allowed us to get a grasp on the science-policy interface for the Mexican context around the topic of UWS. The insights retrieved improved our understanding of the policy decision making processes.
(3) Survey – Approach of critical actors to retrieve information by means of a questionnaire about their knowledge regarding the UWS situation of the area (more information about the questionnaire is provided in Section 5 and Appendices 4 and 5.

5 Results – Upgraded UWSD Approach

This section contains the main output of this research: the design of an indicator-based framework that can function as a boundary object. The first sub-section provides a review of the performance of the original UWSD in terms of the design requirements presented in Table 2. The second one, the design of the upgraded UWSD where the flaws found in the previous step have been addressed. A detailed review of the original UWSD approach developed by van Ginkel et al. (2018) and the design hereby presented can be found in the Appendix 3.

5.1 Review of the Original UWSD

Table 3 provides a description of the components of the UWSD. In terms of *credibility,* the indicators composing the UWSD have a strong theoretical basis and their influence on the UWS picture is clearly justified. They are able to capture levels and changes in aspects that are being measured. The data to populate the indicators comes from trusted sources as a result of an extensive search procedure. However, such search procedures, in some cases, are time consuming since the information is not easily available.

The *legitimacy* is partially addressed in the development of indicators, where the search procedures cover a wide range of studies before issuing a judgement. However, external actors are not included in the development of indicators. External actors are only consulted to give a score to the response dimension based on their perceptions.

Salience is partially covered in the development of indicators. The UWSD is focused on the city proper scale. Accordingly, most of the indicators require to be populated with local data. However, the data required to fit the local scale are sometimes hard to find and, as a consequence, some indicators are populated with data at the national scale. This threatens an accurate representation of the local context. Furthermore, the original UWSD serves the purpose of systematic cross-comparison between different cities. This means that the selection of indicators is generalized up to the extent where the local context cannot be accurately represented. This has two major consequences. On the one hand, some indicators are not applicable to certain contexts at all. For example, Mexico City is not a coastal city; therefore, all indicators related to the coast are of null importance for this context. This is partly solved by the protocol of assigning to such indicators the highest score. However, interviews disclosed that indicators that are not applicable to the context interfere with the identification of the actual challenges by adding irrelevant information to an already large knowledge base. On the other hand, a generalized selection of indicators, may leave important aspects of the local context behind. For example, one of the biggest environmental pressures for Mexico City corresponds to the seismic hazard. Mexico City is an area subjected to high seismic activity, where earthquakes, for example, can have large impacts on the water infrastructure. However, such pressure is not included in the set of indicators developed for the original UWSD.

Table 3. Description of the components of the original UWSD.

Parts	Description	Description on the original UWSD approach
Indicators	Basic unit of analysis.	56 static indicators that cover relevant aspects for UWS.
Analytical base	Structure of analysis.	System approach: pressure-state-impact-response (PSIR)
Portrayal	Representation of the indicators and the analytical base.	Dashboard.
Development of indicators	Definition and/or selection and/or population of indicators.	Procedure described in article by van Ginkel et al. (2018) and its supplementary data.

In terms of visualization, one of the main criticisms towards the UWSD corresponds to the ability for the users to spot clear interrelations between indicators. Even though the PSIR approach comprises its analytical base, the UWSD fails to provide a clear system understanding. Characterizing UWS with appropriate indicators and recognizing their causal mechanisms with the help of a system approach, can assist the operationalization of the concept in "a broad, yet practicable, way" (van Ginkel et al., 2018, p.9). Nevertheless, the UWSD lacks a clear way to provide the user with the visualization of well-defined interrelations among elements and their causal mechanisms. Furthermore, a dashboard approach makes it even more complicated. A dashboard constitutes the UWSD choice of portrayal for the opportunity it provides to prevent information loss by displaying all variables at once (Hoekstra et al., 2018). However, information obtained in the experts' consultation brought to light that the PSIR approach is complicated to understand, especially when there is a large number of variables displayed.

The *context of use* and *flexibility* are not considered to any extent in the original UWSD approach. Table 4 provides a summary of the assessment of the UWSD. It provides a short description on if and how the UWSD is addressing the success criteria of a boundary object.

Table 4. Quick assessment of the UWSD in terms of UWS indicator-based boundary object success criteria.

Success Criteria	Meaning for original UWSD
Credibility	Indicators are scientifically valid.
Legitimacy	Considered to certain extent in the comprehensive search procedures found in the *Indicators Formalisation* and in the score of the elements that belong to the response dimension.
Salience	Considered to certain extent in the search procedures found in the *Indicators Formalisation*.
Visualization	Analytical base: In theory PSIR allows to see issues as interconnected. In practice it is too complicated, and it does not give room for a clear visualization of the relationship between issues. Portrayal: dashboard. In theory it allows to show all variables at once to avoid information loss. In practice is overwhelming and distracting.
Context of use	Not considered.
Flexibility	Not considered.

5.2 Design: UWSD Approach (UWSDA)

Reacting to the weaknesses found in the original UWSD, an upgraded UWSD together with a methodology that dictates it, from now on referred to as the UWSD Approach (UWSDA), were developed. We put emphasis on both the object (i.e. UWSDA) and the specifications to obtain it. The UWSDA is displayed in Figure 4. The UWSDA involves not only the boundary, or internal actor, behind its development, but also the potential users, or external actors, related to the object.

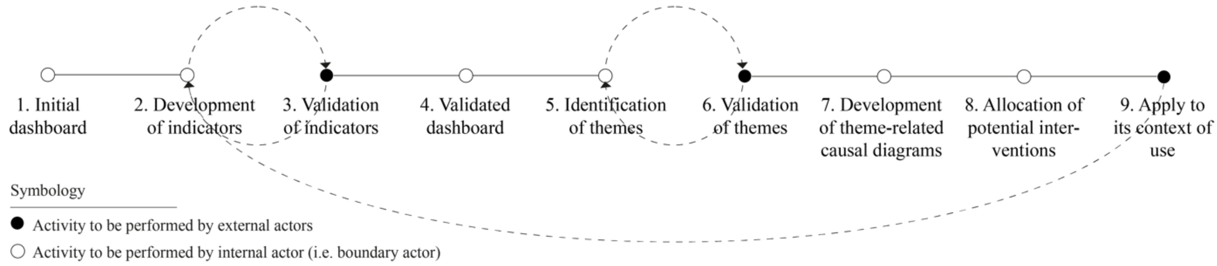

Figure 4. Upgraded UWSD Approach.

The situation of UWS for a given area is context dependent (Cook & Bakker, 2012). Therefore, an integrative definition of UWS applied to a certain context must consider different variables. The notion of a static indicator-based framework contradicts the aforementioned condition. Accordingly, we take a step back and conceive the UWSDA as dynamic in a relatively similar way as the SETEG framework developed by Romero-Lankao & Gnatz (2016). This involves that we assert that the boundary actor who applies the UWSDA has the liberty to select adequate indicators and data sources to fit the categories proposed in Figure 5 for the area to be studied. The main changes and additions correspond to a rearrangement of the original UWSD categories and several additions. For *pressures* and *state*, the new categories are a logical partition from the originals. In the *impact* dimension we kept many of the original categories and developed three new categories: (1) *basic water services* replacing the original categories of *water supply* and *sanitation,* to capture the fulfilment of the population's basic water needs; (2) *conservation of natural resources,* for the long-term sustainability of the natural water system; and (3) *environmental protection*, for the state of the water system in terms of pollution. These categories are derived in the same way as the original dashboard with an origin in the classification of the functions of the water systems provided by Brown et al. (2008). For the *response* dimension, an important addition was made: the inclusion of the *individual and community capacity*. While the original UWSD has a strong focus on governmental capacity, the UWSDA acknowledges that the societal response is equally important (Hoekstra et al., 2018). We conceptualize this category as the capacity of individuals and community to respond to water-related challenges when the government is unable or fails to provide (Krueger et al., 2019). The supplementary material *Indicators Formalisation* provides a full explanation of indicators that corresponds to the *Step 1- Initial Dashboard* of the UWSDA, which contains a set of indicators for each category and explains if they are either likely to be found in every context despite of its particularities from now on referred as static, therefore part of the *Initial Dashboard*, or are more likely to belong only to certain contexts from now on referred as dynamic. The development of indicators described earlier in this paragraph is consistent with the *Step 2 – Development of Indicators*. It is important to mention that, beyond the process of selection of indicators, the processes of definition and population of indicators can also change. For example, if a detailed study regarding flood propensity has been performed for the area and is publicly available, the boundary actor can change the search and score methods proposed to fit the study. This is also addressed with the static and dynamic labels in the *Indicators Formalisation*.

To address the legitimacy and the salience in the UWSDA, we combined and adapted the methodologies proposed by Jensen & Wu (2018) and Pires et al. (2017). We propose a validation of indicators through a consultation of relevant actors by means of a digital questionnaire. The general questions include whether the indicators provide a representative picture of the following aspects: (1) the UWS pressures, states, impact and/or responses for the area; (2) whether their own perspective on the UWS for the area was reflected by the set of indicators, (3) whether any UWS concern was omitted, (4) whether any additional indicators should be included, (5) whether any indicator was poorly chosen, hard to understand and/or interpret, (6) whether any score was a source of disagreement, and (7) whether they were aware of other local sources of information. Furthermore, just as in the original UWSD, data on actors' perceptions for the scoring of the response dimension was collected. The actors approached for the validation correspond to those likely to be the users of the object and their variety is attributed to the type of knowledge they provide. We consider that the required types of knowledge correspond to expert (or scientific), bureaucratic and stakeholder knowledge (Edelenbos et al., 2011). This procedure corresponds to the *Step 3 – Validation of Indicators*. The questionnaires to be applied for this step can be found in Appendices 4 and 5.

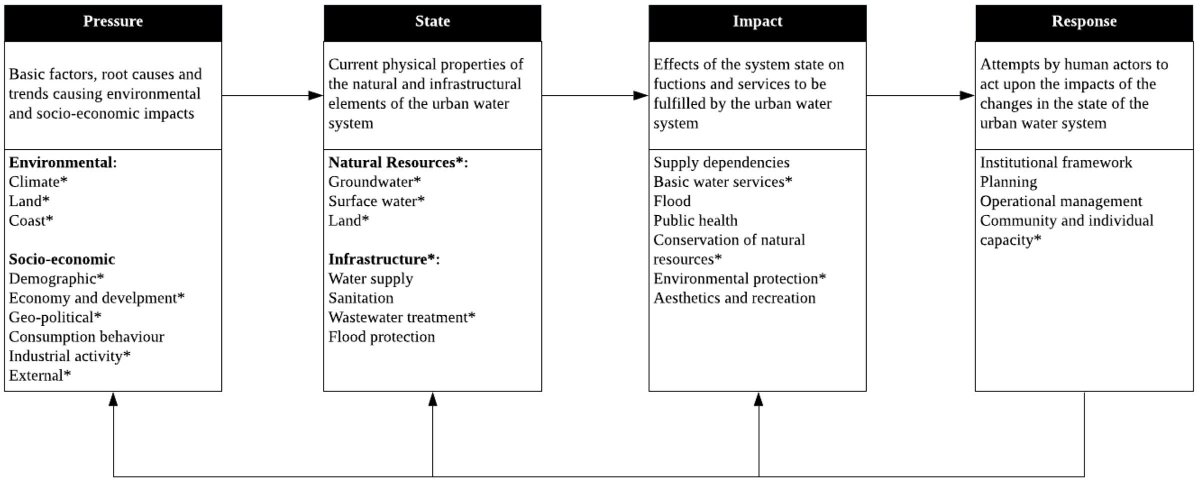

Figure 5. UWSDA theoretical and Analytical Base. *corresponds to change and additions from the original UWSD.

In terms of visualization, we developed a layered dashboard. The layers allow the user to choose the level to which they want to explore information. This technique was suggested in the interviews. We used the WaterLOUPE tool developed by Deltares (Deltares, 2019) as an example for this type of visualization. Once the iteration between *Steps 2* and *3* (*Development and Validation of indicators*) has taken place, we can apply the layered dashboard approach to the indicators and arrive at *Step 4 – Validated Dashboard*. Figure 6 provides a graphic that illustrates the layered dashboard approach and its characteristics.

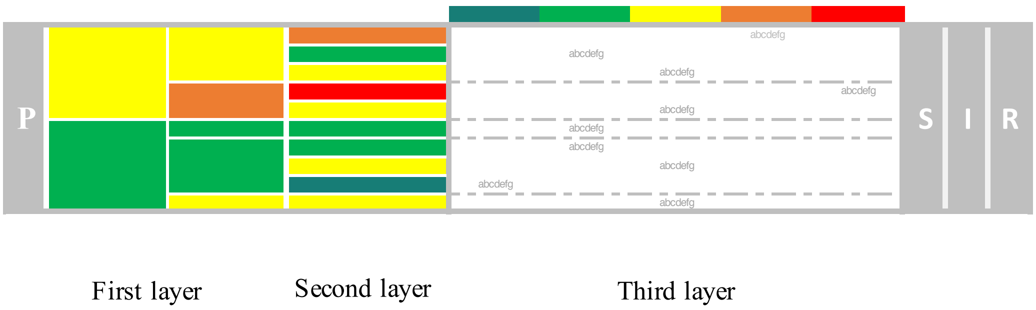

Figure 6. Layered dashboard approach. Users of the dashboard can visualize the information in three layers, where the deeper you go, the more information you get. The first layer provides the upgraded UWSD categories and their correspondent score in the form of colours. The second layer provides the indicators that are behind the score of the category and their correspondent score. Lastly, the third layer provides the key aspect from which the score of each indicator was derived.

Furthermore, to make the interrelations among indicators visible, we propose the development of theme-related causal diagrams. Due to the many variables that the dashboard comprises, the issues of major concern need to be isolated. We followed the methodology of Linster (2003) who identifies the issues of concern for a selected area and breaks them down into a PSIR scheme. In the UWSDA, the main issues of concern, or themes, can be derived and broken down into elements with the indicators from the validated dashboard. This corresponds to the *Step 6 – Identification of themes*. Still, we propose a validation in *Step 7 – Validation of themes* to prevent the omission of any issues of concern. This question is included in the digital questionnaire from *Step 3 – Validation of indicators*. Once the issues are identified and validated, we can proceed to *Step 7 – Development of Theme-Related Causal Diagrams* and map the causal diagrams for the selected themes. It is very important to stress that the more specific and narrowed down the theme is, the clearer the diagram will be. The process for the development of the causal diagrams is illustrated in Figure 7. The response dimension is not mapped with the interrelation since it is assumed that it is a measure of the capacity to develop/or implement specific interventions. It can be argued that good response capacity, such as the governmental or the institutional, is a necessary mean to improve water security rather than an outcome. One may therefore argue that it might not be scientifically correct to include response capacity as part of the assessment for UWS. Nevertheless, it is an important precondition to achieve a water secure future and it should be considered in its evaluation (Beek & Arriens, 2014).

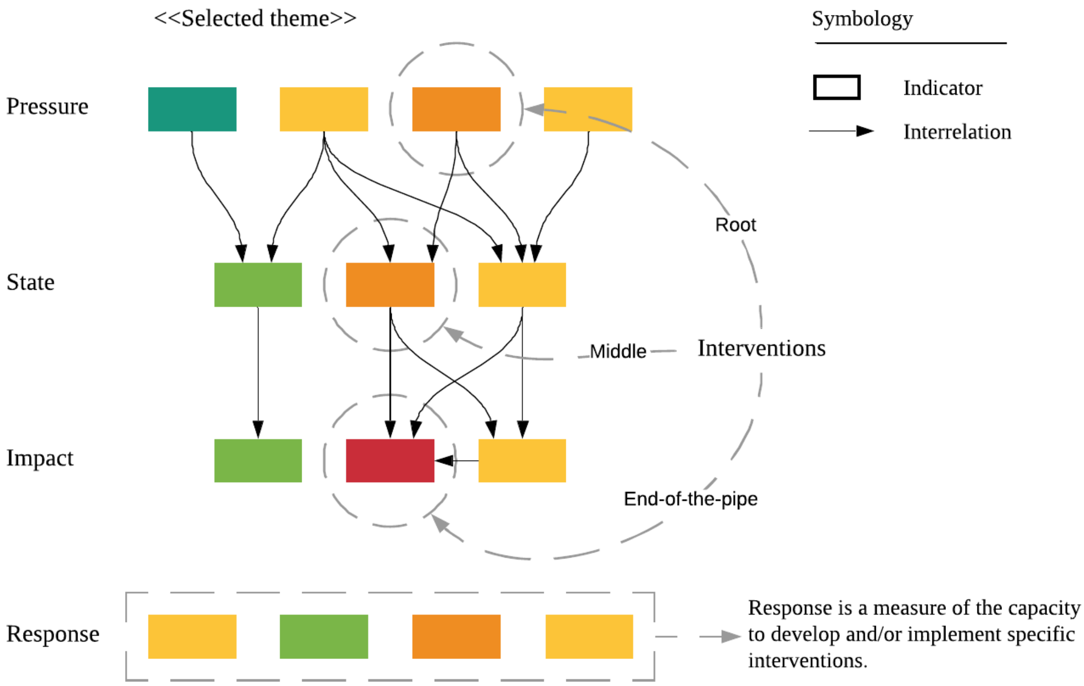

Figure 7. Causal diagrams composition and interpretation. The colour of the indicators corresponds to their assigned score. Interventions are allocated by their level of action.

Step 8 – Allocation of Potential Interventions corresponds to the allocation of possible measures and takes place after the build-up of the theme-related causal diagrams. The logic behind this action is that more detailed solutions can be reached through a broad understanding of the system and its functions and the potential impacts of possible interventions. As an example, system approaches had been used as a common approach to develop causal loop diagrams under participatory processes for environmental and water management issues (Basco-Carrera & Francisco-Mendoza, 2017; Voinov & Bousquet, 2010; Voinov et al., 2016). This approach has proven to enhance social learning by creating a shared understanding of the problem which eventually leads to the development of potential solutions (Basco-Carrera & Francisco-Mendoza, 2017). A study performed by Basco-Carrera et al (2017) used a co-constructed model that does justice to system dynamics that characterized system interactions and cause-effect relations in the context of water management. The authors proved that due to the use of such model, the awareness between the interconnections of the elements increased, even for those actors with non-technical backgrounds. It supported the policy decision making process by increasing the understanding of the different actors regarding the system and its functions so as the potential impacts of possible interventions. This eventually led to more detailed solutions such as decision support systems, awareness raising, and regulations and licensing, compared to those obtained in traditional processes such as better land use measures or better water resources management. The authors thus demonstrated that a lack of good understanding of the physical, socio-economic and institutional system will likely result in generic solutions whereas improved understanding results in more sophisticated measures. In addition, the PSIR approach allows to define their level of action: those interventions that take place in the impact dimension are considered end-of-the-pipe solutions whereas those that take place at the state are considered as root interventions. 'Quick fixes' or end-of the-pipe solutions to water security often result in new and more complicated problems (Hoekstra et al., 2018; Nazemi & Madani, 2018). This is why this approach gives the opportunity to allocate solutions higher in the chain. The interventions level is illustrated in Figure 7.

For the *context of use*, it is of key importance to include the boundary actor(s) that developed the object in the process. Ideally, the actor must be neutral, and even though the actor should pre-structure the problem, and give direction to the process and the use of the object, they should be outside the formal policy decision making process to avoid the use of the indicators as political tools with the purpose of defending one's own interests (Howlett & Cuenca, 2017; Lehtonen, 2013; Molle & Mollinga, 2003). Furthermore, it is also important to keep in mind that actors should have been introduced to the object and its use before it is formally used in the policy decision making processes to make an efficient use of time and avoid confusions.

A description of the components and an assessment of the upgraded UWSD approach are provided in Table 5 and Table 6 respectively.

Table 5. Description of the components of the UWSDA.

Parts	Description	Description on the upgraded UWSD approach
Indicators	Basic unit of analysis	'n' dynamic indicators that cover relevant aspects for UWS in base of its theoretical base (Figure 5)
Analytical base	Structure of analysis	System approach: pressure-state-impact-response (PSIR)
Portrayal	Representation of the indicators and the analytical base	Layered dashboard and causal diagrams.
Development of indicators	Definition and/or selection and/or population of indicators	Dynamic procedure (see details in Supplementary Material S.2.)

Table 6. Quick assessment of the UWSDA in terms of UWS indicator-based boundary object success criteria.

Success Criteria	Meaning for original UWSD
Credibility	Indicators are scientifically valid capture levels and changes in the phenomena of interest.
Legitimacy	Considered to certain extent in the comprehensive search procedures found in the *Indicators Formalisation* and in the score of the elements that belong to the response dimension.
Salience	Considered to certain extent in the search procedures found in the *Indicators Formalisation*.
Visualization	Analytical base: In theory PSIR allows to see issues as interconnected. In practice it is too complicated, and it does not give room for a clear visualization of the relationship between issues. Portrayal: dashboard. In theory it allows to show all variables at once to avoid information loss. In practice is overwhelming and distracting.
Context of use	Considered in the actors involved in the validation of indicators and themes.
Flexibility	Additions can be made to the upgraded UWSD during the process.

6 Application

This section describes the results of the application of the UWSDA to the case study of Mexico City and the Deltares experts' session. Detailed information about the application to Mexico City can be found in the supplementary materials *Indicators Formalisation* and *Mexico City UWSDA* and the Appendices 4 and 5.

6.1 UWSDA Applied to Mexico City

The UWSDA was applied to the case study of Mexico City. The development of indicators for Mexico City considering the dynamic framework concept can be illustrated with two examples. First, economic stress for this case is measured by the gross income (UNDP, 2019) since precise data about GDP PPP (economic stress indicator proposed in the original UWSD) was not available. Gross income data information was publicly available for each of the boroughs of the city. This implies that not only the method changes, but also the scoring. The second example corresponds to the fact that the original UWSD conceives the areas below one meter above mean sea level as vulnerable to coastal flooding. Mexico City is not subjected to coastal flooding, but it is to urban floodings where the inherent topographic characteristics exacerbate the vulnerability to flooding of certain areas. Mexico City has an official in-depth study regarding areas prone to flood (Gobierno de la Ciudad de México, 2018) that takes topographic characteristics and historical floods data for their results. In face of this information, it was decided decided that it was an important addition for the Mexico City pool of indicators.

Table 7. Stakeholder analysis for the context of Mexico City. Classification by the knowledge distinctions introduced by Edelenbos et al. (2011).

Expert Knowledge	Bureaucratic Knowledge	Stakeholder Knowledge
Universities (UNAM, LANCIS, IPN, UAM, etc.)	Governmental agencies (CONAGUA, SEDEMA, SEDUVI, IMTA, etc.)	Water utilities (SACMEX)
Knowledge agencies (Rockefeller Foundation, WRI, World Bank, etc.)	Authorities (head of government, public space authority, city major, etc.)	Designer firms and professional stakeholders (architects, engineers, contractors, consultants (e.g. Agencia de Resilencia Urbana, Isla Urbana, etc.)
		Representatives of the communities
		NGO's (e.g. Agua para todos)

Subsequently, the selection of indicators obtained was subjected to the validation process. To select the actors, we first conducted an analysis for their identification. The results of this analysis are listed in Table 7 where the main organizations related to water for the Mexican context are presented. We sent the validation questionnaire (results found in Appendix 4 and 5) to a large variety of actors considered as relevant for the context and kept it short (15-20 minutes as expected time of completion) with the purpose of ensuring a sufficient response rate. We evaluated the questions in a scale from 1 to 5, 1 being the lowest and 5 the highest. The average of the answers for each of the criteria assessed in the validation questionnaire was in all cases 4. This suggests that, in general, the different actors approached were satisfied with the overall selection of indicators. However, the lack of an indicator that measures the consumer willingness to pay for water was brought to light in the answers of the validation questionnaire. It is important to mention though, that this indicator could not be assembled into the final dashboard because the majority of the responses to the questionnaire were received outside the timeframe were changes could still be implemented.

Once the selection of indicators was validated, the validated dashboards were assembled. The indicators selected for Mexico City and their score are presented in Table 8. The dashboard for the state dimension is displayed in Figure 8 as an example. The rest of the dashboards for Mexico City can be found in the supplementary material *Mexico City UWSDA* and more information about the indicators selected can be found in the one called *Indicators Formalisation*. Once the complete dashboard was filled out, important themes were identified. They were validated with the perception of the actors approached. The key validated themes were:

(1) Local groundwater drawdown: Around 60% of the water supplied in Mexico City has its origin in the local aquifers (CONAGUA, 2016, 2018; Tortajada & Castelán, 2003; World Bank, 2013). They represent the most important source of water for the city. Yet, half of them are classified as overexploited (World Bank, 2013). Still, relevant studies regarding the expected time of depletion of the Mexican aquifers are scarce.

(2) Water quality: Mexico City has the worst surface water quality of the entire country (CONAGUA, 2018; Tellman et al., 2018; Tortajada, 2006a). The levels of BOD (biochemical oxygen demand), COD (chemical oxygen demand), TSS (total solids suspended), and fecal coliforms are beyond the acceptable thresholds (CONAGUA, 2018). Groundwater has generally good quality with anomalies detected near to contamination hotspots (Alfredo Ramos Leal et al., 2010). However, in recent years, it has been reported to be degrading with more than 20% of the aquifers reported to being polluted (Godinez Madrigal et al., 2018).

(3) Water image: In general, the inhabitants of Mexico City have a negative perception of water in the city. This comes as a result from the combination of the water-related problems to which the city is subjected. The case study revealed that this is one of the issues of most concern for most of the actors.

(4) Stormwater flooding: Mexico City is regularly flooded in the rainy seasons (about half of the year) (De Urbanisten, 2016). Such floodings are characterized for their long duration, and the large societal disruption and damages that they cause (El País, 2017).

(5) People with adequate water supply: Although most of the inhabitants have access to piped water either in the premise or in a radius of 10 minutes from the premise, the service is unreliable,

intermittent and of dubious quality (Espinosa-García et al., 2014; González-Villarreal et al., 2016; INEGI, 2017; Tortajada, 2006b; WHO & UNICEF, 2015).

Table 8. Selection of indicators for case study of Mexico City.

Pressure Index		State Index		Impact		Response	
Environmental pressures	2	**Natural resources**	2	**Supply dependencies**	2	**Institutional framework**	2
Climate	2	Groundwater	4	Water supply conflicts	3	Clarity of roles and responsibilities	3
Precipitation and variability	3	Groundwater availability	4	Dependency on external resources	3	Horizontal coordination and communication	2
Rainfall intensity	2	Groundwater quality	3	Dependency on overexploited resources	1	Vertical coordination and communication	2
Freshwater scarcity	1	Surface water	1	**Access to basic water services**	4	Corruption	2
Land	2	Surface water availability	1	People with adequate water supply	3	Accountability	2
Area prone to flood	3	Surface water quality	1	People with adequate sanitation	4	Regulatory agreements	2
Seismic hazard	1	Land	2	**Flood**	2	Enforcement capacity	2
Subsidence	1	Green spaces	1	River flooding	3	**Planning**	3
Socio-economic	2	Garbage in surface and subsurface	3	Stormwater flooding	1	Data and information	2
Demographic	3	**Infrastructure**	2	**Public health**	2	Finance	3
Population	2	Water supply	3	Water-associated diseases	2	Participatory decision-making	3
Population Growth	4	Water supply coverage	3	**Conservation of natural resources**	1	Strategic planning (disaster, water efficiency, sustainability, etc.)	3
Economy and Development	3	State of the water supply infrastructure	3	Local groundwater drawdown	1	**Operational management**	2
Economic stress	3	Adequacy of the water supply service	2	Overexploitation of surface water bodies	1	Monitoring system	3
Inflation rate	4	Sanitation	2	**Environmental protection**	3	Maintenance	2
Education	3	Sanitation coverage	2	Pollution of surface water	1	Efficiency	2
Slums	2	State of the sewer	1	Pollution of groundwater	3	Redundancy of critical nodes	2
Geo-political	3	Wastewater treatment	3	Salt water intrusion	5	**Community and individual capacity**	2
Political stability	3	Water treatment coverage	2	Garbage in surface water	2	Individual water efficiency measures	2
Immigration rate	2	Water treatment adequacy	3	**Aesthetics and recreation**	1	Active community structures	2
Consumption behaviour	2	Flood protection	2	Water image of the city	1	Awareness and sense of urgency	2
Domestic water use	1	River protection	2				
Water footprint of consumption	2	Stormwater urban drainage	2				
Industrial activity	1						
Water-intensive industry	1						
External	2						
Condition upstream or significant outside watersheds	2						

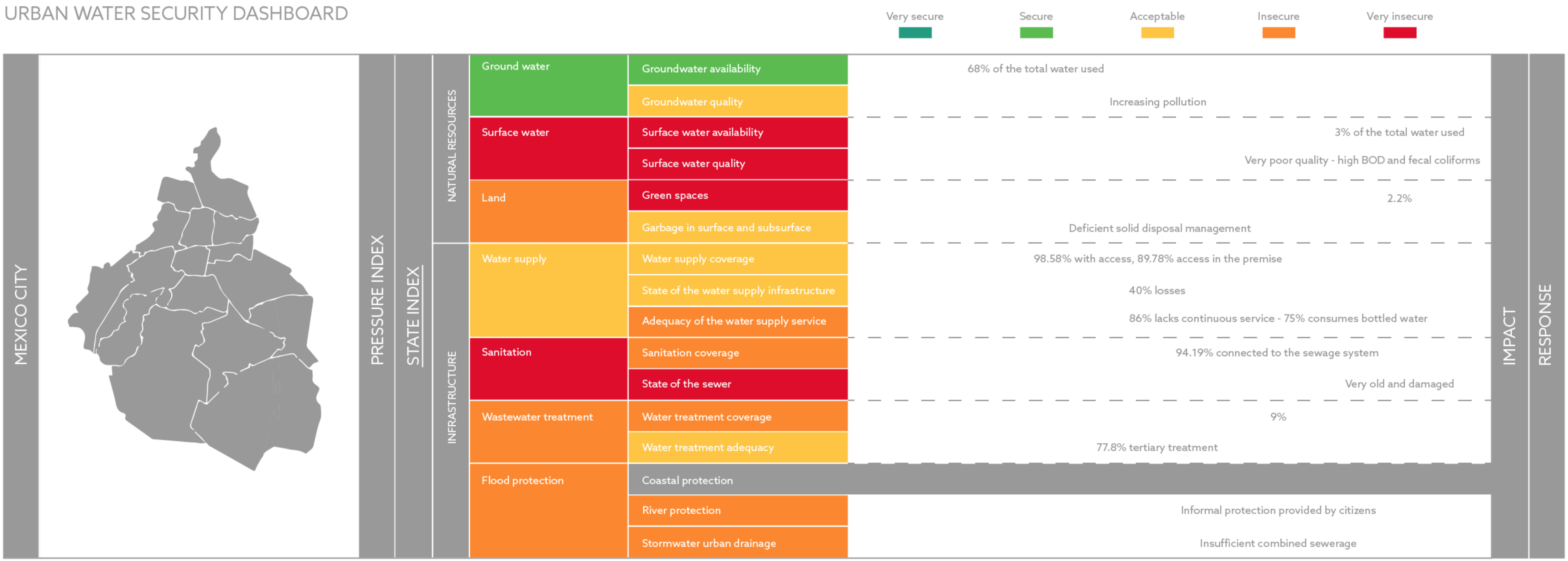

Figure 8. State UWSDA dashboard for Mexico City. Indicators in grey are not applicable for the context and should be dismissed.

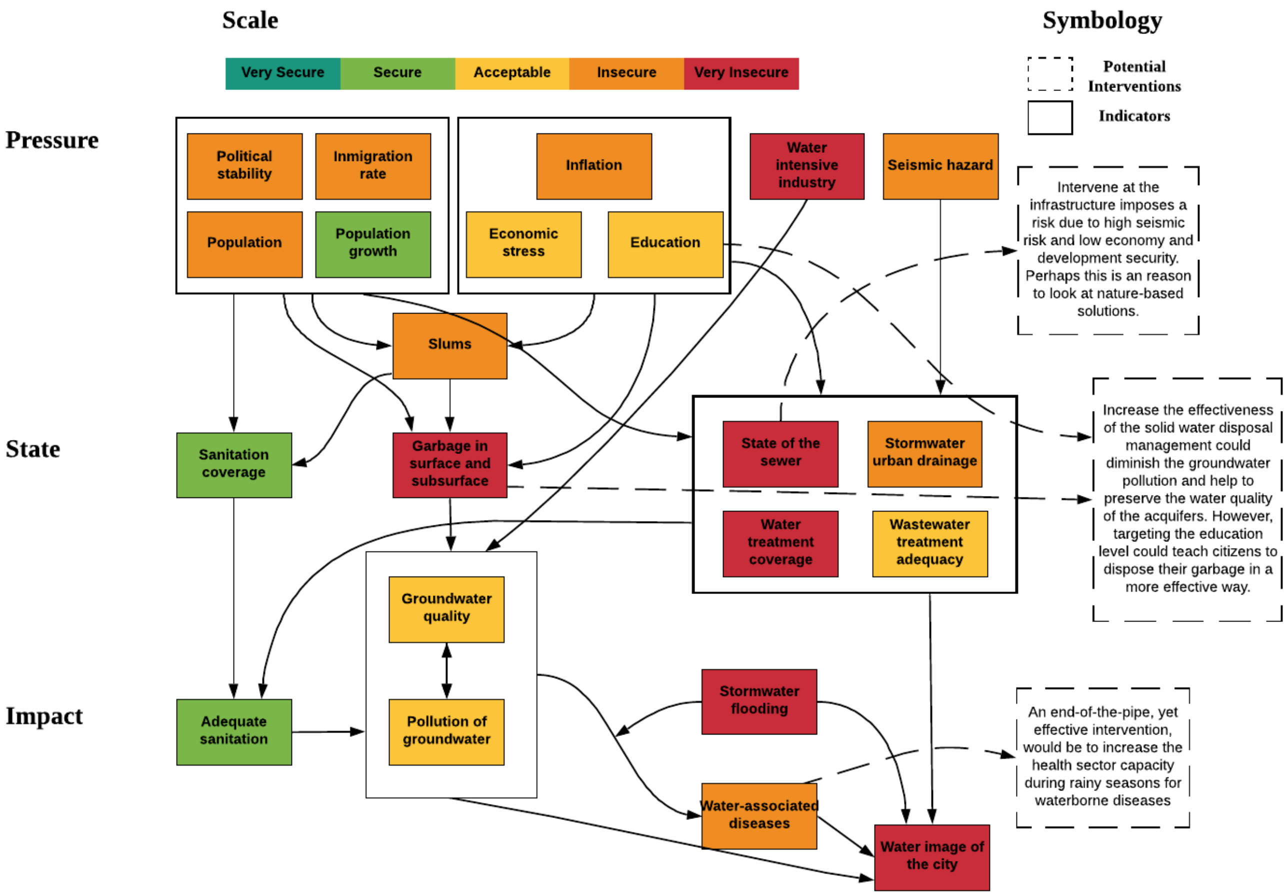

Figure 9. Sample PSIR diagram for groundwater pollution in Mexico City.

Figure 9 displays the causal diagram for groundwater pollution. It can be seen that groundwater pollution is connected to many elements higher in the PSIR chain. For example, the state of the sewer is very insecure, some parts are almost 300 years old and it's full of leakages (Tellman et al., 2018; Tortajada & Castelán, 2003). Those leakages allow untreated wastewater to perm to the aquifers and contribute to the groundwater pollution. Furthermore, the rainy seasons in combination with the garbage stored in the land subsurface, decreases the quality of the stormwater that infiltrates to the aquifers. The diagram also shows that during the rainy seasons, the drainage is insufficient and the wastewater in combination with the rainwater produces water associated diseases (Baeza et al., 2018). Figure 9 also displays potential discussions that can arise about possible interventions and how are they related to the system.

6.2 *UWSDA in its Context of Use: Deltares Expert Session*

We conducted the Deltares Expert session to evaluate the effects produced by the UWSDA in its context of use. Appendix 6 contains the actors involved in the session and their expertise. The role of the boundary actor in the experts' session was assigned to the authors of this study.

At the beginning of the document, we characterized the expected result of this research, the UWSDA, as a boundary object. From the definition of boundary object, we can derive five main goals, namely (1) *instrument that functions as a knowledge base and (2) is capable of enabling effective communication across different scientific domains, policy divides and stakeholders in the science-policy interface. It has the purpose of assisting knowledge co-production to arrive at an (3) integrative definition of the problem, (4) establish a priority agenda, and (5) serve as a solid base for an enriched policy decision making towards effective action perspectives for urban water security*. Following, we will address each of the goals and will explain the related effects produced by the UWSDA in its context of use:

(1) The UWSDA and its products, namely the dashboards and diagrams, acted as a very comprehensive knowledge base regarding the UWS situation of Mexico City. The provided the actors involved in the meeting with relevant information regarding the water situation of Mexico City;
(2) Since the actors that were approached for validation were those that actually belong to the context of use of the UWSDA applied to Mexico City, there were many sources of conflict about the indicators selected, their composition and their scores for the actors involved in the session. This situation imposed a more intensive role to the boundary actor in clarifying confusions. Furthermore, the experts gave some feedback on how to introduce the object to the intended audience to facilitate its comprehension;
(3) Nevertheless, the participants of the session engaged into a joint problem formulation process that considered different perspectives through dialogues inspired by the indicators and its measurements;
(4) Conclusions about the key concerns for Mexico City and their causality were developed. As expected, new information was brought to light, especially regarding the causality of the problems and the interconnections between different indicators, which confirms the importance of the *flexibility* for the object. In fact, the causal diagrams had to be almost fully mapped during the session. This revealed that the understanding of the interrelations of the water system and among different issues increases when the maps are drawn together with the actors;
(5) Finally, discussions around potential interventions took place, and although there was no consensus on concrete solutions, actors acknowledge that they were much more aware of the limitations of the system. Furthermore, they were able to perceive a link between the measures that they were proposing and the influence that they would have on the phenomena that the indicators were measuring and vice versa.

7 Discussion

The present section provides the discussion about key important findings of the application of the design and a comparison between the UWSDA and other similar objects.

7.1 Application of the UWSDA

For the development of indicators, there are five important points to discuss. First, different trade-offs are in place between credibility, salience and legitimacy. As identified by Sarkki et al. (2014), these are context dependent and must be treated according to the situation. For example, as mentioned before, Mexico City suffers from a lack of information regarding the levels of the aquifers. Given the importance of the aquifers for the Mexican context, the government could issue mandates to develop the necessary studies. This argument brings an important point to light, the credibility, legitimacy and salience of a boundary object are highly dependent on external factors. Perhaps, the only decision given to the boundary actors corresponds to a balance in terms of the indicators' selection. To exemplify this, we make use of the following statement: Zeitoun et al. (2016) argue that for policy decision making regarding water security to be sustainable, 'nexus' issues, such as the water-energy-food nexus, must be considered. Although we agree with the aforementioned statement, to preserve the balance of the boundary object, important cross-sectoral interdependencies may not be illustrated in depth in the UWSDA. This may reduce credibility but increases salience and visualization. Now, if the context corresponds to a city where the economy is driven by coal energy production, such nexus cannot be neglected. This emphasizes the argument that the trade-offs are context dependent. Other examples of trade-offs found within the results of the application of the UWSDA to Mexico City are: credibility vs legitimacy where extensive research procedures enhance legitimacy but might decrease credibility for the difficulty of access the information; legitimacy vs salience where including a wide-variety of perspectives enhances legitimacy but might decrease salience due to an increased number of indicators;

salience vs credibility where data from trusted sources (e.g. UN) increases credibility but might decrease salience if there is a mismatch on the spatial scale. This example can be illustrated with the indicator of *urban water footprint of consumption.* It cannot be populated with data at the local scale. However, its importance for UWS cannot be neglected.

Secondly, although a dynamic framework limits the opportunity of cross-comparison, it makes the scores assigned to the indicators more meaningful as "they represent their ability to attend to their own challenges" (Vink, 2019, p.35). However, in contrast with the SETEG framework, we provide concrete examples of indicators that may be used and are likely to be found across contexts. This creates a balance between customization and standardization for the UWSDA.

Thirdly, engaging actors into the process of consultation remains a difficult task, especially when this consultation does not take place physically. Even though the fact that physical consultations result in extensive and detailed feedback on the part of the actors (Jensen & Wu, 2018), we propose a less resource intensive alternative to consult actors. Still, it is unknown to us which alternative produces the most efficient results. It is important to mention that the validation process proposed in the upgraded UWSD methodology brought very little changes. The theoretical and analytical base of the approach are already so comprehensive that it is inclusive of different perspectives even before including actors in its development. Furthermore, the extensive research procedures offered an opportunity to strengthen internal validity. This can be partly proven by the general satisfaction expressed by the actors consulted in the validation for the case study of Mexico City. While we cannot provide a proper judgement related to this situation, it might be worthwhile asking if legitimacy could be characterized as a social convention rather than a fruitful validation process. However, this process showed that, in most cases, the disagreements caused by the selection of indicators were a product of the visualization. As mentioned before, indicators embed large quantities of information in their composition. Although the construction is transparent and can be found in the supplementary material *Indicators Formalisation,* not every variable that compose the indicators is displayed in the dashboard. This could be partly solved by the integration of more layers in the dashboard. The addition of more layers of information stresses the importance of familiarizing the potential users of the UWSDA with the object.

Fourthly, the identification of the important themes offers the possibility to quick-scan the city in terms of the fulfilments of the functions of the water system. Using the classification provided by Brown et al. (2008), we can direct the efforts to the issues that are related to the most basic water needs. For example, according to their water transitions framework, which resembles a water pyramid of Maslow, Mexico has strong flaws in the bottom of the pyramid. In a decreasing order of importance, we found inadequate water supply services. severe and recurrent flooding, increasingly polluted natural water resources, unsustainable use of the natural water resources, and a general negative perception of water from the inhabitants. Following Brown et al. (2008), the issues at the bottom of the pyramid would be considered as more urgent that those and the top. This suggest that, although Mexico City considers the water image of the city as a major issue of concern, perhaps it would be more imperative to attend those issues located lower in the pyramid. Another classification of the performance of the system in terms of UWS that the UWSDA could provide corresponds to the Equilibrate Environment versus a Degraded Environment (Pedrazzini, 2011). In an Equilibrate Environment, resources and services are ready and available, whereas in a Degraded Environment, resources are available in low quantities, services are insufficient, and there are conflicts that eventually can result in displacements of populations (Pedrazzini, 2011). The UWSDA provides the opportunity to measure the extent to which the area's water system can be considered as degraded.

Lastly, the relationship among indicators following a PSIR approach can be very complicated (OECD, 2003; Pires et al., 2017; UN-Water, 2006). For example, in Mexico City, subsidence can be both a pressure and an impact. As a pressure, it increases the vulnerability to floods and is positively related to the seismic risk (Auvinet et al., 2017; Illades & Pérez, 2015; Mancebo, 2011) and as an impact, it is derived from overexploited aquifers. Also, floods in Mexico City are caused by, among other things, the climate pressure and the state of the infrastructure. Flood events in return, increase the occurrence of water-associated diseases in certain areas of the city. Two main conclusions can be derived from this. First, indicators can take different roles (P, S, I, or R) according to the situation (e.g. subsidence as impact and pressure, and flood as an impact and pressure). Second, assuming that subsidence now exists as a pressure, it'd be implied that pressures also influence each other whereas the PSIR scheme obeys a vertical causality among dimensions and leaves the horizontal effects in the background. The implications of such conclusions are related to the role of the researcher (boundary actor) to consider these multi-roles and the way the relationships surrounding an indicator are interpreted and used. This can partly be solved by the visualization of the causal diagrams where the arrows provide an opportunity to understand causality without restrictions of direction or linearity. In relation to the last argument found in the previous paragraph, there are two main topics regarding the interrelations between the indicators measured in the upgraded UWSD that we would like to discuss. On first place, almost all socio-economic pressures are linked to the indicators on the *state* dimension. This makes the mapping task complex and messy. Perhaps a potential solution would be to bring back the 'Drivers' dimension from the original DPSIR framework (Linster, 2003). The 'Drivers' dimension captures underlying 'driving forces' in a given environmental system such as those exerted by the economic and industrial sectors (Linster, 2003; Sekovski et al., 2012; Vink, 2019). As a last comment, we would like to mention that, as proven by means of the Deltares experts' session, the relationships are clearer when they are drawn together with the actors found in the process than when they are already given by the researcher.

7.2 Trade-Offs with Similar Objects

There are two similar objects that will be discussed in this section. During the application in the experts' session, the upgraded UWSD approach was compared to the problem-tree approach which is an example of a participatory modelling process (Veneklasen & Neighbors, 2002). The object tree shares many similarities with the upgraded UWSD approach. It breaks down a given problem and maps the interrelations among the different elements. Thus, it facilitates a shared sense of understanding regarding complex problems. However, as a normal participatory modelling process, bringing all relevant actors together imposes an intensive use of resources (Jordan et al., 2018; Veneklasen & Neighbors, 2002). The UWSDA offers a less resource intensive alternative since it does not require to bring actors together for its development. It does not mean of course that it can substitute the participation of different actors during the policy decision making processes, but it does imply that it can reduce their complexity. Still, it is unclear to what extent the resources invested in the development of the UWSDA are more efficient in comparison to the resources invested in a participatory modelling process. Perhaps a more realistic measurement should not only evaluate the resource intensity but also the overall results achieved in the process.

In terms of other indicator-based frameworks, there are several frameworks similar to the one proposed by van Ginkel et al. (2018) that work with system approaches to characterize the urban water system of a local context. As acknowledged by Van Ginkel et al (2018), the City Blueprint Frameworks (CBF) (trends and pressure, and governance capacity), developed by Van Leeuwen et al. (2016), bear a resemblance to a system-dynamic approach. However, the CBF is said to be considered as an "assessment of integrated urban water resources management performance than a comprehensive water security index (Hoekstra et al., 2018, p.11)". Among other examples, the tailored approach to quantify UWS developed by Jensen & Wu (2018) and the Capital Portfolio Approach developed by Krueger et al. (2019) are found. However, the overlap between different indicator-based frameworks has been too small to substantially compare the impact of different approaches to assess urban water security; there is a lack of consistency in their analytical and applicational scales (Wilder, 2016). Furthermore, aspects such as the institutional context and the target groups of knowledge use are so manifold that a selection of indicators is a set of heterogeneous indices (Hoppe, 2010, p.171). Therefore, the strength of our study relies in the basis that we provide for instruments such as the aforementioned indicator-based frameworks to be enhanced into a boundary object, which in turn increases the external validity of our results. Perhaps the most important theoretical contribution derived from this research is not the UWSDA itself, but the conceptual framework that we propose and the certainty that it can be incorporated into the design of an indicator-based framework.

8 Conclusions and Recommendations

The aim of this study was to design a comprehensive indicator-based framework, careful of including practical and political aspects of its use as a boundary object. To achieve this aim, we made use of the boundary object concept and linked its success criteria to indicator-based frameworks characteristics. Furthermore, we provided a series of requirements that can be implemented in the composition of indicator-based frameworks different than the UWSD to improve their likeliness of success in the role of boundary objects. We stand by the use of the UWSD because, even with its remarkable weaknesses such as the PSIR inconsistence, it provides an opportunity to characterize the UWS of a given area in an integrative yet efficient way. It is important to keep in mind that sometimes an imprecise model is better than no model at all (Voinov & Bousquet, 2010).

The approach developed here incorporates two often contrary visions: analytical and participatory. On one hand, analytical approaches assume that problems are solely technical in nature and are often addressed by instruments with a strong scientific background such as indicator-based frameworks. On the other hand, participatory approaches pay attention to co-production of knowledge as a way to overcome divergent perceptions (Crona & Parker, 2012; Hommes, 2008). Here, we made a bridge between both approaches thanks to the interplay between credibility, legitimacy and salience, and the incorporation of the remaining aspects of visualization, the consideration of features of the context of use, and the flexibility of the object to adapt to new information.

Still, attributing the success of an object to its composition is mistaken. One of the main findings of this study corresponds to the fact that the role of the boundary actor is crucial. This person has to make important decisions and assumptions for the construction of the object that are almost entirely dependent on his/her criteria. Hence, they often come from a scientific background. Also, given the fact that indicators are constructed upon a large underlying base of information, it is very important for the boundary actors to assist the process. They are the only ones who can answer questions that may arise about the composition of the object and the context to which it is applied. Under the light of these arguments, the statement made by Hoppe (2010) in which he claims that a one-directional piece of advice, such as the one provided by the indicators, is not translated into immediate and effective uptake in the policy decision making processes, gains weight.

Following next, we provide theoretical and practical recommendations to be considered for the results obtained by means of the research conducted.

8.1 Recommendations for Future Research

There are five recommendations that we would like to make for future research. First, information regarding all of the aspects regarding UWS can be hard to obtain and its reliability can be doubted. Furthermore, many aspects considered are limited in science. For example, there's a lack of research conducted in the field of pollution due to pharmaceutical drugs (Daughton, 2016). This hinders the task of picturing the real situation regarding certain topics. Insufficient science is considered as one of the primary obstacles interfering with UWS operationalization (Bakker & Morinville, 2013). Due the inherent variability of the urban contexts caused by the current and future trends, a lack of information regarding water security will be a recurrent phenomenon. Therefore, it would be unrealistic to think that uncertainties will be absolutely removed from policy decision making processes. It is important to keep in mind that tools, such as the developed boundary object, will need to be adapted in the face of new information and discoveries. They should also be further developed and tuned-in to fulfil the evolving needs of the natural and socio-economic systems. But overall, they should be consciously used considering that the real world is far more complex that what can be expressed by means of them; "models do not solve the decision problem but make problems manageable" (Kolkman et al., 2005, p.325). That is why a boundary object is inherently connected to its process of use: "they are weakly structured in common use but become strongly structured when applied to specific environmental management issue or conflicts" (Voinov et al, 2016, p.121).

Secondly, the process of development of indicators remains a delicate subject. As mentioned before, the overlap between different indicator-based frameworks has been too small. The importance of the indicators selected for each framework is substantiated by the value they provide; and, in all cases, their value for water security is supported. Perhaps, a study similar to the one performed by Pires et al. (2017), regarding a wide set of different indicators related to UWS found across literature, could provide insights about the general opinion of different actors about the current existent indicators in terms of salience, legitimacy and credibility, for example. Or could partly solved the issues of the interrelations of the PSIR scheme by reaching a general consensus of the right dimension for a given indicator. This exercise could provide a more standardized database of indicators that could add value to the integrative discourse of UWS.

Thirdly, although the UWSDA provides a clear way to visualize the influences between the different indicators, it fails to provide a way to quantify them. While assuming equal weights for all the aspects considered may be a practical solution, it is wrong to assume that the influences exerted on the water system are somewhat the same. For example, in Mexico City, small floods are, among other things, related to solid waste production and landscape characteristics, and even though a proper solid waste disposal programme may be useful, small floods would not disappear if we take into account the topographic characteristics (Zambrano et al., 2018). Following the recommendation issued by Romero-Lankao & Gnatz (2016), we suggest approaches such as the analytical hierarchical process and cognitive fuzzy mapping as a next step for continuous development.

Fourthly, we studied the role of indicators as boundary objects. However, indicators can also take roles at later stages of the policy decision making processes (Howlett & Cuenca, 2017; Jensen & Wu, 2018; Lehtonen, 2013, 2015) such as ex-ante or ex-post appraisal instruments. Perhaps the life-cycle of indicators operating as a boundary objects can be extended to those stages. We suggest that these roles are also studied to understand the extended potential of tools such as the one developed in this study.

Last, societal issues are without any doubt important for UWS. Equity issues are connected to them and should be addressed through policy decision making as they are part of an integrative definition of UWS. The UWS of a community might be compromised by actions performed by another group of people. Often those who set the thresholds of tolerable risks for groups different than them are the most benefited due to the trade-offs made when equal benefits are not an option. This leads to the question, *who benefits?* (Zeitoun et al., 2016). The equity dimension is not accurately captured by our approach, and future research should be directed to visualize these trade-offs.

8.2 Practical Recommendations

The upgraded UWSD approach could not be applied to its actual context of use. Nevertheless, we have four key recommendations. These are nor arbitrary and are sustained by theory and what we learned from the case study and the experts' session.

First, during the application of the object in the experts' session, the terms 'secure' and 'insecure' were a source of conflict and disagreement. The reason behind it was that cataloguing an indicator as such does not necessarily mean that there is a negative impact on the system. It is important to mention that, even though a single indicator is categorized as secure or insecure, it is the reading of the indicators all-together what allows to issue an evidence-based judgment. This should be clearly known by the users of the object which suggest that the users should be familiarized with the object beforehand.

Secondly, during the application, we learnt two things regarding the use of the tool. On the one hand, the object can be introduced starting from the impacts and working towards the pressures that are causing those issues. In this way, the UWSDA is more usable with actors that are not experts and might be confused by having all kinds of indicators that might not seem to matter according to their perspectives. On the other hand, starting with the pressures and working towards the main issues can be a good alternative when actors want to grasp the overall water security situation from the start. However, this alternative may be more adequate for actors considered as experts and focuses on the entire system at once rather than by parts.

Thirdly, still related to the object's use, it is a basic requirement that the boundary actors are present during the use of the UWSDA in its context of use. Only they can answer certain questions that may arise during its application. Furthermore, they are in charge of steering the process and help the actors found in the setting to navigate through the pre-structuration of the problem (Voinov et al., 2016). Also, they are the only ones who can make pertinent changes to the composition of the object considering information that arises during the process. It is worth mentioning that the boundary actor in place (at least one) should be familiar with the language of the area selected. If the boundary actors fail to comply with this, important information is in risk of being disregarded or ignored. This is a direct threat to the successful development and use of the object. Also, the communication with the stakeholders is sometimes reliant on the domain of the language of the boundary actor.

Lastly, the selection of the actors must be coherent with the actors that were approached for the validation of the object. Ideally, the same actors that were consulted during the build-up should be present during the process. If that is not possible, then actors that belong to their same field, organization and/or group should be present during the process under the assumption that they probably share the same perspectives as the actors previously contacted.

9 References

Alfredo Ramos Leal, J., Noyola Medrano, C., & Tapia Silva, F. O. (2010). Aquifer vulnerability and groundwater quality in mega cities: case of the Mexico Basin. *Environmental Earth Sciences*, *61*, 1309–1320. https://doi.org/10.1007/s12665-009-0434-5

Arcadis. (2015). *Sustainable Water Cities Index*. Amsterdam.

Auvinet, G., Méndez, E., & Juárez, M. (2017). Recent information on Mexico City subsidence. *ICSMGE 2017 - 19th International Conference on Soil Mechanics and Geotechnical Engineering* , *2017*, 3295–3298. Retrieved from https://www.issmge.org/uploads/publications/1/45/06-technical-committee-24-tc305-02.pdf

Baeza, A., Estrada-Barón, A., Serrano-Candela, F., Bojórquez, L. A., Eakin, H., & Escalante, A. E. (2018). Biophysical, infrastructural and social heterogeneities explain spatial distribution of waterborne gastrointestinal disease burden in Mexico City. *Environ. Res. Lett*, *13*, 64016. https://doi.org/10.1088/1748-9326/aac17c

Bakker, K., & Morinville, C. (2013). The governance dimensions of water security: a review. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *371*(2002), 20130116–20130116. https://doi.org/10.1098/rsta.2013.0116

Basco-Carrera, L., & Francisco-Mendoza, G. (2017). *Collaborative modelling – Engaging stakeholders in solving complex problems of water management.*

Basco-Carrera, L., van Beek, E., Jonoski, A., Benítez-Ávila, C., & PJ Guntoro, F. (2017). Collaborative Modelling for Informed Decision Making and Inclusive Water Development. *Water Resources Management*, *31*(9), 2611–2625. https://doi.org/10.1007/s11269-017-1647-0

Basco-Carrera, L., Warren, A., van Beek, E., Jonoski, A., & Giardino, A. (2017). Collaborative modelling or participatory modelling? A framework for water resources management. *Environmental Modelling and Software*, *91*, 95–110. https://doi.org/10.1016/j.envsoft.2017.01.014

Beek, B. E. Van, & Arriens, W. L. (2014). TEC BACKGROUND PAPERS Water Security : Putting the Concept into Practice. In *Stockholm Environment Institute*.

Bigas, H. (2013). *Water Security & the Global Water Agenda - A UN-Water Analytical Brief*. Ontario, Canada.

Biswas, A. K., & Tortajada, C. (2016). *Water Security, Climate Change and Sustainable Development: An Introduction*. https://doi.org/10.1007/978-981-287-976-9_1

Bogardi, J. J., Dudgeon, D., Lawford, R., Flinkerbusch, E., Meyn, A., Pahl-Wostl, C., … Vörösmarty, C. (2012). Water security for a planet under pressure: Interconnected challenges of a changing world call for sustainable solutions. *Current Opinion in Environmental Sustainability*, *4*(1), 35–43. https://doi.org/10.1016/j.cosust.2011.12.002

Brown, R., Keath, N., & Wong, T. (2008). Transitioning to Water Sensitive Cities : Historical , Current and Future Transition States. *11th International Conference on Urban Drainage, Edinburgh, Scotland, UK, 2008*, 1–10.

CONAGUA. (2016). Atlas del agua en México 2016. In *Comisión Nacional del Agua y Secretaria de Medio Ambiente y Recursos Naturales*. Retrieved from http://201.116.60.25/publicaciones/AAM_2016.pdf

CONAGUA. (2018). Estadísticas del Agua en México. In *2018*.

Cook, C., & Bakker, K. (2012). Water security: Debating an emerging paradigm. *Global Environmental Change*, *22*(1), 94–102. https://doi.org/10.1016/j.gloenvcha.2011.10.011

Crona, B. I., & Parker, J. N. (2011). Network Determinants of Knowledge Utilization. *Science Communication*, *33*(4), 448–471. https://doi.org/10.1177/1075547011408116

Crona, B. I., & Parker, J. N. (2012). Learning in support of governance: Theories, methods, and a framework to assess how bridging organizations contribute to adaptive resource governance TL - 17. *Ecology and Society*, *17 VN-r*(1). https://doi.org/10.5751/ES-04534-170132

Daughton, C. G. (2016). Science of the Total Environment Pharmaceuticals and the Environment (PiE): Evolution and impact of the published literature revealed by bibliometric analysis. *Science of the Total Environment, The*, *562*, 391–426. https://doi.org/10.1016/j.scitotenv.2016.03.109

De Urbanisten. (2016). *Hacia Una Ciudad De México Sensible Al Agua Towards a Water Sensitive Mexico City*. Retrieved from http://www.urbanisten.nl/wp/wp-content/uploads/2016.07.21_Reporte_CAF_Urb-AEP_lr-2.pdf

Deltares. (2019). WaterLOUPE.

Dunn, G., & Bakker, K. (2009). *Canadian Approaches to Assessing Water Security: An Inventory of Indicators*. Retrieved from www.watersecurity.ca

Edelenbos, J., van Buuren, A., & van Schie, N. (2011). Co-producing knowledge: Joint knowledge production between experts, bureaucrats and stakeholders in Dutch water management projects. *Environmental Science and Policy*, *14*(6), 675–684. https://doi.org/10.1016/j.envsci.2011.04.004

El País. (2017). Las lluvias paralizan Ciudad de México durante horas | Internacional | EL PAÍS. Retrieved April 26, 2019, from El País website: https://elpais.com/internacional/2017/08/31/mexico/1504189322_978073.html

Espinosa-García, A. C., Díaz-A ´, C., González-Villarreal, F. J., Val-Segura, R., Malvaez-Orozco, V., & Mazari-Hiriart, M. (2014). Drinking Water Quality in a Mexico City University Community: Perception and Preferences. *EcoHealth*. https://doi.org/10.1007/s10393-014-0978-z

Garfin, G. M., Scott, C. A., Wilder, M., Varady, R. G., & Merideth, R. (2016). Metrics for assessing adaptive capacity and water security: common challenges, diverging contexts, emerging consensus. *Current Opinion in Environmental Sustainability*, *21*, 86–89. https://doi.org/10.1016/j.cosust.2016.11.007

Gerlak, A. K., House-Peters, L., Varady, R. G., Albrecht, T., Zúñiga-Terán, A., de Grenade, R. R., … Scott, C. A. (2018). Water security: A review of place-based research. *Environmental Science and Policy*, *82*(February), 79–89. https://doi.org/10.1016/j.envsci.2018.01.009

Gobierno de la Ciudad de México. (2018). Atlas de riesgo - Inundaciones — Datos CDMX. Retrieved August 6, 2019, from https://datos.cdmx.gob.mx/explore/dataset/atlas-de-riesgo-inundaciones/custom/?fbclid=IwAR117rP0eahcd2WyT99OdIdaV8SRKaTo5JqLBobjjTGts0PTUn53baF0rxY

Godinez Madrigal, J., Van Der Zaag, P., & Van Cauwenbergh, N. (2018). A half-baked solution: drivers of water crises in Mexico. *Proc. IAHS*, *376*, 57–62. https://doi.org/10.5194/piahs-376-57-2018

González-Villarreal, F., Aguirre-Díaz, R., & Lartigue, C. (2016). Percepciones, actitudes y conductas respecto al servicio de agua potable en la Ciudad de México. *Tecnología y Ciencias Del Agua*, *VII*(6), 41–56. Retrieved from http://usc.elogim.com:2202/ehost/detail/detail?vid=5&sid=5adb3470-0edf-4991-9c4e-a012c4911dbf%40sessionmgr102&bdata=Jmxhbmc9ZXMmc2l0ZT1laG9zdC1saXZl#AN=125261109&db=fua

Grey, D., Garrick, D., Blackmore, D., Kelman, J., Muller, M., & Sadoff, C. (2013). Water security in one blue planet: twenty-first century policy challenges for science. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *371*(2002), 20120406–20120406. https://doi.org/10.1098/rsta.2012.0406

Gustafsson, K. M., & Lidskog, R. (2018). Boundary organizations and environmental governance: Performance, institutional design, and conceptual development. *Climate Risk Management*. https://doi.org/10.1016/j.crm.2017.11.001

GWP. (2014). *Proceedings from the GWP workshop: Assessing water security with appropriate indicators*. Retrieved from www.gwp.orgGlobalWaterPartnership

Hegger, D., Lamers, M., Van Zeijl-Rozema, A., & Dieperink, C. (2012). Conceptualising joint knowledge production in regional climate change adaptation projects: Success conditions and levers for action. *Environmental Science and Policy*, *18*, 52–65. https://doi.org/10.1016/j.envsci.2012.01.002

Hoekstra, A. Y. (1998). Aqua: a tool for integrated water assessment. *Perspectives on Water - An Integrated Model-Based Exploration of the Future*, pp. 65–111. Retrieved from http://repository.tudelft.nl/view/ir/uuid:bb7eaa6b-012e-453c-ab81-b6b40cc2e3ff/

Hoekstra, A. Y., Buurman, J., & Van Ginkel, K. C. H. (2018). Urban water security: A review. *Environ. Res. Lett*, *13*, 53002. https://doi.org/10.1088/1748-9326/aaba52

Hommes, S. (2008). *Conquering complexity - Dealing with uncertainty and ambiguity in water management*. Retrieved from http://doc.utwente.nl/60258/1/thesis_S_Hommes.pdf

Hommes, S., Vinke-De Kruijf, J., Otter, H. S., & Bouma, G. (2009). Knowledge and Perceptions in Participatory Policy Processes: Lessons from the Delta-Region in the Netherlands. *Water Resour Manage*, *23*, 1641–1663. https://doi.org/10.1007/s11269-008-9345-6

Hoppe, R. (2010). From “knowledge use” towards “boundary work”: sketch of an emerging new agenda for inquiry into science-policy interaction. In *Knowledge Democracy - Consequences for Science, Politics, and Media* (pp. 169–186). Heidelberg: Springer.

Howlett, M. P., & Cuenca, J. S. (2017). The use of indicators in environmental policy appraisal: lessons from the design and evolution of water security policy measures. *Journal of Environmental Policy & Planning*, *19*(2), 229–243. https://doi.org/10.1080/1523908X.2016.1207507

Illades, J. M. L., & Pérez, M. Á. C. (2015). El hundimiento del terreno en la ciudad de México y sus implicaciones en el sistema de drenaje. *Tecnología y Ciencias Del Agua*, *13*(3), 13–18. Retrieved from http://www.revistatyca.org.mx/ojs/index.php/tyca/article/view/805/798

INEGI. (2017). *Anuario estadístico y geográfico de la Ciudad de México 2017*. Retrieved from www.inegi.org.mx

Jensen, O., & Wu, H. (2018). Urban water security indicators: Development and pilot. *Environmental Science and Policy*, *83*(February), 33–45. https://doi.org/10.1016/j.envsci.2018.02.003

Jordan, R., Glynn, P. D., Sterling, E. J., Leong, K., Carrera, L. B., Jetter, A. J., … Voinov, A. (2018). Twelve Questions for the Participatory Modeling Community. *Earth's Future*, *6*(8), 1046–1057. https://doi.org/10.1029/2018ef000841

Kimble, C., Grenier, C., & Goglio-Primard, K. (2010). Innovation and knowledge sharing across professional boundaries: Political interplay between boundary objects and brokers. *International Journal of Information Management*, *30*, 437–444. https://doi.org/10.1016/j.ijinfomgt.2010.02.002

Kirchhoff, C. J., Esselman, R., & Brown, D. (2015). Boundary organizations to boundary chains: Prospects for advancing climate science application. *Climate Risk Management*. https://doi.org/10.1016/j.crm.2015.04.001

Kolkman, M. J., Kok, M., & van der Veen, A. (2005). Mental model mapping as a new tool to analyse the use of information in decision-making in integrated water management. *Physics and Chemistry of the Earth*, *30*(4-5 SPEC. ISS.), 317–332. https://doi.org/10.1016/j.pce.2005.01.002

Koop, S. H. A., & van Leeuwen, C. J. (2015). Assessment of the Sustainability of Water Resources Management: A Critical Review of the City Blueprint Approach. *Water Resources Management*, *29*(15), 5649–5670. https://doi.org/10.1007/s11269-015-1139-z

Koop, S. H. A., & van Leeuwen, C. J. (2017). The challenges of water, waste and climate change in cities. *Environment, Development and Sustainability*, *19*(2), 385–418. https://doi.org/10.1007/s10668-016-9760-4

Krueger, E., Suresh, P., Rao, C., & Borchardt, D. (2019). Quantifying urban water supply security under global change. *Global Environmental Change*, *56*, 66–74. https://doi.org/10.1016/j.gloenvcha.2019.03.009

Lang, D. J., Stauffacher, M., Swilling, M., Wiek, A., Moll, P., Bergmann, M., … Martens, P. (2012). Transdisciplinary research in sustainability science: practice, principles, and challenges. *Sustainability Science*, *7*(S1), 25–43. https://doi.org/10.1007/s11625-011-0149-x

Lehtonen, M. (2013). The non-use and influence of UK Energy Sector Indicators. *Ecological Indicators*. https://doi.org/10.1016/j.ecolind.2012.10.026

Lehtonen, M. (2015). Indicators: tools for informing, monitoring or controlling? In *The tools of policy formulation* (pp. 76–99). Retrieved from http://sro.sussex.ac.uk/id/eprint/54033/1/Lehtonen_2015_-_final.pdf

Linster, M. (2003). OECD Environmental Indicators: Development, Measurement and Use. In *OECD*. Retrieved from http://www.oecd.org/env/

MacDonald, B. H., Ross, J. D., Soomai, S. S., & Wells, P. G. (2015). How Information in Grey Literature Informs Policy and Decision-Making: A Perspective on the Need to Understand the Processes. In *TGJ* (Vol. 11). Retrieved from https://eiui.ca/wp-content/uploads/2015/05/BHMacDonald-JDRoss-SSSoomai-PGWells-How-information-in-grey-literature-informs-policy-TGJ-2015.pdf

Mancebo, F. (2011). Natural hazards and urban policies in Mexico City. *Revue de Géographie Alpine*, (95–2), 108–118. https://doi.org/10.4000/rga.266

Molle, F., & Mollinga, P. (2003). Water poverty indicators: conceptual problems and policy issues. *Water Policy*, *5*, 529–544. https://doi.org/10.1007/s11269-006-9044-0

Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., Hoffman, A., & Giovannini, E. (2005). *Handbook on Constructing Composite Indicators: Methodology and User Guide*. Retrieved from https://www.oecd.org/sdd/42495745.pdf

Nazemi, A., & Madani, K. (2018). Urban water security: Emerging discussion and remaining challenges. *Sustainable Cities and Society*, *41*, 925–928. https://doi.org/10.1016/j.scs.2017.09.011

OECD. (2003). *Environmental Indicators - development, measurement and use*.

Padowski, J. C., Carrera, L., & Jawitz, J. W. (2016). Overcoming Urban Water Insecurity with Infrastructure and Institutions. *Water Resources Management*, *30*(13), 4913–4926. https://doi.org/10.1007/s11269-016-1461-0

Pedrazzini, F. (2011). A View of the Main Environmental Security Issues and Policies. In *Water Security in the Mediterranean Region NATO Science for Peace and Security Series C: Environmental Security* (pp. 1–9). https://doi.org/10.1007/978-94-007-1623-0_1

Pires, A., Morato, J., Peixoto, H., Botero, V., Zuluaga, L., & Figueroa, A. (2017). Sustainability Assessment of indicators for integrated water resources management. *Science of the Total Environment*, *578*, 139–147. https://doi.org/10.1016/j.scitotenv.2016.10.217

Romero-Lankao, P. (2010). Water in Mexico City: what will climate change bring to its history of water-related hazards and vulnerabilities? *Environment & Urbanization*, *22*(1), 157–178. https://doi.org/10.1177/0956247809362636

Romero-Lankao, P., & Gnatz, D. M. (2016). Conceptualizing urban water security in an urbanizing world. *Current Opinion in Environmental Sustainability*, *21*, 45–51. https://doi.org/10.1016/j.cosust.2016.11.002

Sarkki, S., Niemela, J., Tinch, R., van den Hove, S., Watt, A., & Young, J. (2014). Balancing credibility, relevance and legitimacy: A critical assessment of trade-offs in science-policy interfaces. *Science and Public Policy*, *41*(2), 194–206. https://doi.org/10.1093/scipol/sct046

Sekovski, I., Newton, A., & Dennison, W. C. (2012). Megacities in the coastal zone: Using a driver-pressure-state-impact-response framework to address complex environmental problems. *Estuarine, Coastal and Shelf Science*, *96*(1), 48–59. https://doi.org/10.1016/j.ecss.2011.07.011

Srinivasan, V., Konar, M., & Sivapalan, M. (2017). A dynamic framework for water security. *Water Security*, *1*, 12–20. https://doi.org/10.1016/j.wasec.2017.03.001

Star, S. L., & Griesemer, J. R. (1989). Institutional Ecology, `Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social Studies of Science*, *19*(3), 387–420. https://doi.org/10.1177/030631289019003001

Sullivan, C. (2002). Calculating a Water Poverty Index. *World Development*, *30*(7), 1195–1210. https://doi.org/10.1016/S0305-750X(02)00035-9

Sullivan, C., Meigh, J., Giacomello, A., Fediw, T., Lawrence, P., Samad, M., … Steyl, I. (2003). The Water Poverty Index: Development and application at the community scale. In *Natural Resources Forum* (Vol. 27). Retrieved from https://onlinelibrary-wiley-com.ezproxy2.utwente.nl/doi/pdf/10.1111/1477-8947.00054

Sullivan, C., Meigh, J., & Lawrence, P. (2006). Application of the Water Poverty Index at Different Scales: A Cautionary Tale. *Water International*, *31*(3), 412–426. https://doi.org/10.1080/02508060608691942

Tellman, B., Bausch, J. C., Eakin, H., Anderies, J. M., Mazari-Hiriart, M., Manuel-Navarrete, D., & Redman, C. L. (2018). Adaptive pathways and coupled infrastructure: Seven centuries of adaptation to water risk and the production of vulnerability in Mexico city. *Ecology and Society*, *23*(1). https://doi.org/10.5751/ES-09712-230101

Tortajada, C. (2006a). Water management in Mexico City Metropolitan Area. *International Journal of Water Resources Development*, *22*(2), 353–376. https://doi.org/10.1080/07900620600671367

Tortajada, C. (2006b). *Who Has Access to Water? Case Study of Mexico City Metropolitan Area*. Retrieved from http://hdr.undp.org/sites/default/files/tortajada_c.pdf

Tortajada, C., & Castelán, E. (2003). Water Management for a Megacity: Mexico City Metropolitan Area. *AMBIO: A Journal of the Human Environment*, *32*(2), 124–129. https://doi.org/10.1579/0044-7447-32.2.124

UN-Water. (2006). *UN-Water Task Force on Indicators, Monitoring and Reporting Final Report*.

UNDP. (2019). *Transformando México desde lo local - Informe de Desarrollo Humano Municipal 2010-2015*. Retrieved from http://www.mx.undp.org

van Bruggen, A., Nikolic, I., & Kwakkel, J. (2019). Modeling with stakeholders for transformative change. *Sustainability (Switzerland)*, *11*(3), 1–21. https://doi.org/10.3390/su11030825 van Ginkel, K. C. H., Hoekstra, A. Y., Buurman, J., & Hogeboom, R. J. (2018). Urban Water Security Dashboard: Systems Approach to Characterizing the Water Security of Cities. *Journal of Water Resources Planning and Management*, *144*(12), 04018075. https://doi.org/10.1061/(asce)wr.1943-5452.0000997

van Leeuwen, C. J., Frijns, J., van Wezel, A., & van de Ven, F. H. M. (2012). City Blueprints: 24 Indicators to Assess the Sustainability of the Urban Water Cycle. *Water Resources Management*, *26*(8), 2177–2197. https://doi.org/10.1007/s11269-012-0009-1

van Leeuwen, C. J., Koop, S. H. A., & Sjerps, R. M. A. (2016). City Blueprints: baseline assessments of water management and climate change in 45 cities. *Environment, Development and Sustainability*, *18*(4), 1113–1128. https://doi.org/10.1007/s10668-015-9691-5

Varady, R. G., Zuniga-Teran, A. A., Garfin, G. M., Martín, F., & Vicuña, S. (2016). Adaptive management and water security in a global context: definitions, concepts, and examples. *Current Opinion in Environmental Sustainability*, *21*, 70–77. https://doi.org/10.1016/j.cosust.2016.11.001

Veneklasen, L., & Neighbors, W. (2002). Problem tree analysis. *World*, (July), 73120.

Vink, C. (2019). *The city of Jerusalem : A case of Urban Water Welfare ? A study exploring the relation between capabilities and Urban Water Welfare*. (July).

Voinov, A., & Bousquet, F. (2010). Modelling with stakeholders. *Environmental Modelling and Software*, *25*(11), 1268–1281. https://doi.org/10.1016/j.envsoft.2010.03.007

Voinov, A., Kolagani, N., McCall, M. K., Glynn, P. D., Kragt, M. E., Ostermann, F. O., … Ramu, P. (2016). Modelling with stakeholders - Next generation. *Environmental Modelling and Software*, *77*(March), 196–220. https://doi.org/10.1016/j.envsoft.2015.11.016

White, D. D., Wutich, A., Larson, K. L., Gober, P., Lant, T., & Senneville, C. (2010). Credibility, salience, and legitimacy of boundary objects: Water managers' assessment of a simulation model in an immersive decision theater. *Science and Public Policy*, *37*(3), 219–232. https://doi.org/10.3152/030234210X497726

WHO, & UNICEF. (2015). Joint Monitoring Program for water supply and sanitation.

Wiek, A., Scheringer, M., Pohl, C., Hirsch-Hadorn, G., & Valsangiacomo, A. (2007). Joint Problem Identification and Structuring in Environmental Research. *GAIA*, *16*(1), 72–74. Retrieved from www.oekom.de/gaia%7CGAIA16/1

Wieringa, R. (2014). Design science methodology. In *Springer Heidelberg New York Dordrecht London*. https://doi.org/10.1007/978-3-662-43839-8

Wilder, M. (2016). Metrics: moving beyond the adaptation information gap — introduction to the special issue. *Current Opinion in Environmental Sustainability*, *21*, 90–95. https://doi.org/10.1016/j.cosust.2016.11.008

World Bank. (2013). *Agua urbana en el Valle de México: ¿un camino verde para mañana?* Retrieved from www.bancomundial.org.mx

Yin, R. K. (2017). *Case Study Research and Applications*. Retrieved from http://ir.obihiro.ac.jp/dspace/handle/10322/3933

Zambrano, L., Pacheco-Muñ Oz, R., & Fernández, T. (2018). *Influence of solid waste and topography on urban floods: The case of Mexico City*. https://doi.org/10.1007/s13280-018-1023-1

Zeitoun, M., Lankford, B., Krueger, T., Forsyth, T., Carter, R., Hoekstra, A. Y., … Scott, C. A. (2016). Reductionist and integrative research approaches to complex water security policy challenges. *Global Environmental Change*, *39*, 143–154. https://doi.org/10.1016/j.gloenvcha.2016.04.010

Appendix 1. Expert Consultation

Table 9. List of interviewees

Interviewee	Organisation	Expertise	Date	Ref.
Saskia Hommes	Deltares	Process and conversation guidance, and decision-making under complexity	5-4-2019	EI.1
Dimmie Hendricks	Deltares	Integration of local and scientific knowledge, WaterLOUPE tool development, presentation of complex information and simplification of information without compromising the results	19-4-2019	EI.2
Willemijn Tuinstra	Tuinstra Kennisadvies	Boundary objects, environmental policy and the science-policy interface	19-4-2019	EI.3

Table 10. I List of extracts from interviews per theme (vertical) and interviewee (horizontal).

Interviewee	Saskia Hommes (EI.1)	Dimmie Hendricks (EI.2)	Willemijn Tuinstra (EI.3)	Summary
E.g. Boundary Object	Business Canvas	WaterLOUPE	No specific object given	-
Composition	(1) Four different dimensions: finance, governance, actors and technology	(1) Considers a city and the adjacent municipalities that fall within the same river basin. (2) Pictures a situation and gives possible future scenarios regarding water scarcity risk aspects	(1) The process in which the object will be used is more important that the object itself	(1) Composition varies greatly among different objects; (2) there's a clear delimitation on the scope; (3) the process is as important as the object
Interface	(1) Four interrelated quadrants (one for each dimension) presented in a canvas at once	(1) Layered approach developed by an interaction designer where information is contained but is only visible if the user wants to explore it. (2) It provides the user with pictures of the area and a map of its location	(3) It needs to propitiate understanding for the negotiators and the science and policy actors	(1) Different categories; (2) layered approach; (3) displays scope; (4) facilitates understanding among different actors
Use / Setting	(1) Land subsidence related projects in localities of the Netherlands. (2) Workshop with different stakeholders where the tool is co-constructed in the workshop	(1) Water scarcity related projects in regions of a country; (2) Co-constructed in a workshop (it considers people's input [30-35] from different backgrounds and multiple disciplines); and (3) is not just a tool but also an approach	(1) It is necessary to know where and with whom in the policy process the object will be interacting	(1) Local and regional scale; (2) scale of action of the object in the process; (3) not just an object but an approach; (4) variety of actors included in the process in which is used
Data	(1) Input to obtain the elements that compose each dimension comes from the stakeholders participating on the workshop	(1) Retrieves environmental risks as experienced by the users in the area. Input comes from local partners and stakeholders, and global datasets and models from Deltares and recognized institutions.	(1) Input should come from different actors that together decide what's important and needed	(1) Input comes from actors included in the process in which the object will be used; (2) Input comes from datasets, models and research from recognized institutions

Strengths	(1) Organized in different categories; (2) visualization technique; and (3) easy language and use. It reduces the complexity thus the resource intensity of conventional participatory modelling processes.	(1) Balance between simplicity and robustness; and (2) enables a discussion of what and for whom are the risks	(1) If the process is successful then the object will be likely to be successful	(1) Organization in categories; (2) friendly visualization; (3) propitiates understanding through easy language and use; (4) balance between simple and robust; (5) Depends on the success of the process
Weaknesses	(1) The tool can be overwhelming when presenting it to the intended audience	(1) Workshop is resource intensive so as the preparation for it	(1) It means different things for different groups; (2) its designation (and extent) as boundary object is dynamic and changes from context to context and scale to scale	(1) Overwhelming; (2) requires extensive preparation, (3) ambiguous meanings; (4) volatile success rate
Threats	(1) Lack of linkage of the tool with the broader participatory process: it is unclear what are the outcomes beyond the session in which is used	(1) The large amounts of data make the task of handling information in a way that is easy to present yet robust hard to accomplish; (2) keeping actors engaged in the process is challenging; (3) keeping the tool alive and useful by expanding its life cycle; and (4) the understanding among actors and their perceptions and visions; scientists think in hazards whilst the rest think in impacts derived from experience	(1) External factors and uncertainties; and (2) the rules of the process	(1) Lack of linkage of the output with the whole process; (2) lack of shared understanding; (3) big amounts of data; (4) external factors that cannot be accounted; (5) rules of the process present an obstacle
Opportunities	(1) Present tool by parts and co-construct it in a modular way; and (2) know your actors and the behaviours they are likely to show towards both the process and the object	(1) Know your audience and frame information in a simpler way that facilitates understanding.; (2) ask participants about the future and desirable and undesirable situations; (3) clearly explain how the tool works (e.g. webinar); and (4) continuous development of the tool	(1) Consider different perspectives to increase success rate and agreements	(1) Modular approach; (2) know the target group and consider it for the use of the tool; (3) clear explanation of the intended use and how to use the tool; (4) continuous development of the tool
Essential requirements for boundary object	(1) Clear link to the participatory process; (2) friendly visualization; and (3) easy language	(1) Simplicity to understand it, (2) functionality as knowledge base, (3) enabler of discussions, and (4) it should be accompanied by neutral party that steers its use in the process	(1) Vary from context to context and scale to scale	(1) Plastic to fit different contexts; (2) linked to the whole process; (3) friendly and simple; (4) function as knowledge base; (5) dialogue enabler; (6) facilitated by a neutral party.
Extra comments	Salience is the most important dimension since it leads to action. Achieve it through the examination of local policy documents regarding water plans	(1) In multi-actor settings some actors are quickly to speak about solutions instead of clearly defining the problem; (2) actors without a scientific background are more likely to take narrow approaches based on their experience and vision of the problem; and (3) legitimacy is hard to achieve because getting actors together presents a challenge	(1) There is not a set pathway to achieve salience, credibility and legitimacy, sometimes it just happens; and (2) the success or failure can only by real for the people that participates in the process	See separately
Indicator systems' weaknesses	(1) Difficulty to find information; (2) difficulty to understand by different actors; (3) complicated due to large amounts of information to take in; (3) lack the perspective of many actors which can lead to conflicts not only about the indicators but the measurements; (3) assumptions are made about a situation.	(1) Indicator systems tend to favour credibility before salience and specially before legitimacy; (2) they are too general and lack salience due to a lack of focus in the context (3) scores and metrics can lead to disagreement	(1) Actors might focus in a handful of indicators instead of the whole.	(1) Finding information is hard; (2) overwhelming; (3) lack of inclusiveness; (4) built on assumptions; (5) too general
Suggestions	(1) Inclusion of two different metrics: one from science with concrete data and	(2) Dynamic metrics that retrieve both scientific and perceptive information.	(1) Focus on what's important (indicators) for the actors	(2) Flexibility; (2) focus on what is important

	numbers and one that asks for the perception of the people.			
PSIR weaknesses	(1) Complicated for the different actors involved in the decision-making	(1) Too complicated for actors to understand	-	(1) Difficult to understand
PSIR strengths	(1) Causality is important for the formulation and understanding of a problem.	(1) The opportunity it gives to understand causality	-	(2) Displays causality
Suggestions	(1) Clear visualization of the relationships between the elements that compose the PSIR in a way that is simple and with easy language	(1) Introduce it by parts and by issues to facilitate understanding; (2) breakdown to achieve simplicity through specific diagrams or causal chains for one issue; (3) creation of an underlying model to combine quantitative and qualitative approaches	-	(1) Clear visualization of the causality; (2) Break into parts; (3) creation of model that combined a quantitative and qualitative approach

Appendix 2. Requirements Rationalisation

Table 11. Underlying rationalisation of the requirements. References allude to the experts' consultation process or relevant literature found in the *references* section.

Success Criteria	**Indicator-Based Framework Component**	**Requirement**	**Rationalisation**
Credibility	Indicators: single unit	Are coherent with UWS and theoretically well founded in technical and specific terms.	Indicators should provide a representative picture of environmental conditions, pressures on the environment or society's responses related to the phenomena being measured (OECD, 2003). They should be theoretically and scientifically valid in specific terms (Jensen & Wu, 2018; OECD, 2003). They need to be credible and accurate (Beek & Arriens, 2014; Dunn & Bakker, 2009; UN-Water, 2006).
		Accurately capture levels and changes in the aspect of interest.	Indicators need to have a threshold or reference value against which to compare it, so users can assess the significance of the values associated with it (Jensen & Wu, 2018; Nardo et al., 2005; OECD, 2003)
		Data comes from trusted sources.	The data required to support an indicator must be retrieved from a trusted sources of known quality (Beek & Arriens, 2014; Dunn & Bakker, 2009; Jensen & Wu, 2018; Nardo et al., 2005; OECD, 2003; UN-Water, 2006, EI.2)
		Data is updated regularly.	The data required to support an indicator must be timely (Beek & Arriens, 2014; Dunn & Bakker, 2009). It should be updated at regular intervals in accordance with reliable procedures (Jensen & Wu, 2018; Nardo et al., 2005; OECD, 2003). UN-Water (2006) proposes a periodicity of 1-5 years.
		Data is easily available.	Sometimes, the data required to support an indicator is hard to find (Garfin et al., 2016; Molle & Mollinga, 2003; EI.1) while it should be achievable (UN-Water, 2006). It should be easy to access, preferably using publicly accessible data or with data that can be made available at a reasonable cost/benefit ratio (Beek & Arriens, 2014; Dunn & Bakker, 2009; Jensen & Wu, 2018; OECD, 2003).
		Its construction is transparent	If the build-up process lacks transparency, the set of indicators may cover serious flaws and action perspective based on it may not be appropriate (Jensen & Wu, 2018; Nardo et al., 2005; EI.1).
		The set of indicators is comprehensive enough to accurately represent UWS with an integrative vision.	An integrative vision of UWS comprehends the fulfilment of the 'urban water system services' considering four different focuses: the use of water (1) in such way that the economic welfare increases, (2) the social equity is enhanced, (3) there's a move towards long-term sustainability, and (4) water-related risks are diminished (Hoekstra et al., 2018). Accordingly, water security is not only attributed to the local hydrological conditions and the science approaching them, but it is also related to the response of the institutional actors which procure and manage water resources and systems (Padowski et al., 2016). The aforementioned arguments make water security a very complex matter. Indicators tend to oversimplify complex situations (Garfin et al., 2016; Wilder, 2016). The indicators systems on which most of the water-related assessment frameworks are based, tend to overlook the causes, impacts, and remedies regarding a complex set of problems (Molle & Mollinga, 2003). When dimensions of performance are neglected or ignored (e.g. because they are difficult to measure), the adequacy of policies is compromised thus their measures may be inappropriate (Nardo et al., 2005).
Legitimacy	Development of indicators	There is a representative sample of actors included in the development of the indicators.	Lack of relevance for the decision-making (Garfin et al., 2016; Wilder, 2016) can be caused by a lack of participation of different actors in the construction of the instrument. A consultation process, inclusive in terms of both a representative size and variety of the types of people and organization involved, is the path to follow to conceptualize a legitimate indicator tool (Sullivan, 2002). Including the right sample of actors, and collecting the right information are crucial tasks to ensure and validate the legitimacy of the tool (Sullivan, 2002).

		The perspective on the situation of the different actors is reflected through the indicators.	Development of indicators should involve the most extensive possible range of perspectives to avoid the exclusion of perceptions that might result into conflict or lack of perceived legitimacy (Jensen & Wu, 2018; Molle & Mollinga, 2003; Sullivan et al., 2006; EI.2; EI.2; EI.3)
		The different actors agree with the score of the indicators.	The score given to an indicator can lead to conflict (Jensen & Wu, 2018; Nardo et al., 2005, EI.1; EI.2).
		The different actors agree with the metrics and thresholds set for the indicators.	Secure and insecure does not mean the same from different contexts (E1.1: EI.2); water secure implies thresholds that vary from context to context. They should be defined to prioritize and get a prominent picture of the urgencies that a location might be experimenting in relation to its situation. A 'combined metrics approach that favours the development and use of well-designed quantitative metrics, coupled with in-depth qualitative methods that provide rich context and local knowledge, may on balance be the ideal (Romero-Lankao & Gnatz, 2016, EI.2; EI.2).
Salience	Indicators	The indicators are populated with data according to the spatial scale selected and the specific context.	The interpretation of indicators is subjected to the context and must be populated with information that fits the urban scale to obtain full significance (Jensen & Wu, 2018; UN-Water, 2006; EI.3)
		The indicators are applicable to the local area situation.	Indicators must be relevant for the specific issues involved in the selected area (Beek & Arriens, 2014; Dunn & Bakker, 2009). They should be applicable to environmental issues that are significant for the area (OECD, 2003). If the condition fails to be met, indicators might focus in a handful of indicators and neglect the rest (Jensen & Wu, 2018; EI.3).
		The indicators are simple to understand and interpret	Sometimes, indicators can be difficult to understand by different actors (EI.1). Indicators should be easy to understand for the users (Beek & Arriens, 2014; Dunn & Bakker, 2009). If this condition fails to be met, indicators might be disregarded or neglected, or may lead to incorrect conclusions derived from misinterpretations (Jensen & Wu, 2018; Nardo et al., 2005).
Visualization	Portrayal	The framework helps visualize large amounts of information as required.	Indicators embed large quantities of information in their composition (Howlett & Cuenca, 2017; Molle & Mollinga, 2003; Sullivan, 2002; Wilder, 2016; EI.1; EI.2; EI.3). Visualization techniques are basic to explore and understand the resulting large set of information and knowledge (Voinov & Bousquet, 2010).
		The framework presents information in a simple and inspiriting manner (it's not overwhelming).	Presenting indicators can be overwhelming (E1.1; EI.2; EI.3)
		The framework is visually appealing.	The visual communication enabled by the boundary object is in part responsible for the compelling and persuasive capacity of the artefact and should not be neglected. It propitiates an engaging and substantial process due to its capacity to improve communication of information, data and knowledge (Voinov et al, 2016). The visual format should appeal to the object's interaction with the targeted users (EI.2).
	Analytical base	The relationships between indicators are visible, clear, and simple to understand.	Causality is important for the formulation and understanding of a given problem (EI.1; EI.2). A set suggests an overall picture of the water situation but does not allow in-depth analysis leading to an intervention (UN-Water, 2006). Significant and correct conclusions derived from the analysis of indicators will be elusive until their relative influences are known (Romero-Lankao & Gnatz, 2016). A study performed by Basco-Carrera et al (2017) proved that by means of the use of a co-constructed model involving system dynamics that characterized system interactions and cause-effect relations between issues under the context of water management, the awareness between the interconnections of the elements increased, even for those actors with non-technical backgrounds. It supported the different actors in the decision-making process by increasing their understanding of the system and its functions so as the potential impacts of possible interventions. This eventually led to more detailed solutions such as decision support systems, awareness raising, and regulations and licensing, compared to those obtained in traditional processes such as better land use measures or better water resources management.
Context of use	-	The actor(s) that built-up the object (i.e. boundary actor(s)) are neutral, objective, and placed outside the formal policy- and decision-making processes.	The role they play is commonly compared to the facilitators or moderators and are behind of the development of boundary objects. They are objective and impartial and are place outside the formal decision-making processes (Voinov & Bousquet, 2010; EI.2)
		The actor(s) that built-up the object (i.e. boundary actor(s)) is(are) present in the context of use.	"Some may have strong skills and experience in water resources planning; some may have expertise in developing models and analytical tools for decision analysis; some may have implemented effective methods for stakeholder participation; and others may have used methodologies to enhance negotiations among competing interests (Basco-Carrera & Francisco-Mendoza, 2017, p.14)". Kimble et al. (2010) identified that literature regarding

			boundary objects implied that choosing between them is relatively technical in nature and relies in the selection of the right object to fit the purpose. The authors contrarily suggested that the process is more complex than that and involves not just the artefact but the role of the 'broker' (i.e. boundary actors and/or organization). Therefore, for a boundary object to reach its full potential, it may be accompanied by a boundary organization. They play a key role in the pre-structuration of the problems and in giving direction to the process through leadership. Their aim is to assure transparency, credibility and robustness, and also to provide scientific expertise, supply information about data sources and provide access to relevant networks (Hegger et al, 2012). An unidirectional transfer from scientific knowledge to policy uptake has been catalogued as deficient and is subjected to different judgements and interpretations provided by different actors (Hoppe, 2010). It can be stated then that a one-directional piece of advice, such as the one provided by the frameworks produced, is not translated into immediate and effective uptake in the planning and policy-making processes: "Shapes, time, loci, institutional contexts and target groups of knowledge use are so multidimensional and multifaceted that a set of indicators is just a garbage can of heterogeneous indices (Hoppe, 2010, p.171)".
		The users (i.e. actors that will interact with the object) are considered for the development of the object.	Acceptancy of a tool composed by indicators is subjected to a collaborative development with those who are likely to use it (Basco-Carrera & Francisco-Mendoza, 2017; Kolkman et al., 2005; Sullivan, 2002).
		It is clear in which part(s) of the context of use the object will be operated.	The success of the object is subjected to its use in the part of the process for which it is designed (EI.3).
		It is clear how will the object be operated.	Much time during the process can be saved if actors are familiarized with the object and its composition beforehand (EI.2).
		Object considers and complies with the rules of its context of use.	If the rules of the process are not considered for the development of the object, they might present an obstacle for its success (Hegger et al., 201, EI.3).
		The output of the object is linked with the rest of the policy- and decision-making process.	An object serving as boundary object and its correspondent output should be link with the whole decision-making process to make the results valuable and purposeful (EI.1; EI.2; EI.3)
Flexibility	Various	The object remains flexible to allow changes and to be responsive when new information arises.	Lists of indicators are neither final, nor exhaustive; they keep evolving over time and space (UN-Water, 2006). Objects in participatory processes should be ready to be adapted when new information arises (van Bruggen et al., 2019; Voinov & Bousquet, 2010; E1.1; EI.2; EI.3). Furthermore, indicators should be responsive to changes in the environment and related human activities (OECD, 2003) subjected to the context (UN-Water, 2006).

Appendix 3. Does the Design Satisfy the Requirements? Qualitative Review of the UWSD and the Upgraded UWSD.

Table 12. Qualitative description of how the original UWSD and the upgraded UWSD perform against the design requirements.

Success Criteria	Indicator-Based Framework Component	Requirement	Original UWSD		Upgraded UWSD	
			Description	Application Example	Description	Application Example
Credibility	Indicators: single unit	Are coherent with UWS and theoretically well founded in technical and specific terms.	The theoretical relevance of each indicator is well-founded on relevant studies and its relation to urban water security is explicitly stated in the supplementary material *Indicators Formalisation.*	The total size of a city in terms of inhabitants puts a pressure on the water security of a given area. The larger the city, the larger the infrastructure needed to fulfil the required water services, and the larger amount of water resources claimed.	The theoretical relevance of each indicator is well-founded on relevant studies and its relation to urban water security is explicitly stated in the supplementary material *Indicators Formalisation.*	The total size of a city in terms of inhabitants puts a pressure on the water security of a given area. The larger the city, the larger the infrastructure needed to fulfil the required water services, and the larger amount of water resources claimed.
		Accurately capture levels and changes in the aspect of interest.	The scales for the scoring (1 very insecure - 5 very secure) allow to capture levels and changes of the phenomena being measured. In some cases, it is a qualitative assessment, and, in some others, a quantitative assessment takes place.	Domestic water use is measure as: 1. DWU ≥ 300 L cap-1 d-1 2. 200 ≤ DWU < 300 L cap-1 d-1 3. 150 ≤ DWU < 200 L cap-1 d-1 4. 100 ≤ DWU < 150 L cap-1 d-1 5. DWU < 100 L cap-1 d-1. The scales allow to measure the level of urban water security and track changes.	The scales for the scoring (1 very insecure - 5 very secure) allow to capture levels and changes of the phenomena being measured. In some cases, it is a qualitative assessment, and, in some others, a quantitative assessment takes place.	Domestic water use is measure as: 1. DWU ≥ 300 L cap-1 d-1 2. 200 ≤ DWU < 300 L cap-1 d-1 3. 150 ≤ DWU < 200 L cap-1 d-1 4. 100 ≤ DWU < 150 L cap-1 d-1 5. DWU < 100 L cap-1 d-1. The scales allow to measure the level of urban water security and track changes.
		Data comes from trusted sources.	The data used to populate the indicators come from official documents, national data bases, Deltares research, and expert's opinion.	-	The data used to populate the indicators come from official documents, national data bases, Deltares research, and expert's opinion.	-
		Data is updated regularly.	Some studies are dated to studies in the early 2000's.	Studies that describe the water management of Mexico City are from 2006-2008. However, data found in there is triangulated with data from more recent studies and official sources.	Some studies are dated to studies in the early 2000's.	Studies that describe the water management of Mexico City are from 2006-2008. However, data found in there is triangulated with data from more recent studies and official sources.

		Data is easily available.	Some indicators are subjected to very intensive research procedures.	Finding information about water intensive industries is very time consuming. Many sources have to be consulted before obtaining enough information.	Some indicators are subjected to very intensive research procedures.	Finding information about water intensive industries is very time consuming. Many sources have to be consulted before obtaining enough information.
		Its construction is transparent	The supplementary material I*ndicators Formalisation* provides a detailed transparent explanation of the rationale behind the indicators, the data that populates it, and the scores.	-	The supplementary material I*ndicators Formalisation* provides a detailed transparent explanation of the rationale behind the indicators, the data that populates it, and the scores.	-
		The set of indicators is comprehensive enough to accurately represent UWS with an integrative vision.	There are indicators from many encompassing categories related to water that consider too much water, too little water, and too dirty water.	See van Ginkel et al. (2018)	There are indicators from many encompassing categories related to water that consider too much water, too little water, and too dirty water.	See Section 5.2 and supplemental material *Indicators Formalisation.*
Legitimacy	Development of indicators	There is a representative sample of actors included in the development of the indicators.	Actors are only consulted to score the indicators that correspond to the response dimension.	See van Ginkel et al. (2018)	Actors are included in the development of indicators through a validation questionnaire and are also consulted to score the indicators that correspond to the response dimension.	See Appendix 5. Validation of Indicators
		The perspective on the situation of the different actors is reflected through the indicators.	This is considered to a certain extent due to the intensive search procedures needed to score the indicators. They take into consideration a wide range of studies that take into accounts different perspectives.	See supplementary material from van Ginkel et al. (2018): *Indicators Formalisation.*	Actors are included in the development of indicators through a validation questionnaire. Furthermore, the intensive search procedures considered of different perspectives are maintained.	See Appendix 5. Validation of Indicators
		The different actors agree with the score of the indicators.	Actors are only consulted to score the indicators that correspond to the response dimension.	See supplementary material from van Ginkel et al. (2018): *Indicators Formalisation.*	Actors are consulted to score the indicators that correspond to the response dimension and are asked to provide their opinion regarding the scores that belong to the rest of the dimensions.	See Appendix 5. Validation of Indicators
		The different actors agree with the metrics and thresholds set for the indicators.	The thresholds related to the scoring are based in international consented standards. However, that doesn't necessarily mean that actors agree with the metrics.	See supplementary material from van Ginkel et al. (2018): *Indicators Formalisation.*	The thresholds related to the scoring are based in international consented standards. However, that doesn't necessarily mean that actors agree with the metrics. This may be partly solved to the customization of the scoring thresholds to the selected context.	Area prone to flood and seismic hazard are given levels that were set for the context of Mexico in relation to its conditions.

Salience	Indicators	The indicators are populated with data according to the spatial scale selected and the specific context.	Indicators such as 1203, 1206, 3102, and 3201, to name a few, are subjected to national data. This compromises the context representation.	In the case of 1206, the GDP PPP is trying to depict the economic pressure. However, reliable data regarding the GDP is only available for the national level. Although PPP offers the opportunity of cross-comparison, the lack of information at the local scale compromises the context representation.	Indicators can change their methods and scorings to adapt information that is a better fit for the scale and the area chosen. However, some indicators cannot be adapted to the local scale but are still important in terms of credibility (e.g. water footprint of consumption).	For the case of Mexico City, gross income information is available at the municipal level which provides a more accurate picture of the situation. Besides gross income, information such as the percentage of people with access to adequate healthcare or education is also accessible to the local level. Such data can provide a more accurate picture of the economic development of the city. This exercise concluded that flexibility in the indicators gives room for better context representation while still representing what was intended in first instance.
		The indicators are applicable to the local area situation.	It serves the purpose of systematic cross-comparison between different cities. This means that the selection of indicators is generalized up to certain extent where the local context is not accurately represented.	Mexico City is not a coastal city. The indicators *rainfall intensity and variability, storm surge hazard***,** and *tsunami hazard* are not applicable in any way, which gives the city the highest score (very safe) in automatic. Still, having them in the selection of indicators brings information that, except for comparison motives, is not relevant for the decision-making.	Indicators can be included or disregarded according to the needs of the area selected.	Indicators related to the coast can be disregarded from Mexico City and are not considered for the development of the dashboard. Still, for cross comparison, they should receive the highest score as intended in the original UWSD.
		The indicators are simple to understand and interpret	Sometimes composite indicators embed different phenomena where one has more weight than the other and the score then can be hard to understand and/or interpret.	Indicator *area below msal+1m and subsidence* is a special case, because even though the part that refers to the mean sea level is not applicable for Mexico City, subsidence is. The indicator then receives a score of 3 (safe) which does not represent accurately the problem of subsidence for the area. This indicator then is considered as misleading and hard to interpret.	Indicators that embedded different phenomena in a disbalanced way subjected to subjectivity were separated.	Wastewater treatment adequacy and coverage were separated.
Visualization	Portrayal	The framework helps visualize large amounts of information as required.	Information is presented in dashboards but the reason behind an assigned score is found in the *Indicators Formalisation* supplementary	See van Ginkel et al. (2018)	A layered approach to the dashboard allows to display information by levels and provides the opportunity to offer information behind the assigned score to the indicators.	See dashboard.

			material and not in the dashboard.			
		The framework presents information in a simple and inspiriting manner (it's not overwhelming).	The dashboard is too overwhelming because it presents too much information at the same time (PSIR at once) which distracts the user (EI.1; EI.2)	See van Ginkel et al. (2018)	The dashboard uses colours and images of the location and the diagrams	See dashboard.
		The framework is visually appealing.	Not considered	-	Dashboard was developed following the Design of the WaterLOUPE tool developed by Deltares.	See dashboard.
	Analytical base	The relationships between indicators are visible, clear, and simple to understand.	The UWSD is based on a system approach and the dashboard visualization allows to place indicators in their correspondent category according to the PSIR scheme. However, the relationships among the indicators and the phenomena that there is measuring are not visible nor clear. This partly makes the PSIR approach too complicated (EI.1; EI.2)	Selected themes, according to the biggest water-related issues identify in the dashboard, are broke down into elements portrayed by indicators and place into a PSIR specific diagram that displays interrelation with arrows.	Selected themes, according to the biggest water-related issues identify in the dashboard, are broke down into elements portrayed by indicators and place into a PSIR specific diagram that displays interrelation with arrows.	See causal diagrams
Context of use	-	The actor(s) that built-up the object (i.e. boundary actor(s)) are neutral, objective, and placed outside the formal policy- and decision-making processes.	The actors that build the object belong to the academic and research fields. Hence, they are considered as boundary actors.	Actors belong to The University of Twente, National university of Singapore and Deltares.	The actors that build the object belong to the academic and research fields. Hence, they are considered as boundary actors.	Actors belong to The University of Twente and Deltares.
		The actor(s) that built-up the object (i.e. boundary actor(s)) is(are) present in the context of use.	Not considered	-	The selection of the actors must be coherent with the actors that were approached for the validation of the object. Ideally, the same actors that were consulted during the build-up should be present during the process. If that is not possible, then actors that belong to their same field, organization and/or group should be present during the process under the assumption that they probably share the same perspectives as the actors previously contacted.	-

		The users (i.e. actors that will interact with the object) are considered for the development of the object.	Not considered	-	Actors are involved in the validation processes.	Actors are involved in the development of indicators and their visualization as causal diagrams
		It is clear in which part(s) of the context of use the object will be operated.	Not considered	-	It will be used in the science-policy interface during collective learning and joint problem formulation.	-
		It is clear how will the object be operated.	Not considered	-	Actors should be introduced to the object before its use and be familiarized with it.	Webinars or explanatory documents should be handed with anticipation (E1.2).
		Object considers and complies with the rules of its context of use.	Not considered	-	It considers the three types of knowledge found within the science-policy interface: expert, bureaucratic and stakeholder.	-
		The output of the object is linked with the rest of the policy- and decision-making process.	Not considered	-	Not considered.	-
Flexibility	Various	The object remains flexible to allow changes and to be responsive when new information arises.	Not considered	-	The object is not static. Changes can be made to add or remove indicators as wished, and modify causal diagrams as needed.	If during the use, an indicator, for example consumer willingness to pay, is considered as important and it's not located within the designated set, it can be added in the category that fits it better, which in this case would be in *individual and community capacity* located in the response dimension.

Appendix 4. Response Dimension Scores.

Table 13. List of actors approached.

Label	Organisation	Expertise	Classification
MX.1	UNAM	Hydraulic engineering	Expert
MX.2	Oficina de Resiliencia Urbana	Strategic urban water resilience planning	Stakeholder
MX.3	Isla Urbana	Water scarcity and rainwater harvesting	Stakeholder
MX.4	UNAM	Hydraulic engineering	Expert
MX.5	UNAM	Socio-ecological vulnerabilities	Expert
MX.6	UDLAP	Hydrology	Expert
MX.7	CONAGUA	Hydrology and hydraulic engineering	Bureaucratic
MX.8	LANCIS	Water governance and sustainability transitions	Expert

Table 14. Questionnaire, scores, and motivations behind the scores assigned to the response dimension.

			Actor								
Category	**Indicator**	**Question**	**Average answer**	**MX.1**	**MX.2**	**MX.3**	**MX.4**	**MX.5**	**MX.6**	**MX.7**	**MX.8**
Institutional framework	Clarity of roles and responsibilities	Is the division of roles and responsibilities for the development of public water policies, implementation, operations management, and regulations clear and effective?	3	3	3	2	3	2	1	5	2
				-	It is clear but it is the institutional fragmentation that hinders implementation and management	Many institutions and organisms involved with deficient communication and transparency	-	Not effective at the basin level	-	Conagua is in charge of the water policies and their implementation	-
			2	2	1	2	3	2	1	5	1

Horizontal coordination and communication	How effective is the cross-sectoral (horizontal) coordination between different institutions on issues related to water and their public policies (e.g. environment, health, energy, agriculture, industry, spatial planning, land use, etc.)?		-	-	Scarce or null collaborations.	-	Not between boroughs	-	E.g. the national committee of hydraulic works, where several institutions meet weekly to discuss hydraulic infrastructure matters	-
		2	2	1	3	3	3	1	4	2
Vertical coordination and communication	How effective is the (vertical) coordination between different government levels on issues related to water and their public policies (e.g. between government on district-municipal-urban-national level)?		-	-	Extremely variable. Sometimes even antagonism occurs	-	Top-down approach	-	The three governmental branches align their work towards the implementation of objectives, strategies and action perspectives although political disagreement hinders it occasionally	-
		2	2	4	1	3	1	1	2	1
Corruption	In your opinion, is corruption a problem for water management in the area?		-	Preference for large centralized projects	-	-	-	-	Conagua digital' platform as a way to ensure transparency	-
		2	2	2	2	4	1	1	4	1
Accountability	Are politicians, policy-makers and those in charge of urban water management held accountable for their results?		-	-	-	-	-	-	-	-
		2	2	1	2	2	3	1	5	3

	Regulatory agreements	How effective are the regulations (e.g. agreements and laws) regarding the use of water (e.g. water withdrawals, water discharges, construction requirements, etc.)?		-	Lack of a circular economy approach where extractions are favored. Lack of regulations for new buildings. Potable water cheaper than treated (e.g. irrigation)	-	-	It is over regulated, but it is not articulated to response to the emerging issues	-	The implementation of such regulations can lead to disagreement due to unconformities, personal interests, and/or lack of legitimacy from the users. Basin councils may partly solve this	-
	Enforcement capacity	To what extent are the authorities capable to put into practice and enforce the mandatory compliance of the water-related regulations?	2	2	2	1	3	2	1	5	2
				-	-	Not even the operation agencies comply with the law, much less they enforce other. Laws and regulations are rather a recommendation than an obligation in practice. There are no enforcement mechanisms	-	Restricted by time and resources	-	If the general public is required to participate, then enforcement is less likely to occur	-
Planning	Data and information	How effectively is water-relevant data and information systematically captured, updated, and shared with different agencies, institutions, organizations and stakeholders?	2	2	2	2	3	2	1	5	1
				-	Incipient data bases	It is very hard to acquire data about the water situation of the city	-	-	-	Information is processed, analysed and revised in a hierarchical way until approved and it is consequently shared	-
	Finance		3	2	3	3	3	2	1	4	2

	How effective are governance arrangements in ensuring mobilization and allocation of necessary financial resources for water-related operational needs and future investments?		-	Ensured for large scale projects. However, budget not allocated for an urban master plan that encompasses a centralized and decentralized approach	-	-	-	-	Effective when they comply with temporal restrictions and the rules of operation, and the normative of the SHCP	-
Participatory decision-making	To what extent are the government actors involved together with non-governmental actors (e.g. NGOs, academics or the general public) in the formulation and implementation of water-related policies and decisions?	3	2	3	4	3	2	1	4	2
			-	It's recently thriving (e.g. SEDUVI, WRI, Actuación por cooperación)	The are many participations by the civil society and the academic actors. However, an increased participation is not translated into effectiveness in the elaboration of public policies and their implementation	-	-	-	Integrates resources management exist at the basin council level. It concerns the three branches of the government, users and organizations	There is participation but it is not transcendental
Strategic planning	In your opinion, how adequate would you regard the mid- and long-term strategic planning concerning situations and problems associated with water (e.g. adaptation to climate change, population growth, etc.)?	3	2	3	3	3	1	1	5	2
			-	Aperture for new paradigms of use. However, most of the ambitions revolve around extraction schemes (e.g. Cutzamala system expansion, wells)	The authorities understand the situation, but they still haven't employed measures to face the severity of the problem	-	-	-	E.g. National Hydraulic Program	-
		3	1	3	3	3	3	1	5	2

	Monitoring system	How adequate are the monitoring measures to identify or predict necessary interventions in the water infrastructure system in response to weaknesses or threats?		-	-	-	-	-	-	Infrastructure protection and emergency attention agency	-
			2	1	2	3	2	3	1	5	2
	Maintenance	How adequate is the (preventive and corrective) maintenance and/or upgrade of the water infrastructure and its related services to ensure the functionality of the system?		-	-	-	-	-	-	Conagua has infrastructure rehabilitation and modernization, and maintenance and conservation programs	-
			2	1	2	2	3	3	1	2	2
Operational management	Redundancy of critical nodes	To what extent does the urban water system possess multiple critical nodes to maintain its vital functions (e.g. multiple treatment plants, alternative water supply sources, etc.) in case of failures?		-	-	High dependency on external resources (Cutzamala system). Insufficient drainage. There is just one inefficiently operated water treatment plant	-	-	-	The uncontrolled city growth puts a pressure in the exploitation of the supply resources. There are not appropriate alternatives to fulfil the demand. This is caused either from social disconformities or technical and environmental limitations	-
			2	1	4	3	2	4	1	1	2

	Individual water efficiency measures	To what extent does the general population has implemented individual measures and strategies to increase their accessibility to water in case of insufficient and/or unreliable services (e.g. elevated tanks, cisterns, filters, rainwater harvesting in the premise, etc.)?		-	-	Very variable	-	Not to increase but to guarantee	-	In mega cities the implementation of individual efficiency measures is hard (e.g. shut down of the Cutzamala system supply for 9 days)	Dispersed local efforts
Community and individual capacity	Active community structures	To what degree does formal or informal are the communities actively organized to make front to water-related threats (e.g. rationing water in case of shortage, reducing water consumption in drought seasons, organized demand of water supply from the government, etc.)?	2	2	5	2	2	3	1	2	2
				-	-	Few examples	-	-	-	Few organizations proposing resilience alternatives. They rather demand solutions	Dispersed local efforts
	Awareness and sense of urgency	What extent of information, perception, and awareness of the severity of water-related problems does the general public experience?	2	1	4	3	2	1	1	2	2
				-	-	There is awareness but a lack of deep understanding on the severity	-	-	-	Increasing implementation of mechanisms to increase awareness of the value of water	There is awareness but a lack of deep understanding on the severity

Appendix 5. Validation of Indicators.

Table 15. List of actors approached.

Label	Organisation	Expertise	Classification
MX.1	UNAM	Hydraulic engineering	Expert
MX.2	Oficina de Resiliencia Urbana	Strategic urban water resilience planning	Stakeholder
MX.3	Isla Urbana	Water scarcity and rainwater harvesting	Stakeholder
MX.4	UNAM	Hydraulic engineering	Expert
MX.5	UNAM	Socio-ecological vulnerabilities	Expert
MX.6	UDLAP	Hydrology	Expert
MX.7	CONAGUA	Hydrology and hydraulic engineering	Bureaucratic
MX.8	LANCIS	Water governance and sustainability transitions	Expert

Table 16. Questionnaire, scores, and motivations behind the validation of the indicators.

		Actor							
Question	**Average answer**	**MX.1**	**MX.2**	**MX.3**	**MX.4**	**MX.5**	**MX.6**	**MX.7**	**MX.8**
Do the selected indicators provide a representative picture of the urban water security pressures, state, impact or responses for the selected area?	4	4	3	5	5	4	2	4	5
Do you think that your perspective on the urban water security for the selected area can be reflected through this set of indicators?	4	4	3	5	5	4	2	4	5

In your opinion, which aspects were not considered and to which dimension are they related, and/or which considered aspect do not apply, and/or what should be change, and why?		-	Institutional fragmentation, awareness of the cost of water (subsidies)	-	-	Equity	Age of the sewer and leakages. Lack of documentation. Illegal takes. Water subsidies and lack of payments.	-	-
Do you agree with the score assigned to the indicators?	4	4	4	4	5	2	5	4	4
Which indicators should be revalued and re-scored and why?		Analysis should consider the metropolitan area and even the whole basin	Differences among certain indicators (e.g. population and population growth) and justification of scores	-	-	Dependencies are not reflected	-	-	-
Extra information sources		.	100 Resilient Cities	-	-	CONEVAL, CONAPO, COLMEX	UNAM, IMTA	Plan Nacional Hidráulico, Plan Maestro para la Sustentabilidad en el Valle de México	Oxfam report by Beth Tellman regarding Isla Urbana
Do you think that the indicators hereby presented are easy to understand and interpret?	4	4	2	5	5	3	5	4	5
Which indicators should be redefined to make them more understandable and easier to interpret and why?		-	-	-	-	Scale is not clear, especially for the socio-economic pressures	-		-
Clear visualization	4	3	5	4	5	2	5	4	4
Why?		-	-	-	-	The score is not justified and what the scale is trying to capture is not clear	-	-	-

Attractive visualization	4	4	2	4	5	3	5	4	4
Why?		-	-	-	-	The map is distracting	-		-
Do you have any further comments?		Consider basin level	-	-	-	Long questionnaire and hard to answer (dashboards are in one section and questions in the other). Unclear relation between score assigned and its origin.	-	Consider Lerma and Balsas (Cutzamala system)	-

Appendix 6. Deltares Experts’ Session

Table 17. List of interviewees

Interviewee	Organisation	Expertise	Date
Judith Blaauw	Deltares	Mexico City’s expert in water resources and management	17-07-2019
Marco Hoogvliet		Urban water and subsurface management	17-07-2019
Ad Jeuken	Deltares	Climate change adaption and water management	17-07-2019
Helena Hulsman	Deltares	Urban resilience and water resources management	17-07-2019