Overview of resilience concepts, with application to water resource systems

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eWater Technical Report

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1. This report reviews existing approaches to consider and express system resilience, and discusses possible directions of measuring and maintaining resilience of water resource systems. Management and consumption of water resources involves a dynamic, complex system comprised of subsystems that may be roughly classified as ecological, engineering, economic, and organisational subsystems. In this report, the concepts of resilience commonly used are first reviewed for the following three subsystems: ecological, engineering, and organisational subsystems.
2. In general, ecological systems research has been focused on the interactions between the physical system and natural species, and the concern has been more on the system being in a favorable state, whether the original or an alternative. Due to the complexities of nature and (often profound) human intervention, almost all existing studies express resilience of ecological systems in qualitative terms.
3. Studies on resilience of engineering systems are more focused on the built physical components, with some consideration of human impacts and little consideration of the natural world. Typically the effort concentrates on the impact of low-frequency, high-consequence events and the subsequent system response and recovery. Engineering resilience has generally been able to be expressed in a quantitative way, since built systems are artifacts and their behaviors are more comprehensively understood.
4. Studies on resilience of large institutions (e.g., NASA, transportation systems management) attempt to account for the impact of the adaptive capacity of institutional management and operation on the occurrences of incidences and accidents. It emphasises the importance of constantly monitoring the institutional safety performance, proactively looking for signs of drifting towards fragile situations, and implementing corrective strategies and interventions when necessary.
5. Adequate description of resilience of water resource systems needs to take a synergistic view that takes into account the emergent properties arising from the interaction of the component subsystems. The major concerns for a water resources system – subject to ambient disturbances and at times large shocks – are whether (1) the system

will cease to function; and (2) if recovery is possible, how quickly can it bounce back to a satisfactory condition to service both mankind and the natural environment. Alleviation of both concerns will obviously be helped by the existence of adaptive capacity and management. Therefore, water resource systems resilience should be considered: (1) against a background of slow regime change, and (2) in terms of response and recovery after a shock. Both types of resilience can be modified by the system's adaptive capacity, supported by either endogenous or exogenous forces, or both. A schematic representation of resilience for water resource systems is described in this report.

6. Because of the dynamic and evolving nature of water resource systems, proper consideration of uncertainty and associated information, whether obtained from well-defined numerical data or vague linguistic articulation, are essential for better understanding and proper management of such systems' resilience. This report gives a brief overview of the existing uncertainty and ignorance theories which could potentially be applied to the modelling and resilience assessment of water resource systems.

7. Past and ongoing studies that have attempted to quantify resilience of water resource systems are reviewed. Examples that placed the concept of resilience in practical terms are given as illustration. From this study, it is concluded that resilience could be increased by (1) undertaking a course of action that leaves room for alternatives – especially in cases of irreversibility, options should be kept open; (2) resilience should be expanded to allow a buffering capacity; and (3) cross-scale management and communication should be enhanced in order to get early warnings acknowledged and potentially serious problems dealt with in a timely fashion.

1 Introduction

A water resource system, as discussed in this paper, includes all aspects of the water cycle and its impact on humans, living organisms, and the natural environment. With the looming threat of climate change asserted by the Stern Report (Stern 2007) and the ICPP reports (ICPP 2001 and 2007), as well as increasing demands by a still-expanding global population, the current consumption pattern of freshwater is beyond levels that can be sustained by future supply. A recent assessment estimates that half of the world's population will live in water-stressed river basins by 2025 (Millennium Ecosystem Assessment 2005). In recognition of this, the need for wise use of freshwater and improvement of current water management practices, in order to perpetuate sustainable development of human society and the environment, have become priority tasks to tackle.

Sustainable development, as stated in the Bruntland Report (Bruntland 1987), is development that "meets the needs of the present without compromising the ability of future generations to meet their own needs." To counter the likelihood of future water shortages, the World Summit on Sustainable Development, held in Johannesburg, South Africa, in September 2002, made a commitment (WSSD 2002) of "halving the proportion of people without access to safe drinking water by 2015." The commitment made and implementation activities recommended at the Johannesburg Summit are being taken by the US engineering community (ASCE 2004) to move "beyond Johannesburg." Though significant efforts have been made, much more needs to be done to realise this grand goal

To achieve sustainable development of water resource systems, a key property to consider is resilience (e.g. Carpenter et al. 2005; Walker & Salt 2006). The essential aspect of a resilient system is a system that has adequate capacity to avert adverse consequences under disturbances and therefore has a greater capacity to provide wanted services that support our, and the environment's, quality of life.

The management and consumption of water resources typically involves a number of subsystems such as ecological, engineering, economic, and social subsystems (Pahl-Wostl 2004). Interactions and interdependencies may exist among these subsystems. For example, some or all of them may be dictated or influenced by human regulations and policies such as construction of dams, irrigation, and urban water distribution. Human actions invariably cause disturbances and induce responses, sometimes unexpected, of the subsystems, which may be considered consequently as a complex adaptive system. Resilience of water resource management may thus be considered as an emergent property of its constituent subsystems; the property of a system as a whole cannot be adequately represented by simply summing up that of each subsystem. Traditionally, however, the constituent subsystems have been treated independently in different disciplines.

In general, ecological systems research has focused on the interactions between the physical system and natural species. Even though the effects of both small and large spatiotemporal disturbances have been considered, effort has been concentrated on the effects of small disturbances, and the concern is more on the system being in a favorable state, whether it is the original or an alternative state. Due to the complexities of nature and (often profound) human intervention, almost all existing studies express resilience of ecological systems in qualitative terms. Conversely, studies on resilience of engineering systems are more focused on the built physical components, with some consideration of human impacts and little consideration of the natural world; typically the effort concentrates on the impact of large disturbances (low-frequency, high-consequence events) and the subsequent system response and recovery. Engineering system resilience has generally been able to be expressed in a quantitative way since built systems are artifacts with some degree of certainty in their designed properties, and their behaviors are more comprehensively understood. Studies on resilience of large institutions (e.g., NASA, nuclear power plants, transportation systems management) attempt to account for the impact of the adaptive capacity of institutional management and operation on the occurrences of incidences and accidents. It emphasises the importance of constantly monitoring the institutional safety performance, proactively looking for signs of drifting towards fragile situations, and corrective strategies and interventions being implemented when necessary.

From the discussion above, we see that so far three types of resilience that concern the relationship between human and the natural environment have been considered in the literature: (1) resilience against regime change, (2) resilience for response and recovery after disastrous events, and (3) resilience related to adaptive capacity and management. Studies on resilience of other systems often fall into one or more of these three types of consideration; for example, resilience of economic systems is usually referred to as the ability of an economic body, whether an individual or a society, to recover from or adjust to the negative impacts of external economic shocks (e.g. Briguglio 2004; Rose 2004). In this sense, the concept of resilience in economic systems is partly in line with the consideration in engineering systems and partly with that in institutional management.

Assessment of emergent system resilience requires synergistic treatment of the subsystems as a whole. One objective of this paper is to bring these contrasting but complementary concepts of resilience into the context of the resilience of water resource management characterised by the interaction of socio-economic, technical, and ecological processes. Practical quantitative resilience assessment procedures that take into account associated uncertainty and information are favorable for the purpose of system planning, maintenance, and management.

As previous pointed out, resilience is a key property for sustainable development; however, the process of maintaining system resilience must be dynamic in nature because of the inherent uncertainty and complexity of human behavior and natural systems, and the ability of human society to innovate (Newman 2005). Furthermore, positive feedback that can reinforce a change or trend sometimes leads to accelerating deviation from the expected path of development; we can never have a perfect model to fully predict the future and society is never statically permanent or sustainable. Thus system resilience management is an ongoing process rather than a static, fixed goal.

This calls for a program that indefinitely monitors and adjusts the track which the system heads towards, with every successful adaptation being only a temporary solution to the system operating at the time (Rammel & Van Den Berg 2003).

In the following, the contemporary development of the three types of resilience are first reviewed, followed by an introduction of the classification of uncertainty and information (both of which are invariably present in a dynamic complex system) and the associated existing theories that are able to handle them in a consistent and coherent manner. Efforts of existing research to express resilience of water resource systems quantitatively are surveyed, and then a way of quantifying resilience and potential extension of the developed methodologies are pointed out. Finally, examples of practical application of resilience principles – guided by constantly monitoring system performance, adjusting to the challenges arising, and a willingness to take alternative course of action – are given.

2 Resilience against Regime Change

The resilience of systems against regime change, referred to as "ecological resilience", is most often considered in the study of ecological systems; in the context of water resource systems, it consists of hydrological and ecological components concerned with both the physical environment and living organisms inhabiting the system. This implies that understanding the resilience of the hydrological component alone is insufficient if the associated resilience of species under influence is not taken into account.

Ecological systems are recognised to possess multiple alternative states and disturbances to a system can cause a shift from one state of behavior to another. System resilience against regime change is then defined as the magnitude of disturbance that can be absorbed without flipping into an alternative state. While engineering systems, to be discussed in the next section, emphasise efficiency, constancy, and predictability, ecological systems are typified by persistence, change, and unpredictability (Holling 1973). Resilience against regime change is often shown schematically as in , in which the basins represent alternative stable states and the width of a basin is a measure of the resilience of the system (e.g. Gunderson et al. 2002).

Studies reveal that variability in system performance, diversity in system constituents, and functional overlap and reinforcement are important attributes for maintaining the resilience of a system. Controlling the system performance variability, e.g. regulating water levels in the Everglades via water control devices (Light et al. 1995), encourages the dependence of the system on continued controls while at the same time eroding ecological support, which may lead to the loss of absorptive capacity of the system to a sudden disturbance. Replication of function of constituent elements – across a diversity of similar but different functional groups within and across scales – compensates and reinforces the roles of each element in promoting and maintaining system resilience (Peterson et al. 1998; Holling et al. 2002). In some cases living species evolve to increase their capacity to cope with frequent but inevitable disturbances. For example, if the occurrence of periods

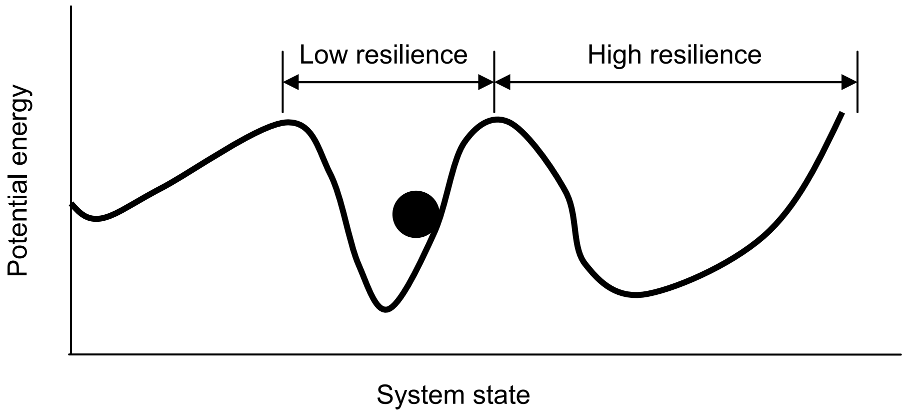


Fig. 1. Schematic representation of system resilience against regime change

without flow in a river is frequent and unpredictable, an aquatic species may evolve to cope with droughts (Begon et al. 1996) in ways that enable them to either re-colonise from other places (e.g. high mobility, weak habitat preferences) if local populations are nearly eradicated, or to survive the disturbance in situ (e.g. clinging to the substratum, streamlined body) (Townsend et al. 1997a, 1997b).

Human activities to intervene and manage a system are critical driving forces for change in ecological resilience. Human intervention causes deterioration of resilience through four major processes (Gunderson et al. 2002): (1) Mining: when the rate of extracting ecosystem capital exceeds that of renewal, the ecosystem is driven to become barren and brittle; (2) Eutrophication: increased run-off of nitrogen and phosphorus from human activities has accelerated the process of eutrophication in freshwater bodies; (3) Modifying key ecosystem relationships: removal of keystone species in a system (e.g. commercial fish species in a freshwater lake) alters the predation pattern of other species; and (4) Reducing temporal and spatial variability: removing some species in an ecosystem results in spatial homogeneity of the kept species, which effects a loss of resilience (Gunderson & Walters 2002). An ecological system is inherently a complex adaptive system governed by four key properties: resilience, complexity, self-organisation, and emergence (Gunderson et al. 2002). Resilience, as stated previously, is the ability of a system to withstand disturbances without shifting into another system state. Complexity results from a variety of elements and components, and their interdependent behaviors, which compose the system. Self-organisation is the ability, due to the interaction of constituent elements, which mutually reinforce or hamper each other; this ability enables the system to re-establish order from disorder after a perturbation. Emergence derives from the nonlinearity of the element interaction and cannot be expressed simply as additive properties of the elements.

Recently quantification of resilience of social-ecological systems has been attempted by the development of resilience surrogates (Carpenter et al. 2005). The main reason for using resilience surrogates rather than direct resilience measures is the acknowledgment of difficulties in measuring the boundaries between stable regimes. Typically, the only way to measure a boundary directly is to cross it; forcing a crossing to occur may be highly costly or unethical, or both. The use of surrogates offers a way to infer, indirectly, the resilience of a social-ecological system. Early exploratory studies have been carried out for resilience surrogates in lagoon system fisheries in Brazil, India, Sri Lanka, and Turkey (Berkes & Seixas 2005), and the impact of infrastructure on forests in the southwestern Amazon region (Cumming et al. 2005). Both studies offer conceptual frameworks for establishing resilience surrogates, but acknowledge that more rigorous efforts in both theoretical and empirical development are needed beyond this earlier stage. Besides, multidisciplinary involvement will be necessary for the concept of resilience surrogate to become operational (Carpenter et al. 2005).

3 Resilience for Post-Disaster Response and Recovery

This type of resilience addresses damage due to external disturbances which could impair the intended service functions of infrastructure, and hence impact on human and natural recovery. After a shock the main concern is to minimise economic and life losses via appropriate, swift responses, and to promote speedy recovery of the affected community back to a viable state. The system under consideration naturally includes the social, infrastructure, and natural components, all of which should be regarded important for the wellbeing of the system.

The earliest, and simplest, concept of resilience in engineering is equivalent to elasticity: i.e. the elastic deformation capacity of an element that, when subject to load, deforms and stores energy and, upon unloading, releases stored energy and returns to its original form. Over time, the concept has been augmented through systems thinking and now is generally understood, according to Bruneau & Reinhorn (2006), to be the ability of an infrastructure to reduce the chances of a shock, to absorb a shock if it occurs, and to recover quickly after a shock. More specifically, a resilient infrastructure is one that shows (a) reduced failure probabilities; (b) reduced consequences of failure, in terms of lives lost, damage, and negative economic and social consequences; and (c) reduced time to recovery (restoration of the system to its normal level of performance).

A conceptual definition of resilience for response/recovery is shown in Fig. 2. If the quality of the system, Q, which varies with time, is taken as a measure, then the performance can range from 0% to 100%, where 0% means no service is available and 100% means there is no degradation in service. If an adverse event of magnitude *m* occurs at time t_0, it could cause system damage such that the quality of service is significantly compromised. Restoration of the system will occur over time for a period of time, t_m, as shown in Fig. 2, when the system is fully restored. The loss of system resilience, L_R, may be quantified by the size of the expected degradation in service over time until full recovery; i.e.

$$L_R = \int_{t_0}^{t_0+t_m} \left[100 - Q(t)\right] dt \qquad (1)$$

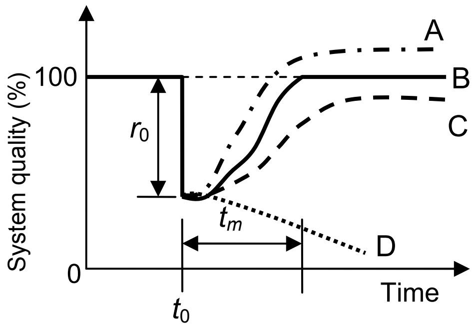


Fig. 2. Conceptual definition of system resilience for response/recovery. Time interval t_m is for case B. Cases A–D are described in the text.

Note that the two parameters that affect the magnitude of L_R are the time to satisfactory recovery and the residual quality of the system. This definition is consistent with the objective of infrastructure to provide a desirable service to society, which focuses on reduced loss of the service and subsequently rapid recovery of the system. Note in Fig. 2 that a community may not necessarily return to its original state (as it does in case B) after a disaster. It may exceed it because of effective recovery planning, substantial inflow of disaster assistance, or taking advantage of opportunities by fixing pre-existing problems (case A). On the other hand, it may suffer some permanent loss and equilibrate below the original state (case C). The worst case is that the community suffers almost total destruction and rebuilding is deemed unviable (case D). Moreover, recovery may be a long-running, multifaceted process without a distinct beginning or end. The more time that has passed after a disaster, the more difficult it is to identify specific activities of recovery, which in turn makes it difficult to define when the recovery process has stopped.

Infrastructure and urban ecosystems interact dynamically and evolve over time through physical and socio-economic processes. Therefore, a definition of resilience should be able to account for the ability of both physical and socio-economic systems to withstand disturbances and to cope with impacts through situation assessment, rapid response, and effective recovery strategies. These may be measured in terms of reduced failure probabilities, reduced consequences, and reduced time to recovery. Resilience for both physical and socio-economic systems, therefore, consists of the following properties (Chang & Shinozuka 2004):

- Robustness: The strength or ability of systems to withstand a given level of stress or demand without suffering unacceptable degradation or loss of function;
- Redundancy: The availability of elements or systems that are substitutable and can be activated when disruptions due to disturbances occur;
- Resourcefulness: The capacity to identify problems, establish priorities, and mobilise resources in the event of disruptions. It can be further conceptualised as consisting of the ability to apply material and human resources to meet established priorities;

- Rapidity: The capacity to meet priorities and achieve goals in a timely manner.

Of these properties, robustness and rapidity can be viewed as the desired ends for a resilient system, whereas redundancy and resourcefulness are the means to support the desired ends.

Resilience is also conceptualised as encompassing the following interrelated dimensions (Chang & Shinozuka 2004):

- Technical: The ability of physical systems to perform to desired levels when subject to disturbances;
- Organisational: The ability of organisations or governing bodies that manage the system and have the responsibility for making decisions and taking actions that contribute to achieving the properties of resilience;
- Social: The measures designed to lessen the extent to which the systems and society suffer negative consequences due to loss of services as a result of adverse events;
- Economic: The capacity to reduce both direct and indirect economic losses resulting from adverse events.

Eq. (1) suggests a quantitative measure for loss of resilience. Conversely, resilience may be also directly quantified in a probabilistic way as follows.

Let q^* and t^*, respectively, be the predefined allowable losses of system quality (related to robustness) and maximum acceptable disruption time (related to rapidity). If resilience refers to a capacity for dealing with potential future events, it may be estimated as the probability that the system will meet predefined performance standards *S*. Therefore, for a given scenario event of magnitude *m*, the resilience given the occurrence of this event, R_m, may be estimated by

$$R_m = P(S \mid m) = P\left(q_m < q^*\right) \cap P\left(t_m < t^*\right) \tag{2}$$

where q_m and t_m are the reduction of system quality and the time taken for full recovery, respectively, of the system after the event of magnitude *m*, and $\cap$ means the intersection of the events $q_m < q^*$ and $t_m < t^*$.

If the entire range of possible adverse events is considered, then the resultant system engineering resilience R_r may be expressed as the total probability of meeting the performance standards *S* as follows,

$$R_r = \sum_m P(S \mid m) P(m) \tag{3}$$

It is clear from the above discussion that the definitions of performance standards and allowable losses of the system performance and time to satisfactory recovery are pivotal to the quantification of resilience. These definitions, ideally, should be developed in deliberation with decision-makers, stakeholders, and other end-users, rather than by the analysts alone. This may require opinion surveys and consensus-seeking discussion.

As an example to show how the concept of resilience outlined above may be employed, the performance measures and standards for a hypothetical water supply system are given in Table 1.

Table 1. Example performance measures and standards.

Dimension	**Performance measure**	**Robustness**	**Rapidity**
Technical	Water supply physical system	≤ 2 major pump station loses function	< 1 week until all pump stations working
Organisational	Water service	< 5% of population loses service	< 1 week until 99% of population serviced
Social	Population living at home	< 5% of population displaced from homes	< 2 weeks until 99% of population living at home
Economic	Economic activity	< 5% of gross regional product (GRP) lost	< 1 month until return to 99% of GRP

Quantification of resilience may be carried out in tandem with risk and loss analysis, as shown schematically in Fig. 3. Since resilience in this context is defined in terms of the probabilities of events and economic impact, the outcomes in various steps of risk and loss estimation could be used as inputs to the evaluation of resilience, as depicted by the dashed lines in Fig. 3.

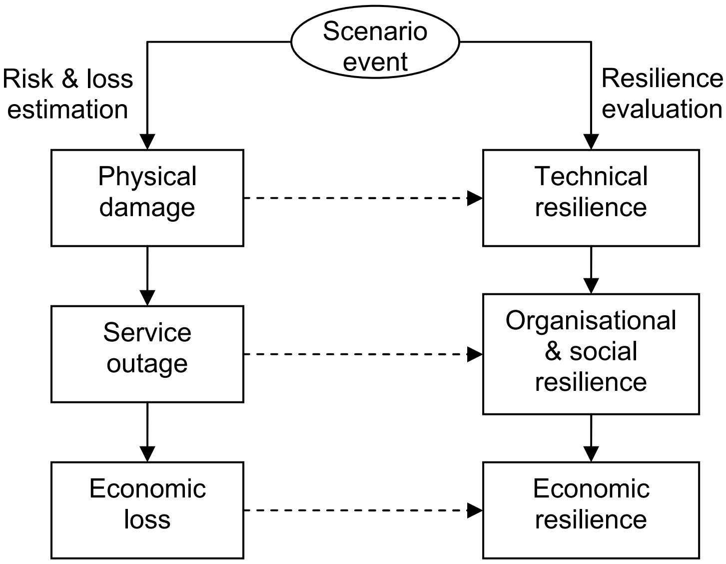


Fig. 3. Conceptual steps for evaluation of system risk, economic loss, and resilience given the occurrence of a scenario event (adapted from Chang & Shinozuka 2004)

4 Adaptive Capacity and Management

Around 1950, researchers and practitioners involved in accident analysis for social-technical systems and organisations found the causes of accidents were primarily related to technology and equipment. As technology and equipment improved, the major blame for accident occurrence since the 1970s has been largely shifted to human performance (Hollnagal 2004). The Three Mile Island nuclear accident in 1979 marked the emergence of organisational factors as an important source of accidents (Hollnagel 2004). The number of accidents attributed to technology has been falling steadily due to continuing improvement in engineering and manufacturing, whereas the number attributed to organisational factors has been increasing. The reason is that systems and organisations have become ever more complex, with interactions among the components generally exhibiting nonlinear and emergent, rather than simply linear, resultant behavior.

Classes of resilience emerge from studies of incidents and accidents in large social-technical systems and organisations such as the nuclear power industry, railway systems, health care systems, and NASA (e.g. Hollnagel et al. 2006). Since the consequences of a major accident in social-technical systems usually involve large economic loss and, more tragically, human deaths, it is desirable that such a system has the ability to preempt, and to some extent avoid, the occurrence of major mishaps. In light of this, system resilience related to adaptive capacity and management, the so called “institutional resilience” or “organisational resilience” (Hollnagel et al. 2006), emphasises proactively monitoring the effects of existing management and operational approaches to system performance, and adjusting the approaches if an audit indicates a drift towards the boundary between safe and unsafe regions. In this sense, a system is resilient if it is able to recognise, adapt to, and absorb variations, disturbances, and surprises.

The concept of resilience based on adaptive capacity is schematically represented as shown in Fig. 4. An institution is essentially a social-technical system whose dynamic nature is due to the variability of the environment in which it operates and the variability of its constituent subsystems. Therefore the essence of this type of resilience is the system’s ability to maintain a dynamically stable state that allows continuing operation after an accident or in the presence of ongoing stress. To achieve this, resilience of a system should encompass the following three potential states:

- The ability to foresee and prevent adverse events from happening, the so called “requisite imagination” (Adamski & Westrum 2003; Hollnagel 2004). There are two basic types of foresight. The first refers to learning from experience, by which a system is programmed to remember the lessons learned. The second is related to awareness and response to symptomatic events, drifting trends, and some intelligent speculation, by which a system is able to proactively detect potential disastrous events and eliminate them before they materialise.
- The ability to prevent an adverse event from becoming worse by responding quickly or revamping itself in the midst of trouble. This requires the system to be adaptive enough to take an unusual course of action in

coping with an ongoing event, or to be able to mobilise available resources to combat and contain the event's development.

- The ability to recover from a disastrous event. The emphasis is on minimisation of loss and speed of recovery to an operational state, often a function of the scale of damage and the probability of the event's occurrence.

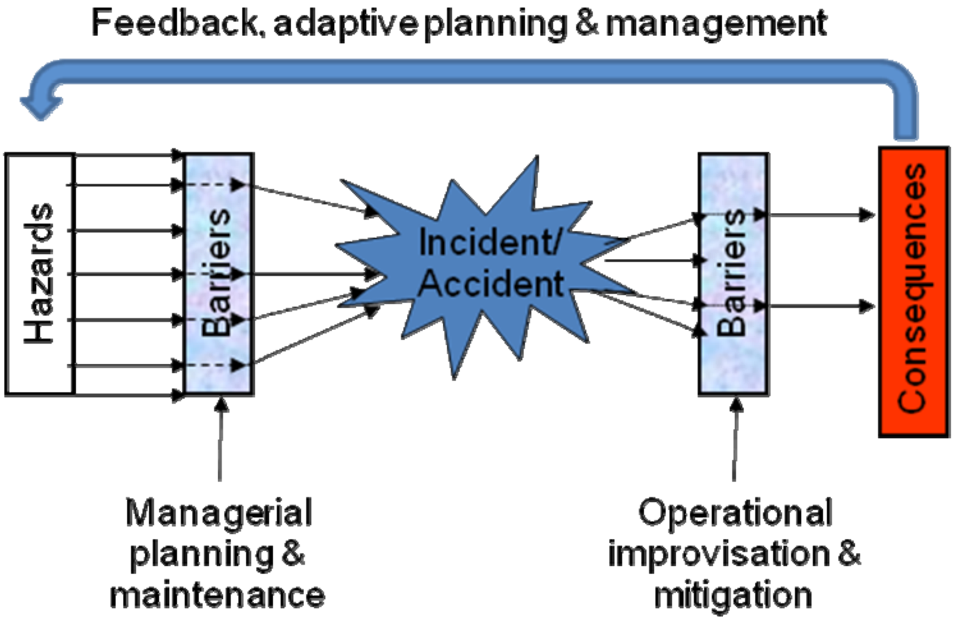


Fig. 4. Schematic representation of system resilience for adaptive capacity/management.

One important driving force of social-technical systems in relation to resilience is the pressure to be "faster, better, cheaper", which puts organisations under fundamental pressure from stakeholders (Woods 2003). This pressure demands that systems increase their performance with reduced resources while at the same time meeting shorter production schedules. Experience has shown, however, that this type of policy often leads to cutting costs, personnel, and product development time while trying to sustain the same level of "success" as before. The result is a gradual erosion of safety margins and a drift towards unsafe boundaries. Even at times when some improvement, e.g., new technology, is made to fulfil the "better" goal, it is exploited when in place to meet performance and efficiency demands. It is clear, therefore, that the "faster, better, cheaper" policy conflicts with safety and desired resilience, as illustrated by the US health care policy to simultaneously achieve the following six conflicting goals: safety, effectiveness, patient-centeredness, timely treatment, efficiency, and equitable access (IOM 2001). Achievement of all the conflicting goals at the same time is, obviously, a mirage. The question now rests on how to make a balanced trade-off across these goals. In the case of health care, the goals may be classified into two categories: acute goals (timely treatment, efficiency, effectiveness) and chronic goals (safety, patient-centeredness, equitable access) (Gehman 2003). One potential difficulty is that efforts made to advance the acute goals often result in a sacrifice of the chronic goals, and vice versa.

Often the decision is made to value acute goals over chronic ones, which results in riskier operations. An explicit guideline is needed on how to make balanced trade-offs, so called sacrifice judgments (Woods 2000), in order to achieve a level of acceptable safety and desired production. It is argued, therefore, that a resilience paradigm should be able to provide the means for doing this.

The discussions above reviewed the concerns of system resilience in various disciplines for a range of systems, and concluded that at present three types of resilience have been defined: (1) resilience against exceeding the failure threshold; (2) resilience for system response and recovery after negative impacts; and (3) resilience for adaptive capacity and management. This indicates that system resilience is a family of ideas, not a single thing. Contrasts and comparisons of the three types of resilience are tabulated in Table 2. Considerations of the ways in which systems can perform produce different types of challenges, which in turn call for various metaphors of resilience. A system that is deemed resilient against regime change may, on the other hand, be not so resilient in its response and recovery to a disastrous event (it takes more time and resources than desired to recover to an adequately functional state).

Table 2. Comparison of attributes of the three types of resilience.

Attribute	Resilience against regime change	Resilience for response/recovery	Resilience for adaptive capacity/management
Definition	Magnitude of disturbance that can be absorbed without flipping into an alternative state	Speed or rate of system recovery after disturbances	Ability to preempt and avoid major mishaps in institutions
Objective	Positioning the system in a favorable regime (original or alternative)	Returning the system to an operational status in the original regime	Reducing incident and accident occurrences, and impact if occurred, in institutions
Emphasis	Persistence, change, unpredictability	Efficiency, constancy, predictability	Proactively monitoring the effects of existing management and operational approaches
Controls and factors	Slow and fast variables	Slow and fast variables	Management and operational variables
Concern	Small and large disturbances	Concentrating on low-frequency, high-consequence disturbances	Disturbances originated from organisational management and operation
Assessment	Mainly qualitative	Mainly Quantitative	Rules and operational procedures

5 Schematic Representation of Resilience for Water Resource Systems

Although the adaptive capacity and management of an institution has been treated as a type of resilience, in water resource systems it may be better treated as a parameter of the other two types of resilience.

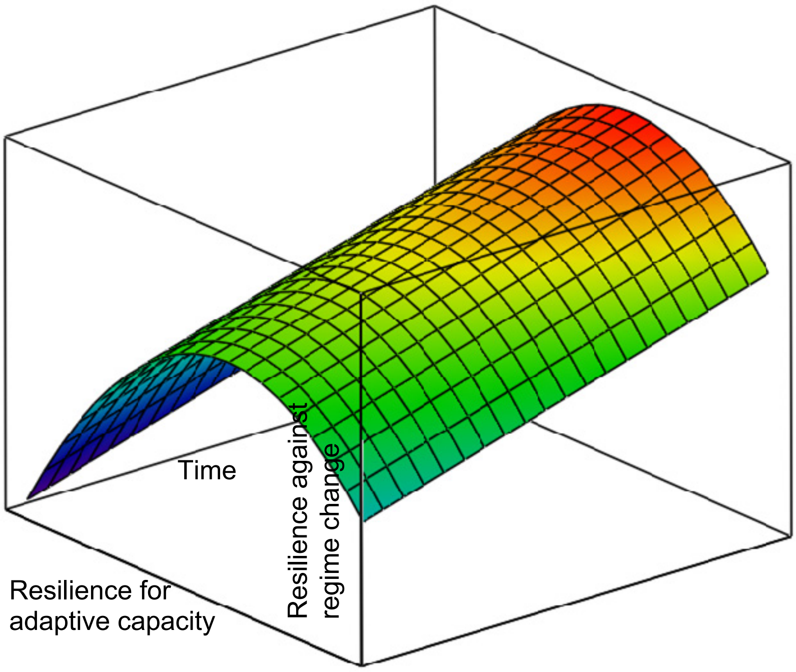
For a water resources system, which supplies the needs of dynamically changing urban/ecological communities and which are subject to ambient disturbances and at times large shocks, the major concerns are whether: (1) the system will cease to function; and (2) if recovery is possible, how quickly it can bounce back to a satisfactory service condition (for both humans and the natural environment). Alleviation of both concerns will obviously be helped by the existence of adaptive capacity and management.

Therefore, we believe that resilience should be considered for water resource systems in terms of: (1) how well it resists slow regime change, and (2) how well it favours response and recovery after a shock. Both types of resilience can be modified by self-organisation, redundancy, human actions and governance, etc.; therefore, they are dependent to some extent upon the system's adaptive capacity, supported by either endogenous or exogenous forces, or both.

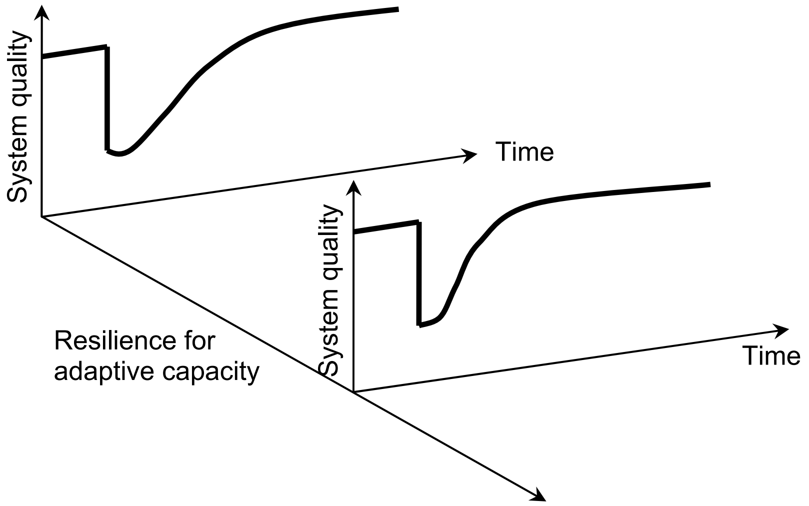
Assuming that relationships between the two types of resilience and adaptive capacity exist, and all of them can be quantified, then assessment of system resilience may consist of the following two steps: (1) estimate the resilience against regime change; and (2) estimate the resilience for disaster response and recovery.

Fig. 5 shows schematically the evaluation of the two types of resilience, both of which are functions of time and the level of system adaptive capacity. To enable an assessment shown in Fig. 5, significant research efforts would be needed, the most important of which are as follows:

- Modelling the uncertainty, information, knowledge, and ignorance with respect to a water resource system;
- Quantitative expression of the system's adaptive capacity;
- Measurable and understandable definition of the system's threshold against regime change;
- Relationship between the system's adaptive capacity and the two types of system resilience;
- Quantitative expression of the resilience against regime change.



(a) Resilience against regime change



(b) Resilience for response and recovery

Fig. 5. Conceptual steps for system resilience assessment.

6 Modelling Uncertainty, Information, Knowledge, and Ignorance

Typical water resource systems are nondeterministic, involving some uncertainty and possibly ignorance which should be properly incorporated and treated in any analytical description of the system. This section gives a brief overview on the existing uncertainty and ignorance theories which could potentially be applied to the modelling and resilience assessment of water resource systems.

As asserted, the complexity and component interactions that characterise an ecological-technical-social system make certain prediction of future system behavior impossible. Furthermore, because of inevitable ignorance, either nonintentional or intentional, there will be aspects of the system that are unknown to us. That is, complex adaptive systems have emergent behavior that cannot be satisfactorily predicted by understanding and modelling separately the individual properties of its constituent components. Instead, a water resource system is better considered as having emergent properties that encompass the resilience of its subsystems; in this way an assessment of resilience might be useful for the system planner and manager. We need practical quantitative resilience assessment procedures that take into account associated uncertainty and information for system planning, maintenance, and management. Quantitative assessment of resilience thus requires proper consideration of knowledge and information, and sometimes the subjective opinions of experts.

Treatment of uncertainty has traditionally been achieved by applying probability theory, which is perfect for problems with crisp sets and elements having unique memberships of those sets. The forms of information gathered, however, are likely to range from well-defined numerical to vague verbal articulation. Under these circumstances, classical probability theory is no longer adequate. Fortunately, the concept of uncertainty has been augmented from the classical probabilistic paradigms through the generalisation of two important aspects. One is the generalisation of classical measure theory, which is based on the requirement of additivity, to generalised non-additive measures (Choquet 1953–54). The second is the generalisation of classical set theory to fuzzy set theory (Yen & Langari 1999), a move that abandons the requirement of crisp boundaries of classical sets. These generalisations expand substantially the framework for formalising uncertainty and result in development of a number of new theories of uncertainty (Klir 2006; Zadeh 2005): possibility/necessity theory, monotone measures, belief/plausibility theory, imprecise probabilities, evidence theory, interval probabilities and analysis.

Uncertainties of a complex, emergent system arise from a number of sources. Uncertainty in engineering analysis and design is typically classified as (e.g. Ang & Tang 2007): (a) Aleatory uncertainty, which represents inherent randomness attributed to the physical world because it cannot be reduced or eliminated by enhancing the underlying knowledge, e.g. tensile yield strengths of steel and wood belong to this type of uncertainty; (b) epistemic uncertainty, which is the uncertainty due to lack of complete knowledge and therefore could be reduced if the state of knowledge were improved. This classification, however, is still insufficient in completely characterising the nature of uncertainty and covering all its aspects. The difficulty stems from the complex nature and the existence of uncertainty at all the hierarchical levels of a system.

For analysis and design, a complex system needs to be modelled by an abstract representation. The process of modelling and abstraction is largely dependent on the analyst who is to perform the analysis: i.e., the analyst needs to decide what aspects should or should not be included in the model. Therefore, uncertainty could come from two sources: abstracted aspects that the analyst takes into consideration and non-abstracted aspects that the analyst chooses to brush aside. Contribution of non-abstracted aspects to uncertainty due to deliberate inattention is sometimes termed conscious ignorance (Smithson 1985). In addition to the abstract and non-abstract aspects of a system, there may be unknown aspects of the system that result from the unawareness of the analyst, the so called blind ignorance (Ayyub & Klir 2006) or meta-ignorance (Smithson 1985). Aspects neglected due to blind ignorance are more difficult to deal with because of their unknown nature, sources, extents, and impact on the system.

The division between the three aspects of a system (i.e., abstracted, non-abstracted, and unknown) may be driven by the objectives of system modelling, or simplification of the model, or simply the knowledge base of the analyst.

The sources of uncertainty from the abstracted and non-abstracted aspects of a system may be classified as follows (Ayyub & Klir 2006):

- Inconsistency: Distorted information because of wrongful substitution (confusion), bias and distortion (inaccuracy), or contradictory assignments (contradiction).
- Ambiguity: The possibility of having multiple outcomes. It could be further divided into two types of uncertainty:
    - Unspecificity: The identified list of outcomes might be only a partial list of all credible outcomes; i.e. incompletely defined.
    - Nonspecificity: The identified outcomes may not all be credible outcomes; i.e. erroneously defined.
- Approximation: Resulting from use of vague semantics and approximate reasoning. It includes
    - Vagueness: Imprecise belonging of elements to a set.
    - Coarseness: Approximating a crisp set by subsets of an underlying partition of the set's universe that bounds the crisp set of interest.
    - Simplification: Assumptions introduced to make problems solvable.
- Likelihood: Characterised by inherent randomness of properties and acquisition of samples instead of the underlying populations.

Modelling uncertainty originating from an array of disparate sources is a challenging task, if not impossible. A range of mathematical theories that are capable of modelling different types of uncertainty is needed.

At present, development of theories for uncertainty modelling is an active research area (e.g. Zadeh 2006; Klir 2006). Theories that have matured to a stage of being practically applicable include: classical sets, fuzzy sets, rough sets, probability and Bayesian theories, evidence theory, possibility theory, monotone measure, interval probability, and interval analysis. In general, the applicability of these uncertainty theories to the types of uncertainty described above is roughly as follows (Klir 2006; Ayyub & Klir 2006):

- Inconsistency: Probability, evidence, possibility, interval probability and analysis.
- Ambiguity: Classical sets, probability, Bayesian, evidence, interval probability and analysis.
- Approximation: Fuzzy sets, rough sets, probability, Bayesian, possibility, interval probability and analysis.
- Likelihood: Probability and Bayesian.

A complex system such as a water resource system typically involves uncertainties of some or all of the types elucidated above (Dewulf et al. 2005; Brown & Lall 2006). An important step is to synthesise the uncertainty and information gained, and to understand how they propagate through the system.

7 Review of Quantitative Water Resource Systems Resilience

Since water resources and water supply systems are vital to the natural environment and human society, there have been a number of studies, some as early as the 1960s, on robustness and on developing quantitative resilience of such systems.

The most widely used and cited definition of resilience of water resource systems may be the one by Hashimoto et al. (1982), though a similar concept has been applied earlier to show the sensitivity of a water supply system to drought (Fiering 1969), and water resources system robustness and resilience with respect to data collection programs (Matalas & Fiering 1977). Hashimoto et al. (1982) defined resilience as the average probability of recovery at time step $t+1$ from a failure state at time *t*. By this definition, the higher the probability of recovery, the higher the resilience; therefore, in essence it represents the rapidity of the system returning to a satisfactory state after an occurrence of failure (i.e. resilience for system recovery). Moy et al. (1986) used the maximum time duration of failure as a measure of resilience; the longer the duration, the less resilient the system. Moy's definition of resilience obviously is monotonic with respect to the duration of records; i.e. it guarantees a longer period of records will have a resilience measure less than or equal to that given by a shorter period of records. Kundzewice & Kindler (1995) argued that a measure using the maximum duration is better than one using the average value, for the presence of insignificant events will lower the average value and may lead to a non-monotonic measure. Kjeldsen & Rosbjerg (2004) showed that the relationship between resilience measured using the maximum duration of failure and the volume of water taken indeed exhibits monotonic behavior, but it does not when resilience is represented by the average duration of failure. Though monotonicity may be a preferred property, and it is typically observed that a sustained period of failure causes greater negative impact than a series of shorter, intermittent failures, Srinivasan et al. (1999) further argued that neither Hashimoto's nor Moy's definition alone expresses resilience satisfactorily. As an example similar to one presented in Srinivasan et al. (1999), let *F* denote a failure time interval and *O* an operational time interval. Consider the following two scenarios with the same number (6) of failure intervals out of a period of 18 intervals:

Scenario 1:

$$\left(O \quad O \quad F \quad F \quad F \quad O \quad O \quad O \quad F \quad F \quad F \quad O \quad O \quad O \quad O \quad O \quad O \quad O\right)$$

Scenario 2:

$$\left(O \quad O \quad F \quad F \quad F \quad O \quad O \quad F \quad O \quad O \quad O \quad F \quad O \quad O \quad O \quad O \quad F \quad O\right)$$

Because both scenarios have the same maximum number of consecutive failure periods (3), Moy's definition would assess the resilience of both of them to be the same, whereas Scenario 2 would be a preferred one according to Hashimoto et al. (1982) as it shows a higher recovery rate and would generally result in a less adverse impact. In this regard, it makes sense if the two variants of resilience can be considered alongside one another. The resilience measure by Hashimoto et al. (1982) has been used, for instance, to study the response of dissolved oxygen in the Willamette River, Oregon (Maier et al. 2001), and in scenario analysis to examine the performance of the water resources system in Yorkshire, England (Fowler et al. 2003). Kjeldsen & Rosbjerg (2004) studied the monotonic behavior and the reliability–resilience–vulnerability relationship of the two alternatives.

Rather than focusing on system recovery after disturbances, Fiering (1982a) suggested a number of alternative definitions of resilience that take into account the size and landscape of a basin, a metaphor of the regime in which the system resides. In principle, Fiering's (1982a) definitions were proposed on the basis of the following two categories:

- A resilience measure based only on the threshold of the system regime. In this case, the measure of resilience is proposed to be the average distance of a ball anywhere in a basin to the nearest boundary of threshold. For example, if the threshold boundary is circular and of radius *r*, then the average distance of the ball to the boundary is $r/3$. Note that this type of measure does not consider the rate of change of the ball's position, but consideration of change of the shape of the threshold boundary over time is possible.
- A resilience measure considering the size and shape of the basin and the effect of time. By dividing the state basin into a set of concentric regions, the system's movement can be further classified into three types of movement: transitioning from one region to another in the basin, migrating to another acceptable basin, and reentering the basin. Regardless of whether such classification of movement is reasonable, the essence is to employ the concept of Markov chains for the solution. Therefore, the state transition probabilities, steady-state probabilities, mean residence time in the basin, and time of first passage to the threshold were used explicitly for defining 11 alternative resilience indices (Fiering 1982a). Fiering went on to use Monte Carlo simulation to determine how well the resilience index can be estimated without performing a tedious and expensive simulation for

each new reservoir configuration or each new hydrologic regime (Fiering 1982b). He applied canonical correlation analysis (e.g. Anderson 2003) in an attempt to define how a linear combination of a set of output variables (system performance indices) might best be estimated from a linear combination of input variables (basin descriptors) and, in addition, suggested one more resilience index to account for the geographic location of a reservoir and the connection between the reservoir and its upstream neighboring reservoir (Fiering 1982c).

While Fiering proposed a significant number of resilience indices and undertook a respectable amount of work to investigate the efficacy of them (Fiering 1982a, 1982b, 1982c), unfortunately, to our knowledge, little follow-up work has been carried out.

According to their respective definitions, it is fair to say that the resilience measures of Hashimoto et al. (1982) and Moy et al. (1986) are representative of resilience for response and recovery after damaging events, while those suggested by Fiering (1982a, 1982c) conform to the line of resilience against regime change. Studies of the effect of adaptive capacity on the resilience of water resources systems, however, are still lacking. It is not accidental that acknowledgment, at global and regional scales, of the lack of access to water of sufficient quantity and quality arises not only because of technical and environmental problems but also largely from the absence of effective and adaptive governance. This calls for actions from many people, ranging from those in water management and policy making to those involved in public knowledge and participation (Newig et al. 2005); it led to the creation of the World Water Council (WWC 2007) and Global Water Partnership (GWP) (GWP 2007), both established in 1996 to promote sustainable Integrated Water Resources Management (IWRM) based on regional governments and public participation. An IWRM defined by the GWP is “a process that promotes the coordinated development and management of water, land and related resources in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” (GWP 2006).

Some initiatives attempting to make the principle of IWRM practical for policy planning and management have taken place. One example is the establishment of the eWater CRC joint venture in Australia whose mission is to “build and deliver the next generation of water management decision tools needed to efficiently manage Australia’s increasingly scarce surfacewater and groundwater resources, in both urban and rural catchments.” The *Water for a Healthy Country Flagship* within CSIRO, Australia, also has a component on resilience and sustainability of urban water systems (Blackmore & Plant 2008). Another example is an EU-funded NeWater project (*New Approaches to Adaptive Water Management under Uncertainty*), whose task is “… to understand and manage the transition process towards more adaptive water management regimes given the high interconnectedness and complexity of riverine water systems” (Pahl-Wostl et al. 2005). It sets out the objectives of developing a conceptual framework for understanding and a comprehensive methodology and a range of tools for analysing and implementing transitions to adaptive water management.

8 Qualitative Resilience Concept in Action

The previous section reviewed the development of quantitative resilience in water resource systems. In the following subsections we discuss two examples of application of a qualitative concept to resilience: the salinity crisis of a catchment, and the transformation of a sheep farm into a plant/seed farm with a beef cattle enterprise. We then present a case of bushfire, the risk of which is tipped to go up in Australia, a country in the firm grip of drought over the last decade, because "…there are clear links between summer droughts and bushfire incidence…" (van Dijk et al. 2006), and we point out the direction of studies on resilience of water resources affected by bushfires.

8.1 Salinity in Goulburn–Broken Catchment, Victoria, Australia

The Goulburn–Broken Catchment (GBC), covering about 2400 km^2, is located in the northeast of the state of Victoria and belongs to the Murray River Basin, the largest and most important river system in Australia. Though the land area of the GBC is only 2% of the Murray River Basin, the GBC contributes about 11% of the water flow of the Murray River. The fertile plain of the GBC was noticed in the 1830s when the first European settlers arrived and ever since it has been one of the most important agricultural areas in Australia. With a current regional population of about 200,000, its economy is based primarily on irrigated dairy, horticulture, and food processing, accounting for 25% of Victoria's export earnings (Anderies et al. 2006).

Prior to European arrival, the catchment was covered by native, deep-rooted woody vegetation that maintained the hydrological balance of the region. Over time, 70% of the land has been cleared for shallow-rooted crops and pastures, with the remaining 30% mostly in mountainous terrain in the upper catchment and in small strips along waterways and roadsides. Within the irrigation region, less than 2% of land is covered by native vegetation.

The most serious problem now facing the GBC is rising water table levels, which bring to the surface dissolved salt (previously carried inland by wind and which over time has accumulated in the soil strata); some areas are estimated to have up to 15,000 tonnes of salt per hectare. Prior to European settlement, the water table was about 25 to 50 m under the ground. Now, because deep-rooted woody vegetation has been largely replaced by shallow-rooted crops and pastures, and because irrigated water adds to that from rainfall, water infiltration has significantly increased, meaning that water tables have risen.

The past deep water table served as a buffer to absorb fluctuations in rainfall and prevented rising salt, but a wet phase in the 1950s brought the water table to within 5 m of the surface. Another wet phase in the 1970s effectively eliminated the buffer by bringing the water table to a critical level of 2 m below the surface in some areas. This has resulted in large production losses for dairy pastures, high-value horticultural crops, and some stone fruit crops. It was assessed (BGRSAC 1989) that more than half the irrigation region (about 274,000 ha) is at risk from high water tables. If the problem is not addressed, annual economic losses could reach A$100 million, 50% of remaining woody vegetation cover might be threatened, and 40% of wetlands could be impacted by 2020.

Crisis spawns actions and opportunities. The opportunity that the 1970 wet period revealed was to seriously examine whether to keep the current trajectory of intensive farming or to transform the region into other economic forms. The first response to address the problem of rising water tables, however, was to use groundwater pumps to keep the water table down so that the farmers could keep on with their existing practices of intensive irrigation farming. As a result, the opportunity was lost to transform the region to an alternative that would avoid the encroaching salinity problem.

The pumped water was discharged into the Murray River, which in turn became salinised, adding to its already deteriorating water quality. It was conceded there should be wider coordinated actions to address the multitude of problems across subcatchments. The Murray–Darling Basin Commission (MDBC) was subsequently established in 1986, a state and federal government partnership agency in charge of the water management in the Murray–Darling catchment. Prior to the Commission's establishment, centralised government control with little input from local communities was the norm for crisis management. The Commission recognised the value of input from regional communities and encouraged their involvement in decision-making. The management model of the Commission was considered a revolution in natural resources crisis management in Australia and subsequently many similar catchment management authorities were established around the nation (Langford et al. 1999).

The reforms implemented by the Murray–Darling Basin Commission to engage the regional communities fostered high adaptability to crises and, luckily, after the 1970s crisis, persistent drier-than-average rainfall patterns kept the water table under the 2-m critical threshold, and the GBC had been able to sustain regional vitality and a productive base. Because of the seemingly successful outcomes and improved water-use efficiencies, as well as engineering solutions, all efforts have been directed at getting back to business as usual. Nevertheless, MDBC has been unable to reestablish a significant water table buffer to cope with future wet phases (Power et al. 1999), and the "solution" only reinforces the problem, locking the region into even bigger crises down the track. It has been a failure in this account to fully acknowledge the underlying cause of the problem and to explore alternative futures for the region. Catchment communities responded to the crisis by spending all their efforts to keep irrigated dairy running rather than by asking: "Is irrigated dairy farming a logical business in the GBC, given the adverse bio-hydrological factor that inevitably threatens the system? If not, what changes would move the region to a more reasonable, sustainable economic basis?" Some studies (e.g. Anderies 2005) suggest that the most environmentally viable long-term solutions are groundwater pumping and large-area woody revegetation; but these are economically unattractive primarily because water is valued too low for revegetation and uses other than agriculture. Effective policy for salinity management, therefore, must include mechanisms to increase the value of water in uses other than irrigated agriculture to achieve sufficient long-term revegetation (Anderies 2005). Some immediate practical options may involve a combination of switching from the higher water uses of crops and pastures to lower water uses of horticulture, gradual revegetation of the catchment, pumping, and development of high-value land use that does not require irrigation.

The example of the GBC salinity predicament, and the associated response of federal and state governments and regional communities, demonstrates that adaptability within the current state of affairs is necessary, but may not be sufficient. Transformability of a system to an alternative state in which it functions more sustainably needs to be recognised and implemented when circumstances arise, such as in the GBC crisis. The following section shows an example in which adaptability and transformability were both utilised after a drought-related crisis, a coping strategy and response that showcases the essence of dynamic sustainable development.

8.2 Drought on Lyndfield Park, New South Wales, Australia

This exemplary case is about the transformation of Lyndfield Park, a 356-ha (about 900-acre) farm in the southern tablelands of New South Wales, Australia (Weatherstone 2003). Prior to 1982, Lyndfield Park was a grazing property, with the main enterprise of herding merino sheep. The owner employed the best knowledge and practice at the time for farm plan development, focusing on improving pasture, lifting the farm stock rates, and experimenting with new crops. Though all the efforts produced a significant rise in short-term productivity, some problematic symptoms emerged over time (Weatherstone 2003): (1) Deteriorating soil structure due to over cultivation; (2) soil erosion due to structural decline and loss of organic matter; (3) declining response to fertilisers; (4) increasing salinity; (5) reduced number and species of native biota; and (6) increasing incidence of new pests and diseases. All of these signs went either unrecognised or ignored until a severe drought in 1982–83 that turned the property into a barren dustbowl with literally no grass. With his livelihood at stake, the owner accepted that “traditional farming practices were placing large stresses on the land, and limiting its ability to cope with environmental stresses such as drought,” and began to address those symptoms.

The major changes made following the break of the 1982–83 drought were: (1) Reducing stocking rates to allow the land to heal and for soil organic matter to rebuild; (2) planting a diversity of trees and shrubs to protect both livestock and soils; (3) reducing the amount of cropping; (4) treating eroded areas and preventing further erosion; and (5) establishing perennial pastures for better water use, soil protection, and livestock productivity. After 20 years of moving away from traditional practice and implementing these changes, the farm became a native plant and seed farm with a beef cattle enterprise. Compared to its past, the farm was assessed to be a healthier and more pleasant environment to live and work in, and worth more. The eastern part of Australia, including the region in which the farm is situated, has now been undergoing another severe drought, believed to be the most serious in 100 years; however, the owner expressed his confidence in facing this drought by saying that “the changes… have gone a long way to protecting us from stresses that go hand in hand with farming.” His attitude was to “…listen to the land, respond to its needs, be prepared to continually change your approach and to constantly try new things.” All these elements are ones that enhance system resilience.

The story of Lyndfield Park tells us that application of resilience thinking does not necessarily require complicated and mathematical analysis. The property owner is a farmer, not a trained scientist. At the time he strove to transform his farm the formal concept of resilience was at an early stage. With crisis looming, he adopted changes based on his gut reaction; he abandoned traditional farming practices that placed large stresses on the land, and performed steps that restored the soil structure and made it more resilient to stress. He did not study theories of resilience, yet his assessment and remediation were in line with them. This story shows that practical approaches to improve and enhance resilience are feasible, even when formal quantitative expressions of resilience are absent.

8.3 Bushfire in Victoria, Australia

The Upper Murray River in the state of Victoria, southeastern Australia, supplies 38% of the water flowing into the Murray–Darling Basin, the most important catchment system in Australia. Bushfires during January and February 2003, the worst since 1939, burned 1.39 million ha of mainly native forested land in this region (Lane et al. 2006; van Dijk et al. 2006). A study (EarthTech 2003) immediately after the 2003 event suggested that inflows to the Murray could be reduced by as much as 430 GL per year by around 2020, though it made the point that better estimates of the degree of burning were needed. A subsequent study (SKM 2004), using satellite images and information on the type and age of burnt forests, estimated that an initial increase of 14% to 106% in stream flows of different catchments will last until about 2010; after this period there will be a decrease in stream flows, with the maximum change in total inflow to the Murray varying between –129 and +4 GL per year. This wide range of prediction reflects the uncertainty in the relationship between fire severity and tree death.

The two studies cited above (EarthTech 2003; SKM 2004) and past pieces of evidence (Langford 1976; Kuczera 1987) indicate that when bushfires sweep across the landscape, severely burnt trees die and the subsequent regrowth may affect groundwater runoff, both in quantity and quality, over many years. When fires kill many trees, there is less water use by the vegetation and thus increased stream flows and groundwater recharge in the first 2 to 6 years immediately after the fires. Subsequent to this stage the vegetation will undergo vigorous regrowth and water use will be higher than the pre-fire state. The period of this regrowth phase may last from 20 to 200 years, depending on the plant species involved (van Dijk et al. 2006).

Bushfires can also have a serious consequence on water quality. Runoff after rainfall can carry charcoal, sediment, nutrients, and organic matter into streams and reservoirs, processes that depend upon catchment characteristics, fire severity, and the particular rainfall events that occur before the soil regains sufficient vegetation protection. Typically, water quality first deteriorates in streams that drain fire-affected areas, although the extent of the problem lessens over time as the catchment stabilises. Some 2 years after the 2003 bushfire, many streams in affected catchments still had high pollutant loads, from 2 to 100 times pre-fire levels (van Dijk et al. 2006).

The looming prospect of climate change has a serious implication for bushfires. Climate change is generally expected to increase the frequency of bushfires (Pittock 2003). Large-scale bushfires in the Murray–Darling Basin are often correlated with incidents of drought, and the severity of the 2003 events were suspected to have been aggravated by the increasingly severe drought Australia has been facing in the last decade (Nicholls 2004). Change in future climate, therefore, may become a dominant force in the frequency and intensity of bushfires.

While the prediction and modelling of the effects of bushfire on hydrology has been an active research area (e.g. Van Wagner 1975; Turner 1978; Kulik 1990; Argent et al. 2005; Murray et al. 2005), and there are some limited studies on resilience (defined as recovery rate of bio-species to their pre-fire state) of stream ecological communities after a bushfire (e.g. Gresswell 1999; Bisson et al. 2003; Vieira et al. 2004), in general there has been little effort on the impact of bushfires on the resilience of water resources in affected catchments. Studies of stream insect communities in fire-ravaged catchments show that repeated post-fire flash floods, which constantly reset recovery trajectories, were primarily responsible for their low resilience (Vieira et al. 2004). Traits of species are also ecologically and evolutionarily relevant (Poff 1997); specifically, species with traits of strong dispersal ability, multi-voltinism, and high tolerance to hydrologic disturbance are generally more resilient with higher recovery rates (Townsend et al. 1997a, 1997b).

Since bushfires affect both the quantity and quality of water draining from ravaged catchments, study of the resilience of water from such sources requires proper consideration of the variation of water quantity and quality, as both are equally important to humans and ecological resources. The immediate task, obviously, is to understand more of the processes causing change. The 2003 bushfires in southeastern Australia, for example, provide a valuable opportunity to extend understanding on these topics and research efforts are underway (e.g. EarthTech 2003; SKM 2004; Sheridan et al. 2004; Cary 2005; Govinnage-Wijesekera et al. 2005; Lane et al. 2006).

Management of the resilience of catchment water may need to consider other factors – such as associated terrestrial and aquatic ecosystems and ethical issues – as well as the impact of management action on the catchment system as a whole. In some cases the potential risks and benefits of a particular action are clear, but in most cases they are not (Bisson et al. 2003). Experience reveals that continually learning from the outcomes of management actions, and adjusting to the needs when necessary, is critical in circumstances where high uncertainties persist (Walters 1997).

9 Concluding Remarks

We live in a world comprised of ecological, technical, and social subsystems, as exemplified by a water resources system; however, we traditionally treat and study the whole system by focusing on one of its subsystems. Ecologists attempt to unravel the biophysical nature of ecosystems; engineers concentrate on the efficiency and optimisation of technical systems; and sociologists are dedicated to explaining the behavior and evolution of human communities. They all generate useful insights into the respective subsystems, but those insights are invariably partial: The behavior of the system as a whole normally cannot be explained by simply summing up isolated understanding of the component subsystems (e.g. Holling & Meffe 1996; Hollnagel et al. 2006). Therefore, the management and intervention strategies derived from the perspective of subsystems sometimes yield surprising and, even worse, undesirable outcomes as changes made to one part of the system inevitably stimulate feedback responses in other parts of the system.

Because a water resources system is invariably managed by human decisions, its system resilience is a property that was built into it and, at the same time, responds to what human actions do to it. In many cases human intervention is actually the dominant force for changing resilience (e.g. Grima 1993; Rockström 2003; Hoko and Hertle 2006). Hence resilience is the capacity that a system has, and what it does, to anticipate and adjust to changes, to absorb impacts and disturbances in order to retain its structure and function. From the discussion in this paper, the importance of resilience has been recognised and studies to make it operational have been an active research area (e.g. Carpenter et al. 2005; Cimellaro et al. 2006).

Past research efforts on developing resilience measures for water resources systems had been somewhat in line with the resilience concerned with response and recovery (Hashimoto et al. 1982; Moy et al. 1986) and with resilience against regime change (Fiering 1982a, 1982c), but efforts to consider the effect of institutional adaptive capacity on the two types of resilience are still lacking. It is clear from the purview of this paper that both of these are important for water resource systems that function as resources for humans and for the viability of other species affected by change. Furthermore, given the complexity of water resources systems, the inherent variability of system properties, and the limited existing knowledge of such systems, a deterministic methodology that adequately expresses system resilience is unattainable. For this reason, in any assessment of resilience we would emphasise the importance of uncertainty and information, knowledge and ignorance. Though still an active area of research, the development of measures for various types of uncertainty, information, and ignorance has reached a stage at which they could be successfully employed to express, quantitatively at least, a wide range of uncertain and unknown aspects of systems, in much the same way, perhaps, as measures of distance, mass, and temperature (Rényi 1987). Nonetheless, methodologies for appropriate inclusion of uncertainty and ignorance, and the associated computational algorithms, in the study of water resources systems have yet to be developed.

Thus one may ask, even before a comprehensive and operational framework is proposed, could the concept of resilience be applied to practical problems?

As exemplified in the management of the Goulburn–Broken Catchment and the transformation of Lyndfield Park, some practical approaches to improve and enhance resilience are possible. Specifically, resilience could be increased by: (1) undertaking a course of action that leaves room for alternatives; especially in cases of irreversibility, options should be kept open (Arrow & Fisher 1974); (2) resilience should be expanded to allow a buffering capacity (Gunderson 2000); and (3) cross-scale management and communication should be enhanced in order to get early warnings acknowledged and potentially serious problems dealt with in a timely fashion; communicating across scales may be difficult, but is critical to resilience (Peterson 2000). In a study of historical social collapses, a sequence of failure points are highlighted: failure to anticipate problems, failure to perceive the problems once they exist, failure to act on problems, and failure of actions to solve problems (Diamond 2005). Constantly monitoring, adjusting, and engaging in long-term planning towards enhanced resilience, and an openness to transition to a desirable alternative regime, are essential for building resilient systems.

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