Risk and Resilience to Enhance Sustainability with Application to Urban Water Systems

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Jane M. Blackmore[1] and Roel A. J. Plant[2]

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[1] Principal Research Scientist, CSIRO Sustainable Ecosystems, PO Box 310, North Ryde, New South Wales 1670, Australia. Telephone +61 2 9490 5475 Fax +61 2 9490 5537
Email: Jane.Blackmore@csiro.au.

[2] Research Director, Institute for Sustainable Futures, University of Technology Sydney, PO Box 123, Broadway, New South Wales 2007, Australia. Telephone +61 2 9514 4973 Fax + 61 2 9514 4941
Email: Roel.Plant@uts.edu.au.

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Abstract:

Many cities in water-stressed environments are seeking sustainable alternatives to traditional solutions such as supply augmentation and water restrictions. One alternative is to upgrade urban water systems in an integrated manner. Design of an Integrated Urban Water System (IUWS) requires understanding the risk of the IUWS failing to deliver sustainable outcomes. We present a rationale for enhancing well-established risk assessment and management tools with concepts of ecosystem resilience. While traditional risk assessment focuses on the states of controls that operate on specific system components and the likelihood and consequences of control failure, resilience theory addresses whole-of-system behavior. In identifying critical controls, risk management focuses on the ability to prevent failure and stabilize a certain system state, while resilience focuses on the 'uncontrollable' to identify pathways for managing system adaptation to change. Based on conceptual analysis of two key resilience metaphors, the 'stability landscape' and the 'adaptive cycle', we investigate pathways towards risk-based IUWS design and management that explicitly include system resilience as an over-arching measure of sustainability. Areas for future research include development of methodologies for measuring system adaptive capacity, and identifying and quantifying emerging thresholds.

The challenge for the risk assessment community is to reconsider what 'risk' is: in a resilience context, events traditionally seen as risky are not necessarily bad, and may become opportunities. The challenge for the resilience community is to identify thresholds and the system's proximity to them.

Introduction

Increasing demands for urban water services driven by rapid population growth in the face of climate change and the related risks of longer droughts and more erratic rain storms are pushing urban water systems to the limits – limits that water planners have been comfortable with for decades. Traditional command-and-control style solutions such as supply augmentation and water restrictions are no longer guaranteed to deliver system sustainability. Jurisdictions are therefore forced to seek alternatives to manage the sustainability of utility provision while also managing the sustainability of the larger system that generates the utility.

One approach to sustainable urban water service provision is the design and implementation of Integrated Urban Water Systems (IUWS's). The IUWS takes a three-pronged approach, considering such options as storm- and wastewater substitution as a source of supply, increasing water efficiency through demand management and seeking new supply sources. Well-established technologies are being supplemented with new approaches and techniques, and the scale of application of these technologies ranges from individual households to whole cities and regions. IUWS design incorporates economic, technical, environmental, social and health-related aspects of water service provision.

For an IUWS to be sustainable, its design process needs to consider the vulnerability of the system to natural hazards, malfunctioning, misconstruction, misuse, operational failure, etc. Options selection and system design should be informed by an analysis of the risk of ‘unsustainable functioning’ due to these threats.

However, conventional risk assessment carries the assumption of predictability whereas the empirical reality is that an IUWS is inherently unpredictable because it is interlinked with other systems (e.g., the human economy and surrounding ecosystems). Ultimately, its sustainability performance relies on the functioning and interaction of these interconnected sub-systems rather than on just the stability of the physical components of the IUWS. Conventional risk management does not consider such interlinked factors (Hollnagel et al. 2006); rather, traditional risk analysts ‘isolate’, or deconstruct, their systems for mathematical convenience.

In addition, the negative connotations of the term ‘risk’ will advocate management of the identified risks to pre-empt and avoid breakdowns by maintaining a system in its current state whereas system ‘collapse’ may actually be a prerequisite for sustainability of the IUWS.

Thus, to properly inform the design of an IUWS in the context of sustainability, risk assessment and management needs to be amended with notions of persistence, change and unpredictability.

In recent years, increasing attention has been drawn to resilience as a key system property underpinning sustainability. The term resilience, initially used in mechanics to indicate the power of an object or system to ‘recoil’, or to resume its original shape or position after reacting to an applied force, was brought into the realm of ecosystem analysis and management in the early 1970s (Holling 1973). The resilience of a coupled system of people and nature, termed ‘Social-Ecological System’ (SES) by resilience theorists (Berkes et al. 2003), is now seen by many as the key to

sustainability in the wider sense (e.g., Common 1995; Perrings 1996; Ludwig et al. 1997; Brock et al. 2002). However, in spite of thirty years of scientific analysis and debate, no consensus on how to operationalize resilience has been reached.
Klein et al. (2003) reviewed a wide range of ecological and social perspectives on resilience and concluded that the definition of resilience has become so broad that it renders the concept “almost meaningless”. They advocate that resilience is best defined as 1) the amount of disturbance a system can absorb and still remain within the same ‘attractor basin’, and 2) the degree to which the system is capable of self-organization. Klein et al. (2003) argue that both attributes are amenable to measurement and monitoring, but also warn that the challenge remains to transform the concept of resilience into an operational tool for policy and management purposes.

Given the intuitive similarities between the fields of risk assessment and resilience concepts, an in-depth comparison is pertinent to conceptualizing a more comprehensive risk management framework. In this paper, we articulate how risk and resilience approaches in the context of sustainable urban water systems may complement each other. We review early work in this area (e.g., Hasihimoto 1982; Fiering 1982a-d) and analyze two resilience metaphors; the ‘adaptive cycle’ and the ‘stability landscape’ and explore how they could potentially be incorporated into risk analysis and management for sustainable urban water design.

The paper comprises seven sections. Following the Introduction, we take a brief look at sustainable urban water practice. We then review the state of the art in risk assessment and management from a whole-of-systems perspective, and look at resilience concepts and applications to water resource management. We summarize the concepts that are common to risk and resilience before exploring a notional pathway for incorporating resilience into practical applications of risk management to sustainable urban water systems. Results and implications of our research are summarized and discussed in the final section.

Sustainable Urban Water Systems

Bruntland (1987) first defined sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. From this definition extensive debate ensued as to the nature of sustainability and the derivation of appropriate measures (e.g., Bell and Morse 1999; Moffatt et al. 2001). Measures of sustainability can apply to the performance of the whole system, or require an aggregation of the performance of individual parts of the system. The most frequently used measures generally address social, environmental and economic performance (the ‘Triple Bottom Line’ approach; see e.g. Foran et al. 2005).

In endeavoring to achieve a sustainable IUWS, an approach commonly adopted by practitioners in the water industry is to compare the social, economic and environmental (‘Triple Bottom Line’) performance of selected options against current practice (business as usual), in terms of agreed measures (see Maheepala et al. 2003). Measures that are evaluated for IUWS are generally limited to those for which calculation methods exist, such as use of potable water, World Health Organization water quality measures, lifecycle costs and nutrient flows. Measures of ecological health of urban waterways and groundwater systems, or greenhouse emissions relating to water supply and use might also be included. Social performance is harder to measure, and in practical applications social values are often derived from small samples or expert opinion. The performance of each option is appraised in terms of agreed measures and criteria, and multi-objective analysis is then applied to assist identification of preferred options. Comparison avoids the need to seek absolute measures of sustainability.

If sustainability is to be achieved, the performance of an IUWS must be assessed in such a way that controls on their continued performance can be identified, monitored and managed throughout their lifetime. Further, the ability of the system as a whole to accommodate innovations and changes, such as new water-conservation technologies, the introduction of full-cost water pricing or the impacts of climate change, should be maintained and enhanced.

Current risk assessment methods are typically limited to a pragmatic evaluation of the risk of the system failing to meet the traditional ‘Triple Bottom Line’ sustainability criteria, and they do not take into account evaluation of the resilience of the system. Yet without comprehensive evaluation of the risk of ‘unsustainability’, the impact of human actions into the future cannot be well understood and our decisions will be flawed. An exception is the work of Hashimoto et al. (1982). To address issues related to temporal variability in water supply, Hashimoto et al. (1982) defined the criteria of reliability, resilience, and vulnerability to evaluate water resources systems. They defined reliability as the probability that system benefits or performance will be within an acceptable range (e.g., water demands met sufficiently), and resilience as a measure of the speed of recovery from an unsatisfactory condition. Hashimoto et al.

(1982) defined vulnerability as a measure of the extent or severity of the unsatisfactory condition.

Simulation of time series of Hashimoto's indices and subsequent summarization using statistical measures has recently been suggested as an alternative, whole-of-system approach to sustainability assessment (Kjeldsen and Rosbjerg 2004). However, Hashimoto's definition of resilience classifies as 'engineering resilience' (Holling 1996) and, although a quantifiable parameter, may effectively constitute a partial sustainability indicator from the resilience perspective. This issue is discussed in more detail later.

Risk Assessment and Risk Management

Australia was one of the first countries to develop a national risk management standard; Australian Standard 4360 defines risk as "the chance of something happening that will have an adverse impact upon objectives, and is measured in terms of consequences and likelihood" (Standards Australia 2004). The basic risk management process is summarized in Figure 1. Steps to establish the context and identify, analyze and evaluate the risks and controls are termed 'risk assessment'. Controlling and mitigating the risks, monitoring and reassessing comprise the 'risk management' process.

[FIGURE 1 NEAR HERE – THE RISK MANAGEMENT PROCESS]

Risk management requires that risks be reduced when some nominated value, representing unacceptable risk, is exceeded. Risk is generally quantified by evaluating a function of the frequency of an event or change occurring (or the frequency of controls failing) and the magnitude of the consequence. The ability of an IUWS to deal with - or benefit from - shocks, malfunctions, misconstruction, misuse and operational failure from the perspective of sustainability will vary with the nominated technologies and management strategies, and the environment in which it operates. Each IUWS will therefore have a different risk of failing to deliver, and this risk can be seen as the over-arching indicator of its sustainability. Of two systems that have the same nominal performance, the one with the lower risk of failure will be preferable; a system with lower risk of failure might even be preferred over one with "better" nominal performance (Blackmore and Diaper 2004). Some form of risk assessment, leading to conscientious risk management, is therefore a necessary component of sustainability assessment.

In theory, if all interactions within and around the system could be fully described and all different modes of failure identified, the impacts of all control failures on the system could be properly evaluated in terms of risk and procedures put in place to avoid or mitigate adverse consequences. In reality, resource constraints and the dynamic nature of the operating environment make such comprehensive evaluation of IUWS impossible, and systems often fail to perform as expected because of unforeseen events or unexpected combinations of events. Nonetheless, the risk assessor endeavors to identify and treat critical risks.

Comprehensive risk assessment of large, interconnected, multi-component and multi-functional systems is rarely attempted at the present time, but the techniques are similar to those applied within individual domains. Key components of comprehensive risk assessment are:

- *Clearly stated objectives, with clearly identified measures* (Bernstein 1996)

  For an IUWS, the main objective is generally to achieve sustainability. Sustainability assessment has already been described.

- *Comprehensiveness*

  As many controls and influences on system performance as can be reasonably identified should be considered in the risk assessment. It is apparent that policy decisions, for example, such as recent decisions on the construction of a desalination plant in Sydney, and a decision to keep the Snowy River Hydro Scheme in public ownership, will affect the performance of any future IUWS in Australia's major cities, and related risks should be carefully evaluated in the strategic decision processes. Ceasing to provide a subsidy for the installation of rainwater tanks (a change at local government level), or instigating compulsory tests for household greywater treatment plants (a change to the national plumbing code), would similarly affect sustainability. Controls that address both prevention and mitigation should be analyzed, and mitigation should include emergency response and recovery as well as response to more frequent and less severe events.

A simple conceptual model illustrates the components of comprehensive risk assessment. To assist identification of the wide range of influences on system performance, the space within which the system operates can be considered as a series of domains (see e.g. IMO 2002), which can be independent, intersect each other, sit within each other, or interact with each other. Domains that might be considered in the design of sustainable IUWS are shown in Figure 2.

[FIGURE 2 NEAR HERE – URBAN WATER SYSTEM DOMAINS]

From a risk management perspective, the state of all controls on the system (the 'control state'), which defines the functioning of the system at any given time, is of critical importance. It is the risk of the system entering a control state that results in adverse consequences that is the concern of the risk assessor (Green and Leivesley 2001). In Figure 3, the arrow represents controls in each domain combining to influence the function of the system. Adjusting controls in any domain will change the angle of the arrow, and hence influence the overall system performance. In practice there will be many controls in each domain, and their possible states can be represented by a distribution varying from a simple 'on/off' to a complex probability distribution function.

[FIGURE 3 NEAR HERE – CONTROLS]

- *Controls and factors*

In a risk context, controls act to prevent unwanted events or mitigate their consequences. At any time, the state of the system depends on the state of its controls (which can be adjusted) and factors acting upon it (which cannot). The controllability of the system depends on the ability of stakeholders to influence system performance. Each stakeholder may be concerned with a different target population, and context-specific institutional arrangements determine stakeholder power and legitimacy to control. For example, a utility may be concerned with the water users and the environment within its jurisdiction, and might have power to adjust technologies, system design, maintenance procedures, operations, and pricing structures, and even influence regulation. Householders, on the other hand, will only influence technologies and water consumption within the household, in the best interest of the family members and their immediate surroundings.

- *Understanding relationships between the system and its controls*

  Change and failure will occur within and between domains. Quantifying change within each domain is the subject of specialist studies. Changes across domains are harder to predict. For example, increasing periods of drought will affect both water usage (more garden watering) and water supply (less water in the dams); these affects might be accompanied by compulsory restrictions, as well as reduced infiltration (and hence slower flows) in sewers. Identifying all possible failures and feedbacks is practically impossible, and is a shortcoming of most current risk assessments. Consideration of holistic system performance, based on historic data, together with consideration of total system potential for malfunction, could overcome some of the problems. Such analysis might allow the integration of traditional engineering risk analysis with the precautionary approach of ecological risk assessment (Parkin et al. 2003).

- *Accounting for time*

  Fully comprehensive, dynamic risk assessment for IUWS should aim at addressing three time frames. First, there is the risk of failure given current external conditions, including the impact of seasonal fluctuations and other 'fast' variables. This is the time-frame of most current risk assessments. Then there is the risk of the system failing because of changes in 'slow' external variables such as climate and demographics. Third, there is the risk of failure due to changes in the system itself and its control state. Examples include the introduction of new technologies, provision of additional elements, natural adaptations or the removal or introduction of regulatory controls and financial incentives. Additional complications could arise from changes to objectives (which represent mankind's current perception of the nature of the problem), and changes in the way in which achievement of performance is measured.

- *The risk function, episodic and chronic risk*

  Risk is evaluated as a function of frequency and consequence. Where consequence is inversely proportional to frequency, simple multiplication provides an appropriate function; more complex functions are needed where the relationship is non-linear and where discontinuities or breakpoints occur (Drexler 1992). The frequency/consequence method of evaluation is suitable for chronic risks and events with relatively small consequence. However, the catastrophic consequences caused by a rare, episodic event might be disproportionately intolerable (incidentally, the risk might also be hard to calculate since there is likely to be very little data upon which to derive a frequency distribution). It might be desirable to consider alternative treatment for such events, possibly identifying controls that prevent such catastrophes whatever their predicted frequency, or ensuring that emergency management procedures are in place. This reasoning is demonstrated by the precautionary principle, which advocates the use of precautionary measures where there is seen to be threat to human health or the environment even though relationships between cause and effect cannot be fully established scientifically (CEC 2000). The ability of systems to withstand or recover from severe shocks is rarely considered in current risk assessment, since the very low likelihood renders the risk acceptable despite the potential magnitude of the consequence.

- *Thresholds*

  Risk assessment is complicated by non-linear behavior. The existence of critical thresholds in control states (e.g., a valve functions correctly until a certain pressure is reached, at which point it seizes; funding for construction is withdrawn following a change in government), non-linear behavior of factors acting upon the system and non-linear responses of the system itself are all commonplace. While consequences can escalate dramatically due to non-linear system behavior, the compound effects of passing thresholds in multiple control and factor states can also lead to catastrophic consequences. Analysis is further complicated by non-linearity in calculation methods and data, incomplete knowledge of parameter values for model inputs, inconsistency in the collection of base data and step functions in the algorithms of deterministic modeling. The combined effects of non-linearity are often unrecognized in current risk assessment.

- *Frequency data*

  Failure characteristics in the technical domain (System Infrastructure in Figure 3) are typically well known. For example, technical controls (pumps, pipes) in an urban water system are used in large quantities and their failure characteristics are well documented and quantified. 'Collapses' in the natural and human domains are generally much less well understood (Reason 1990), and feedbacks less well defined. There is still much research to be done in understanding and predicting interactions between man and physical aspects of systems, and in predicting the effectiveness of economic incentives (Berkes et al. 2003). This is of particular concern because the consequences of change in the human domain (e.g., the market uptake of a new appliance causing an unforeseen increase in water use or risk to life) might be much more severe than failure of a control in the technical domain (e.g., failure of a pump in a sewage treatment plant, causing temporary congestion in the wastewater system). Further, human controls are more readily adjusted and provide a potential fast-track lever for enhancing sustainability.

The reality is that comprehensive control for large, interconnected multi-functional, multi-component systems such as the IUWS is rarely achievable. At best, current practice might achieve comprehensive control within individual domains.

Resilience and Adaptive Capacity

According to the Oxford English Dictionary, resilience is the act of rebounding or 'springing back'. The term refers to the power of an object or system to 'recoil', or to resume its original shape or position after compression, bending, etc. A second definition of resilience given by the Oxford English Dictionary is 'elasticity'. In a purely mechanical sense, resilience is the energy per unit volume that can be absorbed by a material when it is subjected to strain (or rather the maximum value of this when the elastic limit is not exceeded).

Resilience in Environmental Management

Klein et al. (2003) provide a comprehensive overview of the conceptual development of resilience within the context of environmental management, with Holling's seminal work from the early 1970s as a starting point. Rather than repeating this excellent work here, we focus on recent conceptual developments in resilience thinking and applications of the resilience concept to water resources management and planning. Conceptual developments in resilience thinking in the context of environmental management are summarized in Table 1.

[TABLE 1 NEAR HERE – DEFINITIONS OF RESILIENCE]

Holling (1996) emphasized the difference between *engineering resilience* and *ecological resilience* to draw attention to the difference between efficiency, constancy, and predictability on the one hand and persistence, change and unpredictability on the other hand (Gunderson 2003). Engineering resilience (Pimm 1991) considers ecological systems to exist close to a stable steady state. In this context, resilience is defined as:

> *the return time to a steady sate following a perturbation.*

This definition carries an assumption of a single, global equilibrium. Ecological resilience, on the other hand, emphasizes instabilities which can 'flip' the system into another regime of behavior (also known as an 'attractor basin'). Here resilience is defined as:

> *the magnitude of disturbance that can be absorbed before the system redefines its functional structure by changing the variables and processes that control behavior.*

An emerging third definition of resilience, also termed 'adaptive capacity' (Peterson et al. 1998), attempts to capture changing systems in the context of ecological change.

Both the engineering resilience and ecological resilience definitions are based on the notion of a stationary stability domain. However, empirical evidence suggests that the structures and procedures that produce stability change over time and space (Gunderson and Holling 2002), hence the emergence of this third definition. In ecological systems, adaptive capacity is created and maintained by such factors as genetic diversity, biological diversity, and the heterogeneity of landscape mosaics (Peterson et al. 1998). In social systems, key parameters are the existence of institutions and networks that learn and store knowledge and experience, create flexibility in problem solving and balance power among interest groups (Scheffer et al. 2000; Berkes et al. 2003).

Klein et al. (2003) argue that some researchers define resilience as a system attribute (i.e., engineering and ecological resilience), while others use it as an 'umbrella concept' (i.e., adaptive capacity) of a range of desirable system attributes. They stress that these umbrella concepts have not been made operational to support planning and management, and recommend that resilience only be used in a restricted sense, i.e. to describe specific system attributes concerning 1) the amount of disturbance a system can absorb and still remain within the same attractor basin, and 2) the degree to which the system is capable of self-organization. Klein et al. (2003) propose to adopt the concept of adaptive capacity as the umbrella concept where resilience will be one factor influencing adaptive capacity.

Walker et al. (2004) acknowledge that the different interpretations of resilience cause confusion, and argue that the resilience of a system needs to be considered in terms of the attributes that govern a system's dynamics. They define resilience as:

the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks

and propose four components that constitute resilience: resistance, latitude, precariousness, and panarchy. These components are most readily portrayed using the metaphor of a ‘stability landscape’ (Figure 4). The metaphor depicts the various states of a system as a series of ‘attractor basins’. When the system state is near the lowest point of a deep basin, it is stable and requires a substantial shock or change to ‘flip’ into an alternative regime. As the system moves closer to a threshold (see below) or if the current state is within a small, shallow basin, the shock or change required for transition is less.

[FIGURE 4 NEAR HERE – ATTRACTOR BASINS AND THRESHOLDS]

In Figure 4, the depth of the basin (R) is an indication of the ease or difficulty of changing the system (i.e., the ‘resistance’ of the system). The latitude of the system (L) indicates the ‘width’ of the attractor basin: wider basins can accommodate a greater number of system states without crossing a threshold. The distance of the system from the threshold (Pr) indicates the ‘precariousness’ of the system at a given time (Walker et al. 2004). The ‘panarchy’ component of resilience (Gunderson and Holling 2002) acknowledges that systems are dynamic and are continually passing through ‘adaptive cycles’ at various linked scales.

[FIGURE 5 NEAR HERE – THE ADAPTIVE CYCLE]

The adaptive cycle is a conceptual model of the dynamics of coupled systems of people, nature and technology (Gunderson and Holling 2002). They have been shown to continually go through dynamic phases of exploitation, conservation, release and reorganization (Figure 5). As a system passes through the different stages of the adaptive cycle, its resilience is subject to change. Resilience typically declines during long, undisturbed phases of stability (the ‘front-loop’ of the adaptive cycle; Berkes et al. 2003). During such phases, the tendency of system actors is to promote efficiency by removing redundancies in human resources, natural resources, infrastructure and operational procedures, and reduce investment in coping and recovery strategies. Such control adjustments increase the vulnerability of the system, potentially rendering it fragile and prone to collapse when hit by a disturbance (e.g., a disease outbreak). As exploitation of the system increases, the net accumulation of system growth (in terms of increased functionality or capital) asymptotically approaches zero. At some point the system is no longer able to function and collapse becomes the only option. Collapse is followed by reorganization and recovery of the system (the ‘back-loop’ of the adaptive cycle; Berkes et al. 2003) into a form that might, or might not, be desirable. Favorable reorganization and recovery are likely to be accompanied by fresh investment, with new components and processes resulting in a reconfiguration of the system and increased adaptive capacity. The new extant conditions will diminish through the next prolonged phase of stability. The point at which collapse becomes inevitable marks a ‘threshold’ in the performance of the system.

The ‘rims’ of the metaphorical attractor basin (Figure 4) indicate thresholds of change that can broadly be defined as breakpoints between two regimes of a system (Walker and Meyers 2004). Thresholds can be characterized in terms of the variables along which they occur, the variables that they affect, the factors that drive the change, the feedbacks that affect the change, and the scale at which the thresholds manifest themselves. Thresholds are not constant. They are the result of the interplay between factors whose individual dynamics and feedbacks change over time. A system that is operating in a seemingly steady state well away from any critical thresholds might become threatened by a change that brings the threshold closer to the current state of the system; or a threshold that exists today may become irrelevant if a future configuration of the system altogether eliminates the feedbacks among variables that define the current threshold.

Resilience in Water Resources Planning and Management

As discussed in Section 2, Hashimoto et al. (1982) proposed and defined the criteria of reliability, resilience, and vulnerability to address temporal variability issues related to water resource system performance evaluation. Another example of resilience thinking in water resources planning and management is the work by Fiering from the early 1980s. Fiering (1982a) applied the concept of resilience as used in statistics and biology to water resource systems. He argued that a resilient water supply system

> *‘does not respond precipitously to a major surprise or perturbation during the course of its economic life, and that neglecting this resilience factor in planning an optimum design may produce a system which is cost-effective but intolerant of perturbations’.*

In a second paper, Fiering explored and compared several mathematical definitions for resilience of water resource systems (Fiering 1982b). None of the definitions, all of which were based on the time required to pass from one system state to another, was designated as the best. Some of the definitions involved the probability of recovery from failure to an acceptable state within a specified time interval. Fiering (1982c) also developed some insights into the resilience of the system in the vicinity of its global or local cost optimum and presented a simulation study to define and assess the 'basin property' of resilience. Resilience indices were calculated according to previously published formulas for several reservoir configurations. Fiering (1982d) also explored the suitability of canonical correlation for predicting system resilience to provide an operational definition of resilience.

Kjeldsen and Rosbjerg (2004), building on the work of Fiering and others, carried out a behavior analysis addressing monotonic behavior, overlap and correlation between indicators of reliability, resilience and vulnerability of a water resources system. Watkins et al. (2004) discussed indices related to a managed system's ability to cope with extreme events and hydrological variability. They proposed robustness as a sustainability index, defined a robust system as 'one that performs optimally, or nearly so, under a wide range of conditions' and referred to the work of Fiering (1982a-d) and Hashimoto et al. (1982) for numerical approaches. Watkins et al. (2004) argued that these approaches assume that historical hydrology is representative of variability in future conditions, and also that water demand can be predicted accurately.

The literature addressed above suggests that resilience has a long history in water resources planning and management. However, the existing formal definitions largely encompass what has been termed ‘engineering resilience’ by Holling (1996). Although the concepts of reliability, resilience, and vulnerability as defined by Hashimoto (1982) may be useful in the context of traditional reservoir management, they are not capable of addressing the sustainable performance of the IUWS because they largely focus on maintaining constancy and, moreover, carry the assumption of predictability.

A Pathway towards Comprehensive Evaluation of Risk in IUWS

Both risk assessment and resilience thinking are concerned with maintaining the performance, or the existence, of systems. It is not surprising then that there are commonalities, nor that attention has previously been drawn to the interface between risk management frameworks and resilience studies. The different assumptions around resilience, resistance and reliability are highlighted in the following examples.

> De Bruijn (2004) describes a new way of looking at flood risk management by applying a systems approach to better suit it to the socio-economic context in which it occurs. The systems approach allows the definition of ‘resilience’ (minimizing impacts) and ‘resistance’ (prevention) strategies for flood risk management. De Bruijn hypothesizes that a resilience strategy is better able to cope with uncertainties, such as inevitable changes in land use and policy, than a resistance strategy. It could, however, be argued that these concepts are already addressed by risk management that considers prevention, mitigation

and emergency response as a spectrum of actions available to control risky situations.

Hollnagel (2006), in considering the role of engineering resilience in system safety, argues that safety is a system property that emerges from interactions between many components including technical, human and organizational factors. Insights from complex systems failure studies indicate that safety, reflected in normal performance as well as failure, is an emergent rather than resultant property of a system (a system 'does' rather than 'has' safety, often as a result of unpredicted actions of operators to unanticipated environments). We should actively ensure that systems are, and remain, safe in the face of inevitable change. To achieve this, systems should be made resilient (to the unknown) rather than reliable (against the known). Focusing on reliability (keeping accident probability low by monitoring and adjusting the behavior of components) is not enough.

[TABLE 2 NEAR HERE – COMPARISON OF RISK MANAGEMENT AND RESILIENCE APPROACHES]

In Table 2 we summarize the approaches taken in risk management and resilience theory. While risk management provides a practical and well accepted framework for predicting and managing system performance into the future, its current application has a number of shortcomings which are exacerbated when applied to integrated (complex) systems; concepts from resilience thinking might well fill some of the gaps. A combined risk and resilience approach has potential to:

- Overcome the gaps of incomplete prediction and lack of comprehensiveness experienced by current risk assessment;
- Improve anticipation of system failure and hence improve the ability to respond in an adaptive way;
- Provide a method for evaluating response to unforeseen impacts and disturbances;
- Respond in such a way that the resilience of the system is not diminished;
- Extend the range of responses to allow consideration of alternative, stable system states.

We submit that risk assessment's current lack of comprehensiveness, due to difficulty in evaluating interactions and feedbacks, could be partially overcome by evaluating the whereabouts of the IUWS on the (metaphorical) adaptive cycle and in the stability landscape. Since adaptive capacity is reduced as realization of the capital of the system increases (see Figure 5), awareness of the position in the adaptive cycle can indicate when the system is becoming vulnerable. If the phase in which the system operates is known, premature disturbance and reorganization with its associated small disruption to performance becomes a viable option.

A key measure of a system's position on the adaptive cycle is the adaptive capacity of the system. Possible parameters to describe adaptive capacity include redundancy and connectivity (or 'buffering capacity'), flexible or 'adaptive' operational management, knowledge of the behavior of the system as it approaches a critical threshold (does it accelerate towards disaster, or slow down?) and the value of reusable capital following collapse. There is potential to reduce risk of failure (and possibly increase resilience) by adjusting the parameters that increase adaptive capacity. For example, establishing laws to rapidly introduce water use restrictions in times of drought will increase the system's adaptive capacity; when the risk of service delivery failure becomes unacceptable, the process of introducing restrictions can be smooth and rapid. Evaluation of parameters that indicate the system's adaptive capacity could, at least, be employed to check that proposed risk treatments are unlikely to reduce system resilience. The adaptive capacity of the system could also be used to provide an indication of its ability to respond to unforeseen impacts and disturbances. Adaptive capacity, therefore, becomes a measure of system performance that improves risk management and that could be included in the suite of performance measures used to evaluate sustainability (see Figure 3).

Risk assessment thresholds, based on man-derived criteria, often fall short of representing true system failure, whereas break-point thresholds in resilience theory represent changes in system performance that lead to collapse. If risk assessment were informed by identification of critical, break-point thresholds, and if proximity to catastrophic failure could be anticipated, then the risk could be appropriately handled. The risk function, which currently allows infrequent events and slow change to be disregarded however catastrophic the consequence, could be supplemented by consideration of the proximity of the system to collapse and its likely response to unexpected shocks, and the chance of catastrophic failure could be reduced. Such an approach would partially overcome the 'wicked' nature of the system's performance, which prevents it from being amenable to micro-management based on identified causal paths (Rittel and Webber 1973). Greater awareness of the dynamics of the system and the environment in which it functions would encourage consideration of transitions to alternative states as viable management options.

From the perspective of resilience, knowledge of the uncertainty associated with the control state and its sensitivity to small changes in controls provides additional understanding of the system's ability to remain within an 'attractor basin' or to move to a desirable alternative (see Figure 4) and hence stay within an 'acceptable' range. As the system moves towards a threshold, analysis of the control state can identify individual controls within each domain that have potential to bring the system back into an acceptable (low-risk) state, or hasten transition to a desirable new state with enhanced resilience. Thresholds themselves could be managed using a similar approach to decrease the risk (Walker and Meyers 2004).

In summary, the challenge is to understand both the thresholds in and the adaptive capacity of urban water systems, and to utilize this understanding to identify and modify controls in such a way that the risk of uncontrolled system collapse is reduced and its sustainability is maintained or enhanced.

We suggest that incorporating the following activities into a risk management framework would help to identify options and system configurations with a reduced risk of the IUWS becoming unsustainable:

1. Analysis of the system to determine thresholds, especially irreversible thresholds, and analysis of the consequences of crossing them. Criteria for unacceptable risk can then be determined with reference to these thresholds.

Example: Reduced and highly concentrated flow in the wastewater system caused by greywater recycling might lead to eutrophication, gasification or stasis, with associated degradation and collapse of infrastructure. The effect is likely to be exacerbated by increasing average annual temperatures causing accelerated chemical reactions. By determining and monitoring the conditions under which such changes occur (flow rate, temperature, concentrations), breakdown of the system could be avoided.

2. Assessment of the adaptive capacity of urban water systems. A highly adaptive system accommodates risk reduction and consequence mitigation more readily.

   Example: A currently unknown pathogen is found to evade the standard test for greywater treatment processes. All treatment plants must be modified to remove the pathogen. It might be easier to upgrade catchment- or neighborhood-scale plants than to upgrade individual household-scale plants.

3. Maintenance of adaptive capacity. The capacity of the system to remain adaptive and resilient should be maintained; it should not be depleted by over-zealous or ill-informed risk management practices.

   Example: An IUWS has been modified by introducing overflows between stormwater and wastewater systems that allow stormwater to flow into the wastewater system during times of heavy rain. As the wastewater system becomes more stressed, sewage is inadvertently introduced to the stormwater system through the overflow. The original design was more adaptive, as there are more options for disposal of uncontaminated stormwater than for stormwater that has been contaminated with raw sewage.

The above activities can become an integral part of the risk management process (see Figure 2) if they are recognized at the outset. It might be possible to include consideration of critical thresholds in the selection of criteria for acceptable risks, and evaluation of risks could include assessment of the adaptive capacity of the system. Proposed treatment of risks should ensure that adaptive capacity is maintained. Adoption of such a comprehensive risk assessment framework would greatly improve the potential for risk management to contribute to sustainability.

Discussion and Conclusions

Comprehensive risk management that addresses controlling factors within and across a wide range of domains, and that considers how these controls can be managed to enhance the system’s adaptive capacity, will enhance the sustainability of integrated urban water systems (IUWS). Having identified commonalities and differences between the two fields of risk assessment and resilience thinking, we have concluded that detailed consideration of the adaptive capacity, and analysis of system thresholds, would provide worthwhile amendments to current risk assessment practices for the IUWS. We suggest that such a comprehensive risk management framework would not only support decision-making based on sustainability principles, but would also have application to system design, maintenance and monitoring.

Our discourse emphasized that a key commonality is the identification of the potential of a system to fail, or ‘collapse’. While resilience theory has the potential to allow identification of the proximity of the system to thresholds bordering undesirable or new, more desirable regimes, risk management has the tools to identify relevant controls, prevent unwanted transitions and enhance transition to new, more stable ones.

Resilience theory highlights the importance of the location of the system on the adaptive cycle, reflecting its adaptive capacity and taking account of the complex interactions of multiple controls. Risk assessment can be enriched by embracing the concept of adaptive capacity, ensuring that changes to controls to reduce risk do not reduce adaptive capacity. Indeed, risk can often be reduced by enhancing adaptive capacity.

Research into practical methods for evaluating the adaptive capacity should be encouraged. Ultimately, adaptive capacity resides in institutions and individuals rather than in physical system parts such as pumps and pipes. A full resilience perspective on risk management, therefore, would require quantification of such abstract system features as diversity, efficiency and connectedness. However, given the current lack of practical tools, efforts to evaluate adaptive capacity would initially need to focus on system parts that are more easily quantified, for example using network analysis or agent-based modeling.

The single value criterion or risk curves favored by current risk assessment methods are a simplified representation of the multidimensional thresholds in resilience thinking. Whereas risk assessment tends to use limited information to select criteria and then regard the values as immutable, resilience thinking acknowledges the evolutionary nature of thresholds. The consequences of crossing a threshold are not always undesirable; collapse into a new ‘attractor basin’ in the stability landscape can give rise to opportunities to increase system potential. For example, when a certain system component breaks down, the part might be replaced with a new part that changes the system’s function and enhances its overall viability and robustness, a benefit that more than compensates for the temporary inconvenience of the initial breakdown. This calls for a rethinking of the word ‘risk’: collapse and control failure that posed a high risk in conventional risk assessment may actually become opportunities when the risk of failure to deliver sustainable outcomes, as informed by the resilience metaphors, becomes the focus of analysis.

In practice, the identification of thresholds could be problematic. Some system thresholds can be characterized because they have been crossed before. In general, though, this is not the case and some means of identifying thresholds is needed. To date there are no examples of where ‘new’ thresholds in coupled social and ecological systems have been predicted (Walker and Meyers 2004), although some approaches to the problem have been suggested (e.g. Anderies 2004; Carpenter and Brock 2004). Identification of thresholds in an IUWS has not yet been explored, although the metaphor of “resilient cities” has been proposed as a promising new tool for promoting closer links among urban designers, ecologists and social scientists (Pickett et al. 2004). Despite the increased awareness of the need to be able to proactively manage thresholds, the question of whether or not a threshold can be identified before it has been crossed remains unanswered.

Currently, managing risk by identifying thresholds and continually monitoring and controlling the system's proximity to them is a long way from realization. However, we have at least provided a rationale for incorporating concepts of thresholds and adaptive capacity into risk management methodologies. By maintaining the system's adaptive capacity, the ability to manage thresholds will be enhanced, since a highly adaptive system is endowed with more options to prevent collapse. If breakpoint thresholds have been identified, critical controls can be monitored and adjusted to maintain sustainability.

The challenge for the risk assessment community will be to reconsider what 'risk' really is: in a resilience context, events traditionally seen as risks are not necessarily bad, and may be turned into opportunities. In addition, comprehensive risk assessment faces the challenge of incorporating aspects of holistic systems performance, to supplement scientific determinacy and accommodate dynamic, indeterminate effects of complexity.

The challenge for the resilience community, on the other hand, will be to demonstrate the ability to identify thresholds and the system's proximity to them – especially in examples from urban systems.

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References

Anderies, J. M. (2004). “Minimal models and agroecological policy at the regional scale: an application to salinity problems in southeastern Australia.” *Regional Environmental Change*, Springer Online First, http://www.springerlink.com

Bell, S., and Morse, S. (1999) *Sustainability indicators: measuring the immeasurable,* Earthscan, London UK.

Berkes, F., Colding, J., and Folke, C. (eds) (2003). *Navigating social-ecological systems: building resilience for complexity and change*, Cambridge University Press, Cambridge, UK.

Bernstein, P. L. (1996). *Against the gods: the remarkable story of risk*, Wiley, New York, USA.

Blackmore, J. M., and Diaper, C. (2004). “Integrated urban water systems – a method to evaluate relative risk.” *Proc., 2nd Int. Water Association Leading-Edge Conf. on Sustainability*, November 2004, Sydney, Australia.

Brock, W. A., Mäler, K-G., and Perrings, C. (2002). “Resilience and sustainability: the economics analysis of nonlinear dynamic systems”. In: Gunderson, L., and Holling, C. S. (Eds.). *Panarchy: Understanding Transformations in Human and Natural Systems*, Island Press, Washington DC, USA. 261 - 292.

Brundtland, G. H. (1987). *Our common future. Report of the World Commission on Environment and Development*, Oxford University Press, Oxford, UK.

Carpenter, S. R., and Brock, W. A. (2004). “Spatial complexity, resilience, and policy diversity: fishing on lake-rich landscapes.” *Ecology & Society*, 9(1), 8, http://www.ecologyandsociety.org/vol9/iss1/art8 (May 17, 2005).

CEC (Commission of the European Communities) (2000). *Communication from the Commission on the Precautionary Principle*, Brussels 02.02.2000, Com 2000(1).

Common, M. (1995). *Sustainability and policy: limits to economics*, Cambridge University Press, Cambridge.

De Bruijn, K. M. (2004). “Resilience and Flood Risk Management.” *Water Policy*, 6, 53-66.

Drexler, K. E. (1992). *Nanosystems: molecular machinery, manufacturing, and computation*, Wiley, New York, USA.

Fiering, M. B. (1982a). “A screening model to quantify resilience.” *Water Resour. Res*., 18(1), 27-32.

Fiering, M. B. (1982b). “Alternative indices of resilience.” *Water Resour. Res*. 18(1), 33-39.

Fiering, M. B., (1982c). “Estimates of resilience indices by simulation.” *Water Resour. Res*., 18(1):41-50.

Fiering, M B (1982d) “Estimating resilience by canonical analysis.” *Water Resour. Res.*, 18(1):51-57.

Foran, B., Lenzen, M., and Dey, C. (2005). *Balancing act: a triple bottom line analysis of the 135 sectors of the Australian economy*, CSIRO Technical Report, CSIRO Sustainable Ecosystems, Canberra.

Green, A. R., and Leivesley, S. (2001). “Limitations of risk assessment methodologies for fire in transport tunnel systems.” *Proc., 5th Asia-Oceania Symp. on Fire Science and Technology*, December 2-6, Newcastle, Australia, 366–378.

Gunderson, L. (2003). “Adaptive dancing: interactions between social resilience and ecological crises”. In: Berkes, F., Colding, J., and Folke, C. (Eds.). *Navigating social-ecological systems: building resilience for complexity and change*, Cambridge University Press, Cambridge.

Gunderson, L., and Holling, C. S. (Eds.) (2002). *Panarchy: understanding transformations in human and natural systems*., Island Press, Washington DC, USA.

Hashimoto, T., Stedinger, J. R., and Loucks, D. P. (1982). “Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation.” *Water Resour. Res.*, 18(1), 14-20.

Holling, C. S. (1973). “Resilience and Stability of Ecological Systems.” *Annual Review of Ecology and Systematics*, 4, 1-24.

Holling, C. S. (1996). “Engineering resilience versus ecological resilience.” In: Schulze, P. C. (Ed.). *Engineering within ecological constraints*, National Academy Press, Washington, DC,USA, 31-44.

Hollnagel, E., Woods, D. D., and Leveson, N. (Eds.) (2006). *Resilience engineering - concepts and precepts*, Ashgate, Aldershot, UK and Burlington, USA.

IMO (International Maritime Organisation) (2002). *Guidelines for formal safety assessment (FSA) for use in the IMO rule-making process,* MSC/Circ.1023, International Maritime Organisation, London.

Kjeldsen, T. R., and Rosbjerg, D. (2004). “Choice of reliability, resilience and vulnerability estimators for risk assessments of water resources systems / Choix d’estimateurs de fiabilité, de résilience et de vulnérabilité pour les analyses de risque de systèmes de ressources en eau.” *Hydrological Sciences Journal/Journal des Sciences Hydrologiques*, 49(5), 755-767.

Klein, R. T. J., Nicholls, R. J., and Thomalla, F. (2003). “Resilience to natural hazards: how useful is this concept?.” *Environmental Hazards*, 5, 35-45.

Ludwig, D., Walker, B., and Holling, C. S. (1997). "Sustainability, stability, and resilience." *Conservation Ecology* (renamed *Ecology and Society*), 1(1), Art 7, http://www.ecologyandsociety.org/vol1/iss1/art7/.

Maheepala, S., Evans, M., Sharma, A., Gray, S., and Howe, C. (2004). "Assessing water service provision scenarios using the concept of sustainability." *Proc., 2nd Int. Water Association Leading-Edge Conf. on Sustainability*, November 2004, Sydney, Australia.

Maheepala, S., Speers, A., Booker, N., and Mitchell, V. G. (2003). "A framework for assessing sustainability of urban water systems. *Proc. 28th Int. Hydrology & Water Resources Symp*., 10–14 November 2003, Wollongong, NSW, The Institution of Engineers, Australia.

Moffatt, I., Hanley, N., and Wilson, M. D. (2001). *Measuring and modeling sustainable development*, Parthenon Publishing Group, Lancaster, UK.

Parkin, S., Sommer, F., and Uren, S (2003). "Sustainable development: understanding the concept and practical challenge", *Proc., ICE Engineering Sustainability*, December 2003, Vol. 156, Issue 4, 221-222.

Perrings, C. (1996). "Ecological resilience in the sustainability of economic development". In: Faucheux, S., Pearce, D., and Proops, J. (Eds.). *Models of sustainable development*, New Horizons in Environmental Economics, Edward Elgar, Cheltenham, UK.

Peterson, G. D., Allen, C. R., and Holling, C. S. (1998). “Ecological resilience, biodiversity, and scale.” *Ecosystems*, 1, 6-18.

Pickett, S. T. A., Cadenasso, M. L., and Grove, J. M. (2004). “Resilient cities: meaning, models, and metaphor for integrating the ecological, socio-economic, and planning realms.” *J. Landscape & Urban Planning*, 69, 369–384.

Pimm, S.L. (1991). *The Balance Of Nature*?, University of Chicago Press, Chicago, USA.

Reason, J. (1990). *Human Error*, Cambridge University Press, Cambridge, UK.

Rittel, H.W.J and Webber, M.M (1973) *Dilemmas in a General Theory of Planning* Policy Sciences, 4, 155-169

Scheffer, M., Brock, W., and Westly, F. (2000). “Socioeconomic mechanisms preventing optimum use of ecosystem services: an interdisciplinary theoretical Analysis.” *Ecosystems*, 3, 451-471.

Standards Australia (2004). *Risk management*, AS 4360:2004, Standards Australia, Sydney.

Walker, B., Holling, C. S., Carpenter, S. R., and Kinzig, A. (2004). “Resilience, adaptability and transformability in social-ecological systems.” *Ecology & Society*, 9(2), 5, <http://www.ecologyandsociety.org/vol9/iss2/art5> (May 17, 2005).

Walker, B., and Meyers, J. A. (2004). “Thresholds in ecological and social-ecological systems: a developing database.” *Ecology & Society*, 9(2), 3, [online] URL: <http://www.ecologyandsociety.org/vol9/iss2/art3> (May 17, 2006).

Watkins, Jr, D.W.W., McConville, J.R., and Barkdoll, B.D. (2004). “Metrics for sustainable water use”, *ASCE Conference Proceedings*, 138, ASCE, Reston, VA, USA, 1-9.

Tables

Table 1 Definitions of resilience and related concepts in the context of environmental management.

Concept	Definition	Assumptions and Objectives
Engineering resilience	the return time to a steady sate following a perturbation	- Efficiency, constancy, predictability - Single static stability domain
Ecological resilience	the magnitude of disturbance that can be absorbed before the system redefines its functional structure by changing the variables and processes that control behavior	- Persistence, change, unpredictability - Multiple static steady states
Adaptability **Adaptive Capacity**[1]	the capacity of actors in the system to influence resilience (in a social-ecological system,	- Persistence, change, unpredictability, slowly changing variables

	essentially to manage it)	- Multiple dynamic steady states
Resilience	the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks	
Transformability	the capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable	

[1] Umbrella concept.

Table 2 Comparison of risk management and resilience approaches.

Risk Management	Resilience
Is generally accepted as a component of strategic and operational planning and practice	Is a theory seeking validation and quantification
Deconstructionist approach, considers component performance; can accommodate local variance	Holistic approach, considers whole-of-system performance
Requires clearly defined objectives and measures	Represents an overall measure of sustainability
Tends to suffer from incomplete prediction arising from unrecognized controls, influences and feedbacks	Relies on total, indiscriminate systems analysis – does not recognize "unusual" influences and local effects
Assessment predicts likelihood of failure and magnitude of consequence	Assessment methods predict position on adaptive cycle, proximity to thresholds
Risk is risk OF something happening – internal causation	Resilience is resilience TO something happening – external causation
Addresses expected perturbations	Tends to address unexpected

	perturbations
“Failure” is determined by man-made thresholds and criteria that are vulnerable to misrepresentation	“Collapse” involves crossing break-point thresholds into new regimes
Analysis accommodates fundamental laws of science, engineering analysis, expert opinion and consultative inputs and probability theory	Analysis based on complex systems and stable states theory, firmly rooted in mathematics
Tends to concentrate on fast to medium-term variables	Pays attention to both fast and slow variables
System state is determined by control state and uncontrollable factors	System state is determined by system position in a ‘stability landscape’ and stage in the adaptive cycle
Adjusts performance to avoid collapse	Accepts inevitability of collapse
Tends to encourage maintenance of known, low risk control states – a defined path to achieve system performance	Multiple stable basins acknowledge alternative resilient states
Failure triggers corrective action	Collapse is followed by natural

reorganization

Figure Captions

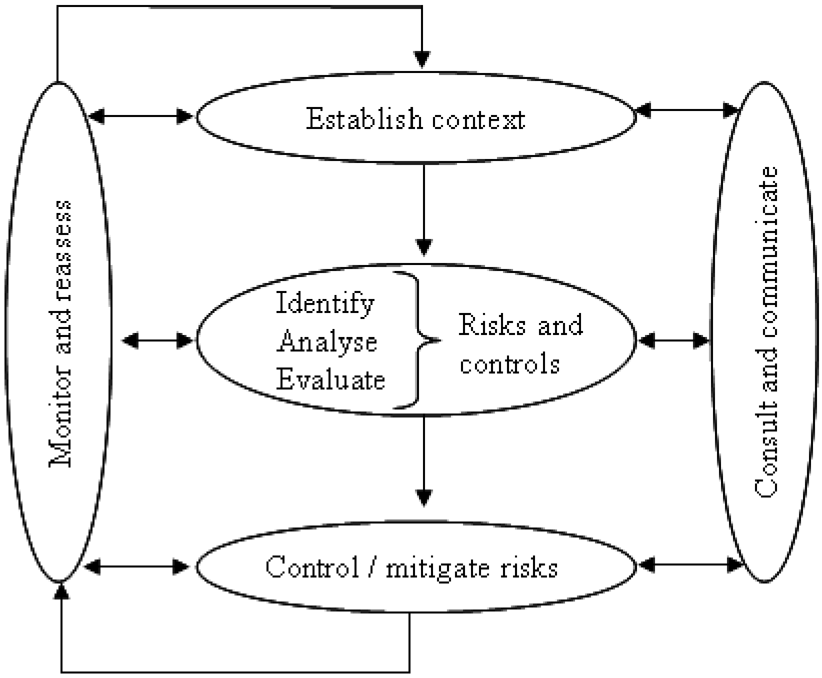
Figure 1. The risk management process

Figure 2. Urban water system domains

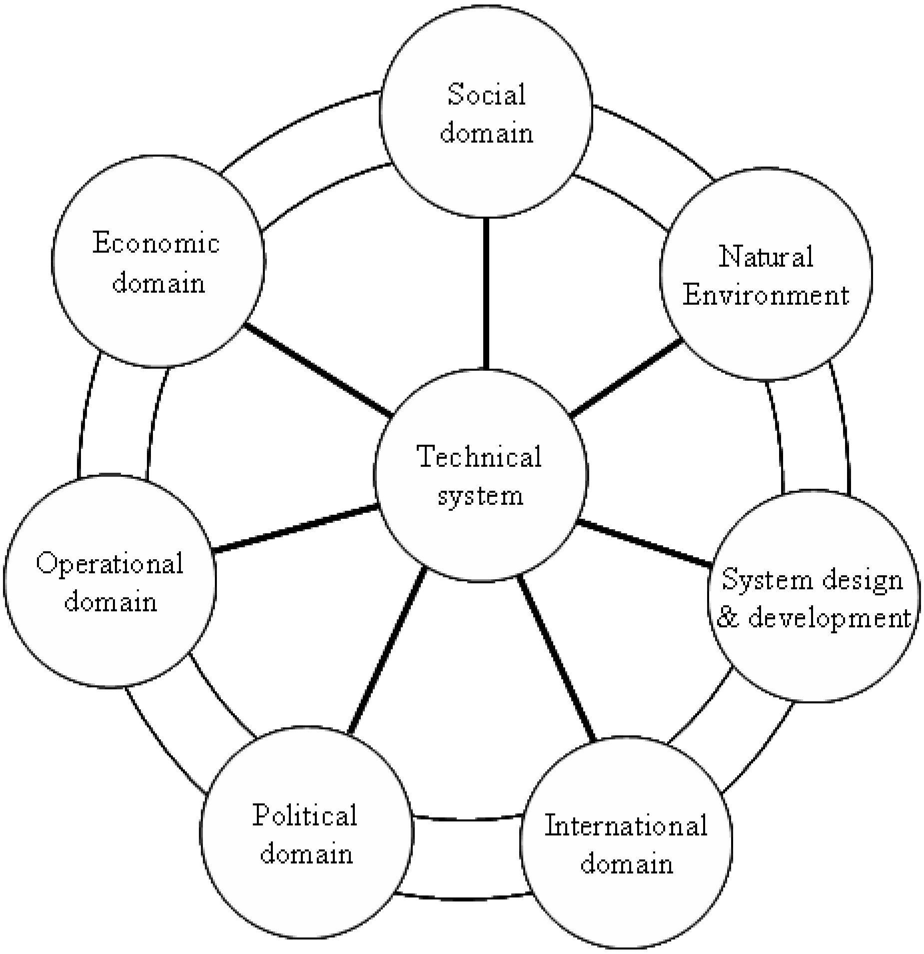
Figure 3. Controls in each domain act upon the technical system to produce a consequence.

Figure 4. Attractor basins and thresholds: L = latitude; R = resistance; and Pr = precariousness (Walker et al. 2004, with permission)

Figure 5. The adaptive cycle (Gunderson and Holling 2002, with permission)



Blackmore & Plant: Figure 1.



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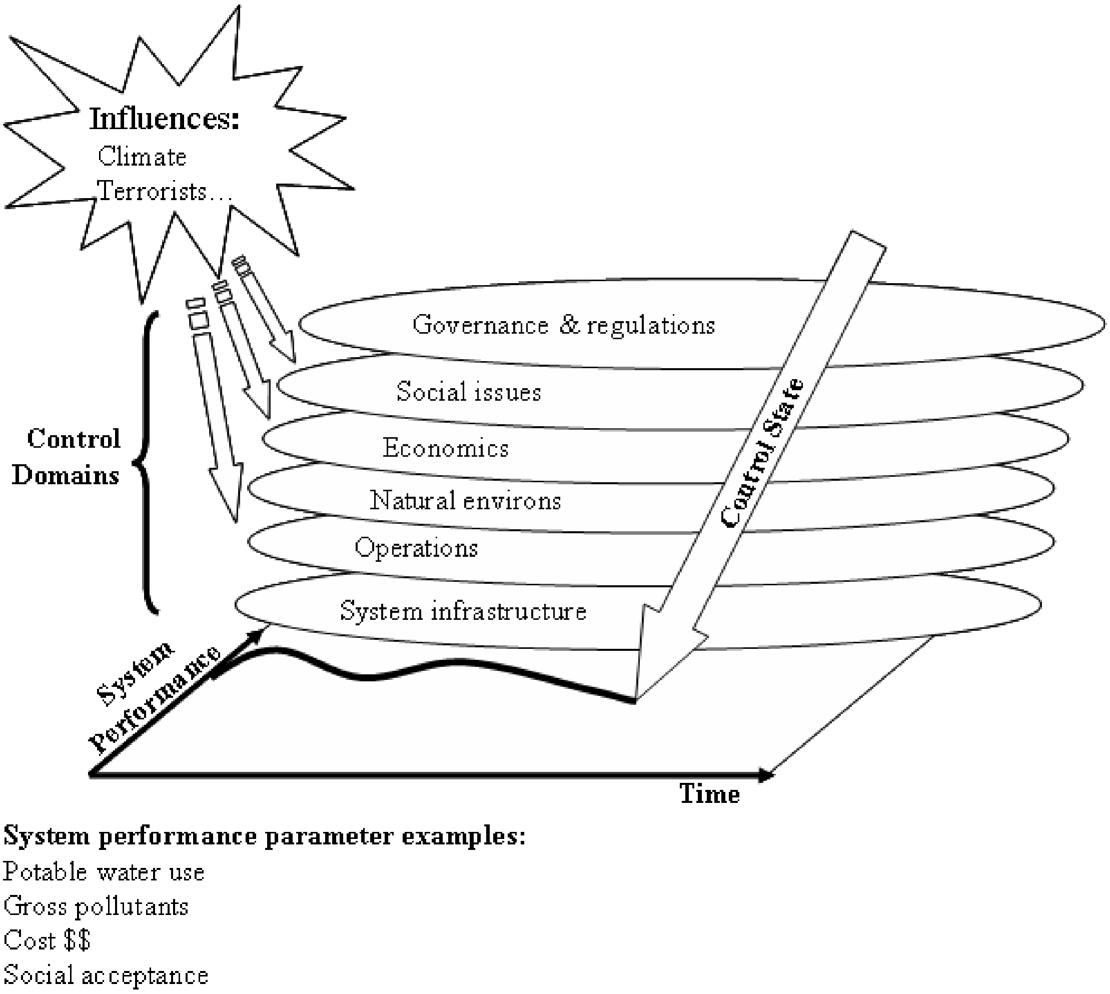

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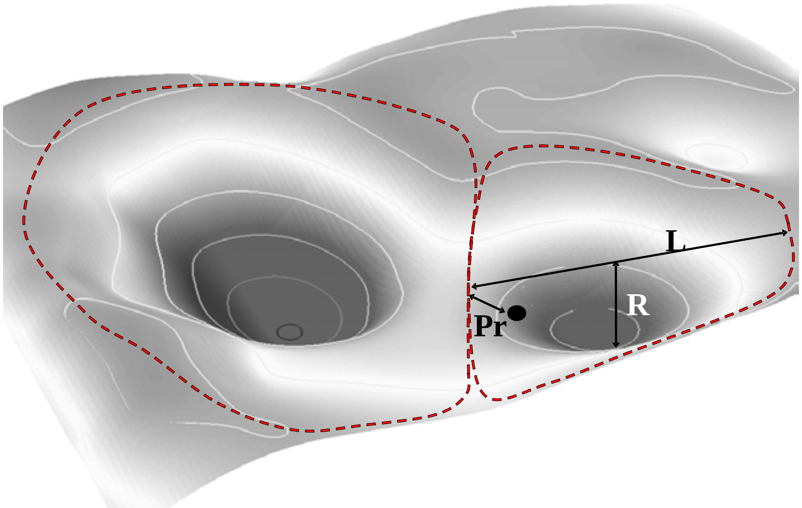

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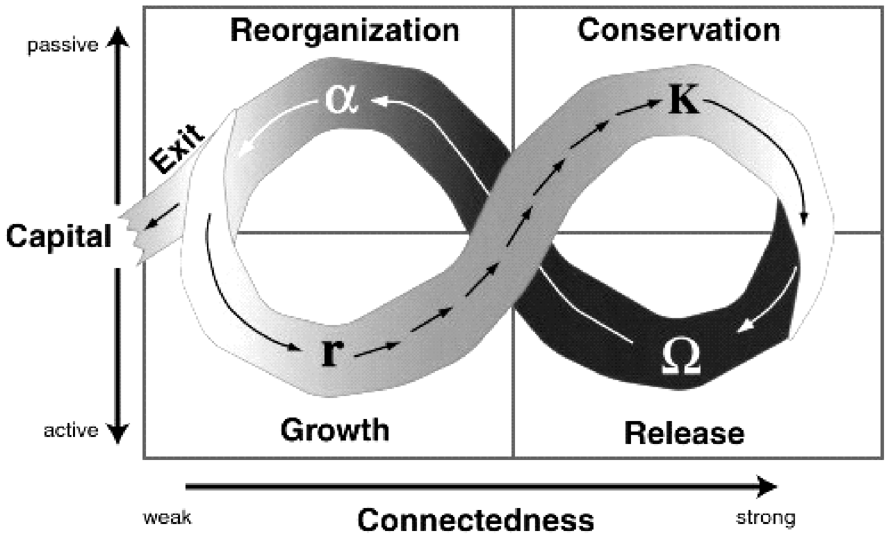

Blackmore & Plant: Figure 5.