Risk, vulnerability, resilience and adaptive management in the water sector

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TRANSITIONS TO THE URBAN WATER SERVICES OF TOMORROW

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EXECUTIVE SUMMARY

Developments in the theories and applications of risk, vulnerability, resilience and adaptive management within the context of urban water services are described and evaluated, facilitating consensus on their interpretation and subsequent management approaches. A synopsis of current thinking in the literature and the models, tools and techniques used in the application of risk, vulnerability, resilience and adaptive management concepts is presented. Representatives from two European water service providers were interviewed to explore whether and how these concepts are understood and interpreted within their organisations.

This report presents evidence that the concepts of risk and (perhaps to a lesser extent) vulnerability are more widely applied and embedded in the water services sector than resilience and adaptive management. Discrepancies in how resilience is characterised were also observed. The engineering-based approach to resilience focuses on improving 'critical infrastructure resilience', whereas the socio-ecological approach seeks to improve flexibility and foster creative re-organisation of complex systems. A case for further exploration of the latter, socio-ecological, concept and its operational aspects in the context of urban water services is provided.

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1. INTRODUCTION

The European project TRUST (transitions to the urban water services of tomorrow) is investigating contemporary thinking about the behaviour of urban water services and how employees in the industry understand and apply concepts such as risk, vulnerability, resilience and adaptive management. These concepts have become an increasingly important basis for water service providers and policy makers to develop appropriate strategies for managing risks and vulnerabilities by improving adaptive capacities in organisations. They are interrelated concepts – and to some degree overlap with one another. For instance, both resilience and adaptability reflect the ability of a system to reorganise itself in a beneficial manner. Likewise, recognising vulnerabilities is often a component of the risk management process. Yet, as standalone concepts, their theoretical development and interpretation in UWCS can vary greatly.

Urban water services are complex systems that bring together human, ecological and technological components. The ways that risk, vulnerability, resilience and adaptive management are interpreted in UWCS can be influenced by various perceptions, agendas and experiences and ultimately affect how management strategies are developed and selected. The chosen strategy may not always facilitate change in a favourable direction. Stakeholders may also have different perceptions of how these concepts should be interpreted and managed. This can, in turn, impede effective implementation of management strategies in UWCS. Clear definitions of how these concepts apply in water utilities are thus essential to the TRUST project.

This report provides a summary of the latest developments around theories of risk, vulnerability, resilience and adaptive management, and critically evaluates the implications of these theories within the context of UWCS. Current thinking in the literature and numerous models, tools and techniques relevant to risk, vulnerability, resilience and adaptive management are reviewed and discussed. Representatives from two European water service providers (WSPs) were interviewed to explore whether and how the concepts are understood and applied within the WSPs. The respondents represented a wide range of positions within the organisations – such as water supply, wastewater, environmental regulation, finance, strategy and planning, and asset management.

The report is structured to firstly introduce the current thinking on the concepts in general terms (Section 2) and then explore how these concepts are understood and applied in the water sector based on evidence in the literature and responses from the interviewees (Section 3). We conclude the report by reflecting on the variations in how the concepts have been interpreted and implemented in the water sector (Section 4).

2. THE CONCEPTS OF RISK, VULNERABILITY, RESILIENCE AND ADAPTIVE MANAGEMENT

2.1. Risk Management

The objective of risk management is to minimise, control or eliminate the likelihood of negative impacts occurring as a result of an event or situation and ensure that any positive outcomes are realised (ISO 31 000, 2009a; UNESCO, 2010). As stated in Vatn (2004), there is no universally agreed definition of risk. Nor is there a universal agreed approach to managing risk. There is some agreement, however, that risk management is an iterative process that typically encompasses the following generic stages (DEFRA, 2011a):

- identifying a problem or opportunity;
- defining its boundaries and the aims of the risk management process;
- identifying the possible negative and positive consequences and assessing their impact and likelihood of being realised;
- evaluating the significance of the risk;
- appraising options for its management; and
- implementing a suitable risk management strategy.

Communicating the risk management process in the form of accurate documentation and appropriate stakeholder engagement is vital to ensuring its success. Also, because risk is based on uncertainty, the entire risk management process must be monitored and reviewed as new information becomes available and as the preconditions change.

2.1.1. Risk identification, assessment and evaluation

An important element of risk analysis is the risk identification process whereby hazards and potential opportunities are defined along with the boundaries of their likely impact. The main aim of the risk identification process is to establish the basic information about the risk, including the risk of 'what', 'to whom' (or which part of the infrastructure or environment), 'where' (location) and 'when' (in time). Comprehensive identification of the events that can occur is critical at this stage since unidentified might be excluded from subsequent analysis (AS/NZS, 2004).

In risk assessment, the risk analyst can proceed with assessing the likelihood (P) and consequences (C) for each potential outcome. An evaluation is then made that involves comparing the level of risk determined in the assessment with pre-established criteria on the desired impact of the risk management process (see section below on modelling). The purpose of the risk evaluations is to decide on the significance of the assessed risk. There are different principles of risk evaluation that are described in the literature. The evaluation principles form the basis for defining risk tolerability. An example of a principle currently much referred to is the ALARP (As Low As Reasonably Practicable). According to this principle, risks that are clearly unacceptable must be reduced or eliminated under any circumstances. Risks that are clearly acceptable can be left without further actions. In between the acceptable and unacceptable risks there are risks that *may* be accepted if it is economically and/or technically unreasonable to reduce them. A principle closely related to ALARP, and with the same meaning, is ALARA – As Low As Reasonably Achievable (Davidsson et al., 2002).

Davidsson et al. (2002) present the following four general approaches that can be used when evaluating risk:

Principle of reasonableness – If it is reasonable with respect to economical and technical means, the risk shall be reduced regardless the level of risk.

Principle of proportionality – The overall risk resulting from an activity should not be unreasonably large compared to the benefits.

Principle of allocation – The allocation of risk in society should be reasonable/fair compared to how the benefits are allocated.

Principle of avoidance of disasters – Risks with disastrous consequences should be avoided so that the consequences can be managed with accessible resources.

2.1.2. Risk treatment

Risks evaluated as unacceptable require treatment to reduce them to a tolerable level of residual risk. When reducing the risk different approaches can be used. Based on the description of risk as a combination of the probability and the consequence of a hazardous event, three different approaches can be identified. Two of the approaches are based on reducing one of the parameters, i.e. the consequence or probability. The third approach is based on reducing both parameters at the same time, e.g. by not starting or discontinuing the activity or process that would be the source of the risk. If, however, the risk is decided to be acceptable it may be enough to control and monitor the parameters. In other cases we are looking for risk optimization; i.e., taking measures to minimize negative consequences while maximising the likelihood of a desirable outcome (e.g. habitat conservation).

To select the preferred management strategy, the potential positive and negative effects associated with each option may be considered with regard to technical, economic, environmental and social factors and organisational capabilities (DEFRA, 2011a).

2.1.3. Modelling

The adoption of a risk management approach and the selection of the method and criteria for risk assessment and evaluation must be defined before the risk is assessed. A number of techniques (e.g., simulation, matrices, spreadsheet analysis, check lists, organizational charts, flow charts, hazard and operability studies, fault or event trees and risk scorecards) are available to help with evaluating and comparing risks. The approach used can be qualitative or quantitative, depending on the level of analysis and whether the output is expressed in broad, verbal categories (High, Medium, Low for example) or numerically.

A simple graphical tool often implied to discriminate the different events is the risk matrix. It provides a process for combining the chance for an occurrence of an event (probability of failure) and the consequences if the event occurred. The risk matrix helps to identify, prioritize and manage events according to the risk magnitude. This method is also widely used for ranking or screening risks when more than one risk is identified, providing a way to select those that require further analysis or to identify those that are broadly accepted or not accepted (ISO, 2009b).

2.1.4. Interdependencies between critical infrastructures

The strong interdependencies between various infrastructures, such as those used in water and wastewater systems, transport systems (roads, bridges etc) and electricity and telecommunication systems are seldom accounted for in the literature on current risk analyses, but there is growing recognition of their importance. Identifying the independencies between infrastructures can help to reduce the likelihood of dealing with crises. Likewise, assessing the components of system that are most vulnerable to failures in infrastructure can help to mitigate the negative impact of failures.

A critical infrastructure *within* the critical infrastructure in the water industry is information and communications technology (ICT). The implementation of ICT systems for monitoring and control makes the water systems more efficient and effective than a manual operated one, however it can on the other hand be much more vulnerable. Integrated operational management in itself is not enough if security is not guaranteed because vulnerabilities are difficult to identify.

In modeling critical infrastructures there are several types of dependencies to take into account: various regimes exist in order to classify types of dependencies, and it is common to use the term *interdependency* between infrastructures, rather than the term dependency. Rinaldi et al (2001) propose to categorize interdependencies under three types of failures:

a. **Cascading failures–** where a failure in one infrastructure causes disturbances in another infrastructure. In this situation there is a functional relationship between two or more infrastructures. For example, water supply is dependent on electricity for water treatment. These types of situations are categorized as *functional interdependency*.
b. **Escalating failures–** where failure in one infrastructure worsens an independent disturbance in another infrastructure. For example, a breakdown in the metro is significantly worse if a main road is unavailable due to a fire in a tunnel. These situations are categorized as *impact interdependency*.

c. **Common cause failures**– where two or more infrastructures are disrupted at the same time due to a common cause. For example, a fire in a culvert may cause interruption of electricity, water and telecommunication at the same time. Often the term *geographic dependency* is used to categorize such failures because one or several elements of the infrastructures are in *close proximity* so that external threats may knock out several infrastructures at the same time.

2.1.5. Dealing with uncertainty

Another key aspect of risk management may involve the characterisation of uncertainty. For instance, uncertainty that results from imperfections in knowledge is often called 'epistemic uncertainty' (Walker et. al, 2003), and to make decisions or give recommendations on the basis of imperfect knowledge results in exposure to 'epistemic risk' (Sahlin & Persson, 1994). On the other hand, aleatory uncertainty relates to the inherent variability of any natural system and arises when the factors that influence a risk are unpredictable (or random). In the literature, many models and mechanisms now exist which can help quantify such uncertainty and manage epistemic risk, but these are much debated (e.g. Parascandola, 2010; Durga Rao et. al 2007). While aleatory uncertainty cannot be reduced, the variability may be projected and the sources and factors contributing to it may be identified through statistical methods. Quantifying and clearly recognising uncertainties in these ways can ultimately improve the decisions made during the risk management process and are becoming increasingly important in relation to technological innovation.

Organisations tend to desire known outcomes, but in order to be innovative they may need to occupy territory that has high degrees of epistemic uncertainty (Stacey, 1996). In today's operating environment, organisations often work within complex adaptive systems that force them into domains of higher uncertainty. By contrast, organisations that are exposed to more regulation (such as in the water sector) tend to exhibit a more risk-averse cultural base that desires greater certainty around the data used for decision making (e.g. Osborn & Hunt, 2007; Tetenbaum, 1998; and Tetenbaum & Laurence, 2011). Within this context, water companies may need to become more risk-mature (MacGillivray et al., 2006; MacGillivray & Pollard, 2008) by developing more appropriate risk management cultures that provide a bridging function between uncertainty and risk. This is becoming a fundamental challenge for a sector that increasingly seeks to foster creativity and innovation to solve ever-more pressing challenges.

2.2. Vulnerability

- Vulnerability can be broadly defined as the 'susceptibility to be harmed'. This 'susceptibility' of a given system may differ according to the scale of analysis, the perception of stakeholders and over space and time. Indeed, the definitions of vulnerability vary so widely between scholarly communities that the term becomes almost useless in an interdisciplinary context without further specification (Füssel, 2009). Vulnerability persists due to the unpredictability of some physical systems and because of how certain risks are perceived (Adger, 2006). One important dimension of vulnerability is thus the capacity of stakeholders to anticipate it. When analysing vulnerability, the challenge is to focus on the scale at which vulnerability is likely to manifest whilst accounting for the interdependency on both smaller and larger scales (Hufschmidt, 2011). Once the focus system has been delineated the vulnerability of this system can be estimated by exposure, sensitivity, and adaptive capacity, as explained below (Adger, 2006).

- **Exposure** – The anticipated frequency, magnitude, and duration, of potentially harmful events is referred to as exposure. Since exposure generally only accounts for those risks that can be quantified with probabilistic statistics, this introduces the prospect of overestimating certainty in vulnerability assessments.
- **Sensitivity** – Assuming constant levels of exposure, the vulnerability of a system may increase or decrease with changes to the internal conditions. Such internal threshold changes represent a capacity to cope that is referred to as sensitivity. In hindsight, sensitivity is characterised by the degree to which the focus system is influenced by the contextual changes. When analysing social vulnerability, sensitivity is often characterised with reference to institutional adaptation.
- **Adaptive capacity** – Adaptive capacity represents the ability of a system to evolve and enact change to reduce vulnerability, the nature of which depends on the degree to which unsafe conditions have been transformed into harm or disaster by triggers. Pre-impact adaption refers to a capacity to learn, anticipate, and prepare. This type of adaptive capacity is often translated into mitigation and planning. After a harmful event has been triggered, adaptive capacity is represented by the potential to immediately react and absorb any adverse effects. Post-impact adaptive capacity is the ability to recover and evolve to reduce future vulnerability.
- The vulnerability of a focus system is thus characterised by its capacity of to anticipate, cope with, resist, and recover from the adverse effects of a hazard. The context of the focus system is, in turn, characterised by changing stressors or unsafe conditions caused by dynamic pressures that result from root causes. There is a trade-off between adaptedness of the focus system to a specific source of harm and its flexibility to adapt to unknown risks. Pre-impact potential for learning, anticipating, and preparing may then be associated with institutional adaptation and sensitivity: the aspect of vulnerability that is defined by the dynamic internal thresholds of the system.
- It is important to note that stakeholders within any given focus system may have different perceptions of vulnerability. Ensuring fairness in these cases can be difficult and adaptation interventions have not always reduced the vulnerability of those most at risk. This may be due, in part, to

overrepresentation of the perspectives of relatively well-off groups in the definition of exposure, sensitivity and adaptive capacity, thus skewing the classification of vulnerability and any response strategies towards their interests.

2.2.1. Application of vulnerability research

Hufschmidt (2011) identified two paradigms that shaped the development of vulnerability research: the 'behavioural paradigm' and the 'structural paradigm'. The behavioural paradigm is associated with the human ecologist school of thought, which focuses on human adjustment to natural hazards. Within this tradition vulnerability is normally defined as 'capacity to be wounded'. This approach focuses on defining the probabilities of natural disasters occurring and adapting behaviour to reduce the adverse effects. The structural paradigm was developed in the 1970s to challenge this dominant behavioural paradigm. It holds socioeconomic and political structures responsible for the harm caused by disasters, and defines disasters as a 'triggers' rather than 'root causes' of vulnerability. The starting point for the structural paradigm is thus social vulnerability.

The number of papers published on the subject of vulnerability has increased exponentially since the 1980s. Much of the recent research on the subject of vulnerability has been associated with global climate change. The IPPC defines vulnerability as a function of a system's exposure and sensitivity to climatic stimuli and its capacity to adapt to their (adverse) effects. This definition reflects an 'end-point interpretation' of vulnerability, which defines climate change as the root problem, and is most closely related to the behavioural paradigm.

2.2.2. Measuring vulnerability

Indices of vulnerability can be deductive or inductive. Inductive approaches identify vulnerability indicators based on statistical links with measurable outcomes such as numbers of casualties. The basis for deductive indices, on the other hand, is a conceptual framework or theory linking the indicator to vulnerability. Either way, scientists have struggled to find suitable metrics for vulnerability. Measurement has proved to be particularly difficult because of the complex, dynamic links between the vulnerability of a system and diverse biophysical and social processes both within that system itself and in its context. Vulnerability is also manifest at multiple scales from individuals up to societies or ecosystems. On top of this are the differing perceptions of vulnerability that stakeholders within a system may have. In many ways it is not beneficial to translate this complex set of parameters into a quantitative metric (Adger, 2006). Essentially, complimentary qualitative and quantitative insights and the involvement of stakeholders in assessments should be ensured.

The most widely recognised model for defining vulnerability based on the structural paradigm is the 'Pressure and Release' (PAR) model (Wisner, 2004). This model describes the pathway of vulnerability as moving from 'root causes' through 'dynamic pressures' to 'unsafe conditions' that may in turn be transformed into harm or disaster by 'triggers'. Hufschmidt (2011) ranks this model with 6 others to compare them against specified criteria. Good models were seen to be applicable to different diverse biophysical and social conditions and account for the multidimensional nature of vulnerability. Other important criteria included a faculty for accommodating the dynamic nature of vulnerability and capabilities for using a multi-scalar approach that allows for scale interdependencies.

2.3. Resilience

The concept of resilience is long established in the study of ecosystems. Holling (1973) defined it as the measure of a system's ability to absorb disturbance and persist, largely unaltered. More recently, the concept has been reviewed by authors such as Walker et al. (2004), Folke (2006), Brand and Jax (2007) and Folke et al. (2010). These reviews illustrate significant shifts in the understanding of resilience, which are intricately linked to shifts in the understanding of complex systems in general. Much of the current thinking around the concept of resilience (as well as adaptive management) stems from theories around the behaviour of complex systems – namely socio-ecological systems (SESs) and socio-technical systems (STSs).

SESs (or coupled human-environment systems) are essentially holistic conceptualisations of the links and interactions between ecological systems and human (social) ones (Berkes and Folke, 1998; Young et al., 2006). STSs essentially reflect a holistic understanding of the links between technology (including its production, diffusion and use) and society (Geels, 2004). SESs and STSs clearly overlap. They both illustrate the extent to which ecological or technological components are intricately intertwined with human components such as policy, institutions, knowledge and culture.

Urban water services are increasingly seen as SESs or STSs – they are highly complex systems that bring together human, ecological and technological components. As a result, contemporary thinking about the behaviour of such complex systems has a significant influence on debates about the future of urban water services. Understanding UWCS in this way sheds greater light on understanding how and why such systems change, and how we might facilitate change in a favourable direction – i.e. towards a more resilient state.

2.3.1. Collapse and reorganisation

One concept that has been used to theorise the evolving nature of complex systems (particularly SESs) is that of 'panarchy'. The term panarchy (e.g. Holling, 2001; Gunderson and Holling, 2001) is used to describe a hierarchical structure of systems, ranging from very small-scale systems (e.g. a single leaf or a single family) to very large scale ones (e.g. biomes or global economies). Moreover, these systems are nested – i.e. the smaller scale systems sit within larger-scale ones. This multi-level (or multi-scale) perspective is key to understanding the behaviour of the overall 'panarchy'.

In the concept of panarchy, each system within the nested structure undergoes a continuous cycle of growth, accumulation, restructuring, and renewal. These cycles include longer periods of slow resource accumulation and relative stability, as well as periods of sudden collapse and rapid reorganisation, which are often triggered by 'agents of disturbance'. These periods of collapse and reorganisation provide opportunities for innovation and novel recombination of the systems resources. The entire cycles can take place over a range of time periods, with lower-level systems (niches) undergoing more rapid cycles, and higher-level systems (landscapes) undergoing much slower ones. While this characterisation of change is highly abstract, it can provide significant insight into the behaviour of such complex systems.

According to Young et al. (2006), a significant and growing need to understand these 'leverage points' within SESs remains. They argue that attention should be given to the dynamics of resilience, vulnerability, and adaptability, rather than focusing on risk, stability, and control in order to work with these complex and uncertain coupled systems.

In the context of urban water services, some indications of such a shift in thinking – away from conventional ideas of risk and stability, and towards more dynamic concepts of vulnerability, resilience and adaptability – are beginning to appear. However, as the sections below will illustrate, in many ways this shift is still in its infancy.

2.3.2. Change and continuity

In ecology, Holling's work in the 1970's essentially tried to redefine the behaviour of complex systems. According to Folke (2006) ecological theory was then dominated by the idea that ecosystems had a single, relatively fixed point of equilibrium – one 'steady state'. As a result of this assumption, resilience was generally seen in terms of the time it takes an ecosystem to recover and return to its steady state. This was referred to as 'engineering resilience' (Folke et al., 2010). Holling (1973) sought to challenge that assumption, proposing instead that ecosystems had multiple 'domains of stability', or multiple steady states. He also argued that systems could (and did) shift between these alternate states. Holling therefore viewed ecosystems as fundamentally dynamic – 'disturbance' was the rule rather than the exception and in response to it, systems were continually changing and developing.

These ideas about the resilience of ecological systems affected how other complex systems were understood (including SESs and STSs). For instance, Adger (2000) drew on these ecological concepts to develop an understanding of social resilience, i.e. the ability of groups or communities to deal with external stresses and disturbances. Walker et al. (2004) departs from this 'shock absorbance' understanding of resilience and describes it as a system's capacity to absorb disturbances *and reorganise itself into a better configuration*, while still retaining its fundamental characteristics. To return to Holling's theories, this reorganisation might allow a system to remain within its current domain of stability, or it might precipitate a more fundamental transformation – i.e. a shift to a new domain.

In other words, a resilient system does not necessarily 'absorb' a disturbance and return to its previous state. Instead, a resilient system is more in a perpetual state of flux, so that it can continually adjust and adapt to new disturbances and a changing context. The concept of resilience is therefore at the cusp of change and continuity – a dynamic interplay of disturbance and reorganisation (Folke, 2006). Furthermore, from such a perspective, any disturbance can be seen as a window of opportunity for creativity and innovation within systems (Folke, 2006; Folke et al., 2010).

2.3.3. Building resilience

While few empirical studies explore real-world examples of SESs and STSs, some normative recommendations for building more resilient management systems have been put forward. For instance, Olsson and Galaz (2009) suggest that building resilience involves:

- incorporating uncertainty and surprise – i.e. more than simply trying to reduce uncertainty, this implies accepting that knowledge will never be perfect, and that unforeseen changes are inevitable;
- enhancing learning and supporting experimentation – i.e. allowing room for innovative management approaches, and learning from the outcomes of such approaches; and
- facilitating participation and collective action – i.e. providing opportunities for interactions, and helping to build the skills for cooperation.

From such recommendations, it is clear is that resilience is closely tied to the concept of adaptive management so much so that the two terms are sometimes used interchangeably. Both concepts are measures of a system's ability to reorganise itself in a beneficial manner – i.e. so that the new configuration is better suited to the context than the previous one.

2.4. Adaptive management

Adaptive management (AM) is a long-established, widely advocated concept within natural resource management. Like the concept of panarchy, AM is rooted in Holling's understanding of ecosystems and their multiple domains of stability (e.g. Holling, 1978). The central tenet of AM is the acceptance of inevitable uncertainty around the behaviour of ecosystems. As complex adaptive systems, ecosystems inevitably shift and adjust to changing circumstances, in response to various drivers (e.g. climate change, human pressures), and those shifts cannot be predicted with certainty. Likewise, the outcomes of management measures are unpredictable and so ecosystems may respond in unforeseen ways. An AM perspective thus treats management measures as experimental, advocates the need to learn from the outcomes, and adjusts management practices accordingly. In this way, management systems can remain flexible, and can adjust in response to unforeseen changes in the ecosystems they manage.

In keeping with this, Pahl-Wostl et al. (2011) described AM as systematic learning from the outcomes of implemented management strategies and proactively considering changes in external factors in order to improve management policies and practices. The process of learning is therefore central to this concept. As a result, adaptive capacity (or adaptability) is often understood as a system's ability to learn from experience, and the ability to adjust management practices as a result of what is learned (Folke et al., 2010; Folke, 2002). Furthermore, in making such adjustments, an adaptive management approach 'draws on experience but [also] allows for novelty and innovation' (Folke, 2002). These elements – the capacity to learn, the capacity to adjust, and the capacity for innovation – are what tie the concept of AM so closely to the concept of resilience, as discussed above. Indeed, instigating AM approaches is often associated with 'building resilience' (e.g. Olsson et al., 2004). They are also closely tied to epistemic risk – i.e. the risk of making decisions based on imperfect information – and therefore the management of uncertainty and epistemic risk within a system is potentially a fundamental aspect of developing resilience and adaptive approaches.

Numerous frameworks for implementing AM approaches have been proposed in the literature (e.g., Foxon et al., 2008). There is also a large body of case study literature examining the implementation of AM initiatives. However, our understanding of how AM and resilience 'work' as practical management concepts still has a long way to go. Even where such initiatives have been put into practice, there has long been uncertainty around how to evaluate their level of success (Pahl-Wostl et al., 2011).

3. APPLICATION IN THE WATER SECTOR

This section considers how the theoretical concepts discussed above have been characterised and implemented in the European water sector using evidence from the literature and the results from the interviews with the two European WSPs.

3.1. Risk-based approaches

3.1.1. Risk management frameworks and methods

There many examples of embedded risk-based approaches to managing drinking water systems in the literature. One recent example stems from the EU project TECHNEAU, which challenged the ability of traditional systems and technology solutions for drinking water supply to cope with present and future global threats and opportunities. The project outputs included recommendations of several possibilities for improving the existing risk management frameworks used in water supply systems. These included specific methods to structure each stage of the risk management process, and to design risk-reduction measures and better communication the risk to stakeholders.

Risk ranking is commonly noted in the literature as the method used in integrated risk assessments of drinking water systems, where the probability and consequence of undesired events are assessed using discretised scales. There is, however, no common, structured way of using risk ranking to prioritise risk-reduction measures. The TECHNEAU project developed alternative models for risk-based, multi-criteria decision analysis (MCDA) to aid the evaluation and comparison of risk-reduction measures (Lindhe et al, 2010). The MCDA models are based on risk ranking, so they can consider uncertainty in estimates and include criteria related to, for example, different risk types and economic aspects. The study also provides good examples of applying these methods in Gothenburg, Sweden, Bergen, Norway and Březnice, Czech Republic. A dynamic fault tree method is presented that enables quantitative, integrated risk assessment of drinking water systems. It is shown how the method can be used to evaluate uncertainties and provide information on risk levels, failure probabilities, failure rates and downtimes of the entire system and its subsystems. The method is combined with economic analysis to identify the most cost-effective risk-reduction alternative.

Another EU project, PREPARED, set up an overall framework for development and implementation of the whole Water Cycle Safety Plans (WCSP), tested and adjusted them in selected case studies of the project (Almeida et al, 2010). The aims of the WCSP are identified as safety and health, security, and environment, and the risks events that can limit the fulfillment of the WCSP aims have to be identified.

In Ugarelli et al (2011) the effects of climate changes in the urban water system in different climate region are described. This study supports the identification of risk events associated with expected climate changes that have to be dealt with by the society in general and by the water utilities and other stakeholders in particular. In Almeida et al (2011) the adopted structure and contents for a risk identification database (RIDB) is presented, providing background information on the data needed for event characterization (event description, hazard, risk sources, contributing causes, existing measures to reduce risk, risk factors, typical consequence dimensions) and on data for estimating the effect of climate changes in event risk. This RIDB is intended to facilitate the task of risk identification in the WCSP. Additionally, a register of historical accidents is proposed.

At a global level, the World Health Organization (WHO, 2005) emphasizes the use of an integrated approach where the entire drinking water system, from source to tap, is considered when assessing and managing risks. Further, the WHO (2007) establishes the need for water utilities to follow risk assessment and risk management approaches by implementing Water Safety Plans (WSP) to consistently ensure the safety and acceptability of drinking water considering health-based targets. This approach incorporates not only end-product testing but also process control from source to tap.

3.1.2. Understanding of risk and vulnerability in WSPs

In the two WSPs investigated, nearly all interviewees characterised risk as a measure that combines the likelihood of an event and the severity of its impact. Vulnerability was often strongly tied to the idea of risk, and the two terms were sometimes even used synonymously. It was clear that risk-based concepts were well-embedded within both organisations, as many interviewees were able to speak at length about the different risks faced and how they were managed – one stated that it was 'part of everyday life to manage risk'. Yet, many of the interview respondents remarked that the direction within the organisation as a whole seemed inherently *risk averse*. This can (paradoxically) create a risk in itself if it results in the postponement or avoidance of inherently risky decisions, which may eliminate the more beneficial outcome.

The types of risks that the interviewees identified by the utilities the most were:

- Lack of funding – this was raised particularly by the utility operating at a national scale, where there was concern that a reduction in government lending to the organisation could impede its ability to meet its key objectives
- Specific instances of asset failure, which could threaten: water quality and public health; the water environment; and/or service delivery to customers
- Failures in information/communication technology (ICT) – particularly where fully automated treatment systems are used
- Disasters or terrorist incidents
- Impacts of climate change – mainly in light of ageing infrastructure
- Public relations failures and risks to reputation

In the utility that operates at a national scale, interviewees discussed several sophisticated tools, techniques and procedures used to assess and manage these types of risks, such as Monte Carlo simulations and risk registers. Overall guidance for such procedures clearly stemmed from very senior levels in the organisation.

In one utility, an interviewee remarked that there is a strong focus on risk and vulnerability analyses in water quality, which is helping to systematize knowledge and prioritise dealing with the highest risks. Other interviewees noted that a full risk and vulnerability analysis of water and wastewater infrastructure was conducted for the utility in 2010-2011, but that the analysis had a narrow one-dimensional engineering approach. In other areas, such as ICT, risk management was characterised as more 'ad hoc'. Nevertheless, some noted that new risk management procedures might be needed as a result of legislative requirements.

3.2. Resilience thinking and adaptive approaches

3.2.1. Asset resilience

When the term resilience is referred to in the literature on the water sector, is often used in the context of assessing 'critical infrastructure' – which includes water assets, as well as roads, energy, telecommunications, etc. The need for more resilient infrastructure is sometimes highlighted, but these portrayals are more in keeping with the concept of 'engineering resilience' – i.e. capacity for shock absorbance.

A good example of building capacity for shock absorbance is noted in the UK government's strategy 'Future Water' (DEFRA, 2008), which equates infrastructure resilience with emergency preparedness and the ability to deal with flooding emergencies. Similar portrayals of resilience are found in the government's more recent strategy for 'Climate Resilient Infrastructure' (DEFRA, 2011b) as well as in Ofwat's report on 'Resilient Supplies' (Ofwat, 2010). Also, the U.S. National Infrastructure Advisory Council recently published a report on critical infrastructure resilience (NIAC, 2009) which states that a resilient infrastructure or enterprise can anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event. In other words, these portrayals of infrastructure resilience are generally about 'delivering the goods' regardless of disruptive events that may occur. Since the focus of these strategies is on physical assets, there is little discussion of system-wide capacity for innovation, experimentation and learning.

Likewise, in the interviews with the WSPs, characterisations of resilience varied more than those of risk, perhaps indicating that the concept of resilience is not as well understood. Several definitions offered by respondents were consistent with the 'engineering resilience' concept. One respondent even defined resilience as the ability to deal with risk, further highlighting the perceived overlap between the two concepts.

In general, interviewees had more difficulty pinning down what resilience means in practice –how it is measured and/or managed. One respondent (from the utility that operates at a national scale) even described resilience as 'easy to talk about, not easy to do'. There were no mentions of any tools or techniques like the ones associated with risk management. Some respondents (from both organisations) remarked that improving resilience meant building up redundancy in assets and infrastructure – asset back-ups, spare capacity, mothballed plants, etc. – which could provide insurance in case of failure in one part of the system. Resilience was also strongly tied to climate change adaptation, but again this emphasised the system's ability to cope with environmental trends (e.g. more severe weather).

Interestingly, in the utilities interviewed, some respondents felt that resilience was tied more to the human aspects of the organisation than to the performance of the physical assets themselves. They thought that the organisation was potentially not very robust, as a result of its inflexibility (not being very 'dynamic') and its fragmentation (the 'distance' from management to ground-level decisions). These characterisations of resilience are more in keeping with the socio-ecological version of the concept, rather than the engineering-based concept.

3.2.2. Adaptive initiatives

While adaptive capacity was not addressed specifically by the interviewees, there is a considerable amount of literature on the implementation of adaptive approaches in the context of water management. For instance, recent reports from European projects TECHNEAU (Pronk and Kazner, 2008) and PREPARED (Staub and Moreau-Le-Golvan, 2011) have listed various 'adaptive' initiatives that have been implemented in the European water sector. In the TECHNEAU report, these strategies are mainly technological solutions to suit particular changing circumstances – e.g. using energy efficient treatment processes to help adjust to the rising cost of energy. There is little evident discussion around systems thinking, the need to accept uncertainty, or the need for systematic efforts to learn from different management measures. The PREPARED report goes much further in discussing these ideas, and is focussed specifically on dealing with the effects of climate change. The report distinguishes between 'hard' initiatives (engineering and physical assets) and 'soft' initiatives (governance, institutions, and socio-cultural initiatives). It acknowledges the inherent uncertainty around climate change impacts, and discusses the need to prioritise flexible and reversible strategies. It also briefly mentions the need for 'active learning' and continuous re-appraisal of system performance. The report offers some examples of these types of adaptive strategies, both from Europe and from elsewhere in the world, which include:

- Plans and strategies that are regularly reviewed and re-evaluated;
- The diversification of urban water supplies to include a wide range of sources, to enhance flexibility to adjust to changing conditions; and
- Forums aimed at building knowledge and capacity among a wide range of stakeholders.

Another relevant case study is the California San Francisco Bay/San Joaquin Delta water management programme (known as CALFED). CALFED began around 1994 as a self-organising, informal initiative (i.e. not the direct result of a policy intervention) which involved government agencies, municipalities, NGOs, and a variety of other actors. It was primarily a means of dealing with the frequent conflicts and stalemates that arose over how to allocate the region's scarce water resources. It became a largely informal decision-making arrangement, with no fixed set of actors, and with a number of innovative governance features, including a distributed network structure, collaborative interaction heuristics, and a non-linear planning method (Booher and Innes, 2010). Over the years, CALFED has become one of the most lauded examples of a flexible, informal governance arrangement based on principles of collaborative and adaptive management.

Some argue that such self-organising initiatives can improve the resilience of socio-ecological systems (Olsson et al., 2004; Olsson et al., 2004; Booher and Innes, 2010), and that policy and regulation ought to lay the groundwork to enable and encourage them (Olsson and Galaz, 2009). However, it is unclear what kind of institutional structures might support the creation of initiatives like CALFED (Kallis et al., 2009), and the evidence that they improve system resilience is still sparse. While CALFED has had many successes, it also has limitations. For instance, Kallis et al. (2009) point out that while CALFED supported the development of innovative management measures in principle, in practice many radical options may have been sidelined for the sake of achieving consensus between stakeholders. Additionally, they argue that there are some fundamentally conflicting objectives in the region (environmental restoration vs. further development) which CALFED cannot hope to resolve – such difficult decisions and tradeoffs must ultimately be the responsibility of government.

4. CONCLUSIONS

The interrelated concepts of risk, vulnerability, resilience and adaptive management are all relevant to the water services sector. However, from both the literature and the interviews it is clear that the concept of risk and (perhaps to a lesser extent) vulnerability are more widely applied, and strongly embedded. This is hardly surprising given the prominence of risk-based approaches across a wide range of public and private sectors. A plethora of tools and techniques are available to assist water service providers in assessing and managing risks, and the terminology is generally well-used and familiar.

Nevertheless, resilience is becoming an increasingly prominent concept, which is reflected in policy terms and in academic literature. However, there is some discrepancy in how resilience is characterised. Literature relating to socio-technical systems seems to be shifting towards ecologically-derived management concepts of resilience and adaptive management. In terms of decision-making, those concepts are quite different to more 'traditional' management approaches based around quantifying and prioritising risk. A socio-ecological resilience approach involves building in more flexibility, explicitly acknowledging uncertainty, and fostering creative re-organisation of complex systems.

In contrast, an engineering-based concept of resilience has developed around water infrastructure - in terms of improving 'critical infrastructure resilience' in the face of (for instance) climate change. This kind of engineering resilience is generally portrayed as the ability to withstand stresses such as weather, natural disasters or terrorist incidents. This ability to maintain the status quo is fundamentally different from the socio-ecological version, which is based around flexibility and change, even radical change.

The interviews underscored the fact that water service providers seem much more comfortable with concepts of risk and risk management, and are generally able to discuss at length the ways in which risk can be reduced within water systems. When asked about resilience, they tended to stick to an engineering-based concept. Only a very few respondents linked resilience with a need for more flexibility and coherence in their organisation's management.

It is difficult to ascertain whether the ecologically-derived concept of resilience would be useful or appropriate for application to urban water services, partly because there is so little empirical evidence of its application. There is considerable operational uncertainty around the concept – e.g. how it can be assessed in practice – which is difficult to resolve. Furthermore, the ability to build flexibility into a system based around hard assets would certainly be challenging, as would the ability to foster creative thinking and innovative solutions (in a sector where there are numerous incentives to stick with 'tried and true' technologies and approaches). The latter potentially requires re-thinking how epistemic risk is treated within a decision making framework, and whether a risk-averse culture in this respect could potentially stifle innovation. Interest in the resilience concept is growing, and further exploration of these operational aspects in the context of urban water services is warranted.

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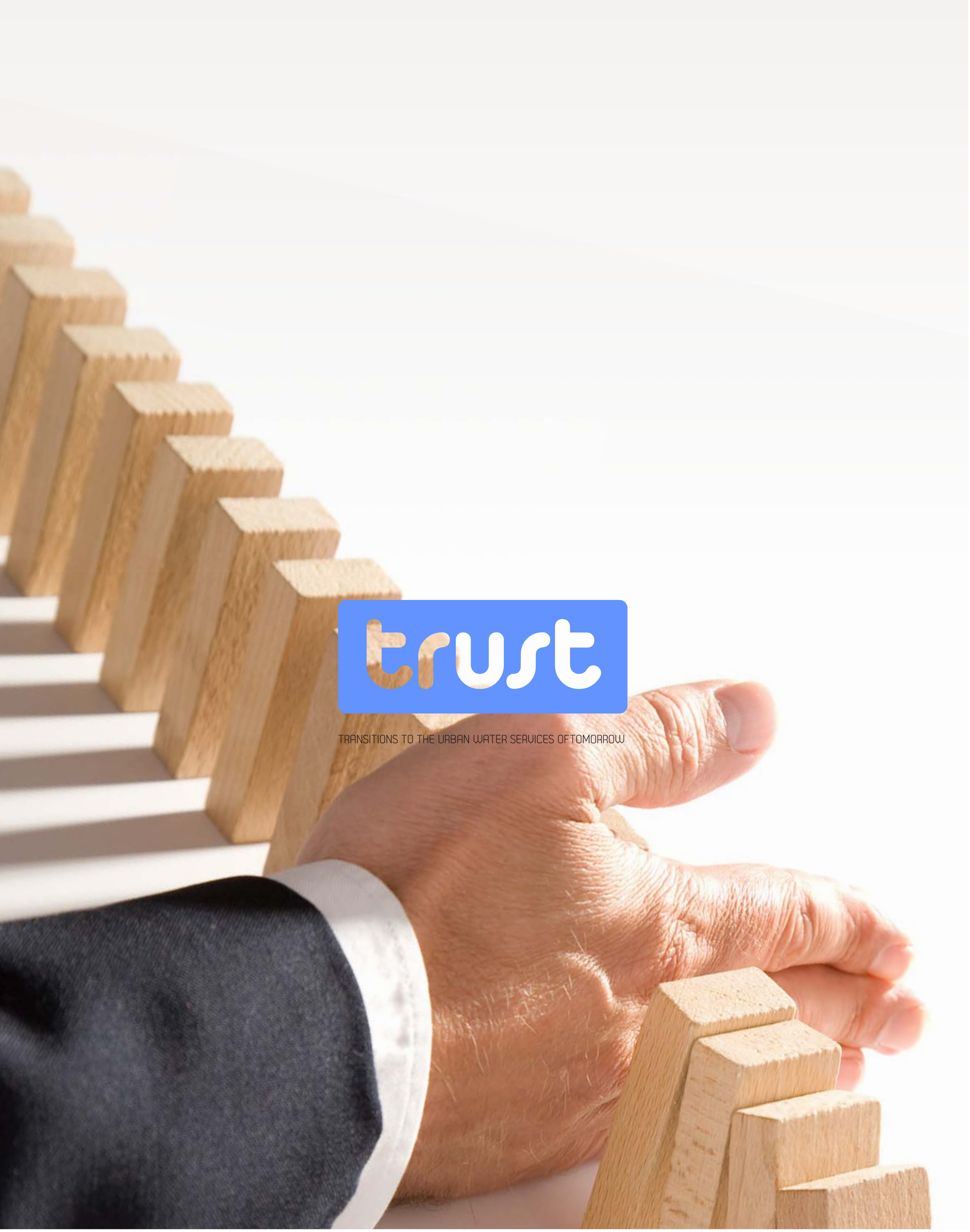

TRANSITIONS TO THE URBAN WATER SERVICES OF TOMORROW

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