

Resilience and water management: a literature review



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Preface and acknowledgements

The authors of the fore lying **discussion document** are involved in several projects and initiatives dealing with water management where the ‘resilience’ issue emerged. Always in the context of discussions about a systemic view on water management¹. Thus it was also noticed that the application of resilience is not straightforward and often met with scepticism, because of questions such as: What is resilience in the water management context, and what does it mean practically and scientifically? To which questions from water management can resilience give an answer, and how?

In order to at least provide a good basis for a thorough discussion on these topics TNO initiated a literature study. The study was paid by using some of the strategic research funding that is provided by the Dutch government to TNO. This type of funding is meant to gain and maintain a knowledge position in domains of research that are or may become of interest to TNO and management and policy making in the Netherlands in general. For this reason, we focus in this study on Dutch examples. However, the topics and examples covered – in our opinion – are also relevant outside the Netherlands.

This study was not intended to be all embracing, but to provide some basic input for further discussion in AquaTerra the Netherlands and RISKBASE about the question whether the concept could be used in these projects, and in case so, how?

We would like to acknowledge Frans Coenen, Arnoud Smit, Geert van Wirdum and Wim Salomons for useful comments and input to our study.

¹ I.e. the view were the biophysical soil-sediment-(ground)water system and the social (management, policy making, society and the economy) system are regarded as one close-knit and dynamic ‘social-ecological’ system. Measures taken (in addition to the background effects of socio-economic and global change) have an effect on the ecological system but the resulting changes in the state of the ecological system will have a reverse effect on the social system.

1. Introduction and guide to the reader

Dutch water management is facing a variety of challenges. The Water Framework Directive sets high ambitions. At the same time, there are uncertainties, such as the effect of climate and global change. These and other developments lead to a lot of questions: How to reach Good Ecological Status? What are effective measures (cause-effect relations)? What are relevant risk indicators/early warning systems? How to put a system approach in practice? How to deal with uncertainty and unpredictable events? How to link the social and biophysical system?

To many of these questions, resilience thinking might be useful.

We will start with sketching the historical context of resilience, especially in relation to sustainability (chapter 2). Also, the conceptual development of the resilience concept will be described and subsequently the theoretical framework of resilience ‘the ‘resilience lens’ (chapter 3). After these historical and theoretical descriptions, we will go to practice by describing two cases from Dutch water management: one from the water quality perspective (eutrophication and clear vs. turbid shallow lakes, chapter 4.1), and one from water quantity perspective (flood control chapter 4.2). In the discussion (chapter 5), some weaknesses or strengths that arise from the previous sections are addressed. We finish with concluding remarks (chapter 5) and recommendations (chapter 6).

2. Historical context of sustainability and resilience

2.1. Resilience and sustainability

The exact origin of the sustainability concept is hard to track. In the course of time, sustainability has been used widely in the environmental debate (Robinson, 2004). A key document in the development and application of sustainability is the Brundtlandt report “Our Common future” (World Commission on Environment and Development, 1987). In the Brundtlandt report sustainable development is defined as a “...development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” Sustainable development has widened the scope of environmental policies to other policy domains and has linked “environmental thinking” to development issues, especially to social and economic policy issues.

The three elements of sustainability (environmental, social and economic) are often considered as isolated and static objectives. For instance, the possibility that technology, and social organization can be improved and renewed to create new options for economic growth and environmental management strategies have been often neglected in the sustainability debate. This emphasizes both the role of technology and social organization in achieving sustainable development, i.e. the role of innovation in both technology and social organization (Slob, 1999). The issue is not how we do the same things in a more efficient way; the issue is that we suggest that another ‘mental approach’ is needed, in other words: a new way of looking and working.

From a system view the three elements of sustainability are not considered as static and isolated factors, but rather as related components of social, economical, and ecological systems. In other words: we need to understand the relations between social, environmental and economic components. This view suggests that the complexity of systems of people and nature emerges not from a random association of interacting factors, but rather from a smaller number of controlling processes (Gunderson & Holling 2002). These systems are self-organized, and a small set of critical processes create and maintain this self-organization. Self organization is a term that characterizes the development of complex adaptive systems, in which multiple outcomes (pathways) typically are possible. If sustainability means anything, it has to do with the small set of critical self-organized variables and the transformations that can occur in them during the evolutionary process of societal development (Holling, 2001).

Over the past 20 years, the sustainability debate has illustrated that there are many feasible futures. We can describe multiple pathways, as there are many options for sustainability (see figure 1). Those pathways are characterized by previous definitions of sustainability, including maintaining options for future generations (World Commission on Environment and Development, 1987).

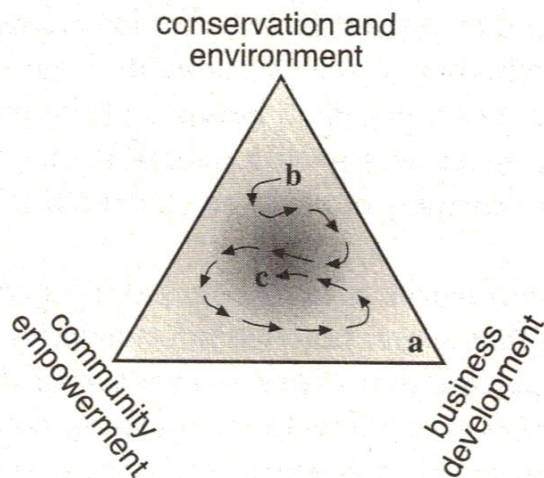


Figure 1. Pathways for sustainable futures (From Yorque et al., 2002)

We suggest that the pathways less travelled are the ones that focus more on the complex relations between social organisation, environmental management and technology. Those relations are playing a crucial role in processes of innovation and renewal. The question is not what the best pathway would be and how to focus on that, but rather how we are able to seek possible pathways to sustainability and keep those options open. We argue that, because of the inherent complexity of interacting components involved in answering such a question, the most pragmatic approach is one based on learning our way to sustainable futures, rather than planning our way (Yorque et al., 2002).

Resilience thinking may provide a promising new approach towards sustainability because it gives options to learn our way to sustainability. We need to learn to direct concrete multiple ways to avoid fragile ecosystems, businesses as well as societies that are becoming more and more vulnerable to exposed turbulent transformations. In this paper we explore options resilience thinking can offer us to build a more comprehensive (holistic) understanding of complex systems to establish sustainable societal development and environmental management.

One of the main issues in resilience thinking is development of understanding of complex systems of interacting social, ecological and economical components, i.e. complex system thinking. In this perspective, the attention is shifting from static and isolated objectives to social learning, renewal and adaptive capacity of complex systems of humans and nature. In resilient systems, dynamic interactions have the potential to create opportunities for new developments (windows of opportunity), for innovation and development (Folke, 2006). Sustainability is the capacity to create, test, and maintain adaptive capability (see figure 2). Development is the process of creating, testing, and maintaining opportunity (Holling 2001). The motto is: learn to manage by change, rather than simply react to it and try to resist change. Uncertainty and surprise are part of the game and we have to learn to live with it.

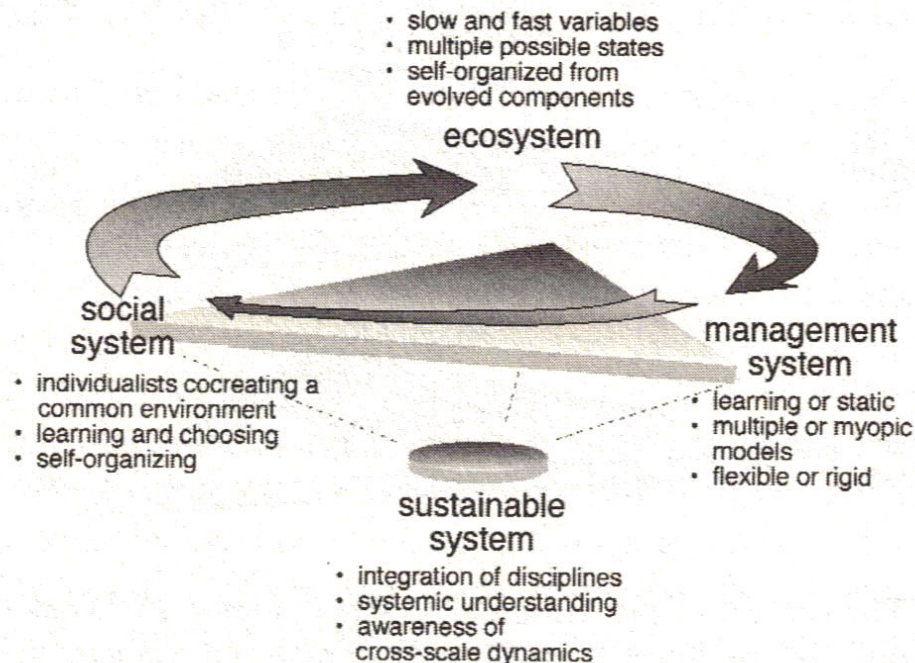


Figure 2. Relations between complex system thinking and sustainability (From Yorque et al., 2002).

2.2. Conceptual development of resilience thinking

Resilience can be described as an inherent property of systems. Resilience is being used in different disciplines, i.e. economy, psychology, systems engineering, ICT, and system ecology.

Economic resilience

Economic resilience is the ability of a local economy to retain function, employment and prosperity in the face of the perturbation caused by the shock of the loss of a particular type of local industry or employer. Communities with resilient economies find that the loss of an employer results in rapid reabsorption of workers made redundant by the closure of an enterprise or industry into new, and frequently more satisfying and stable employment than before. In business terms, resilience is the ability of an organization, resource, or structure to sustain the impact of a business interruption and recover and resume its operations to continue to provide minimum services.

Engineering resilience

Folke (2006) describes that the work about resilience thinking has an original focus on the capacity of ecosystems to absorb shock events and the time these systems need to recover from shock events and return to their former stable, equilibrium state. A resilient ecosystem is forgiving of external shocks. As resilience declines, the magnitude of a shock from which a system cannot recover anymore, will get smaller and smaller. According to Folke (2006) this is

the ‘narrow interpretation of resilience in a technical sense. The single equilibrium view that dominated main stream ecology is also called ‘engineering resilience’ (see table 1).

Resilience concepts	Characteristics	Focus on:	Context
Engineering resilience	Return time to stable state, Recovery	Efficiency, Control	Vicinity of a stable equilibrium
Ecosystem resilience	Buffer capacity, withstand shock, maintain function	Persistence, robustness	Multiple equilibria, stability landscapes
Social-ecological resilience	Interplay between disturbance and reorganization, sustaining and developing (cycle)	Adaptive capacity, transformability, learning, innovation	Integrated system feedback, cross-scale dynamic interactions

Table 1. The conceptual development of resilience thinking (Folke, 2006).

Ecosystem resilience

Ecosystem resilience is defined by the Resilience Alliance (www.resalliance.org) as “the capacity of an ecosystem to tolerate disturbance without collapsing into a qualitatively different state that is controlled by a different set of processes”. A resilient ecosystem can withstand shocks and rebuild itself when necessary. Ecosystem resilience is the ability to absorb disturbances, to be changed and then to reorganize and still have the same identity, while the basic structure and ways of functioning of the ecosystem retains the same (see table 1). Resilience is defined in terms of regimes and regime shifts (Gallopín 2006). This means that ecological systems do not have just one ‘single state stability’, these systems have alternative stable states (regimes or multi-stable-states). A relevant concept in ecosystem resilience is ‘assimilative capacity’. It has been defined as the ability of an ecosystem to absorb various materials, including anthropogenic wastes, at certain concentrations without degradation of the ecosystem (Cairns 1999). Another concept closely related to ecosystem resilience is (bio)diversity.

Social-ecological resilience

Recently, a broader interdisciplinary perspective on resilience thinking is social-ecological resilience (see table 1). Resilience as applied to integrated systems of people and the natural environment, has three defining characteristics:

- The amount of change the system can undergo and still retain the same controls on function and structure;
- The degree to which the system is capable of self-organization;
- The ability to build and increase the capacity for learning and adaptation.

The concept of social-ecological systems refers to the ‘humans-in-the-environment perspective’, that all ecosystems from local to biosphere provide the biophysical foundation for societies. But

also that the ecosystems we observe today have been shaped by human use and decision making in the past and are intertwined with human actions that alter their capacity to sustain societal development (Stockholm MISTRA Institute, 2006: 9; Folke et al., 2007). Thus, when we refer to a social-ecological system, we are referring to a system comprising at least the three domains of social, ecological and economic as a level of analysis (see figure 3). Resilience in social systems has the added capacity of humans to anticipate and plan for the future. Human systems comprised of individuals, groups, networks and institutions (rules, regulations and procedures) intervene to obtain goods and services from ecosystems. Actions and interventions include the removal or planting of vegetation, harvest of animals, irrigation of landscapes, and construction of systems to control floods. These interventions directly and indirectly modify ecosystem structure and functions (Resilience Alliance, 2007).

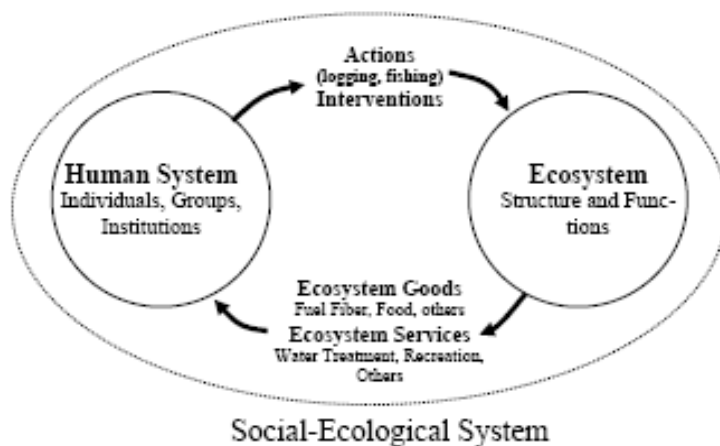


Figure 3. Conceptual diagram of elements of a social-ecological system (www.resalliance.org).

In this study we want to relate to this interpretation of resilience (social-ecological, see table 1), as it addresses adaptive capacity, transformability, learning, and innovation. These parameters can be used to identify system properties that are important for the renewal of water management. In the context of water management (or river basin management), the concept of social-ecological systems refers to the structure and functions of biophysical system components of river basins: soil, groundwater, surface water, and sediment. Example of human system components are institutional rules (i.e. laws and risk standards) and structures that shape the cooperation and decisions of actors involved in water management practices. In chapter 3 we will focus more in detail on social-ecological resilience, presented as a framework of related concepts (the 'resilience lens').

For other definitions of resilience, that all have in common that there is a recovery from a disturbance or shock, one can read the Wikipedia encyclopaedia (<http://en.wikipedia.org/wiki/Resilience>).

3. The resilience lens: key concepts in resilience theory

According to the Stockholm Resilience Centre, the “resilience lens provides a new framework for analyzing social-ecological systems in a changing world facing many uncertainties and challenges. It represents an area of explorative research under rapid development with major policy implications for sustainable development.”

The resilience lens is a framework on a systems level that deals with complexity and dynamical processes of change and renewal. It emerged from ecology in the 1960s and early 1970s and has linkages to other theories that describe (in)stable and far and near-equilibrium processes in systems, like thermodynamics and complexity theory (Gallopín, 2006, Cadenasso et al., 2006). The resilience lens emphasizes non-linear dynamics, thresholds, uncertainty and surprise, focuses on how periods of gradual change interplay with periods of rapid change and how such dynamics interact across temporal and spatial scales (Folke, 2006). The resilience perspective is increasingly used as an approach for understanding the dynamics of social-ecological systems (Folke, 2006, Gallopín, 2006), but the way of thinking has also been applied to cities and other social systems (Pickett et al., 2004).

The “resilience lens” contains different concepts : multiple equilibriums and regime shifts, the adaptive cycle, panarchy, adaptive management and adaptive capacity. These key elements are explained below.

Multiple equilibria and regime shifts

System thinking has long been based on a steady-state view focusing on only one unique state. Recent research, especially from ecology, focuses on different steady states and multiple equilibria. This multi-stable state thinking opened new directions of research, focussing on behaviour far from equilibrium and on stability boundaries. When a system loses resilience it becomes vulnerable to exterior influences and pressures and it can pass a certain threshold to shift from one state into a new (sometimes undesirable) state. Historical loss of resilience has put whole regions and cultures into vulnerable states with fewer options for development (Falkenmark & Rockström 1993, Kasperson and Kasperson 1995, Redman 1999). When a system shifts from one state into a new one, this is called a regime shift, because the ‘regime’ of the system is altered, i.e. the systems function, -structures, -feedbacks and –identities (Kinzig et al., 2006). Regime shifts have been extensively described for ecological systems (Kinzig et al., 2006; Walker & Salt, 2006), but can be observed in social systems as well (Pendall et al., 2007). For good prediction of the behaviour of a system a good understanding of the system and its governing variables is needed, and one should discover the key parameters of the system that define the thresholds.

Adaptive cycle

The model of the adaptive cycle focuses upon processes of destruction and reorganization, and on growth and conservation. Including these processes provides a more complete view of system dynamics that links together system organization, resilience, and dynamics. For ecosystem and social-ecological system dynamics four distinct phases have been identified:

1. Rapid growth or exploitation;
2. Conservation;
3. Release or collapse;

4. Reorganisation.

The adaptive cycle exhibits two major transitions (figure 4). The first transition, often referred to as the fore loop, from rapid growth to conservation, is the slow, incremental phase of growth and accumulation. The second one, referred to as the back loop, from release to reorganisation, is the (sometimes very) rapid phase of reorganization leading to renewal.

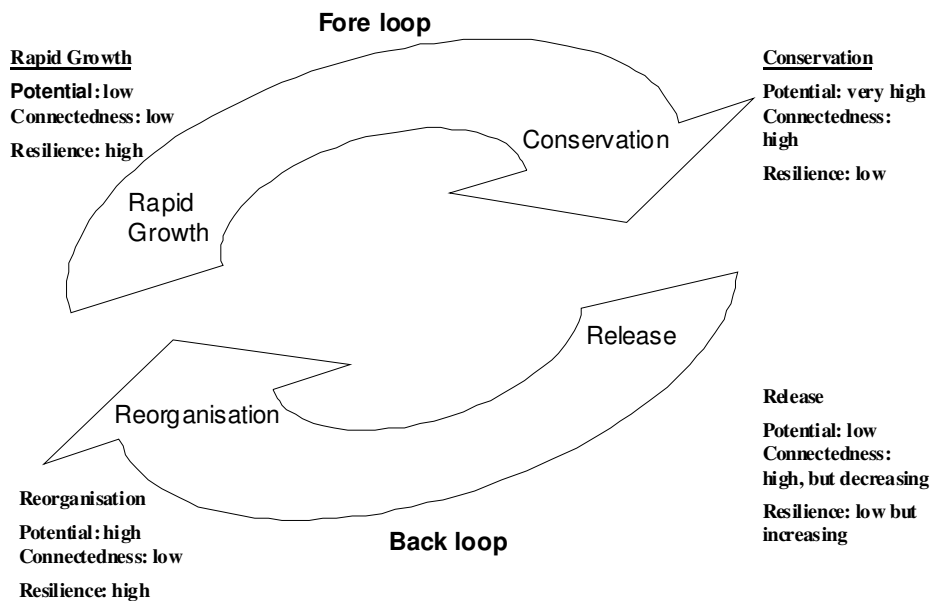


Figure 4. Conceptual diagram of the fore loop and back loop in the adaptive cycle.

The potential says something about the capability to change and determines the range of possible future options (Holling 2001). This property can be thought of, loosely, as the wealth of the system, accumulated resources available to the system. It can be expressed in different ecosystem types, as water, soil, groundwater, and sediment system components of river basins. In social (human) systems resilience can be linked to productivity, human relationships, mutations and inventions. Each phase is characterized by varying levels of three variables: 1) potential: accumulated resources available to the system; 2) the internal connectedness of system actors or variables; and 3) resilience, a measure of the system to recover from surprise, stresses, and shocks (see figure 4).

In the early phase of growth the potential of the system is low as resources are available in abundance, but have not yet been accumulated and made available to the systems benefit. During the sequence from exploitation to conservation, the variables in the system are getting better (inter)connected by which stability increases and potential of nutrients and biomass in ecosystems or social potential in social processes are accumulated. For an economic or social system, the accumulation of 'potential' could as well be from the skills, networks of human relationships, and mutual trust that are incrementally developed and tested during the progression from the rapid growth to the conservation phase.

In this progression competitive processes lead to a few species becoming dominant in an ecological system, or few businesses in an economic system, and a certain specialisation is taken place with a high efficiency of using available resources. In the conservation phase the built up potential is very high, because of this high efficiency and connectedness is also high. On the other hand a certain path dependency is introduced and diversity is diminished, at the same time lowering the resilience of the system. The system becomes vulnerable to exterior influences, disturbances or pressures until it collapses. In the quick transition from conservation to release, the system expels and eventually exhausts accumulated resources, and releases built-up potential. In ecological systems it can be a flooding or a forest fire, which burns all available resources. In social systems it can be the collapse of the political system (compare this with the collapse of the communistic system). In the release phase therefore, potential is low (as it is released), connectedness is still high (but decreasing) and resilience is increasing as new relations are being tested and flexibility is growing. The back loop from the release phase to the reorganization phase is a highly uncertain transition with unpredictable outcomes, which takes place very quickly. In this transition experimentation, reorganization and renewal is taken place, which can trigger innovations in the next phase. Old relations have deteriorated, so connectedness is low, but on the other hand potential is again being built-up in a new way different from the way it has been built up in the fore loop.

The adaptive cycle is not a fixed cycle, which means it is not a trajectory that always follows the 4 phases successively. This is depicted in figure 5. All transitions between the different phases are possible, except from the release or reorganisation phase directly to the conservation phase. A rapid growth phase usually proceeds into a conservation phase, but it can also go directly into a release or reorganisation phase. The conservation phase can go directly back to the rapid growth phase but also into the reorganisation phase. This opens up possibilities for management to avoid the total collapse of the system in the late conservation phase and to control the (social, ecological, economical) damage to the system. (Walker & Salt, 2006). Understanding in which phase a system is, is crucial for assessing the resilience of the system and the most appropriate measures to enhance it – or at least not cross its borders.

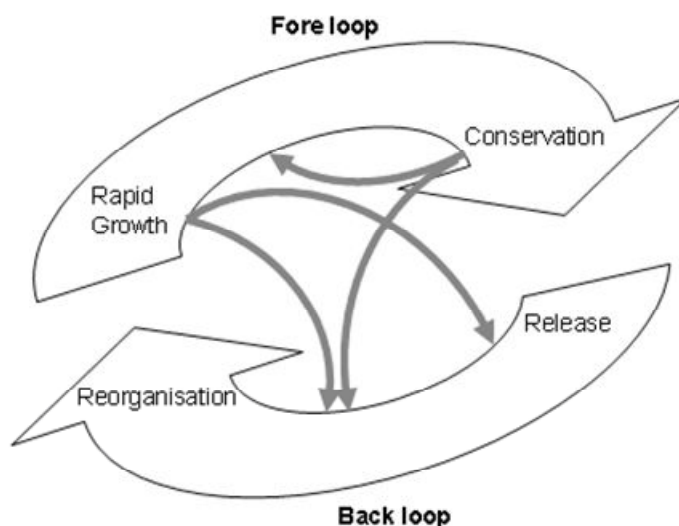


Figure 5. Conceptual diagram of possible pathways for innovation and renewal.

Adaptive cycles exist on various scales, and interact in various ways. Adaptive cycles are nested in a hierarchy across time and space which helps explain how adaptive systems can, for

brief moments, generate novel recombinations that are tested during longer periods of potential accumulation and storage. A nest hierarchy of adaptive cycles represents a panarchy. Panarchy can be opposed to hierarchy, in the sense that panarchy does express effects between scales, but the interactions between these states do not have to be of a top-down hierarchical nature: the interactions can be difficult to predict, depending rather on the nature of the interaction than on the hierarchy. Panarchy means that changes on a lower level for instance the collapse of a habitat can cause changes on a higher level causing a cascading effect on other habitats leading to a collapse of the whole ecosystem. The reverse can also be true. On the other hand adaptive cycles that take place at a certain time can cause effects on a later moment. Panarchy reveals the importance of looking at systems as connected to other systems on a different level and at another moment. Consequently systems always have to be researched in a broader context. In figure 6 a representation of panarchy is given.

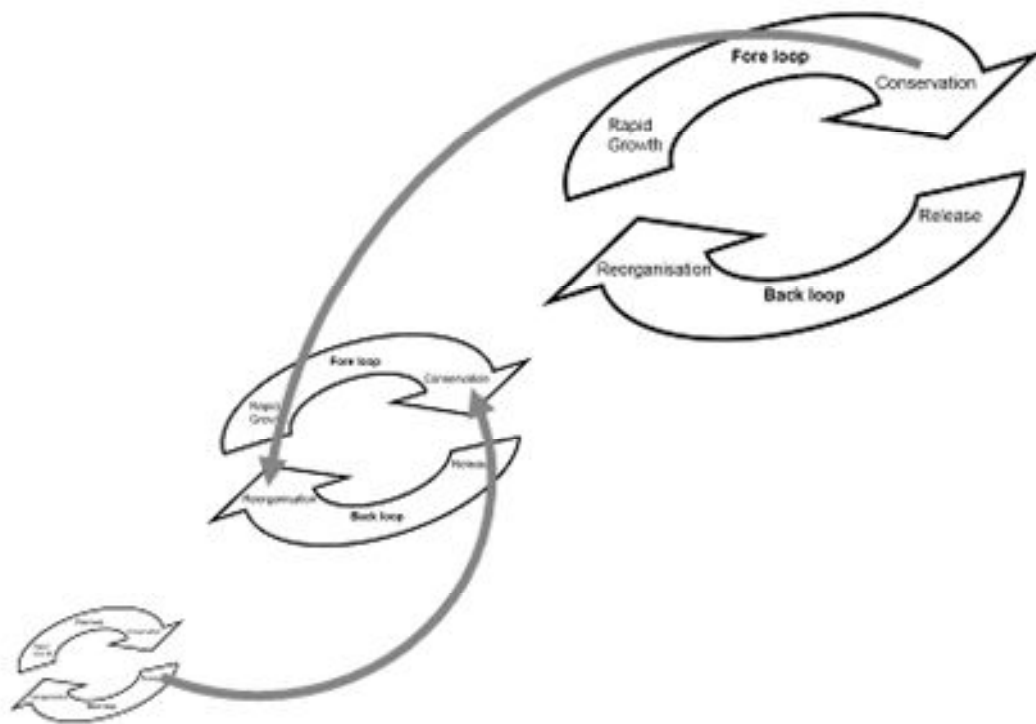


Figure 6. Conceptual diagram of panarchy mechanisms.

Adaptive management

Adaptive management uses management interventions to test key hypotheses about the functioning of the system and by doing this, to understand the system in a progressive way and manage the system at the same time. Adaptive management identifies uncertainties, and then establishes methodologies to test hypotheses concerning those uncertainties.

There are several processes both scientific and social which are vital components of adaptive management (www.resalliance.org):

1. management is linked to appropriate temporal and spatial scales;
2. management retains a focus on statistical power and controls;

3. use of computer models to build synthesis and an embodied consensus;
4. use embodied consensus to evaluate strategic alternatives;
5. communicate alternatives to the political arena for negotiation of a selection.

Adaptive management requires an open management process which seeks to include stakeholders. Consequently, adaptive management must be a social as well as a scientific process. Adaptive management attempts to use a scientific approach, accompanied by collegial hypotheses testing to build understanding, but this process also aims to enhance institutional flexibility and encourage the formation of new institutions that are required to use this understanding. These features can promote an evolving, site-specific governance approach in which strategies are sensitive to feedback (both social and ecological) and oriented towards system resilience and sustainability. Such strategies include dialogue among interested groups and actors (local-national), the development of complex, redundant and layered institutions, and a combination of institutional types, designs and strategies that facilitate experimentation and learning through change. Other important themes in adaptive management include improving evaluation of process and outcomes, additional emphasis on power, the role of social potential, and meaningful interactions and trust building as the basis for governance in social-ecological systems.

Adaptive Capacity

In social systems, the existence of institutions and networks that learn and store knowledge and experience, create flexibility in problem solving and balance power among interest groups. This creates an adaptive capacity of the system that is directly related to the resilience (Scheffer et al. 2000, Berkes et al. 2003). Systems with high adaptive capacity are able to re-configure themselves without significant declines in crucial functions in relation to primary productivity, hydrological cycles, social relations and economic prosperity. A consequence of a loss of resilience, and therefore of adaptive capacity, is loss of opportunity, constrained options during periods of re-organisation and renewal, and an inability to innovate.

The adaptive capacity of a system can be increased by (Folke et al., 2002; Smit & Wandel. 2006; www.resalliance.org):

- creating networks to gain system understanding and to manage the system;
- innovation in a broad sense: technological as well as social (new institutional arrangements, new ways of working together);
- nurturing diversity for resilience, keep different pathways open to prevent to arrive at a “lock-in” situation;
- education and combining different types of knowledge for learning;
- rules and regulations on a level of goals and not on the level of instruments or intermediate goals. The governance system, rules and regulations should encourage that different paths are kept open to avoid lock-in situations that make the system vulnerable.

4. Resilience thinking and water management: two examples of system analysis

In this section the meaning of resilience for research and policy is explored on the basis of examples in (preferably) Dutch water management (see preface). Plenty of examples can be found here: e.g. Remmelzwaal & Vroon (2000) summarized a large number. Roughly speaking, one could classify the largest part into two categories: dealing with water quality and with water quantity. Of both, an example is given here.

4.1. Case 1: Water quality (regime shifts in shallow lakes)

The case of regime shifts in shallow lakes is well known in the Netherlands and beyond, both because the challenge it presents for water managers of reaching good ecological quality as well as because of the scientific questions surrounding it. The case is often described (e.g. Scheffer, 2001a and b), but still a lot not understood and research and debate continue until now (Ibelings, 2007; Scheffer, 2007; Rip et al., 2007; Hosper et al., 2007; Van Nes et al., 2007).

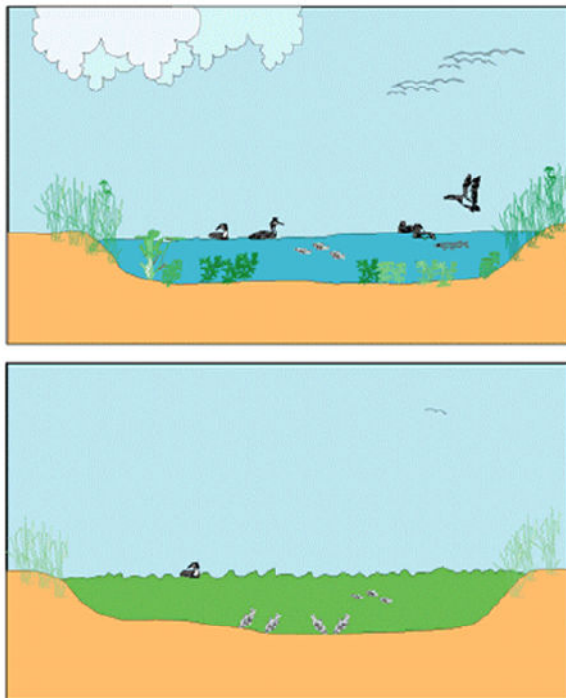


Figure 7. Schematic representation of a shallow lake in a vegetation-dominated clear state (upper panel) and in a turbid phytoplankton-dominated state in which submerged vegetation is largely absent and fish and waves stir up the sediments.

Taken from Scheffer et al., 2001b.

Shallow lakes can exist in different states (fig. 7): 1) clear, with abundant submerged plants, or 2) turbid, dominated by high concentrations of phytoplankton and suspended sediment. The clear situation is regarded as the desired one. This was probably the pristine state of these kind of lakes, and is the state with the richest diversity of plants and animals (e.g. birds). However, mainly because of nutrient loading, many lakes have turned turbid in the past, as was documented clearly for Lake Veluwe (Ibelings et al., 2007). Whereas lakes with low nutrient levels are dominated by smaller plants, increase of nutrients leads to an increase of bigger

plants, which also grow at top water layer and thus take away light. In case these were taken away by weed control programs, turbidity could increase due to algal blooms and wind resuspension of the sediments. Fish that stir up the sediment looking for food can further increase the turbidity. In case no measures were taken, further eutrophication could lead to such dense vegetation that the community collapsed due to light limitation. Both states are stabilized by a set of interactions, some of which are shown in fig. 8.

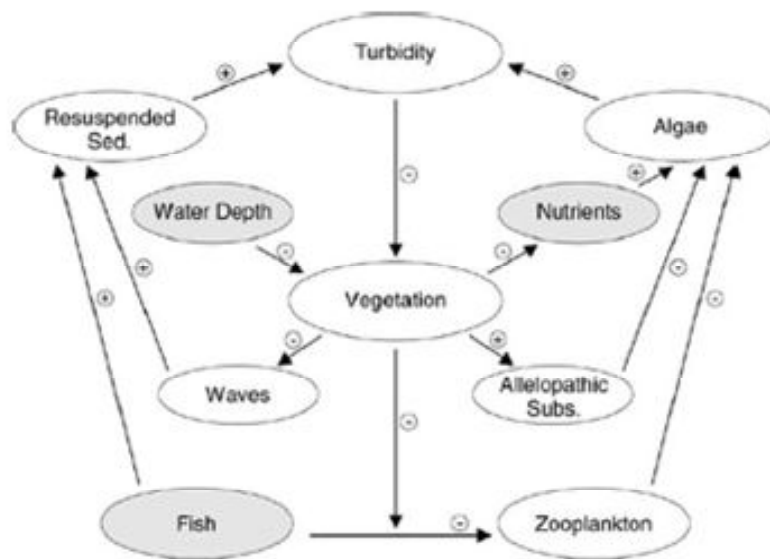


Figure 8. Feedbacks that may cause a vegetation dominated state or a turbid state. Although this schematic picture is not complete (e.g. the role of pesticides was not included), it gives a good idea of the complexity of the feedback network. Taken from Scheffer et al., 2001b.

In the clear state, the small submerged plants offer refuge to zooplankton and take up nutrients, thus preventing algal blooms. Furthermore, they prevent resuspension of the sediment. Together, this provides a buffer against nutrient effects.

In the turbid state however, the light limitation caused by dense vegetation can set in motion a self-stabilizing cascade working the other way around. Due to low light density underwater, the sediment becomes unprotected against resuspension and zooplankton is not protected, thus giving way to phytoplankton blooms. These phytoplankton blooms again diminish the water transparency of the lake, and thus stabilize the turbid state.

In real cases, such as the Lake Veluwe, after a conversion to the turbid state due to nutrients, it took water managers large efforts to get back to a clear state again.

As it was understood at some point that nutrients are the main underlying controlling factor, emissions were diminished. However, it was observed that restoration of clear water happened at much lower nutrient levels than those at which the collapse of the vegetation occurred (fig. 9). In other words: hysteresis occurred: the pathway travelled forward is different than the pathway travelled backward.

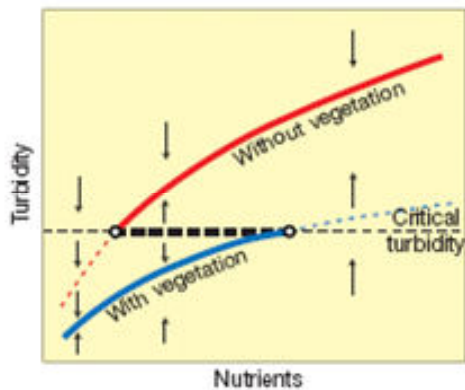


Figure 9. Schematic representation of the pathways of changing the turbidity by controlling nutrient levels. Once the turbid state without submerged vegetation is reached (red line), stabilization of this state is so strong that substantially lower nutrient levels have to be reached to attain a clear state with submerged vegetation again. Taken from Scheffer et al., 2001a.

Taking into account the difficulty of reaching the clear state again due to self-stabilizing factors, and the variety of feedback mechanisms indicated in fig. 8, water managers could opt for additional measures to bring the system into a different state. One successful example for this is the catching away of fish (Meijer et al., 1994). Some of these stabilize the turbid state because they eat Water flea (*Daphnia*), which in their turn regulate phytoplankton blooms, while others play a role in resuspending the sediments.

What does this case tell us about ecosystem management and resilience?

First of all it clearly shows that resilience is not a theoretical construct, but applies very well to real world situation. Almost all theoretical elements described earlier come back in this case. The importance of resilience and regime shifts (in this case between the clear and the turbid regime) is straightforward. Furthermore, also the phases in the dynamics of the system can be recognized, as was described for this case by Carpenter et al., 2001. Once nutrients increase, the systems moves from an r-phase to the K-phase, and resilience declines. This paves the way for a sudden change, which could be triggered by a storm (which could stir up sediment and thus cause a sudden, critical change in turbidity). Now a backward loop is triggered, starting with a chaotic phase and eventually again reaching a (possibly different) stable phase.

Some important lessons from this case are:

- First of all, it clearly shows that high resilience does not have to mean good ecological status. Thus, dealing with resilience means not only stabilizing the resilience of the desired state, but also acknowledging that the undesired state could be resilient as well, and thus that strategies to get out of this could be difficult, and might require extra measures.
- The existence of the system in two totally different states over a broad range of conditions makes it difficult for managers to deal with the system. In two situations where the system might look the same, the risk for passing certain critical thresholds might be totally different. This makes early warning systems difficult. Water managers would need insight in the key parameters controlling the resilience of the system, and overall insight in the various interactions as depicted in fig. 8. For this aspect, it is good to make a distinction between quickly and slowly changing variables. An example of this also applying to lake eutrophication is sediment phosphorus as slow variable and water phosphorus as fast variable. Even if changes in water phosphorus levels are achieved, the pool of phosphorus in sediments might change slowly, thus

acting as a reservoir². In this case, the slow variable sediment/soil phosphorus is more determining for resilience. The effect of such a controlling variable is illustrated by fig. 10: a difference in this condition might lead to a difference in the resilience of the system. However, as stated before, for adequate measures it is essential not only to focus on one such a single parameter, but keep in mind all other relevant interactions.

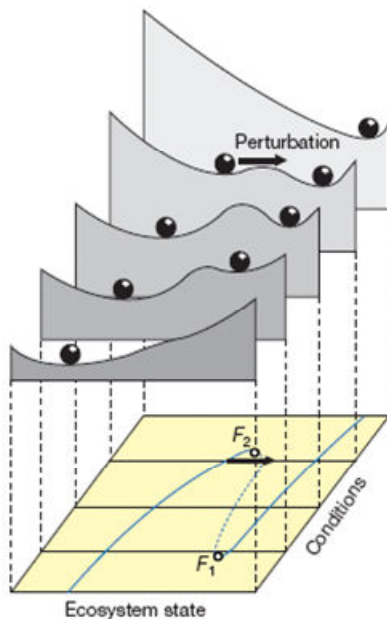


Figure 10. The effect of external conditions on the resilience of multi-stable ecosystems to perturbation. The stable equilibria correspond to valleys. In case this valley is small, resilience is small and even a moderate perturbation might bring the system into another equilibrium state. In case described in this section, phosphorus is one of the most important conditions that might change the 'stability landscape'. (Taken from Scheffer et al., 2001)

- *The linkage between the ecological and the social system:* So far, we have discussed the lake ecosystem case mainly from a biophysical point of view. However, also in this case, one could easily extrapolate to the social-ecological system, as is clearly demonstrated by Carpenter et al. (2001) (illustrated in fig. 11). The authors demonstrated clear cycles of interaction between societal developments and ecosystem changes. The first cycle is characterized by the change of the ecosystem due to intensification of agriculture. In the following cycles, various measures were taken to improve the water quality. In these cycles, the adaptability/rigidity of actors such as water managers and farmers play an essential role. In many cases, water managers or others groups had to adapt their methods, and try new approaches. Interestingly, also indicators for resilience, like sediment phosphorus mentioned above, can be found in the social or economic realm. Some examples are mentioned by Carpenter et al. (2001) and Scheffer (2000): flexibility of farmers to mitigate nonpoint pollution from their lands (institutional), the degree to which externalities were captured by the market, e.g. through a market for P permits or quotas (economic), or the existence of networks that are capable of facilitating appropriate action

² The same is seen in case of loading of soils by phosphate and metals, e.g. Stigliani & Salomons, 1993.

(social). In Dutch water management, adaptive cycles and the role of adaptability can also be clearly seen in many cases where water managers and farmers seek solutions to crisis situations.

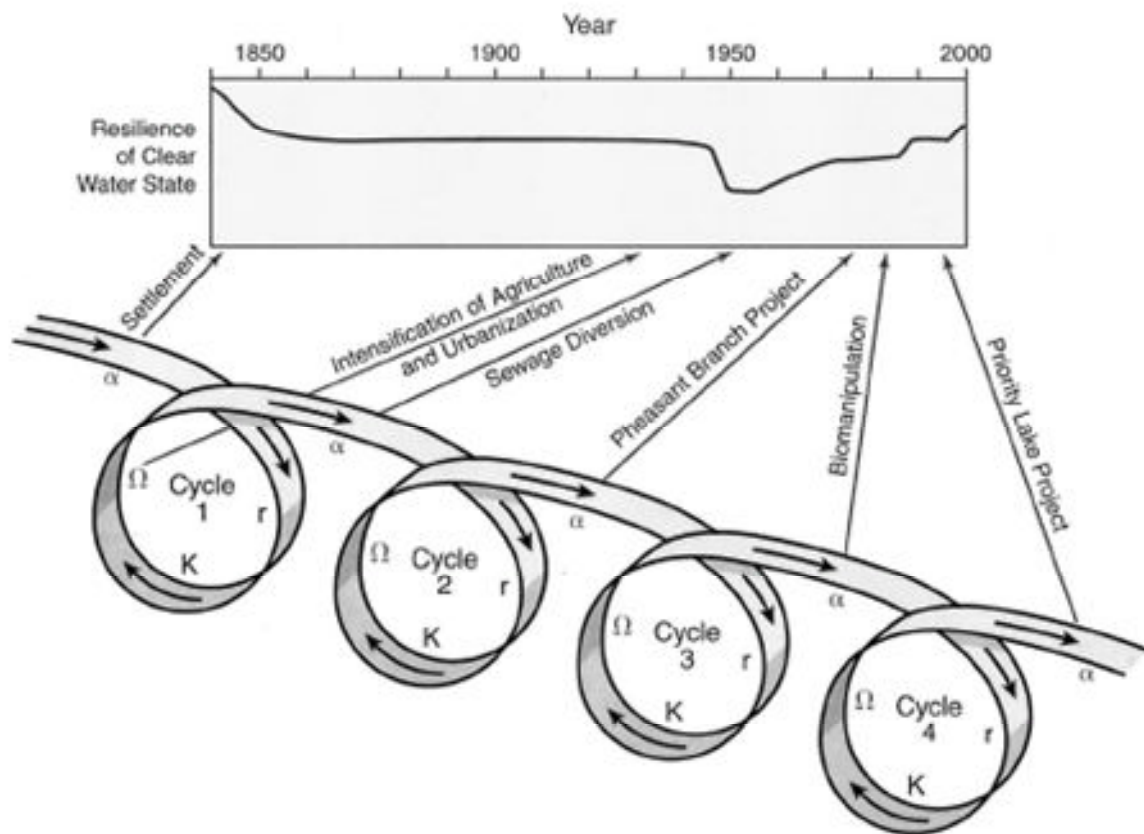


Figure 11. Example of a sequence of adaptive cycles in the water management of Lake Mendoza, Wisconsin. (Taken from Carpenter et al., 2001).

- *Management under uncertainty:* As Ibelings et al. (2007) put it clearly, we still do not understand the exact interactions in lakes, and especially can not foresee the effects of likely, but unpredictable future events such as climate change. This calls for adaptive management: it should be acknowledged that ecosystem behavior is unpredictable and that we should not strive to control this, but rather continuously adapt and respond. This may sound vague, but actually requires (semi)continuous measuring and monitoring of crucial (bio)chemical parameters, such as vegetation, phytoplankton, fish and macrofauna. This might also imply a different approach than only using single fixed norms.

- *Extrapolation to other ecosystems:* The lake ecosystem is only one example of resilience and ecosystem change. Many others are described by Scheffer et al., 2001a (coral reefs, woodlands, deserts, oceans) and show that similar patterns arise. A similar approach could also be applied to soil systems (Stigliani & Salomons, 1993; Wertz et al., 2007).

4.2. Case 2: Water quantity (water safety)

The control paradox is an example from the Dutch context which illustrates the current limited ability to learning of actors involved in water safety policy. The paradox is shown in figure 12.

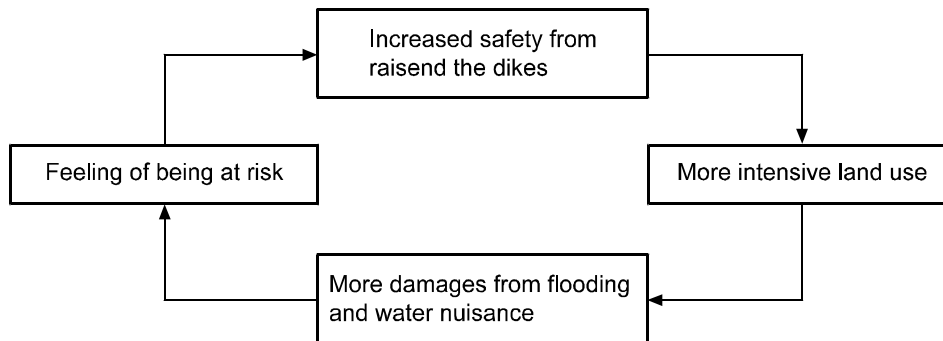


Figure 12. The control paradox (Remmelzwaal and Vroon 2000)

The strategy of the Dutch flood risk policy is based on the idea that the chance of flooding and its consequences can be limited by measures that aim to strengthen and raise the dikes. In this policy system, monitoring is done by means of compliance checking of the standards for water levels and the safety of the dikes (Remmelzwaal and Vroon 2000). There is a feeling of being unsafe after disasters or near disasters, which leads to decisions to strengthen the dikes. Society feels safe again, which leads to spatial planning dynamics behind the dikes with increase capital-intensive forms of land use (urbanization, industry and infrastructure). When another (near) disaster occurs, the feeling of being unsafe returns and again dike improvement is the issue. Adjusting the standards and subsequently strengthening the dikes cannot break through this control paradox.

In flood risk management, risk norms are used to formulate design criteria for mitigation measures, like the design criteria for a river dike. The established view on river is that the river should be controlled by building dikes to reduce the risk of flooding. Offering resistance against the influences of the river is the key issue in this policy system, which reflects a practice of river management that has been a tradition for centuries in the Netherlands (Immink, 2005). The main strategy is 'defending by dikes'. According to this strategy, the dikes will be improved after flooding or critical periods, for example by increasing their height. The consequence is that the dikes will be made higher and higher in the future. Implementation of just one strategy in water management practice (defending by dikes) reduces options to apply other flood risk management strategies.

Thus, the paradox is a 'lock-in' situation caused by the fact that the policy makers responsible for flood risk management are reacting to cross scale dynamics (spatial, environmental and social) using a rigid control strategy aimed at adjusting risk standards and, based on this, improving (raising) the dikes. The control paradox shows that improving the efficiency of the established strategy does not lead to a structural improvement of water safety. In fact, it leads to the opposite: to a less resilient, vulnerable water system and society in case of disaster (Immink 2007; Dircke & Immink 2007). As a result of the 'lock-in' situation, the process of social learning is neglected and feedback loops are ignored. The policy strategy is not renewed, only confirmed (or reproduced).

5. Discussion and conclusive remarks

Resilience thinking seems to provide a supportive framework in a world full of competing explanations. It can help us to define what is known, what is uncertain, and what is unknown (Holling, 2001). We argue that there is a requisite level of simplicity behind the complexity that, if identified, can lead to an understanding of complex systems which can be discussed and communicated among both scientist and practitioners. If we would like to explain the issues of concern using a handful of static and isolated parameters to address causes, then our understanding is too simple. If we require many more than a handful of parameters and suggested causes, then our understanding is unnecessarily complex. Holling (2001) states: “The required level for understanding complex systems is built upon a foundation of adequate integrative theory (see figure 13). This theory should be rooted in empirical reality and communicated with metaphors and examples (case studies). The first requirement is to begin to integrate the essence of ecological, social and economic science theory”. This interdisciplinary base is needed to find new options for community empowerment, environmental management and business development in practice (see figure 2 and 13).

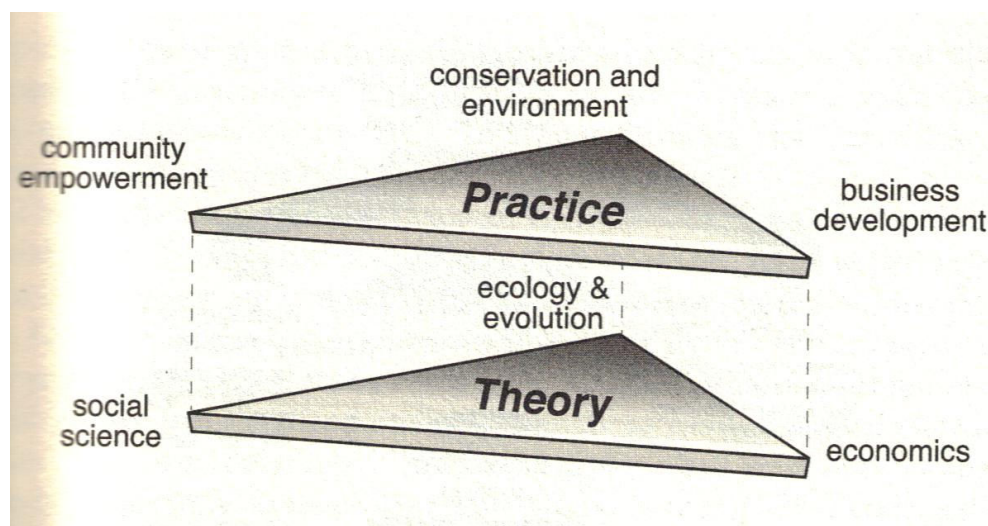


Figure 13. Relation between scientific research and issues for application in practice (From Yorque et al., 2002)

We argue that it is not enough to have a team of researchers and practitioners, each of whom understands a particular component³ in great detail. Understanding the component pieces of complex systems doesn't guarantee our understanding the behaviour of the system as a whole (www.resalliance.org). Mastering that level of understanding is the key to resilience. None of us are experts in all fields. It requires that we must reach out of our own area of expertise to encompass ecological, social and economic domains of a system (see figure 2 and 13). The complex issues addressed with sustainable development are not just solely ecological problems, nor economic, nor social ones, but a combination of all three (www.resalliance.org).

³ Soil quality, water quality, water quantity local markets, and management and policy practices, national and regional regulations.

However, the step to make resilience thinking and system understanding an issue in the 'daily practice' of water management needs more attention. Resilience thinking offers another view on water management: instead to strive to improve the control over water system behavior, resilience can offer a more flexible approach to water management. Although, the essential elements for such approach are addressed in this paper (*i.e.* social learning, understanding complex systems, use of local/system knowledge, multi-actor), it is useful to translate it to practical guidelines which could be easily applied in daily practice. Thus, the applicability of resilience thinking in practice would benefit from practical pilot studies, in a way that both scientist and water managers (practitioners) can become familiar with resilience thinking and are able to learn what options resilience thinking can offer them in their search how to avoid undesirable situations in water management.

The resilience lens may deliver an overarching, interdisciplinary framework in which insights from different viewpoints (social, ecological and economical) will fit, and that can generate results that direct the development water management in a more sustainable way. Hereafter we will briefly address the possibilities resilience thinking offers in addressing issues in practices of water (resource) management.

The main message of this perspective is that understanding of the ecological, institutional and economic (social) dimensions are required to establish sustainable environmental resource management and society (Westley et al., 2002). The complex and dynamic nature of social-ecological systems calls for an approach that takes into account its evolving character, rather than approaches that strive to reach an everlasting, optimal equilibrium between the natural and the human domain (Maarleveld, 2003). The resilience focus shifts from to control change in ecosystems that are assumed to be stable, to managing the ability to cope and adapt to change in social-ecological systems that are complex and dynamic (Folke, 2006). Terms like adaptive capacity of complex systems, reorganization and development, have been less in focus in environmental studies and resource management, but are essential for the sustainability discourse (Folke, 2006).

As a result of interplay between social and ecological components, systems are dynamic, and in a constant flux of change. For example, as a result of human use (resources) ecosystems are changing, and human needs in natural resources management are changing in time. From the interplay of these changes, new often unforeseen interdependencies between stakeholders and resources emerge (feedback). At the other hand, we need to learn more about the biophysical system and its feedback on the actions that were taken, in a way that later actions can be adapted by using this knowledge. This form of management should not be focused on just one considered 'optimum' system equilibrium.

Because there is interaction between ecological and social system components, the institutional interface for natural resource management needs to renew constantly (Holling 1995). When management practices are not able to adapt to constantly changing circumstances and needs, resource and water management practices are not able anymore to accommodate dynamics in ecosystems and resource use (Folke et al., 2007). In this regard, sustainable natural resource management is a never-ending story (Maarleveld, 2003). Sustainable management of natural resources, such as water management calls for policies and actions that not only satisfy environmental, economic, and social objectives, but also achieve continually modified understanding of ecological, economic and institutional dynamics and provide flexibility for adapting to surprises (Gunderson et al., 1995). The issue of continual modified understanding addresses the need for social-environmental learning, a key concept in social sciences. In this perspective, sustainable and resilient natural resource management emerges from the ability to adapt by learning, not from any particular adaptation measure. Adaptive capacity requires an institutional interface that is able to accommodate different pathways for development and keep those options open in order to avoid 'lock-in' situations in water management.

6. Recommendations

In this chapter we give options for methods to establish a comprehensive system understanding for practitioners in water management and researchers involved in interdisciplinary research programs. We suggest that it is important to consider methods that can be applied across disciplines in order to support interdisciplinary research. By doing so, the involved natural, social, and economical disciplines can contribute to complex systems understanding. In this chapter we also pay attention to the organisation of interdisciplinary research programs for social-ecological resilience in the field of water management.

6.1. How to improve our understanding of complex systems?

The application of the resilience lens to water management leads to recommending the following stepwise approach:

Step 1 Description of river basins / regional water systems

Water systems (or river basins) should be regarded as a system. The first step needed to establish a comprehensive system understanding is to describe the water system and the governing variables that constitute it. This description will consist of a picture of the 'state-of-the-art' (the system as it is now) by filling in the indicators for the potential and the relationships in the system that are important to understand dynamics and possible directions of change (pathways). The following questions need to be addressed:

- Is the system in a particular phase of the adaptive cycle?
- What are the possible states the system can be in?
- What are possible regime shifts and thresholds?

The description should be discussed with and validated by regional stakeholders in workshops, so they can bring in their knowledge about the system (variables and state of the art) and their perception of the important issues and 'variables of concern'. By doing so, a joint analysis of the system will be established with contributions by both practitioners and scientists. In the description of the water system (or river basin), the broader context (relations with national and EU-scale and cross-time influences) should be accounted for (panarchy). This step results in a description of the considered water system as it is now.

Step 2 Identify possible futures and vulnerabilities towards trends

In this step the influence of the future trends on the water system and its governing variables should be analysed and made visible. In this way the vulnerability, i.e. the resilience, of the system for these trends is addressed. The possible futures for the water system should be deduced from scenarios. Based on these possible futures the influences of the future trends on

the governing variables and the potential of the water system are researched. Questions that should be addressed are:

- Effects of the trends on the dynamics and governing variables of the system?
- What trends can provoke possible changes of the 'state of the water system' in the future? Which changes are 'irreversible' or hard to change back?
- What are the impacts of the trends on the water system in the future?

This will result in a ranking of the different trends on their impact on the water system. This can serve as a 'sieve' of the most influential trends for the system. With the two most influential trends an in-depth analysis will be executed. Questions that should be answered here:

- What are the changes for feedback mechanisms in the system?
- Possible effects of the changes in the key variables; path dependencies lock-in, regime shifts?
- Which key variables and relationships in the system determine the vulnerability in the system for the trends?
- Possible mechanisms that can make the system more resilient (lower vulnerability)?

This in-depth analysis will be the input for the third step.

Step 3 Explore adaptive management options (governance and measures)

Based on the results of the previous step the possible response from the policy level to gain adaptive capacity will be explored. An analysis will be made along the following questions:

- What kind of potentials are mostly acting as limiting factors for the adaptability?
- How capable are the involved actors to change and respond to the analyzed trends? What determines this capacity (education, regulations?, etc.)
- What are the mechanisms for leadership and leadership skills?
- Where does learning occur (and how does it manifest itself) in the system? What are the 'reservoirs of knowledge' (scientific and local knowledge)?
- By what (diversity of) responses and measures can the involved actors gain adaptive capacity and thus are able to built resilience towards the trends?

In workshops with the involved actors responses and measures should be discussed and evaluated as to arrive to concrete measures that can be implemented for the specific water system. This will give insight in the 'tailor-made' measures for the specific water system in a specific context and should result in a 'learning-case' of these measures and the different kind of support that is needed from the various policy levels (regional, national and EU).

6.2. Recommendations for organizing interdisciplinary research

In order to clarify epistemological dimensions⁴, it is important to organize relevant concepts in closely related research programs, to provide pathways for the development of an interdisciplinary research community. The main task of an international research community is to establish research programs for fundamental, applied and strategic research lines. By doing so, the establishment of generally accepted meanings of concepts across disciplines could be supported. Until now, topics of social-ecological resilience are badly studied because the research groups that are working on social-ecological resilience are fragmented (Folke *et al* 2007). For instance, the establishment of the Stockholm MISTRA Institute on Sustainable Governance and Management of Social-Ecological Systems (2006) is an example of an interdisciplinary initiative.

The following fundamental, applied and strategic research programs can be recommended:

1. Fundamental research programs that provide a scientific base in understanding complex, nonlinear adaptive character of social-ecological systems, in ecosystem dynamics (e.g. regime shifts, thresholds), as well as into institutional dynamics and the interplay between these. Contributions should be made to a common conceptual language across disciplines to exchange insights regarding the same studied complex issues of resilience, vulnerability, panarchy and adaptive capacity (Maarleveld, 2003). In the context of the holo-centric tradition in ecological science, Holling (1995) developed the concept complex, dynamic systems. The contribution of Holling in understanding complex systems is the principle that ecological (physical) systems develop according natural dynamic processes and that steering of such processes by humans lead to unpredictable and unforeseen results. Social research is focusing on the duality between the 'soft' constructed social system and how the 'hard' physical system is perceived in the soft constructed system (Van Slobbe 2002). The interplay between the physical system and the picture of this 'hard' system that is framed in the 'soft' system by people is the central issue in complex systems thinking. For instance, when institutional dynamics are considered, it is important to realize that the nature of these cause-effect relationships (or feedback loops) differ from the determined physical-chemical cause-effect relationships in ecosystems. Institutional feedback loops can be performed in several ways and therefore structure interaction in many different ways. That makes understanding their dynamics and changes an entirely different activity (Maarleveld, 2003). Institutional feedback plays a crucial role in social-environmental learning. So, focusing on the ecological side only, simplifies reality so much that the result leads to an incomplete and narrow understanding of complex systems. Doing natural science first with the social

⁴ The concepts of engineering and ecosystem resilience provide each an established disciplinary lens (engineering versus ecological disciplines) while social-ecological resilience is reshaping the resilience lens in an interdisciplinary way. Brand & Jax (2007) argue: "resilience, conceived as a descriptive concept, should be a clear, well defined, and specified concept that provides the basis for application within disciplines of ecological science."

Contributions by natural science disciplines as well as social sciences disciplines are essential in order to develop concepts and applications that fit into an interdisciplinary way of working (Gallopín 2006). In an interdisciplinary perspective resilience is conceived as a boundary object which should be designed in a manner to foster interdisciplinary work. In this sense, resilience is concept that is used to analyze social-ecological systems, termed as social-ecological resilience (as by Folke, 2006). For instance, the analysis of the concepts of vulnerability, resilience and adaptive capacity from the perspective of social-ecological systems, shows that these concepts are linked in a non-trivial way (Gallopín 2006). There is no generally accepted meaning for these concepts across disciplines. There is a risk that the research field focusing on social-ecological systems stays epistemologically unclear. Interdisciplinary research on social-ecological systems would clearly benefit from having a general, self-consistent set of these basic concepts that could be applied across disciplines (Gallopín 2006).

dimension added later on in the processes misses the essential feedback (Stockholm MISTRA Institute, 2006).

2. Applied research programs should be supportive to facilitate learning processes in the field of practice. Analysis of natural resource management 'command and control' practices established to 'solve' dilemmas may actually be the cause of new resource management dilemmas. Such management copes with the inability to shift their focus when their results showed to be ineffective at the longer term (Walker & Salt, 2006). The development of social-ecological systems is nonlinear and the consequences of human interventions and disturbances (*i.e.* global trends) are unpredictable. Water management should be a matter of experimentation in different contexts, learn to adapt to changing circumstances and 'learning by doing' (Van Slobbe, 2002). There should be a focus on practical insights and tacit, context dependent knowledge that trigger learning processes and improve cooperation between stakeholders in natural resource management. For example, in a Swedish study the following issues are addressed in the daily practice of the European Water Framework Directive (Galaz, 2006):
 - a. Collective action and analytical deliberation are highly limited nowadays;
 - b. Current water management institutions disregard complexity and uncertainty;
 - c. Water policy is poorly prepared to tackle global environmental change.

Several social scientists have been working on the concept of social-environmental learning and soft systems methodologies (Maarleveld, 2003) Also in applied research there an important difference in focus between ecological and social research. The 'Holling School' is focusing on adaptive mechanism in complex (eco)systems, while the 'soft system' school is focusing on the role of knowledge management in social-environmental learning as an issue for adaptive management (Van Slobbe, 2002). Besides soft system methodologies social dilemma research plays an important role here. Social dilemmas arise when individual and collective interests intertwine in such a way that individual decisions, although individually advantageous, are sub-optimal for the collective (Maarleveld, 2003). People's ability to adapt the rules of the game that creates social dilemma interdependencies appears to be a fruitful route for research on how to overcome social dilemma interdependence.

3. Strategic research programs that provide pathways for management of knowledge, social-environmental learning and innovation management. At one hand by reflecting at learning histories of practitioners involved in natural resource management and at the other hand by researchers involved in fundamental and applied research programs. Where first methodologies and tools were mainly developed on the assumption that processes of change are linear and are directed by new technologies, growing insight point towards the importance to create an environment in which stakeholders and researchers can learn from each other and develop and renew practices of management and research (Maarleveld 2003). These feedback loops are useful for the development of sustainable and resilient resource management in reality. Developments in knowledge and innovation management confirm the significance of a social-environmental learning perspective.

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