A guide to complexity theory and systems thinking for integrated water resources research and management

Report to the Water Research Commission

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Progress in and barriers to the internalization of complexity in integrated water resources management: a scoping and synthesis of early lessons and a way forward

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The publication of this report emanates from a WRC project titled *A guide to complexity theory and system thinking for integrated water resources research and management* (WRC Project No. K8/854).

Executive summary

The objective of this consultancy was to explore progress in and barriers to the internalization of complexity in integrated water resources management, and to do this through a scoping synthesis of early lessons*.* In essence then the report seeks to provide a guide to complexity for Integrated Water Resources Management and research endeavours based on the issues identified from interviews with key stakeholders. In these interviews with academics and practitioners, a number of issues were raised regarding the internalisation of complexity and we hope that these have been addressed.

This guide was thus tailored to try to meet these different needs. The report comprises two sections: Section A which details complexity theory and thinking or in Section B which offers a number of case studies that have embraced complexity or that demonstrates properties emergent from complex systems. Section A starts with a history of the genesis and development of complexity theory, which arose as a critique to traditional science and management approaches, which are briefly reviewed. This is followed by an overview of the key principles of complexity theory and characteristics of complex systems as opposed to complicated systems. We examine the uptake of complexity theory and the associated and emergent theories, frameworks and practices. This is followed by a short discussion on 'tools' for complexity research and development although we caution against any strong focus on tools *per se*. In Section B we provide a number of cases that are illustrative of complexity, the first, which traces the adoption of strategic adaptive management by the Kruger National Park, was a process that explicitly recognised complexity. The second and third case studies of water resources management in two catchments, discuss self-organisation and feedbacks, both emergent properties of complex systems.

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SECTION A: An overview of complexity theory and an exploration of what this means for IWRM

1. Introduction

1.1. Introduction to IWRM and report objectives

> *Global freshwater consumption rose sixfold between 1900 and 1995 – more than twice the rate of population growth. About one third of the world's population already lives in countries considered to be 'water stressed' – If present trends continue, two out of every three people on Earth will live in that condition by 2025. –*
> *Kofi Annan, in We The Peoples, 2000*

These are incredible figures given by Kofi Annan. Indeed, we live in a rapidly transforming global environment and the widespread water reform is largely a response to water scarcity and water stress. The adoption of Integrated Water Resources Management – or IWRM – as a framework to confronting such change factors is evidence that there are calls for a new way of doing things (see for example (Fallenmark *et al.* 2004). As stated by the UN World Water Development Report (2006), IWRM represents a 'holistic, ecosystem-based approach which, at both strategic and local levels, is the best management approach to address growing water management challenges and is seen as the best approach for meeting the equity and sustainability. But as Ison (2010) points out we need to keep track of 'doing the right thing in the right way'. And what is that right way?

Ison outlines why systems thinking is so critical to the 'right kind of governance' and this is important when one considers that in Africa alone, IWRM – as a new approach to the governance of water – is being adopted by over 20 countries[1] to-date. In South Africa IWRM is regarded as

> "a *philosophy*, a *process* and a *management strategy* to achieve sustainable use of resources by all stakeholders at catchment, regional, national and international levels, while maintaining the characteristics and integrity of water resources at the catchment scale within agreed limits " (DWAF 2003).

This means stepping back and asking what is it that we want to achieve? The integrated approach implies a number of things: Firstly, South Africa is committed to role water plays in social and economic development, and hence ensuring the sustainability of the resource base itself; secondly the quantity and quality of water is influenced by both water-based and land-based activities and thirdly, because of the nature of water, upstream activities impact on the downstream environment. Thus the imperative is to ensure that ecological, social, economic, technological, political and institutional environments are considered. This outlines no small task ahead. In a world of growing uncertainty and complexity – clearly expressed at the level of catchments – understanding complexity is essential for the successful governance of aquatic ecosystems, where a key challenge is to build the necessary competence for

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[1] In 2004, the Global Water Partnership GWP concluded in a review of the status of national efforts to use an IWRM approach, only six of Africa's 45 countries had made good progress, while 17 had taken some steps and 22 were at the initial stages of the process. According to the UNWDR of 27 countries responding to UN-Water Survey, 6 claim to have fully implemented national IWRM plans; 10 claim to have plans in place & partially implemented. Whilst Africa lags behind it was more advanced in terms of stakeholder participation, subsidies and micro-credit

dealing with uncertainty and to facilitate its uptake in governance. In theory, South Africa has set-up a framework for this through a strategic and iterative process of developing and revisiting catchment management strategies based on learning and adaptation to a complex and changing system (DWAF 2007, Pollard and Du Toit 2008). Nonetheless even this can run the risk of being translated into a linear process because administrative and governance processes are still designed for this.

Complexity is a challenging concept to understand and embrace. The complexity of operating environments (*sensu* Resilience Alliance; Cilliers 1998; Giampetro, 2004) in integrated water resources management is, at least in principle, increasingly recognized in South Africa (see Burns et al. 2006; Pollard and Du Toit, 2008). Although complexity implies little more than the presence of multiple drivers (usually only a few dominant ones), thresholds (sudden sharp rather than linearly progressive change), and feedbacks (either dampening or exacerbating reactions), the outcome of a complex system is a series of alternative trajectories into different states or regimes, which are more – or less – desirable. Snowden (2002) proposes a well-known 'sense-making framework' which distinguishes between these complex issues (much of what we deal with in IWRM) and other classes of issues (i.e. simple complicated or chaotic).

Even when managers or decision-makers have heard about and appeared to understand complexity, experience indicates that this is not easily reflected in their actions. For instance, adaptive management is marketed as generally the most appropriate management style in an ever-changing heterogeneous world (i.e. the most appropriate response to complexity) yet it is notoriously difficult to implement (e.g. Walters 1997). Similar comments can be gleaned from other fields which impinge on complexity – philosophers like Cilliers (1998) point out that internalization by individuals can sometimes require them to behave in a counterintuitive way; in Holistic Management (Savory 1999) it is claimed that most decision-making frameworks are flawed because they do not effectively take into account important 'soft issues' and are not sensitive to complexity.

The objective of this consultancy was to explore progress in and barriers to the internalization of complexity in integrated water resources management, and to do this through a scoping synthesis of early lessons. In essence then the report seeks to provide a guide to complexity for Integrated Water Resources Management and research endeavours based on the issues identified from interviews with key stakeholders (see Deliverable 1). In these interviews with academics and practitioners, a number of issues were raised regarding the internalisation of complexity. Broadly these were as follows:

- Foremost, almost all the respondents felt that organisations did struggle to embrace complexity and noted that habit and familiarity is hard to break. Participants wanted to know why complexity theory had come about and what complexity meant for them both academically and practically (i.e. into the operational world).
- The links between various terms and concepts- all acknowledged as somehow related to complexity – were unclear (for example, systems thinking, resilience, socio-ecological systems, adaptive management, system dynamics and so on).
- Many felt that the literature was so wide and disparate across disciplines and experience that they found it daunting, difficult to navigate and at times even off putting. They requested a relatively simple overview – as a descriptive – of complexity and systems thinking.
- Some participants called for recent cases – especially in South Africa – where complexity theory and systems thinking has been applied and how (this will be dealt with in Deliverable 3). This was particularly important for instance when some felt that complexity (and adaptive

management) was being advocated even when it was not entirely appropriate (i.e. when basic research was needed).

This guide was thus tailored to try to meet these different needs. The report comprises two sections. Section A starts with a history of the genesis and development of complexity theory, which arose as a critique to traditional science and management approaches, which are also briefly reviewed. We then go on to give an overview of the key principles of complexity theory and characteristics of complex systems as opposed to complicated systems (a car engine is complicated, not complex for instance). In section 4 we examine the uptake of complexity theory and the associated and emergent theories, frameworks and practices. This is followed by a short discussion on 'tools' for complexity research and development although we caution against any strong focus on tools per se. We close by reflecting on what complexity means for IWRM in particular: as one attendee put it, "*the resilience and complexity perceptive of looking at ecosystems and socio-ecological systems provides a revealing way of unlocking different links that exit within these systems*". In Section B we provide a number of cases that are illustrative of complexity, the first, which traces the adoption of strategic adaptive management by the Kruger National Park, was a process that explicitly recognised complexity. The second and third case studies of water resources management in two catchments, discuss self-organisation and feedbacks, both emergent properties of complex systems.

2. The history and emergence of complexity thinking

2.1. The world as increasingly complex

Without a doubt most authors dealing with complexity agree that the world is becoming increasingly complex, mainly as the network of interactions that have grown and spread around the globe as well as their interconnectedness (see for example Bogg & Geyer (2007). The economic and technological advances have meant that we interact with ever more people, objects and organisations through communication, production and transport and each of these is increasingly interconnected. And of course as Casti (1994, cited in Urry 2005) pointed out some 15 years ago, the social world has grown in human numbers – to a world of 6 billion, over 700 million cars and I billion internet users. Importantly, complexity is however not the same as complicated and not all sciences – nor all researchers – have embraced complexity and even less so policy makers and managers.

We have made the point in various WRC reports that complexity theory arose as a critique to conventional scientific method, considered to be ill-equipped to dealing with complex inter-dependencies such as those described in the introduction (e.g. (Pollard et al. 2008b, Pollard et al. 2009). In the so-called 'natural sciences' evidence was amassing that despite years of scientific research ecosystems continued to degrade and whole species to decline. In these associated disciplines, researchers and policy makers were asking hard questions. Why was it that despite the enormous resources that had been invested in research we appeared to be facing ongoing degradation and unprecedented crises? The answers appeared to lie in a number of places including the general failure of science to recognise the linkages between disciplines (i.e. systems) through the persistent endorsement of silo approaches as 'good science'; the lack of a meaningful and reflexive interaction between science and society (see Lubchenco (1998); and the use of the conventional scientific method based on a Newtonian world view. Challenging reductionism is not new; indeed complexity thinking builds on *general systems approaches* pioneered in the 1930s, which examined 'wholeness' and how parts operate together, not from examining the parts themselves. In particular Smuts (1926; cited in Von Bertalanffy 1972) is well known for his adage when defining holism "the sum is great than the parts". There are divergences between systems and complexity theories but before we elaborate on these, it is important to provide an overview of the important role that Newtonian science and the 'modernity project' has played.

2.2. Newtonian science and the modernity project

The basis of Newtonian science – a mechanistic worldview – is premised on the thesis that to understand any (complex) phenomenon, it needs to be disaggregated into its individual components. This process of reductionism actually preceded Newton as the founding principle of Descartes work but was embodied in classical mechanics in the early 20th century. Some suggest that it won favour and persisted as a pervasive influence because of its simplicity, coherence and because it dovetailed with intuition and commonsense (see for example Heylighen et al. (2007)). The movement of component parts is governed by deterministic laws of cause and effect such that if you know the initial position of the components (particles) and their velocities together with the forces acting on them, then the evolution of the system can be predicted and is perfectly regular and reversible. The Newtonian epistemology – a rationale view – is based on knowledge being an imperfect reflection of 'the truth' and the role of science is to improve the accuracy of this representation. Thus information can be collected and registered leading to 'improved knowledge'. The ontology is based on matter in space and time, with movement governed by natural laws. Modernism therefore became focused on the search for an overall explanation of 'the truth' – or as stated by Lyotard (1984) a 'single meta-narrative' – a particular way to describe it 'correctly and completely'. This could only be done by reducing complexity, diversity and hence variability to a smaller number of elements through reductionism.

Although a detailed critique of this view is beyond the scope of this paper, suffice to say, many have scrutinised and critiqued this from a philosophical, conceptual and practical perspective (see also below). Some of these relate to a questioning of observer-independence – the assumption that drawing distinctions between components is objective (i.e. irrespective of the observer). Also the assumption that distinct components remain distinct – presupposing constancy and precluding their merging, disappearance or appearance (e.g. emergence) – is questioned. In other words there is no place for novelty and creation. However as Heylighen et al. (2007) point out that from a philosophical point of view, once human agency and freewill is included, there is a basic contradiction with determinism. Classical science ignores issues of ethics and values (see for example Cilliers (1998)) although economic science attempted to address this by introducing the idea of 'rational choice' (i.e. agents will always chose the option that maximises its utility). Also, as pointed out by Capra (1996) in his classic book, 'The Web of Life' and by Prigogine (1997) in his famous book 'The end of Certainty' (1997; which contests that determinism is no longer a viable scientific tenet) classical mechanics was challenged by various successor theories in physics such as quantum mechanics, relativity theory and chaos theory (non-linear dynamics). Of course the father of such thought, Einstein, showed there was no absolute or fixed time, only that relative to the system to which it referred. Chaos theory (possibly a misleading term as suggested by Heylighen et al. (2007)) rejected the notion that large changes in drivers produce large effects. Chaos theory iterates a simple mathematical algorithm demonstrated that small causes – following a deterministic set of rules – can produce unpredicted, yet patterned, large effects. More popularly this was demonstrated through the well-known, so-called 'butterfly effect' by Lorenz in 1961 (Casti 1994) where theoretically the minute movements associated with the flapping of a butterfly's wings in South America could produce weather patterns in Central Park. Moreover, because relationships are non-linear (see later) the same variable can produce different effects. Essentially all these concluded that our scientific knowledge is uncertain leading to a call for a new approach.

2.3. Systems thinking, complexity and postmodernism

2.3.1. Systems thinking

An important concept for our story that emerged in the early 20th century as the early philosophical challenge to reductionism (by Teilhard, Whitehead and Smuts) was that of *holism*. Smuts (1926; see earlier) coined the term which he defined as the tendency for the whole to be greater than the sum of the parts. As Heylighen and colleagues (2007) point out, in contemporary language this means that the whole has *emergent properties*; that is properties that cannot be reduced to the properties of the parts since they are completely different. They use the example of table salt (NaCl) which is edible, forms crystals and is salty – very different from the component properties of sodium (Na), a highly reactive soft metal and chlorine (Cl), a poisonous gas. When we consume salt it is because of its emergent properties. These authors suggest that science managed to ignore emergence and holism for so long mainly because it seemed to lack any credible scientific foundation; this despite the fact that on scrutiny almost all properties that we deal with in our day-to-day are emergent (beauty, ability, life).

In the '70s this started to change with the conception of *systems theory* by the biologist Ludwig von Bertalanffy ((1972). He noted that unlike Newton's mechanical systems, living systems are intrinsically *open*: they interact with their environment through the absorption and release of energy – and must do so to survive. He recognised that unlike the closed systems modelled by Newton, the dependency of living systems on a wider environment meant that they could never be entirely predictable. Other important properties of open systems fundamentally set them apart from closed systems. They are separated from their environment by a *boundary* which gives them their own *identity*. Incoming and outgoing information, matter and energy are exchanged as streams of *outputs* and *inputs*, which also provide a means to *couple* systems. A group of coupled systems form a *network* which, when functioning in a coherent manner comprise a *supersystem* , containing the component *subsystems*. De Rosnay (1979) explains that they are thus part of a *hierarchy* extending upwards and downwards, such that in systems theory both directions are equally important in understanding the nature of the system. Importantly it does not deny the analytical method but complements it by adding an integrative method. In the search for patterns of organisation that are common to different phenomena (such as for example, similar patterns between society and a living organism) Von Bertalanffy (1968) called for a *general systems theory*.

Another important concept emerged in the 1970s with Rittel and Webbers formulation of 'wicked problems' (1973) which implicitly recognised the nature of complexity in that "societal[2] problems are never solved – at best they are only re-solved, over and over again.' He contrasted these with 'tame' problems, which are not trivial problems, but they can be tackled with confidence and are sufficiently

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[2] Although they did make a distinction between social problems and those in the natural sciences, which are '*definable and separable* and may have solutions that are findable' (P. 160, emphasis added) – this has later been contested, the concept has remained useful

understood sufficiently to be analysed using established methods. Later work by Ulanowicz (1997) argues that that in reality even natural systems are unpredictable and complex (albeit difficult to consider a "purely natural system" as "uninfluenced by values" because of the 'artificial' exclusion of humans). A useful description of wicked problems is given by the Australian Public Services Commission (2007, cited in Ison 2010) as problems that

> *'go beyond the capacity of any one organisation to understand and respond to, and [where] there is often disagreement about the causes of the problems and the best way to tackle them…key ingredients in solving or at least managing complex policy problems include successfully working across both internal and external organisational boundaries and engaging citizens and stakeholders in policy making and implementation.'*

Upon reflection, an increasing number of problems that we face in governance and IWRM would be better defined as wicked problems.

As a number of authors point out (Heylighen et al. (2007); (Levin 1998); (Mazzocchi 2008), these shifts in thought and paradigm involve a completely different ontology to that of Newtonian science: the building blocks of reality are not the material particles but abstract relations and the complex organisation that the collectively form. This is because a subsystem is not seen as an independent element but as a particular type of relation mapping input to output. Importantly they are *constrained* through their coupling to other systems; that is they are no longer independent. Campbell (1974; cited in Heylighen et al. 2007) detailed the role of *downward causation* such that not only is the behaviour of the whole determined by the property of the parts (upward causation) but the behaviour of the parts is determined to some degree by the property of the whole (downward causation). For example, how an individual behaves depends not only on their neurophysiology but also on their environment (societal norms).

Critical to systems theory is firstly the recognition that because of dependencies, the properties of components cannot behave independently but must obey certain rules and secondly, it is their relationship that provides for *emergence*. This moved the scientific debate firmly into the world of uncertainty.

Tensions and paradoxes: The coupling of seemingly antagonistic terms and concepts:

A number of tensions exist in the developing fields of complexity and systems theory. One of these is referred to as an impasse by Morin (1992) who argues that general systems theory does not constitute a paradigmatic principle which remains to be debated and clarified. Rather systems theory evokes the principle of holism and, he argues, *seeking holism is subject to the same process as reductionism* (a simplification to the whole and the reduction of complexity to a master concept – see also comments by (Mazzocchi 2008)). Nowotny (2005) argues that we are involved in contradictory processes when analyzing complexity- in that we face oppositionalising tendencies to accept complexity and at the same time 'to sort it out'. Rather, Morin argues the principle should be to seek confluence. He notes that as far back as 1966 Pascal had expressed the view that he considered it "impossible to know the parts without knowing the whole as to know the whole without knowing the parts" – regarded as a 'double-bind' by Gregory Bateson where each cancels the other out. Morin argues for a constructivist understanding wherein these two explanations are complementary by virtue of the motion that joins them (their confluence). Also as he points out we have to deal with poly-totalities where every term (variable) can be conceived of both as a part and as a whole. Ulanowicz (1997) has a compelling argument for suggesting that even composition can be considered to be an emergent property.

Morin suggests that the search for a paradigm of complexity stimulates the search for complex praxis and politics. At the heart of a 'new form of rationality' lies the thesis that it is the interactions between the parts or components of the system that are critical and the set of interactions that constitutes the ***organisation*** of the system. Organisation is the concept that gives constructive coherence, order and regulation to the interactions. Organisation is dynamic in most systems requiring us to conceive of (a) the continual re-organisation of the system towards dis-organisation and (b) self-reorganisation or auto-re-organisation[3]. He notes therefore that organisation cannot be reduced to a few structural rules. With organisation as the higher paradigmatic concept he notes that although classical science held the principle of order as key; it is not that he suggests that order be replaced by organisation but that rather they be combined particularly since the notion of order introduces that of disorder. He stresses that we must no longer disregard disorder or organisation (interrelations).

Cybernetics is an approach closely aligned with systems theory and at times the terms are used synonymously. In essence cybernetics focuses on the study of feedbacks – and especially negative feedback (see Section 6) as maintaining a system in some sort of stable state. Concepts such as communication and control in living organisms and organisations are all key areas for cybernetics which places a strong emphasis on the subjectivity of knowledge (see Heylighen et al. 2007 for more detail).

2.3.2. Complexity science

In the 1980s a new approach emerged known as complexity science (Waldrop 1992) offering the possibility of developing a tenable alternative to the Newtonian paradigm. Interestingly, although complexity thinking builds on *general systems approaches* pioneered in the 1930s (as described above) its origins are largely independent of systems science. Heylighen et al. (2007) trace the diverse roots of complexity thinking to computer science (which allowed the simulation of large complex models), biological evolution (with the appearance of complex forms from variation and natural selection); non-linear dynamics and statistical mechanics (which needed new mathematical tools capable of dealing with randomness and chaos), and the descriptions of certain social systems where emergent structures are widely evident (e.g. stock markets, internet networks or insect societies). Thrift (1999, cited in Urry (2005)) stresses that complexity approaches combine both system and process thinking.

A number of authors suggest that complexity researchers have still to develop sound and credible philosophical foundations asserting that they continue to cling to the Newtonian paradigm, hoping to "discover mathematically formulated 'laws of complexity'" (see Heylighen et al. (2007) and Morin (1992) as summarised above). In this regard it is important to turn to the relationship between complexity thinking and postmodernism. Heylighen et al. suggest that the intersection between complexity and postmodern[4] philosophy could lead to interesting and useful research – specifically allowing <u>insights from both the natural and social sciences</u> without one having to trump the other. Despite their concerns

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[3] He goes on to coin the term auto-eco-re-organisation in recognition of the exchange with the environment which itself furnishes organisation in the form of nutrients etc

[4] Heylighen et al. (2007) note that this term needs to be used cautiously: "it can refer to a wide variety of positions…it will not be used here to refer to flabby or relativist positions" – about which they are deeply critical noting that it has lead to fruitless debates and stressing that "the dismissal of positions that try to be conscious of their own limitations (through the relativist argument) is ..arrogant" – a condition to be expected in new and evolving philosophies.

around the misuse of the term, they note that if postmodernism is a rejection of the dream of modernism (see Section 2.3) – then 'postmodernism can be characterized in general as a way of thinking which is sensitive to the complexity of the world' (see also Cilliers (1998); (2005)).

Surprisingly – given the critique of reductionist science and modernism – these authors suggest that the use of complexity theory to the social sciences has been less than productive. In part this may reflect the strong reductionist elements (informed by chaos theory) still evident in 'hard' complexity theorists that give it a strongly modernist flavor and whilst some postmodern positions are acknowledged as simply 'too flaky' to be of any value, they stress that dismissal will have to be tempered to get any discourse going. (Interestingly they suggest that philosophers from the Anglophone countries still appear to be locked into a tradition of 'analytic' philosophy whilst continental philosophers such as Morin, Stengers and Luhmann appear to be more comfortable with the concepts of uncertainty and the subjectivity it entails!). They note also that when dealing with social systems the boundaries are often unclear and often a matter of theoretical choice. Urry (2007) however points out that in the late 1990s, social sciences began to go complex and – interestingly for our story – in 1996 the Gulbenkian Commission on the Restructuring of Social Sciences advocated breaking down the divide between 'natural' and 'social' sciences through adopting complexity. As he says, 'complexity practices' can themselves be viewed a self-organising network.

3. Complexity science – principles and properties

Complex systems are characterized by a number of important principles and properties. For our purposes we have chosen to start with the central notion of *complex adaptive systems* since the key principles and properties are demonstrated as we unpack the term.

3.1. Complex adaptive (or multi-agent) systems and the importance of self-organisation

Holland (1996) coined the term the *complex adaptive system (CAS),* commonly also called a multi-agent system. However, what distinguishes a CAS from a pure multi-agent system (MAS) is that whilst a MAS is simply defined as a system composed of multiple interacting agents, in a CAS, the agents as well as the system are adaptive: (i.e. the system is self-similar). Complex Adaptive Systems (see Box 1) are characterised by a high degree of adaptive capacity, giving them resilience in the face of perturbation, emergence and self-organization. A CAS behaves or evolves according to three key principles:

- order is emergent as opposed to predetermined (e.g. Neural Networks),
- the system's history and development is non-linear and irreversible, and
- the system's future is often unpredictable.

Box 1
Definitions of CAS

Holland (1994):

> A Complex Adaptive System (CAS) is a dynamic network of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to what the other agents are doing. The control of a CAS tends to be highly dispersed and decentralized. If there is to be any coherent behavior in the system, it has to arise from competition and cooperation among the agents themselves. The overall behavior of the system is the result of a huge number of decisions made every moment by many individual agents.

Eoyang et al. (1998) provide a working definition in the field of public policy decision-making:

> A complex adaptive system (CAS) involves a large number of agents that act as parts and interact with each other to generate emergent, system-wide patterns of behavior for the whole. The macroscopic patterns generated in this way feed back into the system by constraining the subsequent behavior of the microscopic agents. The whole system, or environment, determines the fitness of each part, or agent. At the same time, the interactions of the parts form the environment in which all subsequent interactions take place. This complex and mutually causal relationship between part and whole is the mechanism that generates all other characteristic behaviors of a CAS. These characteristic phenomena include unpredictability, scaling, attractors, butterfly effects, heterarchy[5], dynamical behavior through time, turbulent boundary conditions, emergence, lock in, and so on.

Heylighen and colleagues (2007) consider the concept of CAS to be the most important tool of complexity science and provide an elegant summary of its essential properties. Many of the terms are familiar to those in the biological sciences and yet move beyond biological systems alone as contained in Darwin's theory of evolution. Also it is important to recognise that complexity science is a relatively new science and ideas are still emerging and evolving.

> The key component of complex adaptive systems is *the agent*. The term has a diverse representation from molecules and cells through to ants and people that can be conceived of as autonomous individuals seeking a personal goal or value ('utility' or 'fitness'). In this respect they need not exhibit any specific mental quality or intelligence. Drawing on evolutionary theory, they are typically regarded as ignorant of (a) the wider environment and (b) the long-term effects of their actions, reaching their goals by trial and error (*blind variation* and *natural selection*). Even when agents are intelligent and knowledgeable to select apparently rational or co-operative actions they are *intrinsically uncertain* about the remote effects of their actions. Indeed agents only interact with a few other agents that form their local neighbourhood introducing the principle of *locality*. Nonetheless these local actions can propagate through the system having global consequences, affecting the complex system as a whole. These effects are *emergent* and, because they could not have been inferred or extrapolated reliably from the local rules, unexpected (surprise). Since the goals of the agents are intrinsically independent, they may often be in inherent conflict (a price hike may increase profit for the producer but will be resisted by the consumer for example). This leads to an ongoing process of *co-evolution* with agents *adapting* to changes made by other agents (and modifying the others environment at the same time). Also, since actions are local their effects propagate only step-by-step diffusing through the

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[5] Heterarchy refers to multiple rulers with a balance of powers rather than a single ruler through hierarchy (an example is a group of partners in a law Firm; Fairtlough (2007). The Three Ways of Getting Things Done. Hierarchy, Heterarchy & Responsible Autonomy in Organizations. Axminster: Triarchy Press.

network. Therefore the same action can and likely will have *multiple and different effects* (in time and space). Some causal chains may even close on themselves feeding back to the starting condition leading to feedback loops (such as poverty leading to an increase in drop-out rate at school and increased unemployment feeding back to poverty). The system is thus intrinsically *non-linear*.

Levin (1998) comments that ecosystems are prototypical examples of complex adaptive systems where patterns at higher levels emerge from localized interactions and selection processes. In social science, a dynamic (dispersed and decentralized) network of agents (e.g. individuals, organisations, institutions, nations) acts and reacts to each other. Coherent behaviour in the system can arise from competition and cooperation among the agents themselves.

3.2. When is a system complex? Key attributes of complex systems

As Snowden (2000) points out, not all situations are complex (see Figure 4) and one must seek to understand what therefore are the appropriate sense-making attributes and responses. A key feature of the complex adaptive systems as described above is that of self-organisation where the system 'arranges itself' (through relations between components) and adaptation. This appears to be the rule rather than the exception. Heylighen et al. (2007) coin the term "creative evolution" to describe this evolution that is not only unpredictable but also creative – producing emergent organisation and innovation. They describe this in non-pejorative terms as 'solutions to local and global problems' although it must be recognised that not all creative evolution can be considered in a positive light given today's values (for a time Apartheid or Nazism was highly adaptive and self-organising) but they make a valid point nonetheless. (Self-organisation is further dealt with at some detail in the case study in Section 6).

In addition to self-organisation, a complex system can be distinguished from a simple one, albeit complicated, by a number of attributes including non-linearity, uncertainty, emergence, multiple scales and cross-scale effects, and feedback loops (see also later discussion on resilience). A complex system shows feedbacks (reinforcing or balancing – see Section 6.2) in its cause and effect relationships, which, usually because of operation at different scales, cause emergence (i.e. the feedbacks generate surprising new properties not predictable from the original components making up the system). A simplistic but effective example of emergence is the way in which *words* strung together make up a *sentence* with an emergent meaning, not directly evident from the meaning of the individual words. Almost all ecosystems, and almost any socio-ecological system (see Section 4.2) can be shown to exhibit this complex behaviour and hence emergence. Ironically, complex systems often have only a few predominant drivers – it is the way these interact (and in particular the feedbacks) which produce the complexity (In an ecosystems for example, these typically include factors such as rainfall, fire and herbivory). The drivers invariably vary in strength over space and time, producing different combinations of outcomes. At a certain range (called a *threshold*) in the values of these different drivers, systems can fundamentally change their nature, say from grassland to savanna, or from family to sibling kinship networks. In practice this usually takes place as a series of linked thresholds and system states, called a *regime*, and a regime shift follows (see amongst others (Scheffer *et al.* 2001);(Carpenter 2003); (Folke *et al.* 2004). An example of a regime shift is the change in the nature of rivers in the lowveld from bedrock-influenced, higher-flow, and with lower human utilisation to alluvium-dominated, lower flow, and with higher levels of human abstraction. A series of interlinked thresholds is crossed in each of these factors, leading to a different overall state. Essentially in a new state the rules-of-the-game – or underlying processes – change.

Complex patterns contrast with *complicated* patterns which, in a technical sense, have very many parts but these parts are connected in a way which produces a deterministic (always the same, entirely predictable) outcome (e.g. aircraft or electronic circuit boards). These fundamental concepts are reviewed by Walker and Salt (2006) and a series of thresholds and regime shifts are listed on the Resilience Alliance website (http://resilliance.org (and see Box 3).

Although not as predictable, complex systems show remarkable pattern such that they may be – mistakenly – as being near "the edge of chaos[6]" (Langton, 1990). They can be managed with an appropriate but not exaggerated sense of confidence. Mistaking a complex system for a complicated one leads to problems of rigidity, with the complex system (if one can imagine it as a living or adaptive entity) tending to "outwit" the complicated human plan. An example we see regularly is that of free-flowing rivers versus canalization. Ultimately, the latter system can 'backfire' (some people call this 'nature showing 'revenge'), as demonstrated by, for instance, the Aral Sea saga and in chronic ecological and societal problems with highly regulated rivers (e.g. the Mississippi River). We are fortunate in South Africa to have progressive water legislation consistent with sustainability science principles which recognise complexity (Burns et al. 2006, Pollard and Toit 2008) though this is only in the very early stages of implementation (see also Bammer (2005)).

Table 1 Key attributes of complex systems

(synthesised by Pollard et al. 2008 from Holling (2001), Gunderson and Holling (2002), Berkes et al. (2003), Walker et al. (2004), Allison and Hobbs (2006)

Attribute	Example
Socio-ecological systems are **heterogeneous**, **dynamic** and in a state of **flux**. Variability is essential and not a 'management inconvenience or problem'.	Rainfall may vary around an 'average' of 500 mm per year – from 200 mm in a dry year to 800 mm in a wet year. This brings about different effects each year and cumulatively.
Systems have **multiple drivers**, many of which are non-linear in their effects and which operate at different scales. Hence outcomes are usually not entirely predictable. Also some of these drivers may relate to other 'sub-systems' such as a political or global drivers.	For example, a reduction in base flows may reflect increased abstraction, the impacts of a weir and a political decision to expand agriculture, such as biofuels which are seen as a way to improve our foreign exchange
Components of systems are independent and interacting and understanding the linkages is important. In particular **feedback loops** are an important attribute of complex systems.	For example, a reinforcing loop is evident when wetland health improves, causing an increase in the water table which causes a further improvement in wetland health (Pollard et al. 2008c, Cousins et al. 2009). In Tanzania, despite socio-political change,

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- [6] Although originally a mathematic term, now use in many disciplines to describe a situation where systems operate in a region between order and randomness or chaos and where complexity is maximal. It is sometimes used inappropriately (see G. Langton. "Computation at the edge of chaos". *Physica D*, **42**, 1990.)

	persistent feedback loops between monitoring and action have ensured a resilient management system (Tengo and Hammer 2003)
Multiple drivers and feedback loops often mean uncertainty because we **can't predict exact outcomes**, Moreover they can lead to **unexpected outcomes**	For example, the global drive to reduce dependence on fossil fuels (viewed as a favorable position for sustainability) has increased biofuel initiatives which are impacting on water resources and on food availability. This was not anticipated a decade ago.
Complex systems display **lags**	For example, we are unlikely to see immediate benefits from the policy to determine environmental flows because of the complex socio-economic and political arrangements needed to achieve this
Complex systems are not necessarily complicated, in fact, they often only have a **basic set of drivers and responses**.	For example, fire, rainfall and fire management may be the key drivers of a particular system.

But what does this mean in practice? The essence of these systems is that their inherent variation and novelty in space and time is what determines the system function and adaptation. Gradually we are getting better at understanding and managing such attributes. Importantly, we strive to see the system holistically, with all systems as sub-systems of bigger systems, and invariably interacting with other sub-systems and the bigger and smaller systems to which they relate. Berkes et al. (2003) assert that there are three fundamental implications for resource management of accepting complexity:

(i) models and perspectives based on linear thinking are inadequate (including optimization models);
(2) qualitative analysis is an important complement to quantitative approaches; and
(3) a multiplicity of perspectives is needed to analyse and manage complex systems.

A key lesson for management is that management processes can be improved by making them flexible and adaptive, so as to deal with uncertainty thereby building capacity to adapt to change.

4. The uptake of complexity and development of associated concepts

4.1. A brief overview

Embracing the fundamental conceptual re-orientation that complexity demands has led to a variety of developments in the broad field of complexity science within different disciplines or groups of interest. Complexity sciences have been gradually achieving more influence in academic circles. Here we outline but a few of these.

- Since philosophy involves a critique of the very genesis and basis of new ideas and discourse (such as complexity), we devoted much of the earlier part of this paper to examining the philosophical underpinnings and influence of complexity thinking and the postmodernism to which readers are referred (Section 2).

- In the social sciences *Sociology and complexity science* (SACS) is the term used to describe a growing network of research taking place at the intersection of sociology and complexity science. Urry (2005) dates its emergence to around 1998 when social sciences began to make what he called the *complexity turn* which he defines as 'the critical incorporation of the tools of the complexity sciences into the social sciences'. Since then a number of philosophers such as Luhmann and Morin have been working new ways of thinking about sociological inquiry based on their epistemology of complexity and complex systems (see also Cilliers (2005); and Heylighen et al. 2007). As noted previously the common focus is on complex adaptive systems. Efforts have also been made to inform the curriculum of social science studies (see for example (Byrne 1998)

- In the political sciences, many regard Robert Jervis' book *System Effects: Complexity in Political and Social Life* (1998) as a landmark. Based on insights from complexity theory, he asserts that that the very foundations of many social science theories are questionable. Given that we live in a world where things are interconnected, where unintended consequences of actions are unavoidable and unpredictable, he examines what it means to act in a system. He presses for the anticipation of system effects by political actors. In political science some groups have started to examine the implications of complexity science. For example in Latin America, a number of research centers and programmes have emerged that reflect the interest in complexity such as the Communidade de Pensiamento Complexo (Community of Complex Thought). In public policy and decision-making by acknowledging the nonlinear, iterative, dimensional nature of public policy issues some work has been done for example on proposing processes for policy makers and analysts to adopt a more realistic view of the decision-making process (e.g. Eoyang et al. (1998).

- Confluence between social and ecological sciences. As obvious as it may seem intuitively, in practice the social and ecological sciences (and for that matter most others) have worked in intellectual and geographical isolation for most of the 20th century; totally in keeping with the prevailing pedagogical orientation from day one at school – and despite the contrast with the 'real world'. But as David Byrne (1998) notes when providing an introduction to complexity for the social sciences "ecology keeps coming into the debate" (p.4). Similarly for ecologists, 'social issues' keep coming into the picture influencing seemingly neat outcomes and likewise, there is increasing acknowledgement that they need to be taken into account (see also post-normal science[7] Funtowicz and Ravetz (1993)). In response to the lack of integration and the failure of conventional science to take into account the complex nature of systems two key concepts emerged: those of *socio-ecological systems* and *resilience*. Since both of these are central to our focus on natural resources we detail some of their history and conceptual orientation in the following section.

- In the field of management, strategic adaptive management (see Section B of this report) is being tested as both an orientation to and a process for responding to complexity and uncertainty and some academic institutions are dedicating entire research areas to the study of complexity and management. (For example the Business School of the University of Hertfordshire does just this, aiming to understand complex responsive processes of human organizing, leadership and innovation). We have chosen to elaborate the use of SAM locally in South Africa below because of its profound re-orientation in a world of conventional science and management and because of its potentially powerful catalytic effect (2 cases studies KNP and ICMA). However it must be recognised that despite the focus on management, there has also been a challenge to the managerial imperative where authors such as Bavington (2010) who, through an examination of the annihilation of the Newfoundland cod, argue for a total rejection of the managerial impulse and its replacement with a new philosophy aimed at living within the limits of existing ecosystems. He suggests that when the massive and unintended collapse was realised in 1992 (leading to a loss of 30,000 jobs) neither scientists nor politicians questioned the fundamental tenets of what had brought them to this point but simply introduced a new phase of managerial ecology – which did indeed emphasise risk and uncertainty – in place of "the confident forecasting and control-oriented approach associated with [earlier] single-species scientific management" (p. 83)
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- Knowledge management and organisational theory: Snowden and Boone (Snowden and Boone 2007) stress the importance for an organisation to appropriately "diagnose" the class of challenge (see also Figure 4) being faced, which influences the overall effectiveness of response in the organisational strategy. If their typology of issues (simple, complicated, complex, and chaotic) is not explicitly consulted or at least intuitively used as a basis, the organisation faces the strong possibility of spending fruitless energy trying to solve problems or exploit opportunities inappropriately. This thinking has made several firms or agencies far more cognisant of the detection of complexity, almost embedding it as a culture. Importantly, not all problems are complex, enabling easier conventional solutions to be applied to some areas, though in the natural resource arena, complex structure of situations faced is very common. If complex problems are identified as such, organisational learning should improve sharply once the appropriate orientation is adopted.

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[7] Post-normal science is a term coined to describe a new type of science emerging in response to the challenges of policy issues of risk and the environment. It is appropriate when either uncertainties or decision stakes are high; then the traditional methodologies are ineffective. In those circumstances, the quality assurance of scientific inputs to the policy process requires an 'extended peer community', consisting of all those with a stake in the dialogue on the issue. Post-normal science can provide a path to the democratization of science, and also a response to the current tendencies to post-modernity.

- Organisational development. Much has been written under the rubric of organisational development, complexity and learning where it is recognised that designing an organisation in the same way that engineers design a product is untenable for dealing with complex issues and organisational restructuring provides significant evidence that a different approach is required (see for example Mitleton-Kelly 2005). ; learning is a characteristic of an adaptive organization, i.e., an organization that is able to sense changes in signals from its environment (both internal and external) and adapt accordingly.
    - The work in *organizational learning* can be distinguished from that on a related concept, the *learning organization*. This later body of work, in general, uses the theoretical findings of organizational learning (and other research in organizational development, system theory, and cognitive science) to make recommendations about how to create organizations that continuously and effectively learn, as championed by Senge (1990) in his book *The Fifth Discipline*.
- Economics: In an attempt to bring home the real importance of contributions to human welfare (including previously obscure or unrecognised ones) provided by nature, ecosystem services (MEA ref) have been explicitly articulated. These include fundamental (e.g. nitrogen fixation), provisioning (water, food and fibre), regulating (e.g. flood amelioration; water purification) and aesthetic/recreational (e.g. tourism and recreation). Several attempts have attempted financial evaluation of such a full array of benefits, and a broad-scale global evaluation (Constanza *et al.* 1997) suggests an amount that exceeds global GDP. Natural resource and related benefit accounting sharpens this awareness but may not on its own necessarily engender awareness of complexity i.e. such accounting can be done in a complicated as opposed to a complex way (sensu Snowden). Much standard economic theory depends on conventional notions of equilibrium, often coupled to zero-sum benefits, but in the last decade a minority of economists have started participating actively in transdisciplinary initiatives which treat economic factors as an integral part of a socio-ecological system, and in this way embracing complexity. Even independently of this, some recent economic theory now concerns itself with far more dynamic modelling than the conventionally taught economic thinking, and it is anticipated that this trend will increase as the effect of complexity thinking grows. It is important to remember that "tried-and-tested" conventional thinking is particularly good at a wide range of issues and will persist usefully into the future – the real art will be to find meaningful complementarity between the approaches.

- Education: The role of complexity in education has grown over the last decade as is evident in a recently edited book (Marson 2008) which explores *Complexity Theory and the Philosophy of Education*. But philosophy in general and philosophy of education have had a major influence on ideas that are shared with complexity thinkers. These are mainly related to epistemological questions, specifically the nature and roots of knowledge. Here the shifts in the understanding of knowledge and knowing provided by constructivism have augmented the open-endedness and uncertainty of knowing embraced by complexity theorists. Although the ideas contained in many contemporary educational theories are not drawn from complexity theory *per se*, their shared points have given rise to links that have resulted in a new discourse on education. Complexity science – and in particular the 'logic' of emergence – to 'rethink' practice – has had a profound influence on rethinking the purposes of formal education. In doing this it combines aspects of deconstruction (a philosophical application of Jaques Derrida's thinking, 1976) and complexity science, in the context of critique – i.e. trying to understand education practice that has gone before.

- In struggling with representation (i.e. what is worth knowing and how is it represented), education has looked towards complexity theory (and deconstruction) for challenging the logic of representation. Out of this an 'epistemology' has developed, inspired mainly by Prigogine's critique of determinism and Derrida's critique of presence. This has largely lead to a crisis related to what the implications of such an epistemology for modern Western education might mean. Complexity educationalists (Biesta 2001,) argue that the representational foundation of modern Western schooling – which is representational at the epistemological level– can be replaced by an emergentist 'foundation' – a notion with which complexity theorists with an ecological background would agree. Theorising education from this alternative 'foundation' leads to some surprising conclusions about what education might be 'for' and what might count as 'educational process.'

  Another, intersection between education and complexity is that of sustainability. One of the central concerns of complexity science has been to improve management of natural resources so as to meet the current and future needs of the planet. Linked to this are the ideas of sustainability and resilience (discussed earlier). Much has been written about sustainability and education over the past decade. Huckle (1991, 1996) in particular provides a strong critique of conventional educational models and speculates as to why they have not promoted sustainability (see Fien, 1993; Huckle & Sterling, 1996; Jickling, 1999). These authors maintain that one of the reasons why environmental learning and consequently natural resource management has largely failed sustainability is that it does not adequately recognise the notions of change and open, dynamic systems.

- Social learning: The concept of social learning has attracted attention as a way of responding to complex problems (see (Ison et al. 2004, SLIM and Project 2004, Keen et al. 2005). Uniting theorists who focus on social learning, is a tendency to conceptualise sustainability as a learning process more so than as a given state or outcome. Social learning refers to the collective process that can take place through interactions among multiple interdependent stakeholders who are given proper facilitation, institutional support and a conducive policy environment (SLIM 2004). The process can focus on the co-creation of knowledge and change in behaviours through actions but at the same time it is an *emergent* property of the process to transform a situation (Ison et al. 2004).

- Modeling: The only full model of a complex system is a total reconstruction of the entire system (see Haylighen et al, 2007; Cilliers 2000) where it is clearly re-stated), and even if that theoretical possibility were achievable, the two systems would soon diverge in their respective trajectories. So faced with complexity, the feasible response is to attempt to achieve a requisite simplicity (see Section 6). In so doing, one can never be sure that the subset of relationships identified for such a model produces an adequate or even useful representation, for the specific purpose/s intended. Cross-checking (sometimes even formally validating models) to help grasp the level of usefulness is thus always necessary and ongoing. Changes to the model may need to be made sooner or later, not least because the system can be expected to evolve, according to the theory presented in this report. In effect, this is both guiding, and responding to, any particular adaptive management interventions and findings. "Successful" models of complex systems – rather than enabling accurate predictions – are more usually associated with better understanding, invariably shared between stakeholders, and hence better coping ability in a learning context. They help navigate (*sensu* Berkes) or "nudge" the complex situation into or along a desirable trajectory.

- Aid and development. As noted by Serrat (2009) the use of complexity thinking in aid and development, for instance, where it might collectively and individually help organizations promote the Paris Declaration on Aid Effectiveness, is still rare. However, more locally we are seeing the emergence of a complexity discourse in certain 'action-research projects' with a developmental slant (see for example, (Pollard *et al.* 2008a) (Pollard et al. 2009, Pollard and Du Toit 2011, Cousins and Pollard in prep). Both the recent publications by the ODI on complexity (Ramalingam and Jones 2008) and the Asian Development Bank (Serrat 2009) and explores what complexity offers for development and humanitarian effort. They stress that complexity generates insights to look at complex problems in a more realistic and holistic way, thereby supporting more useful intuitions and actions. By steering a course between induction and deduction complexity thinking supports an understanding of the mechanisms through which unpredictable, unknowable and emergent change happens thereby enabling a re-interpretation of existing systems and the problems they face.

Box 2
One person's story

What Complexity Science Teaches Us About Social Change and how I learnt about complexity

by Virginia Lacayo

From 1992 to 2004, I worked at a Nicaraguan nongovernmental organization called Puntos de Encuentro, which means "meeting points" or "common grounds," a nonprofit organization that believes in the role of communication, research, and education in fostering social change. *Puntos* advocates an innovative approach to designing communication strategies to promote social change, believing that "while societies have to change, they have to decide for themselves how to change."In spite of its wide recognition as an innovative, risk-taking NGO, *Puntos* has been struggling to frame theoretically and justify its outreach strategy… and still has to contend with traditional log frames, planning models, impact indicators and research methods based on behaviour change communication theories, which respond to the standard criteria scholars and granters have established to legitimise project outcomes. Seldom do such methods and indicators reveal the multilevel mechanisms through which social change occurs.

Hoping to find some of the answers I was looking for, I left *Puntos de Encuentro* in 2004 to pursue my master's degree in Communication and Development Studies at Ohio University. At OU, my path crossed with Professor Arvind Singhal, who himself was questioning the relevance and applicability of traditional social science methods in understanding the complexities of social change. Highly intrigued by the complexity science framework, he had become a passionate advocate for its usefulness in providing alternative explanations of how social change occurred. He introduced me to the complexity literature and some of its key practitioners. I saw that complexity science is increasingly used as a framework to analyse complex interactions between various actors in systems, such as stock markets, human bodies, forest ecosystems, manufacturing businesses, immune systems, termite colonies, and hospitals. I was so intrigued by the insight this new science could provide that I read about the topic voraciously.

I started to understand better the role of relationships, connection and interactions. I began to understand the concepts of emerging orders, self-organizing, and nonlinearity. I began to see the importance of pattern recognition, the difference between the whole and the mere sum of the parts, the value of outliers and diversity, and how small inputs can lead to big changes and so on. Even though these concepts were familiar to me, the wholeness of them gave me eyes to see *Puntos* and its work from a different perspective.

Downloaded from http://www.communicationforsocialchange.org/mazi-articles. 3rd February 2011

All of these have bearing for new and evolving approaches to natural resource research and management of course, which has elements of philosophical and conceptual underpinnings, praxis, planning and management, and public policy. Indeed the evolving field of post–normal science has recognised the need to acknowledge an environment wider than simply that of the 'subsystem' at hand. As mentioned above, we now detail some of the key developments for the emerging integrative frameworks and concepts of socio-ecological systems and resilience theory.

4.2. Socio-ecological systems and resilience theory

4.2.1. A discomfort with conventional resource management and the importance of resilience

As briefly outlined above, many workers have grappled with and embraced complexity over the last two decades. One initiative, the Resilience Alliance (http://resalliance.org) has popularized the handling of complexity through the concept of *resilience.* Their work is rooted in complexity science and explicitly focuses on the need for integrative approaches as an antidote to prevailing single-discipline – or silo approaches – of the past century.

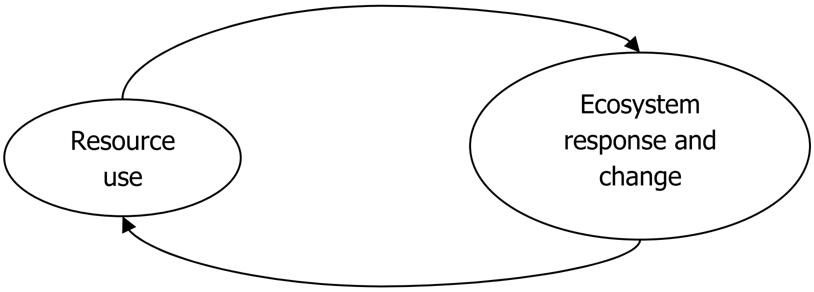

Figure 1 Social-economic, political and ecological systems do not exist in a vacuum but are coupled, dynamic systems (from Pollard et al. 2009)

A landmark in linking ecological to social and economic systems took place in 1995 with the publication of "Barriers and Bridges" (Gunderson *et al.* 1995). They noted that resource use brings about an ecosystem response (change) which in turn influences and changes resource use, representing what they call a 'coupled, dynamic system exhibiting adaptive behavior' – ideas that fundamentally embedded in complexity thinking (Figure 1).

Whilst this might seem obvious, they contended, as do complexity theorists, that conventional science and the associated policies and management approaches that it initiated and influenced, failed to recognise this seemingly simple – but fundamental – point. Much of what concerned them was that practitioners and academics alike firstly, approach natural resources management from a single-domain perspective and secondly, they continued to operate on the frameworks provided by conventional science (see Section 2). As Holling (1995) points out the typical response to threats of fire, insect plagues, droughts and over-grazing is to narrow the purpose, focus exclusively on it and ‘solve the problem’. Whilst technologically and administratively society is able to deal with narrowly defined problems, the issue is that some elements of the system are slowly changing (often due to the initial success of the new policy) and the narrow perspective does not pick these up. Inevitably, society is caught unawares when for example, rangelands lose drought-resistant grasses, insect plagues spread despite initial success with pesticides and natural resource use intensifies as a degraded system improves.

The story of the collapse of the northern Cod fishery which terminated 30,000 jobs and signaled the end of 500 years of one of the most productive fisheries in history is a case in point. The causes appear to be a blend of exogenous, generic factors (such as greed, technology, incompetence, industrial capitalism) and unique factors (environmental conditions, Canada’s failure to regulate) – all of this despite a long history of fisheries science and management intervention. These indicate two important points:

- Firstly, the enormity of the collapse of Cod stocks (to biological extinction) took politicians and scientists by surprise and;
- secondly, the ‘tools’ at hand (referring here to scientific, political and managerial) were intrinsically incapable of anticipating and responding to the wider system, which was never considered as such (an integrated system) in any event.

Within these debates the role of science and management remains controversial with contradictory interpretations of recent events, institutional and scientific texts, and scientific data. Finlayson, a social scientist and author of *Fishing for the Truth* (1994) explores the issue and concludes that the failure to predict fish stocks is closely related to the failure to recognize how scientists' interpretations of natural reality are themselves socially constructed to a crucial degree. In his book *Managed annihilation: The unnatural history of the Newfoundland Cod collapse*, Bavington (2010), heavily influenced by concepts from Holling and colleagues, takes the issue one step further, arguing that many of the problems – which continue today just in a new form – lie with the societal obsession to want to manage, insisting rather for a new philosophy aimed at living within the limits of existing ecosystems (an issue we return to under the Section 5 on adaptive management).

Like the Cod story, global evidence suggests that we are neither using nor managing our resources sustainably despite huge investments in science and management. As Walker and Salt (2006) point out “charting a sustainable future remains an elusive goal”. Much of the critique that has accompanied such disillusionment pointed to the fundamental underpinnings of traditional science which, rooted in a utilitarian framework and a ‘pathology of command-and-control’ that is neither flexible nor reflexive and that convinces and reinforces in politicians the idea that that ‘we have the answers’. Indeed global case studies such as those reviewed by Holling (1986) and in the Millennium Ecosystem Assessment (2003) certainly throws into question the conventional approaches to natural resources management given their continuing degradation. Complexity or systems scientist and practitioners argue that the problems are indicative of a wider malaise. Holling and colleagues (1996) diagnosed the problems of natural resources management and the pathology of the top-down, command-and-control approaches, they key objective of which was to control variability. This lead to a more homogenized system which ultimately was more vulnerable because it was the very variability that provided a buffering – or resilience (a concept coined by (Holling) in 1973) – to disturbances. Ultimately the loss of resilience causes it to flip into a permanently degraded state.

Ecosystems were monitored not for variability and surprise but only for what it could produce – inherent in views such as that of maximum sustainable yield. However, a focus on sustainability – in the wider sense of the word thus implying a socially, ecologically and economically viable relationship between people and the environment – is likely to yield less than maximum possible if the focus is only on short-term goals such as harvest, jobs or profit. This requires a different way of thinking – a different orientation – and hence different management.

The ideas of Holling and Gunderson and their colleagues (1996) were taken up and developed by the Resilience Alliance (http://www.resalliance.org), founded in 1999. Comprising scientists and practitioners from many disciplines, a key focus of their research efforts is to explore the dynamics of social, economic and biophysical 'systems' which they view as just one interacting, integrated socio-ecological system – or SES (sensu Berkes and Folke (1998). They define a socio-ecological system as

> *an integrated system of ecosystems and human society with reciprocal feedback and interdependence. The concept emphasizes the 'humans-in-nature' perspective.*

They contest that approaches which aim at maximum productivity (such as "maximum sustainable yield") tend to be vulnerable because of their underlying assumption of equilibrium and linearity (see (Carpenter *et al.* 2002). These systems assume a single central point of "balance" – or optimisation – which should be strived at or managed for, based on intuitively appealing concept of linear cause-effect responses and equilibrium The Resilience Alliance argues that there is little evidence supporting this linearity and equilibrium, and that systems typically show non-linear behaviour and produce surprises consistent with complex behaviour. They thus propose that a better goal (than one that seeks to achieve maximum or optimum stable production) is to embrace variation. This, they suggest, accepts that all systems show cyclical behaviour through a 'front loop' (consistent with *some* of the assumptions of e.g. continuing growth in economic theory) but followed by a 'back loop' which is seldom taken into consideration. They propose that being honest and explicit about the universality of the 'back loop' opens real opportunities to manage sustainably and to stop seeing surprises (like droughts and floods) as unfortunate accidents interfering with continued growth along the 'front loop'. The aim becomes **resilience**, the ability to keep a system within prescribed 'healthy' but varying bounds (or in the case of undesirable system configurations, to overcome this 'undesirable' resilience and transform the system along a trajectory to a more desirable configuration). The Resilience Alliance (or RA) has defined resilience as: "The capacity of a system to absorb disturbance and re-organise so as to retain essentially the same function, structure and feedbacks – to have the same identity (that is, to remain in the same system regime)".

They propose that "A resilient system is forgiving of external shocks. As resilience declines the magnitude of a shock from which it cannot recover gets smaller and smaller. Resilience shifts attention from purely growth and efficiency to needed recovery and flexibility. Growth and efficiency alone can often lead ecological systems, businesses and societies into fragile rigidities, exposing them to turbulent transformation. Learning, recovery and flexibility open eyes to novelty and new worlds of opportunity".

More recently attention has turned recently to the need understand the somewhat different emphases that each discipline has brought to bear as the discourse on resilience has evolved. A lengthy review of this is given in Brand and Jax (2007) who argue for a clear descriptive concept since this provides the basis for operationalization and application of resilience within ecological science (see also Carpenter et al. 2001). They point out that resilience is increasingly interpreted in a broader meaning across disciplines as a way of thinking, a perspective or even paradigm for analyzing social-ecological systems (Folke (Folke *et al.* 2002a), (Folke 2003, 2006); (Anderies *et al.* 2006), (Walker and Salt 2006). They refer to a tension between the original descriptive concept of resilience first used in ecological science by Holling (1973) and a more recent, vague, and malleable notion of resilience used as an approach or boundary object by different scientific disciplines. Their analysis points to at least 10 different approaches to resilience, although they concede that each holds at its core the notion of sustainability. Each approach emphasizes different aspects of resilience with respect to the specific interest. The ecological aspect is stressed by ecologists, whereas the political and institutional aspects are stressed by sociologists

'Resilience thinking' holds three key concepts at its core (Walker and Salt 2006). Firstly, social systems are inextricably linked with ecological systems within which they are embedded. Thus, we exist within socio-ecological systems. Secondly, these socio-ecological systems are complex adaptive systems. Importantly this means that they do not behave in a linear, predictable fashion. Moreover, because systems are linked, changes in one 'sub-system' will cause changes in other sub-systems. Thirdly, these systems have the capacity to absorb disturbance, to undergo change and still retain essentially the same function, structure and feedbacks. That is, such systems have resilience.

The RA has developed a working draft of attributes (Table 2) that appear to confer resilience Walker (pers. comm) and Walker and Salt (2006). Pollard et al. (2008) added to these following an examination of water security in the Sand River. We have omitted one attribute – that of modularity – due to inadequate definition in the literature[8] which left the team unclear as to the meaning. It is suggested, although not explained, that it is synonymous with connectedness, an idea with which we disagree. There are likely many more attributes and this is an area requiring further work. These attributes then offer a framework for assessing whether or not the configuration of a system is in a sustainable state (see also Levin 1999).

Table 2 Some key attributes of a resilient (favourable) system

(adapted from Walker and Salt 2006; Walker pers. comm. 2008.; and see (Resilience Alliance 2007b) and Pollard et al. 2008

Attribute	**A resilient world would...**
Diversity	..promote and sustain diversity in all forms (biological, landscape, social and economic). *Diversity is a major source of future options and important in a system's capacity to respond and adapt to change (but see comment under Complexity and learning)*
Ecological variability	…embrace and work with ecological variability (rather than attempting to control and reduce it).
Acknowledgement of slow variables	…have a policy focus on "slow", controlling variables associated with thresholds. *Slow variables are often controlling variables. They may result in slow creeping changes which can often go undetected, but which are eventually the signals or drivers of deep change.*
Tight feedbacks	…possess tight feedbacks (but not too tight). *It is the changed feedbacks that lead to the changes in function and therefore structure (RA key concepts). Recognising feedbacks facilitates detecting thresholds before we cross them. Globalisation is leading to delayed feedbacks that were once tighter.*

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[8] A modular system has loosely coupled sub-systems that are internally tightly connected. Modularity slows the spread of pathogens and 'bad ideas' in systems giving time for preparation and re-organisation, and hence makes the system more resilient (Walker, pers. comm., April 2008)

Social capital	….promote trust, well-developed social networks, and leadership (adaptability). *Resilience in SESs is strongly connected to the capacity of people to respond collaboratively and effectively and this relies on trust, networks, leadership and governance (see below).*
Innovation	….place an emphasis on learning, experimentation, locally developed rules, and embracing change. *Our current system seems to focus on getting better at a smaller number of activities rather than fostering novelty and innovation. However innovation is the basis for adaptability.*
Overlap in and polycentric forms of governance	….have institutions that include "redundancy" in their governance structures and a mix of common and private property with over-lapping access rights. *The range of agencies carrying out similar functions is regarded (within reason, and if in concert) as a positive contributor to resilience. This fosters cross-scale awareness and responses.*
Ecosystem services	…..include all the unpriced ecosystem services in development proposals and assessments. *Many of the benefits that society gets from ecosystems are either unrecognized or free (e.g. water purification, pollination). They are often only appreciated when lost due to a regime shift.*
Openness	*Openness applies both to the biophysical and social systems. A closed system does not get the infusion of novelty, organisms and ideas.*
Reserves and reservoirs	*Reserves also applies to both ecosystems and social systems – seedbanks are classic 'reserves' that confer resilience on ecosystems, social memory is a reserve of 'how to do things' that confers resilience in social systems.*
recognition of cross-scale issues, variability and the nature of learning	*By acknowledging the influence of cross-scale issues, the important aspect would be to adopt reflexivity in learning processes so that the systems can respond and adapt appropriately to changing contexts (see CAS). This includes the need to build networks rather than hierarchical structures with poor communication and feedback loops.*

In concluding then, we can discern in complexity and resilience theory, a growing dissatisfaction with single-system, or 'silo' approaches to natural resource management, as evident in increasing calls for integration (Allison and Hobbs 2006). Furthermore, we see increasing concerns in practice that the management of ecosystems as ones which can deliver a constant and maximum yield (such as with fishing quotas) fail to recognise that they are in a state of flux. Complexity and resilience theory has thus arisen partly as a critique of such thinking, noting that variability is an inherent characteristic that confers strength on a system and should be viewed as such rather than dampened through a conceptual and management approach based on averages.

As mentioned much of the work in the complexity arena seeks to identify and understand key (but multiple) drivers and outcomes in a systems – in other words uncovering a requisite level of simplicity but not over-simplifying key processes and functions. Holling (2001) asserts that "there is requisite level of simplicity behind the complexity that, if identified, can lead to an understanding that is rigorously developed but can be communicated lucidly." On the one hand we have to simplify sufficiently to get the cooperation from non-technical groups with different expertise and agendas – from those who providing the financial resources to those who will be affected by the management intervention. At the same time we dare not simplify so far that we fall into the arena of the 'simplistic' – the failure to grasp crucial subtleties of the problem. Most scientists fear the tag of the simplistic, because it is a mark of failure amongst their peers. However the 'requisite simplicity' combines lucidity and rigour, and when identified, provides a platform to move forward (Stirzaker *et al.* 2010).

Some of the key concepts of resilience have already been discussed as part of complex systems theory. The Resilience Alliance introduced two metaphors to illustrate the concepts of non-linearity, adaptive cycles (including multiple scales and cross-scale effects – "panarchy") and alternate regimes and thresholds. These are the reclining "figure-of-eight" (see below) and the "cup-and-ball".

4.2.2. Non-linearity, adaptive cycles and multiple scales and cross-scale effects

The idea of a general adaptive cycle was widely publicised through Gunderson et al. (1995) and refined by the Resilience Alliance into a plausible metaphor which has attracted much attention and is now being increasingly used as a basis for understanding the social, economic and biophysical 'systems' as just one interacting social-ecological system . The Generalised Adaptive Cycle (Figure 2) has attracted much attention and is now being increasingly used as a basis (currently mainly conceptual) for understanding the social, economic and biophysical 'systems' as one interacting system.

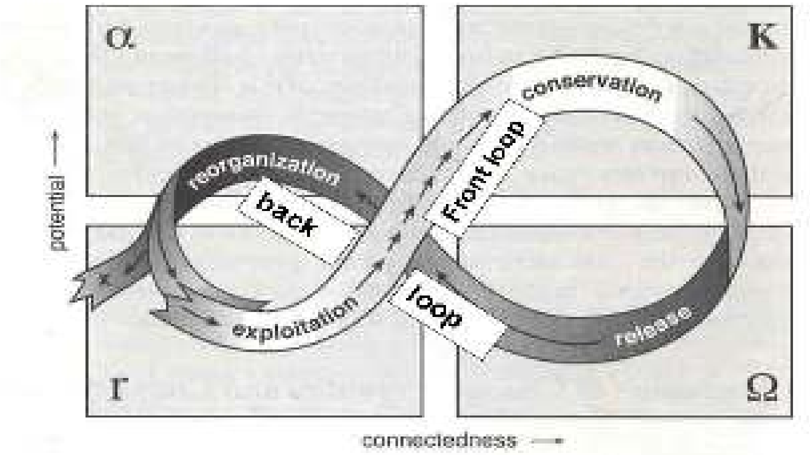

Figure 2 The Generalised Adaptive Cycle. (modified from Gunderson at al 1995) which acts as a generic explanation of how all systems (biophysical, economic, social, and linked social-ecological systems) are believed to evolve.
The vertical axis represents "potential" which can be taken to mean, for instance, accumulation of biomass, financial capital or social capacity. The horizontal axis indicates the cross-linkages or connectedness, such as biomass linkage (of say burnable fuel of the same height in a forest) or similar concepts (such as financial linkages in a market; or social connections in a society). The four phases indicated by the Greek letters represent four phases which characterise stages along this growth path

The general adaptive cycle posits four phases (exploitation, conservation, release and reorganization) as universal to the overall system and to any conceived sub-systems such as socio-political, economic or biophysical (Figure 2). This understanding is largely conceptual although an increasing number of practical examples are emerging (see for example Berkes et al. (2003)). An underlying and fundamental aim is to encourage resilience of desired regimes (in which systems vary but still retain their fundamental identity), and weaken resilience in the case of undesirable regimes (Walker and Salt, 2006).The book

“Panarchy” (Gunderson and Holling 2002) extends the understanding of adaptive cycles into a nested hierarchy at different scales (say local, regional and international), with guidelines to help understand types and actions of inter-scale linkage. The potential relevance of this overall approach to systems in and around the Kruger National Park is discussed in several chapters in a recent book (Du Toit et al. 2003). This has been referred to as a tool for integration (Biggs 2003), and to conceptualise the re-coupling of disconnected social and biophysical systems around local communities to the west of the Park (Pollard et al. 2003).

Two of the four phases (exploitation, conservation) describes what was previously referred to as the front loop reminiscent of conventional thinking (e.g. of plant succession); but then the cycle postulates a back loop (consisting of the two phases release and reorganisation). Rather than seeing a process like plant succession as simply sliding up and down a continuum along various positions on the front loop, the implication here is that the changes following disturbance (e.g. flood, avalanche, fire, pestilence) lead to a discrete new opportunity with its own defining characteristics, one in which differing forces can compete and potentially establish new system trajectories.

The adaptive cycle is intrinsically scaled and nested, in that, for instance, patches fit into (say) ecosystems which fit into (say) biomes. This nesting, and the all-important cross-scale linkages, are discussed in a book describing this so-called ‘panarchy[9]’ or full nested array (Gunderson and Holling 2002); Holling (Holling and Gunderson 2002).

Box 3

An example of a regime shift in the Sahel

(Available from Resilience alliance website http://resalliance.org).

This example cites Sinclair, A. R. E., and J. M. Fryxell. 1985. The Sahel of Africa: Ecology of a Disaster. Canadian Journal of Zoology 63: 987-94.

In the southern Sahel, a rapid increase in the populations of people and livestock has resulted in overgrazing. Constant intensive grazing has destroyed the rootstock of palatable perennial shrubs, giving way to short-lived, shallow rooted annuals. Subsequently, the annuals were grazed out, leaving a landscape of bare soil and shallow rooted unpalatable shrubs. Much of the topsoil with its nutrients was blown or washed away, leaving bare rock. Silt, which settled in drainage areas, baked hard after rain. Roots could not penetrate this hard layer and no germination could occur. The grasslands have been replaced by desert. A continuous drought has accompanied this shift in vegetation.

Did the shift in vegetation type trigger the prolonged drought, or did the drought contribute to the shift? Coupled biosphere-atmosphere simulations (Wang and Eltahir, 2000a) have shown that a warming of 2.5^{o}C sea surface temperature is sufficient to trigger a shift from a self-sustaining wet climate equilibrium to a self-sustaining dry climate equilibrium. A 20% reduction in vegetation cover (i.e. 1% per year for the 20 years preceding the drought onset) is enough to maintain this shift, in the form of a multi-decadel drought. The most likely scenario for triggering the Sahel drought

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[9] Panarchy is a conceptual term first coined by the political economist De Puydt in 1860, referring to a specific form of governance (-archy) that would encompass (pan-) “all others”. In the 20th C the term was re-coined by scholars in international relations to describe the notion of global governance and then by systems theorists to describe non-hierarchal organizing theories (wikipedia.org).

includes regional changes in land cover, and changes in the patterns of global and regional sea surface temperature, which was seen around the time of the onset of the drought. The impact of human activities on the landscape was not included in this study.

Fernandez et al. (2002) produced a model for cropping (subsistence and cash) and livestock farming in Western Niger, in the southern Sahel. Here the soils are sandy, low in organic matter and deficient in phosphorus and nitrogen. Productivity is limited by soil fertility, which is related to a combination of fallowing (for non-manured croplands) and herbage intake by livestock. Some key thresholds in the model include:

1. For unmanured cropland, soil fertility can be maintained when 3/8 of the arable land is left fallow.
2. Soil fertility is affected by the ratio of total herbage intake by livestock to total palatable herbage available during the wet season. The threshold for sustainability is set at 1/3 of the mass of palatable herbage at the end of the growing season, to allow for continual growth of annuals during the wet season and to account for the limits of grazing efficiency.
3. Economic sustainability was measured as a minimum threshold for the basic needs of household members.

During the famines, emergency drought assistance provided food aid for starving people. Some attempts were made to restore the grasslands in bare areas by reducing livestock numbers, but this has had little effect. The bare areas have remained in this state for more than 20 years.

4.2.3. Complexity and learning

In complex systems, learning becomes critical and this is drawing increasing attention in such studies. But what is the role of learning within complex systems? And, more specifically, does learning have a role to play in moving systems towards more resilient, stable and sustainable states? If we regard learning as a socially grounded process (see Von Glaserfeld 1989), the question is how is it grounded within social systems and what are its ultimate outcomes in terms of benefits and consequences for the system as a whole?

Complexity theory proposes that socio-ecological systems derive their essential properties, and in fact their existence, from their relationships (Capra 2007). The character of these relationships is influenced by interactions around events, communication and **learning**. The resilience, and hence sustainability of a system, is not an individual property, but a property of an entire network. One would assume that a vulnerable (unsustainable) system would have weak networks where feedback play little or no role in organizing or regulating the system. This means that learning (from mistakes for example) cannot – or does not – occur. On the other hand, a system that is able to experience events, reflect on them and so learn is assumed to be responsive and capable of adapting to changes that are inherently part of complex systems.

Assessing the modes and modalities of learning within socio-ecological systems potentially provides a way of understanding just how adaptive and resilient the system is or can be. In a sense, such an exploration would look at the 'internal intelligence' or capability of social system to learn and respond to contextual events and changes.

Conceiving of the world as a complex, open system is fundamental to complexity thinking. Embracing change, learning from it and designing appropriate responses is a basic precept of this approach. The characteristics of change, transformation, open systems and constructivist learning are likely to represent a new and unfamiliar approach for water practitioners. Dealing with uncertainty, transformation and reflexive practice are some of the areas that require attention.

We maintain that managing water resources through control and prediction is strongly entrenched in management practices, resulting in many practitioners regarding new and unfamiliar approaches with suspicion. In the section that follows we provide an overview of the key features associated with complexity theory.

We argue that the discourse surrounding water resources management is plagued by a host of practices that are characterised by a technical rationality grounded in a positivist epistemology (i.e. that there is one truth that governs a system). In presenting complexity thinking in IWRM we seek to demonstrate that technicist methods characteristic of modernity (linear, cause-effect models) are inadequate for appropriately understanding the challenges posed by sustainable development (outlined in Agenda 21, UNCED, 1992, WSSD 2001, Millennium Development Goals, 2005) mainly because living systems are **not** closed, predictable linear systems.

Post modernity and its implications for water resources management

Much of the discussion we are presenting is predicated on what Lyotard (1984) termed the 'postmodern condition' where the perspective of the world as a linear, sequential, easily quantifiable, ordered, closed system give way to more complex, pluralistic, unpredictable open systems. The post-modern condition is likely to have considerable implications for knowing and learning but these are, at this stage, by no means clear (Doll, 1993). One of the main tenets that separates science grounded in a modernist framework and post-modern science is the acceptance of change as a 'given' thus rendering the importance of generalisation and generisability less useful. Doll claims that such systems, (and knowing and learning within them) will always be in transition – in process – and that such systems are transformative where prediction and control are less 'ordered'.

In this light we present some of the key conceptual themes that have a potential influence on IWRM.

a. Complex, open systems and learning

Open complex systems are living, not inert, and are better represented by organic rather than mechanical models. Growth, not stasis is their defining feature, directionality not centring, is of key concern. Open complex systems need challenges, perturbations and disruptions to function (Doll, 1993). A closed-system (modernist) perspective sees disruptions or perturbations as a hindrance and an obstacle that needs to be eliminated as soon as possible by means of management and control.

Open systems, such as catchments, are always in transition through processes such as variability of climate, drought, population changes and so on. An open system is transformative and continually emerging – continually presenting people with challenges and possibilities. There can therefore never be a 'correct' answer or collection of answers and closure cannot be reached when it comes to managing the system. Doll (1993) maintains that designers of learning processes should prepare people for a complex world by designing learning programmes that take this as a point of departure. How then does one create learning opportunities within the recognition of such defining features? The processes associated with the development of the Catchment Management Strategy (CMS; see Pollard & Du Toit 2008) is potentially such a reflexive opportunity.

b. Iteration as a source of creation

Drawing on chaos theory Hayles (1990) and Doll (1993) identify iteration as a process central to working in open systems. Although Hayles's work is of less direct relevance to complexity theory it introduces the concept of iteration, in which an individual reflects back on experiences and actions in context, provides the basis for the process of experiential transformation rather than learning for 'mastering a set product'. Personal reflections and collective discussion of these reflections are critical ingredients of such a perspective. It is from iteration that self-organisation emerges and that small changes, if iterated upon, can have major transformative effects over time. Here iteration becomes the source of creation and learning. The question is: how does one build iteration in to the learning process so that it is not an artificial product of linear, inflexible planning?

c. Self-organisation and the learning process

One of the fundamental principles of systems thinking is that of self-organisation (Doll, 1993). This means that elements of a system have the potential to organise themselves within a complex system so that a system need not tend towards entropy and disorder. This perspective can be translated in a learning sense to mean that the self-organising nature of a learner enables opportunities for the creation of options and solutions to contextually-based problems. The deepening of understanding comes from reflecting on actions and experiences not from implementing a set of preformatted solutions to generic problems. The character of the facilitator of learning is therefore not to 'cause' learning but to encourage the kind of questioning that gives rise to reflexivity. The facilitator can 'seed' ideas but the development of these ideas is internal, via the reflective process.

Doll maintains that we still do not know how self–organisation occurs but speculates that it might depend on reflective action and social interaction. The questions are: how do people respond to, and learn from, change processes that are non-linear and unpredictable and how do they self-organise around these events?

d. The importance of dialogue and the collective

Doll (1993) maintains that accepting uncertainty forces us to dialogue with each other in order to respond and cope with elements of change. The kind of learning required within open systems is not prediction and control but rather on what Habermas (1981) terms "dialogic conversation" where transformation of the participants and the situation is pertinent. A key component of such a post-modern perspective is interaction where dialogical processes are catered for. Such an orientation places the learner in the position of "creator of knowledge" rather than in the roles of passive receivers of preordained "truths". Such a perspective rejects the idea of "one right way" and accepts indeterminacy inherent in complexity and multiple perspectives. Further to this, the importance of social elements in processes of learning is recognised by educational theorists such as Bruner (1983) and Vygotsky (1987). Any attempts to establish environmental learning need to recognise the importance of social processes as a way of creating knowledge and responding to contextual change. The question is: how can IWRM encourage social learning processes?

The tendency to look towards analyzing (formal) education systems as a proxy for the kind of learning expressed above is misleading as they are not always set up to support this kind of reflexivity and responsivity. In other words, formal education may be co-opted by specific socio-political agendas and therefore does not tell us much about leaning in response to complexity (see Forrester 1992) for example.

In order to get an understanding of how 'ecological' learning within complex systems proceeds (i.e. taking into consideration feedback loops) requires attention to how a social system utilizes the principles underlying ecological processes in ways appropriate within a particular context (Wals 2007). If flexibility and diversity are key features of a resilient and sustainable system that help it cope with 'disturbances' then these two attributes need to be considered when taking opportunities for social learning into consideration. Note however that as Capra (cited in Wals, 2007) points out, diversity offers strategic advantage for a community only if there is a vibrant network of relationships and if there is a free flow of information through the network. When the flows are restricted, suspicion and mistrust are created and diversity becomes an obstacle rather than an advantage. Where networks do not function or where there is fragmentation, diversity can generate prejudice, friction or destructive conflict.

If we accept that learning has a vital role to play in ensuring that feedback loops have an impact on self-regulation and self-organization then it becomes a critical process in the support for, or hindrance of, establishing resilient, sustainable systems. In this regard, learning is taken to be a social process where engagement, communication and dialogue provide the basis for reflecting on and responding to feedback in a way that is open to change and that encourages creative and innovative responses to an ever evolving context. Some case studies on socio-ecological systems and resilience have started to address the issue of learning (see for example Tengo and Hammer 2003), it is an issue that requires further attention.

4.3. The issue of 'tools' for complexity approaches and praxis

The spread of complexity thinking has been accompanied by a concomitant demand for 'tools' – and of course an ever-burgeoning 'tool box'. Needless to say this has turned into a business in itself. However, probably the most important point to make in this regard is that instead of rushing off looking for new tools, those of us working from the complexity discourse need to be attentive to the ***ways of thinking*** that underlie the prescribed tools and techniques available in each field. As many note (e.g. (Heylighen *et al.* 2007); Ramalingam and Jones 2008) we need to think about *our orientation* by asking some hard questions, as set out by Ramalingam and Jones:

- *Are we using inappropriate mental models and frameworks?*
- *Do we simplify complexities for the sake of convenience?*
- *Are we continuing to act in inflexible, top-down ways? Are we using too many off-the-peg approaches?*
- *Are we driven by naïve expectations of impact?*

In the field of development and aid, Telford and Cosgrave (2006; cited in Ramalingam and Jones (2008) note that "International agencies need to pay as much attention to *how they do things*, and their capacities to do them, as they do to the content of their policies and programmes... sensitivity to context and the flexibility to adapt to evolving realities are essential, instead of applying predetermined strategies and one-size-fits-all solutions..."

Given this, and the fact that a detailed expose is beyond the scope of this report, it is with caution that we outline some of the tools that are currently being used or explored. For convenience we have categorized them as (a) research and modeling tools and (b) planning and management tools, although in reality the boundaries are blurred. A new book by Mitchell (2009) also provides an overview of some of the tools although it tends to be biased towards computer-based tools and modeling. Finally, we give a more detailed account of Strategic Adaptive Management because it is being tested by some organisations in South Africa and because in the interviews, participants often asked but 'what is Strategic Adaptive Management?' or commented ' but we are already doing Strategic Adaptive Management'.

Research and Modelling tools

- The soft systems methodology (SSM) is essentially an action-research methodology intended to bring about improvement. Checkland and others (Checkland and Scholes 1990, Checkland 1999) have developed it over the last three decades by summarising experiences from action research projects where the researchers recognised that they were participants in the problem situation rather than 'external' to the process. A central tenet is that a perceived problem exists in terms of structure and processes and the relation between the two, rather than as a clearly defined problem. Moreover in soft systems, history always modifies the perception of the problem. Checkland (1981) views unstructured (wicked – see above) problems as conditions to be improved, rather than 'problems to be solved'. Through processes of iteration, reflection and negotiation it draws together different perceptions and assumptions those involved in a problem situation in a cycle of learning.
- Hadorn et al. (2006, p. 122) call transdisciplinarity "research that addresses the knowledge demands for societal problem solving regarding complex societal concerns." The authors assert that transdisciplinarity therefore is a process that places knowledge at the service of society so as to deal with complex problems such as climate change. However, the evidence to date is that this sort of collaborative inquiry is easier suggested than done. Max-Neef (2005) introduced a useful layered schema of "disciplines" with diagonal cross-connections which he called the transdiscipline. The top layer is value-driven (ethics, philosophy etc) the second one is normative (planning, design, law etc), the third one pragmatic or purposive (engineering, forestry, water management etc), with the bottom one concerning basic building-blocks of "what exists" (geology, chemistry, sociology etc). While it is not universally necessary to cross-link all these layers in many day-to-day societal problems, it certainly becomes necessary to do so once a complex orientation is employed. To bring in all the necessary stakeholders, it is necessary to use effective multi-stakeholder processes (see for example (Du Toit and Pollard 2008). This multi-stakeholder engagement constitutes a crucial step in key points of the strategic adaptive management cycle, facilitating the formation of the necessary linkages between the various "disciplines".
- The goal of complex social network analysis (CSNA) is to study the dynamics of large, complex networks such as the internet, global diseases, and corporate interactions. *Social network analysis software is* used to identify, represent, analyze, visualize, or simulate nodes (e.g. agents, organizations, or knowledge) and edges (relationships) from various types of input data (relational and non-relational), including mathematical models of social networks. Systems dynamics: The field of systems dynamics originated in the 1960s with Jay Forrester and his colleagues. Forrester started by constructing a model of a city as a system of interacting houses, industries and people. One of the most famous advances on these early ideas was the book entitled Limits to Growth (Meadows 1972) in which the author simulated changed attitudes to population and industrial growth. Essentially system dynamics is an approach to understanding the behaviour of complex systems over time. It is distinguished from other approaches to

studying complex systems in the use of feedback loops and stocks and flows, which help describe how even seemingly simple systems display nonlinearity. A *causal loop diagram* – a visual representation of the feedback loops in a system – is one tool that is common in this arena. An example of this is shown in Figure 3. Dynamic mathematical models and software (e.g. STELLA) then developed as a corollary to systems dynamics thinking. As pointed out in Section 2.3, much of this thinking has influenced other disciplines such as education (see Forrester (1992) for example). (Note that Barry Richmond (1994) contests Forrester's definition of system dynamics, preferring the term 'systems thinking').

- System dynamics models, such as STELLA which is a flexible computer modeling package with an intuitive interface that allows users to construct dynamic models that realistically simulate biological systems. It is designed principally to examine 'what if' questions.

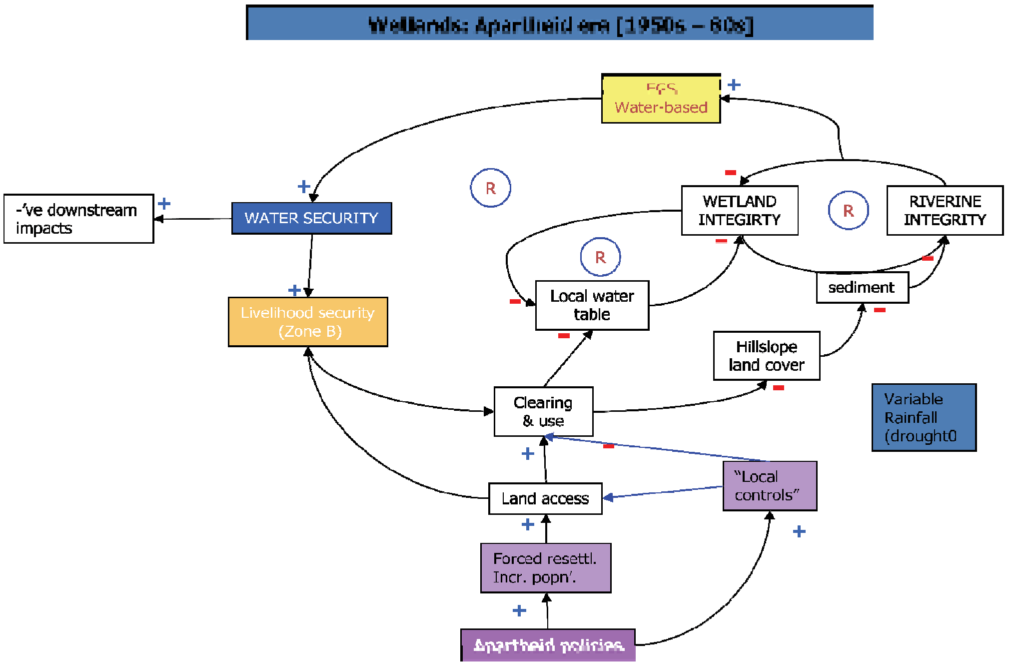


Figure 3 An example of a causal loop diagram exploring wetland degradation (from (Pollard *et al.* 2008a)

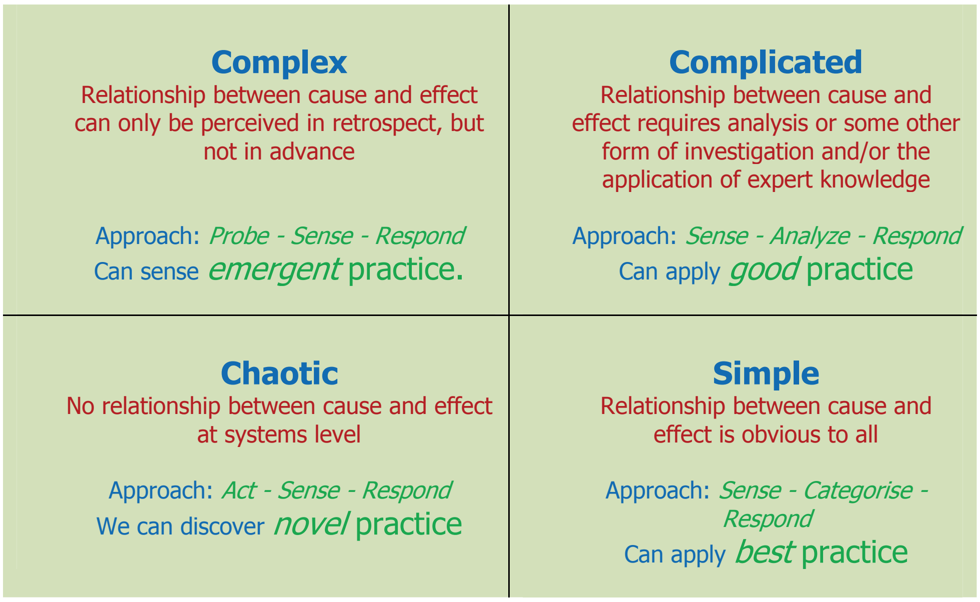
- In organisation theory both Netmap and Agent Based Modelling are being used to explore the interaction of individuals and the *emergent* properties (e.g. patterns of connectivity, informal groups, etc) that arise as a result of interactions (Mitleton-Kelly 2005). The connections are also good indicators of feedback; Netmap in particular acts as an indicator of feedback as it depends on an exchange of emails (or other media) and information (we are aware however that no such tool can provide an exhaustive picture on all feedback processes). Both tools also show *self-organisation* and when repeated they can show the *evolution of relationships* over time. Landscape of the Mind (LoM) also looks at individuals and the way they relate within a group, in other words LoM can show *epistatic interactions.*

- Multi-agent system (MAS) models and companion modelling: Multi-agent systems (MAS) are often used to facilitate negotiation between conflicting stakeholders in natural resources management and are most often discussed with the stakeholders according to a methodology called 'companion modeling'. The main principle of the companion modeling (ComMod) approach is to develop simulation models integrating various stakeholders' points of view and to use them within the context of the stakeholders' platform for collective learning (Röling 1999, Gurung et al. 2006, Etienne et al. this edition).

- The narrative analysis can help identify connectivities, interdependencies, self-organisation, coevolution, far-from-equilibrium conditions, historicity and time, feedback, emergence, path dependence and the creation of new order. As part of the way in which companies or agencies use Snowden's Cynefin framework (Figure 4), a technique called narrative analysis can prove very useful. It encourages open description or story-telling, often in various group settings, and then analyses the content in the way that utilises what he/they (depending which ref you use) term/s pre-hypotheses (the underlying mental suppositions that precede hypothesis formation), thus obviating one layer of assumptions. In other words, narrative analysis techniques make fewer assumptions about how people are thinking, rather inferring this from a thoughtful analysis of how they actually narrate their experiences. This can be used, for instance, to carry out an analysis of what sections of an agency's work is indeed complex and how people are currently handling this (Biggs pers. comm.; Ferreira SANParks, pers. comm.).

Planning and Management

Snowden (2000) developed the Cynefin framework (Figure 4), one of the first practical applications of complexity theory to management science. In the framework he draws on complex adaptive systems to describe problems, situations and systems. The model divides the space in which we make decisions or solve problems into four "domains "and provides a typology of contexts that guides what sort of explanations and/or solutions may apply. The framework helps managers determine the prevailing operative context, enabling appropriate choices and decisions. Using recommendations about what is appropriate from the Cynefin framework, suggestions can then be made as to possible re-orientation in say, a complex mode of thinking.



Complex Relationship between cause and effect can only be perceived in retrospect, but not in advance Approach: *Probe - Sense - Respond* Can sense *emergent* practice.	**Complicated** Relationship between cause and effect requires analysis or some other form of investigation and/or the application of expert knowledge Approach: *Sense - Analyze - Respond* Can apply *good* practice
Chaotic No relationship between cause and effect at systems level Approach: *Act - Sense - Respond* We can discover *novel* practice	**Simple** Relationship between cause and effect is obvious to all Approach: *Sense - Categorise - Respond* Can apply *best* practice

Figure 4 The Cynefin framework
(Note: The fifth domain is Disorder, which is the state of not knowing what type of causality exists, in which state people will revert to their own comfort zone in making a decision).

- Adaptive management has been embraced in a number of ways for example, Adaptive Environmental Assessment and Management or AEAM (see Gunderson 1999) or as Strategic Adaptive Management (see for example (Biggs and Rogers 2003); Pollard and Du Toit 2007; (Van Wilgen and Biggs 2010). When discussing management, Gunderson (1999), notes that "resource managers constantly grapple (explicitly and implicitly) with uncertainty. One approach is to assume most uncertainty away…. and another approach is to seek spurious certitude, by breaking the problem or issue into trivial questions spawning answers and policy actions that are unambiguously "correct," but, in the end, are either irrelevant or pathologic". Perhaps the most common solution is to replace the uncertainty of resource issues with the certainty of a process, whether legal -- such as a new policy, regulation, or lawsuit -- or a new institution -- such as a technical oversight committee or science advisory committee. Yet another solution is to confront the uncertainties, a central tenet of Adaptive Environmental Assessment and Management or AEAM". The important component is that of *adaptive management* has been put forward as an integrated, multidisciplinary approach for confronting uncertainty in natural resources issues (Holling 1978) (Walters 1986). An example of the use of strategic adaptive management in South Africa will be given in the final report.

4.4. Concluding comments on complexity and IWRM

In the introduction, we outlined the principles of IWRM in South Africa as "a *philosophy*, a *process* and a *management strategy* to achieve sustainable use of resources by all stakeholders at catchment, regional, national and international levels, while maintaining the characteristics and integrity of water resources at the catchment scale within agreed limits " (DWAF 2003). We also suggested that this means steeping back and asking what is it that we want to achieve? First and foremost, IWRM is a process not an end in itself. It is about doing things differently as the world confronts diminishing and degrading water resources. It is ***transformative*** in nature as it provides the foundation for a fundamentally different way of managing a basin's water resources. In other words it is guided by principles rather than blueprints. A key principle is that water resources management has to operate in a complex environment and this requires a particular type of orientation that incorporates learns and adapts. This means letting going of determinism and the fallacious idea that we can always predict what is going to happen (if we can just gather more information). Rather we need to accept the uncertainty of many situations and develop practices for governing uncertainty involving problem framing and boundary setting, fresh thinking for intractable problems, working across organisational and disciplinary boundaries; making effective decisions in situations with high levels of uncertainty; tolerating rapid change in the way problems are defined and engaging stakeholders as joint decision-makers (not just providers or recipients of services) (Briggs, quoted in Ison 2010). This does not mean that there is no place for deterministic processes and practices – or "throwing the baby out with the bath water' as one interviewee put it – rather they are subsidiary to systemic and adaptive governance. It is clear from this then that leadership and the ability to think systematically is key – both that which is systemic and that operates for and in the long term.

SECTION B: Cases studies: Water resources and complexity thinking

5. Strategic adaptive management in complex systems: Transforming river management by the Kruger National Park

5.1. Introduction

The aim of this case is to provide an overview of the experience of transforming management practices of the Kruger National Park (KNP) from a conventional, deterministic approach to one which embraced the inherent variability and unpredictable nature of the system under its custodianship. Although still very much in progress it is illustrative of the gradual acceptance of complexity particularly given the changing political, socio-economic and environmental context. We track the Park's management from one of inward looking, isolationist policies to one which adopts responsivity to major change factors seen through the lens of water resource security. Viewing catchments within which the Park is embedded as dynamic, complex socio-ecological systems represented a major shift for both management and research. The KNP first embarked on this approach in the sphere of river management after which it spread to other domains such as fire management. Since the case of river management has been extensively reviewed elsewhere (Rogers and Biggs 1999, Pollard and Du Toit 2007, Kingsford et al. 2010, Pollard and Toit In press), we provide only a synopsis as to demonstrate the influence of complexity thinking and the uptake of a new management approach – that of strategic adaptive management – in response. For the Park, a major outcome has been the emergence of a management framework with its key features of a clear vision informed by stakeholder involvement, an objectives hierarchy guiding management actions, a scoping of management options with associated consequences, a monitoring system for gauging management practice and a reflective evaluation process with feedback loops.

A focus on managing rivers

Although the process of strategic adaptive management or SAM has been applied to the management of other natural resources in the KNP (see for example, (Van Wilgen and Biggs 2010), here we focus on the attempts of the managers and staff of the KNP to develop a comprehensive and holistic approach to SAM for the rivers of the protected area. This is pertinent because the degradation of rivers, together with democratic socio-political changes of 1994 acted in concert as a catalyst for the complete revision of Kruger's management. Moreover, water is the most limited and limiting resource in South Africa and the upstream impacts on all six rivers that traverse or border the Park are acute (see for example (Pollard and Du Toit 2011). In the case of river management, the challenges for the Park of managing the rivers move beyond its borders. Since most of the rivers originate upstream of the Park, managers and staff need to engage with stakeholders of very different interests – and hence demands – on the water resources (Figure 5). Moreover, gaps existed between research and management and this needed to be addressed. This case study provides invaluable insights into addressing these issues.

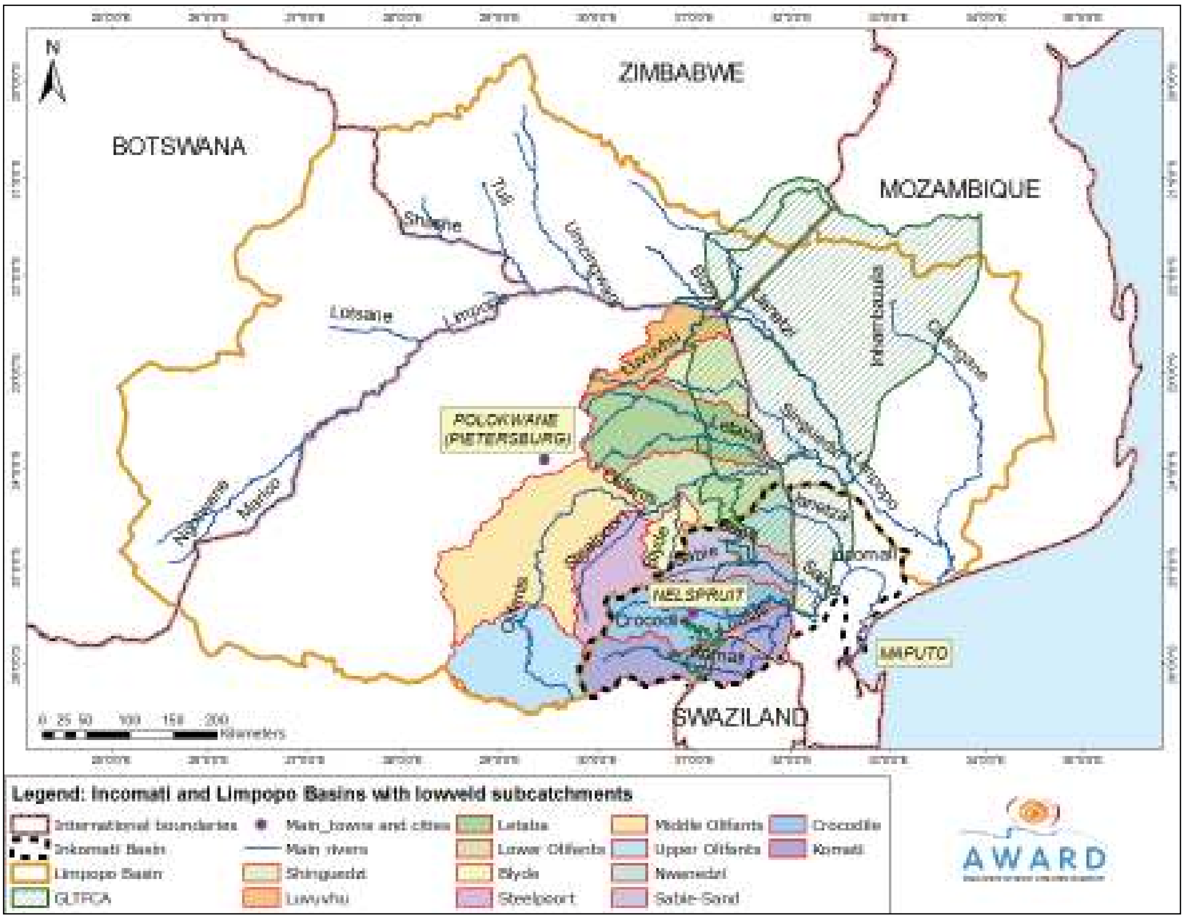


Figure 5 Rivers and catchments of the lowveld (from Pollard & Du Toit 2011)

5.2. The need to shift management paradigms: A brief historical account

Protected areas such as the Kruger National Park face many management challenges of which ensuring a healthy flow of rivers into the park is now acknowledged as one of the most important. Although previous management policies isolated KNP from its neighbours, this position has changed as the Park seeks to negotiate a respected 'place' for water and conservation in a competitive water market. A major catalyst for this re-orientation has been KNP's response to the growing water crisis where its position needed to be seen within the wider catchment and policy context in South Africa.

Within the KNP two key change factors frame today's management practices which are so fundamentally different from those of the past. The first was – and continues to be – the alarming decline in surface water quality and quantity (Pienaar 1970), together with the associated biodiversity changes of the rivers that flow through the KNP (see later). The second is the recognition that lowveld savannas are not stable-state agricultural systems but rather an inherent characteristic is their heterogeneity and flux (Peel 1999); (Du Toit *et al.* 2003). In retrospect, an interesting aspect of both of these is how closely interlinked their histories have been and some suggest that it has been their mutual influence that has transformed the management of KNP in fifteen years (see (Pollard and Du Toit 2006); Van Wilgen and Biggs 2010).

Recognition of the lowveld savanna by KNP as a complex adaptive system necessitated a new approach to management that explicitly recognizes heterogeneity and variability as key characteristics. Questions then arose as how to structure a management system around these characteristics. Kruger then adopted Strategic Adaptive Management (SAM).

Deterioration of river systems and the need for KNP to respond

Changes to the river systems have been evident since the 1960's (Pienaar 1970) and since then most systems have experienced progressive degradation in quantity, quality and the associated fauna and flora. Of the six river systems of the Park, five were perennial and one, the Shingwedzi, was naturally seasonal (O'Keeffe and Davies 1991). The first deterioration was evident some 50 years ago when the perennial Letaba ceased flowing and subsequent cessations have transformed this river into a non-perennial system. A similar situation occurred in the Levuvhu River in the 1960s and later in the Olifants River. The Crocodile River has experienced flow constancy as well as a seasonal reversal as a result of regulation (see Pollard and Du Toit 2011), and both the Crocodile and Olifants have suffered heavy pollution and invasion by alien plant species. The Sabie River is regarded as the least perturbed of the major rivers of the KNP, with relatively small distributional changes in fish species (Russell and Rogers 1988). In comparison, a (at least transient) loss of species has characterised the other KNP rivers: the Letaba, Olifants and Crocodile Rivers appeared to have lost between four and six fish species, and the Luvuvhu River nine species. Most of these have re-appeared at lower abundances.

Box 4
Challenges that the KNP faces with respect to river management

- *Transforming a past management system that viewed water resources management as internal to the park and that constructed and reinforced the KNP as an "island".*
- *Almost all the rivers originate from outside and KNP has historically had little control over upstream users.*
- *The rivers draining through the KNP are greatly over-utilised, mainly through over-abstraction and water quality problems are also widely evident.*
- *Mozambique lies downstream of the Park and also requires water. KNP is often accused when that country's requirements aren't met although in fact the causes lie upstream. Thus KNP's role switches from one of downstream user when viewed within a national context, to upstream user when viewed in an international context.*

In the mid-1990s some managers and researchers started to critique the prevailing management approaches, asserting that the linear, rigid and inward-looking management goals had started to fail the KNP in achieving healthy rivers. With this realisation, the KNP embarked on an approach that explicitly incorporated an experimental orientation in which management was to be adaptive – so that the objectives (and vision) are not immutable but rather are progressively informed by new insights (learning-by-doing). What transpired was the complete overhaul of a management approach from one of immutable goals and objectives based on stable-state ecosystem theory, to one based on learning-management iterations designed to maintain variability – a fundamental attribute of semi-arid savannas and rivers (Davies *et al.* 1995). Another notable aspect to this story is how the practical outcomes of an adaptive approach – the development of an objectives hierarchy, and thresholds of potential concern (TPCs)– has been extended far beyond the management of water alone (Freitag et al. in press) and now frames all aspects of KNP ecosystem management, such as fire and herbivores.

These factors had a number of implications. Firstly because all of the five perennial rivers originate outside of the park, the KNP has had to broaden its areas of engagement to include a catchment-based perspective. This situation is not unique to the KNP since many of the world's protected areas rely on rivers whose catchment areas are not co-incident with those of park boundaries. Secondly, in recognition of the dynamic nature of ecosystems (and indeed the socio-ecological system, see Pollard, Biggs et al. 2008).

In addition to explicitly recognising the characteristics of complex systems (see Section 3.2), there was also the recognition on the part of the Park that a number of important fundamental ideas underpinned such a re-orientation in management and research (Pollard & Du Toit 2007), as follows.

i. Firstly, it meant accepting that (a) socio-ecological systems are complex and that embracing the principles of complexity are an important point of departure for re-orientating a management system and (b) such a reorientation will exact effort, time and resources with the concomitant levels of frustration, resistance and reluctance from practitioners not convinced of its merits.
ii. Variation and heterogeneity of important for building resilient systems and that semi-arid systems are evolved to encompass these features. Management action should therefore not aim to eliminate variation of heterogeneity but rather work with it. Management plans need to accommodate extreme events as 'normal'.
iii. Research and data gathering processes need to inform management actions not drive them. This means that research needs to be an informative inquiry that forms the basis for management responses. In this way research and management are closely aligned partners in the strategic management process
iv. Managing natural resources such as water cannot be conducted in isolation of the socio-political context and within artificially (politically) determined boundaries such as parks, municipalities or even country borders. Ecological systems have boundaries of their own and the management of resources within these should try to align with these boundaries as much as possible
v. An institutional environment needs to be created where all managers and levels of practitioners think holistically about the system (biophysical, socioeconomic and institutional) and events.
vi. Scenario-based planning (aided by mathematical and computer simulation, and statistical analyses if necessary) can help plan and account for random events.
vii. Prudence is required when making decisions with buffers to absorb surprises should things turn out vastly differently.
viii. Recognition that in complex systems there are a number of ways to arrive at the same endpoint or solution.
ix. The KNP decided to adopt strategic adaptive management which seeks to 'learn-by-doing' so that management could adapt direction as new information become available and hence be more responsive to change factors.

5.3. The adoption of SAM and lessons from KNPs approach

The KNP took the decision to adopt Strategic Adaptive Management (SAM) as a formal approach to river management in the late 1990s. As is apparent from the discussion above, Strategic Adaptive Management is a framework for management based on 'learning-by-doing' and represents a fundamental shift from 'command-and-control' approaches of the past. At its heart lies the fact that management recognises complex systems (see Section 3) and that it cannot know or predict everything – underscoring the need to adapt management actions as experience is gained.

The observation that the SAM approach has been taken on widely within KNP, and that no fundamental alternatives for river management have appeared to date, may mean that KNP and other active collaborators are beginning to understand the complexity required to effectively broker decisions on a continuing ('learning by doing') basis.

In its simplest form the KNP approach to SAM is based on a clear statement of vision and mission developed through extensive stakeholder involvement (Figure 6). Flowing from this is a hierarchy of objectives, which, through increasing levels of detail, is ultimately linked to clear, auditable endpoints called *thresholds of potential concern* (TPC) to which are linked clear lines of roles and responsibility.

In setting up a SAM the KNP used a framework involving five key steps:

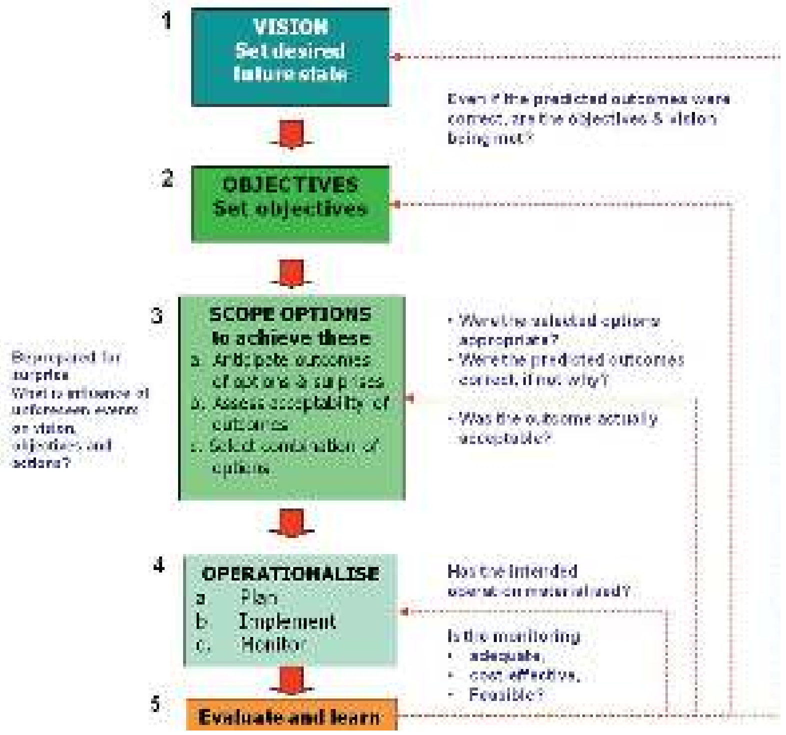


Figure 6 The steps involved in strategic adaptive management that are used by KNP (from Pollard & Du Toit 2007)

The emergence of a new management approach over a fifteen year period yielded a number of lessons stemming from numerous iterations and attempts to grapple with the principles of managing in a complex system. Following the research on key lessons on behalf of the Park, Pollard and Du Toit (2007; in press) together with Park staff, summarised these as follows.

1. The process of adopting SAM was one of recursive action over time. Although the SAM approach began mainly with biophysical aspects within the park, the recognition of wider socio-ecological systems (initially catchments) became central with more active systemic connections being realised. This meant that, initially, management procedures became more inclusive and more complicated. There came a point where managers were overwhelmed resulting in a 'pulling back' into requisite simplicities (Holling 2001, Stirzaker et al. 2010) so that the management process did not become untenable.
2. The fact that there have been ongoing structured research programmes on rivers seems to imply, at least in the KNP context, that active levels of research involvement and structured critical inquiry may be a prerequisite to coping in a fast changing world with difficult resource management issues. Judicious management is predicated on understanding the underlying ecosystem drivers and characteristics of the system in question. Moreover since river systems are dynamic and in a continual state of flux it is necessary to monitor conditions and to revisit management objectives. System dynamics need to be understood in the broader context of what is occurring inside and outside of the protected area.
3. The SAM framework requires that management be directed towards *achieving a desired future state* (Breen *et al.* 2000); Biggs and Rogers 2003). Indeed, this has fundamentally re-orientated the management of KNP, staff and resource allocations. Once this higher-order statement had been debated and captured in a vision, it provides the basis for the development of objectives and endpoints that can be readily tracked back to the vision. This process has allowed a much closer partnership to develop between researchers, managers and field staff with a strong sense of buy-in and collective learning becoming possible (Pollard and Du Toit 2005).
4. The adoption of the SAM framework with its key features of a clear vision informed by stakeholder involvement, an objectives hierarchy, a consideration of management options, an apparatus of TPCs and a reflective evaluation process with feedback loops has been challenging for the staff of KNP and has taken considerable time to be accommodated.
5. Pollard and Du Toit (2007) noted that the *collaborative role in developing TPCs* and the joint role of research and management in ensuring they are set and met has been cited as a powerful motivation for monitoring staff, such as rangers and wardens who then become a key link in the iterative SAM cycle. The role of involving field staff in setting management objectives cannot be underestimated in terms of developing commitment and buy-in. The TPCs are hypotheses and hence the TPCs and 'desired state', must be audited and refined in a reflexive manner (Pollard and Du Toit, 2006, (McLoughlin in prep).
6. Knowledge management is a challenge that needs to be addressed. Biggs and Rogers (2003) point out that after a TPC is tabled there is a tendency for several unpredictable threads of information to emerge as implementation proceeds. These threads may or may not be documented at the appropriate level of quality (i.e. everything is taken to be equally relevant). These authors recommend a continual 'roping together' of the information so that the organisation benefits as a whole, thus averting disparate and isolated approaches.
7. The SAM approach is likely to generate a wealth of *field data that needs to be recorded, captured and made accessible*. (Pollard and Du Toit, 2006, McLouhlin, in prep.) This is seen as one of the challenges for KNP. Today the park is developing a knowledge management system based on GIS as

well as non-spatial databases. The intention is draw science and management together by putting data to productive use rather than archiving for historical purposes only. Once the challenging aspects of knowledge management have been negotiated they lead to the need for *shared learning*. Here KNP has experimented with the formation of 'Communities of Practice' (Lave and Wenger 1991) from, initially, a core of enthusiasts whose task it is to continually rework and improve the SAM system and make it more accessible for use by others.

8. Experience shows that there is a need for the *integration of programmes* run by the KNP so that by drawing on a wider variety of specialists and practitioner experiences it is thought that more realistic TPCs can be set in the future (Pollard and Du Toit, 2006). Nonetheless, lessons for integrating new concepts such as ecosystems services and social ecology with more traditional approaches have yet to be learned.

Pollard and Du Toit (2008) argue that the legislative environment for water resources management and the approach of integrated water resources management afford a particularly strong basis and coherent currency for the adaptive management of river systems. The approach in the KNP thus complements – and puts into practice – the spirit and intent of the NWA. In the case of river management, an additional challenge has been to broaden horizons and deal with the realities of conflicting drivers and objectives.

Fortunately for KNP, the new legislative environment has provided strong support for the concept of sustainability through the provision of the Reserve which not only provides a benchmark against which the Park can monitor, but which also carries legislative 'clout', making the KNP's position as 'watchdog' much stronger (Pollard and Du Toit 2008). This is critical given that infringements of the Ecological Reserve are evident in all rivers flowing through the park (Pollard *et al.* 2010). Importantly, not only do the KNP staff monitor the rivers, but outputs are clearly linked to different actions according to the severity of the infringement; the transparency of which is important for monitoring staff (Pollard and Du Toit 2006). Although the systems are still being strengthened and successful responsive action nonetheless varies, the basis for building feedback loops is in place. Indeed, as mentioned earlier, these feedbacks are essential for adaptive management for without these learning cannot happen (Pollard and Du Toit 2006, McLoughlin in prep; (Pollard *et al.* in prep); see also next case study).

In conclusion, it is important to remember that *adaptive management is not an end in itself*, it is a process that itself evolves as new learnings are brought to bear. As a result of the challenges confronted in addressing changes in rivers, the KNP has charted new ground in management, research and outreach. The approach embraces the challenge of needing to manage a sensitive, complex system within a context where uncertainty is always an underlying factor. It encourages the 'first bold step forward' where often implementation 'paralysis' can hamper decision-making under conditions that are complex and unclear. By using the best available information to set TPCs, it monitors trends and then demands reflection on collaboratively defined goals before agreed-upon action is initiated. The collaborative nature of implementing the SAM system forges a partnership between science and management – an approach that is seen as a way forward for parks, conservation and science (Folke *et al.* 2002b); Van Wilgen and Biggs 2010) and equally important is that such thinking has an institutional home for it to be mainstreamed eventually as management discourse. Kruger National Park might just be providing such a home.

6. Managing in complex systems: Exploring the role of self-organisation and multi-scale feedbacks for learning and responsivity in IWRM of the lowveld rivers

6.1. Introduction

The first case study described the explicit recognition of variability and complexity through the adoption of strategic adaptive management by the Kruger National Park. In this case study we explore the issues of self-organisation and feedbacks as emergent properties of an evolving complex adaptive system (see Section 3). As was stressed earlier, both of these – self-organisation and feedbacks – are important properties of complex and resilient systems particularly since they provide the basis for reflexivity and learning.

In this section we explore the role of self-organisation and feedbacks in water resources management and water reform as it is unfolding in a number of case-study catchments of the lowveld of South Africa (see Figure 5). Self-organisation and feedbacks emerged as key themes in a three-year study designed to understand the examines factors either constraining or enabling implementation of integrated water resources management (Pollard & Du Toit 2011) as envisaged in the National Water Act (DWAF 1998). As we point out (Pollard & Du Toit 2008), South Africa recognises – albeit implicitly – that catchments are complex systems (and the business of water resources management is equally complex) through establishing a process that recognises linkages and that is inherently adaptive, allowing for reflection and learning in complex, uncertain environments. None of these cases have set-out with either of these factors as objectives; rather they are emergent properties of the evolving context of water resources management. Nor are the individual cases necessarily concerned with water reform per se but each occurs within a wider context of water reform in South Africa.

As recognition for the important role that such factors as self-organisation and feedbacks play grows so does the interest in what makes them successful (see Pollard & Du Toit 2011). This question is explored through two cases for the lowveld, those of the Letaba and Crocodile Catchments. In the first case the feedbacks have been operative for over a decade whereas in the second they are more recent, being associated with IWRM efforts of the Inkomati Catchment Management Agency. We start first we an examination of the concepts of self-organisation and feedbacks, followed by a description of both cases and close with an exploration of factors that support the emergence of both of these factors.

6.2. Conceptual underpinnings – complexity, resilience and the role of self organisation and feedbacks

In Section 3.1, we pointed out that self-organisation and feedbacks are essential properties of complex *adaptive* system. Both these and two interrelated concepts that underpin this work – systems thinking and complexity theory – were elaborated in Chapter 2. Complexity builds on *general systems approaches* pioneered in the 1930s, which examined 'wholeness' and how parts operate together (Von Bertalanffy 1972). General systems theory was enhanced by subsequent developments in the field of complexity studies such as those of Checkland (1984) on soft systems methodology, Forrester (1992) on learning, and Holland (1992) on artificial intelligence, to name a few. These foster a broader view of overall context and focus on dynamics of cause-and-effect and feedbacks.

Although we will explicitly examine the role of feedbacks in water resources management, they are conceptually inseparable from the concept of self-organisation (amongst many related and important attributes of complex systems). Thus we outline first the concept of self-organisation and then move on to a description of feedbacks. We introduce the concept of 'self-organisation' as used in the natural and biological sciences and touches on the concept from a social science perspective.

A key feature of the complex adaptive systems (as described in Section 3.1) is that of **self-organisation** where the system 'arranges itself' (through relations between components) and adaptation. This appears to be the rule rather than the exception. Heylighen et al. (2007) coin the term "creative evolution" to describe this evolution that is not only unpredictable but also creative – producing emergent organisation and innovation.

The term 'self-organizing' was introduced to contemporary science in 1947 in psychiatry and later in cybernetics. In the 1960s the concept of self-organization was used by those working in general systems theory, but only became more common in the scientific literature in the 1970s and 1980s when it was adopted by physicists and researchers in the field of complex systems. After Ilya Prigogine's 1977 Nobel Prize, the *Thermodynamic concept of self-organization*, the concept also received wider attention. Like 'feedbacks' the concept is now so widely applied by different disciplines that it is increasingly difficult to determine whether discipline-specific phenomena are all fundamentally the same process, or the same label applied to several different processes (www.wikipedia.com). Thus arriving at a single definition is not possible. The concept is closely linked to others found in the body of complexity literature such as networks and self-regulation.

The field of self-organisation seeks general rules about the growth and evolution of systemic structure, and the potential forms it might take. The results are expected to be applicable to all other systems exhibiting similar network characteristics http://www.calresco.org/sos/sosfaq.htm#1.2. Nonetheless the essence of self-organisation is that the structure of the system often develops without explicit pressure or involvement from outside the system. In other words, the organisation or form result from the interactions amongst the systems components and usually independent of the physical nature of those components. They arise from constraints that are internal to the system. As Cilliers (1998) states 'this process is such that structure is neither a passive reflection of the outside nor a result of active pre-programmed internal factors, but the result of complex interaction between environment, the present state of the system and the history of the system'. The organization can evolve in either time or space, maintain a stable form or show transience. Although general resource flows within self-organized systems are expected (dissipation), they are not critical to the concept itself. This chapter provides an introduction to the concept of 'self-organisation' as used in the natural and biological sciences and touches on the concept from a social science perspective. Some of the definitions given in different fields are given below.

In biology a systems self-organisation (Camazine *et al.* 2003) is

> *'a process in which pattern at the global level of a system emerges solely from numerous interactions among the lower-level components of the system. Moreover, the rules specifying interactions among the system's components are executed using only local information, without reference to the global pattern*

The concept of self-organisation or "autopoiesis" as it is known in classical Greek is elegantly described by Paul Cillier's (1998) in his book *Complexity and Postmodernism*. Cilliers (1998) provides a working definition as follows:

> *The capacity for self-organisation is a property of complex systems which enables them to develop or change internal structure spontaneously and adaptively in order to cope with or manipulate their environment*.

He provides a simple yet useful illustration of a population of a school of fish in a dam – the population size of which is an indicator of their condition. Their condition reflects a variety of factors (temperature, light, availability of food and oxygen and so on) and, as these vary so does the population, adjusting to suit prevailing conditions – despite the fact that each fish can only 'look after its own interests'. The system (the school of fish) organizes itself to match the environmental conditions and is also adaptive in that it is sensitive to changing conditions in the light of past experience. There is no external agent deciding what the fish should do, nor does each fish understand the wider complexity- but the systems organisation emerges from the interaction between the various constituents of the system and the environment (self-organisation).

As noted, the theory of self-organisation is now widely evident in a range of disciplines. The extension of the self-organization to social theory and to the level of social relations among human beings is done most explicitly by Luhmann[10] (see for example (Luhmann 1990) who focused on the role of language and its self-organizing potentials for how we are able to perceive "reality"). For Luhmann the elements of a social system are self-producing communication – that is, a communication produces further communications and thus a social system can reproduce itself as long as there is dynamic communication.

In the fields of education and economics (see below on Ormerod and feedbacks), self-organisation has also come to the fore. This means that elements of a system have the potential to organise themselves within a complex system so that a system need not tend towards disorder (Doll, 1993). This perspective can be translated in a learning sense to mean that the self-organising nature of a collective enables opportunities for the creation of options and solutions to contextually-based problems. The deepening of understanding comes from reflecting on actions and experiences, not from implementing a set of preformatted solutions to generic problems.

In the field of sustainability studies, self-organising ideals have also emerged (see for example the Gaia philosophy, deep ecology and review by Marshall (2002). In 1999, Donella Meadows (Meadows 1999), described twelve leverage points that a self-organizing system could exploit to organize itself. She is one of a school of theorists who asserts that observer is within – or part of – the system, and that an awareness and manipulation of these levers is an aspect of self-organisation. When done collaboratively,

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[10] Luhmann developed an evolutionary theory of Society and its sub-systems, using functional analyses and systems theory.

it can lead to collective intelligence. She notes that the ability to 'self-organize is the strongest form of self-resilience'.

Different systems that demonstrate the property self-organisation do not necessarily exhibit the same range of characteristics such that some may allow for the construction of a deterministic model (such as a living cell) whilst others may not. From this brief synopsis it is apparent that although arriving at a single definition is difficult, the process of self-organisation has a number of attributes many of which recur when examining complex systems. Cilliers (1998; 2000) list a number as follows:

- Absence of external control (autonomy): The structure of a system is not the result of an *a priori* design nor is it determined directly by external conditions. Rather it is a result of the interaction and its environment.
- Adaptation and dynamism: The internal structure of the system can *adapt dynamically* to changes in the environment even if these are not regular.
- Feedbacks: Recurrent positive or negative feed-back loops exist in the system, providing opportunities for maintaining identity but learning lessons to improve that identity – autopoiesis, dissipative structures and self-organisation);
- Self-organisation is not merely the result of processes like feedback or regulation that it can be described linearly. It involves higher-order, non-linear processes that cannot be modeled by sets of linear differential equations.
- Emergence: Self-organisation is an *emergent property* of a system as a whole (or large enough sub-system). The systems individual components only operate on local information[11] and general principles.
- Self-organising systems *increase* in complexity. Since they have to 'learn' from experience, they have to 'remember' previous situations and compare them with new ones.
- Self-organisation is impossible without memory and hence always has a *history*.
- Since self-organisation is not guided or determined by specific goals it can be difficult to talk about the *function* of such a system. When it is described in context of the wider system, then it is possible to talk about the *function of a sub-system in that context*.
- There is *co-operation* between some of the units.
- The interactions between units have to be *non-linear* (small actions can cause large reactions)
- The memory of a system is stored in a *distributed* fashion.

Now we turn to feedback loops about which mention has already been made. Simply expressed, a feedback describes the situation when the output from an event or phenomenon in the past will influence an occurrence of the same event / phenomenon in the present or future. When an event is part of a chain of cause-and-effect that forms a circuit or loop, then the event is said to *"feedback"* into itself. Thus a ***feedback loop*** is the causal path that leads from the initial generation of the feedback signal to the subsequent modification of the event.

The concept of feedbacks is used in numerous applications ranging from biology, engineering, natural and ecological sciences (e.g. climate science), integration and sustainability sciences (e.g. resilience approaches), software and computing systems, economics and finance and social sciences. This of course

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[11] The macroscopic behaviour emerges from microscopic interactions that by themselves have very meager information. By confining ones analysis to the microscopic it is possible to explain the behaviour of each element in terms of a number of simple transformations. Simple, local interactions can result in complex behaviour when viewed macroscopically.

reflects the realities of the real world. Moreover, an examination of the nature of complexity and the role of feedbacks generated much interest and underpinned some of the major theoretical shifts. For example, in his book "The Death of Economics", (1997) Paul Ormerod heavily criticized the conventional economic equilibrium model of supply and demand which supported only ideal linear negative feedback which did not represent the realities of a complex world (he was, in turn, was criticized by traditional economists). This book was part of a change of perspective as economists started to recognise that Chaos Theory applied to nonlinear feedback systems including financial markets.

This brings us to types of feedbacks. In general two types are feedbacks are recognised: negative and positive. These are not value-derived terms (that is a change in A has a positive/ beneficial effect) but rather expresses the stability of a system. Feedbacks are part of causal-chains where the relationship of one variable to another is either negative or positive. A **positive** connection is one in which a change (increase or decrease) in some variable results in the same type of change (increase or decrease) in a second variable (Figure 7). A positive feedback loop tends to be *self-reinforcing,*[12] increasing the event that caused it – the more babies are born, the more people there are to have babies. They can be a smaller part of a larger balancing loop. Sometimes they are also called virtuous or vicious loops.

Figure 7 Illustration of a simple example of the ice-albedo positive feedback loop described in climate science

An example of **positive feedback** is world population with a fixed percentage birth rate, where large populations cause large numbers of births and large numbers of births result in larger population[13]. Positive feedbacks will result in unlimited growth (until checked) and are sometimes referred to as vicious cycles. Not all positive feedbacks give exponential growth but all, left unchecked, will result in unlimited (or unstable) growth. Another simple example is the ice-albedo positive feedback loop where melting snow exposes more dark ground (of lower albedo), which in turn absorbs heat and causes more snow to melt.

A **negative** connection is one in which a change (increase or decrease) in some variable results in the opposite change (decrease/increase) in a second variable. A negative feedback loop (Figure 8) tends to reduce the input signal that caused it, and is also known as a *self-correcting or balancing* loop[14]. Most

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[12] To indicate a negative loop the letter "R" is often used

[13] This idea can be modeled with the differential equation dP/dt=+rP, where P is population and r is the percent birth rate. The solution to this is P(t)=Po(exp[rt]) or exponential growth.

[14] To indicate a negative loop, the letter "B" (for "Balancing") or "C" (for "Counteracting") is used

endocrine hormones for example are controlled by a physiologic negative feedback. They are important therefore in maintaining homeostasis – for example the body's temperature at 37 C. If there is a slight variation the body will shiver or sweat to self-correct. Unlike the virtuous or vicious positive feedback loops, negative feedback loops on the other hand, describe 'goal-seeking' processes that generate actions aimed at moving a system toward, or keeping a system at, a desired state (although as Radzicki and Taylor (1997) point out the goal-seeking logic implied in a loop such as Figure 8 is misleading since the loop implicitly seeks a goals of zero hunger). They suggest that an alternative and (often) more desirable way to represent negative feedback processes via causal loop diagrams is by explicitly identifying the goal of each loop. Also although generally speaking, negative feedback processes stabilize systems, although they can occasionally destabilize them by causing them to oscillate.

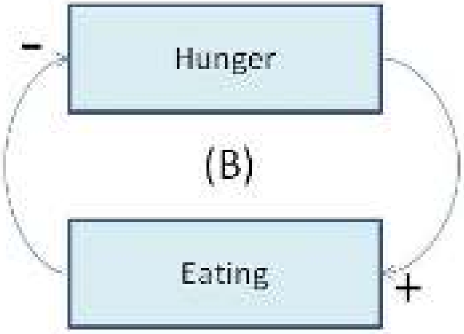

Figure 8 Illustration of a simple example of the hunger-eating negative feedback loop

If one considers the terms and concepts developed by the Resilience Alliance (see Section 4.2) regarding resilience, then feedbacks (and self-organisation) are two of the attributes along with function, structure that describe a particular system regime. If the feedbacks change then the system flips into a different state and a regime shift ensues. (The RA has defined resilience as: 'The capacity of a system to absorb disturbance and re-organise so as to retain essentially the same function, structure and feedbacks – to have the same identity (that is, to remain in the same system regime'). They also define a social-ecological system as

> *an integrated system of ecosystems and human society with reciprocal feedback and interdependence. The concept emphasizes the 'humans-in-nature' perspective* (Berkes and Folke 1998).

A complex system shows *feedbacks* (which may be reinforcing or balancing) in its cause and effect relationships, which, usually because of operation at different scales, cause *emergence* (i.e. the feedbacks generate surprising new properties not predictable from the original individual components of the system). According to a number of authors (e.g. Meadows, Walker (pers. comm) and Walker and Salt

(2006), a number of attributes[15] are believed to confer resilience – one of which is feedbacks (Holling 2001; Gunderson and Holling 2002; Biggs and Rogers 2003). This is the basis for a learning and reflexive system. Where systems often fail is where any of these steps fail such as in cases where the learning is not passed on or is passed to an inappropriate body. In Tanzania for example, despite socio-political change, persistent feedback loops between monitoring and action have ensured a resilient management system ((Tengo and Hammer 2003)).

The cases of feedback loops that we describe in the following sections pertain to water resources management – or aspects thereof – and hence are examples of hierarchies of social networks in a social system concerned with the management of natural resources (either explicitly or as an emergent property). Citing Lyotard (1984), Cilliers (1998) points out that the dynamics of social networks share the characteristics of self-organisation in that they are not designed – but develop in response to contingent information in a dynamic way. The process is complex and involves feedback relations. Individual co-operate but also compete for resources and the history of the system is vitally important for making meaning. We start therefore by giving a brief overview of the context and history of each case before describing the self-organisation and feedback. We then move on to an analysis of what 'makes them work' – or not – as part of a process of 'looking for leverage' in complex systems (see (Meadows 1999).

6.3. Overall approach and contextual overview of catchments

6.3.1. Overall approach

The methodology for constructing a picture of self-organisation and feedbacks was detailed in Pollard & Du Toit (2011). The overall approach was qualitative action-research based on interviews and interactions with key stakeholders both within catchments and at the national level. Stakeholders included representatives of local municipalities, various departments (provincial and national), DWA regional and national offices, irrigation boards, water users associations, commercial forestry, industry, mining, conservation and other interested and affected parties.

The data were analysed according to themes identified from the first round of catchment interviews Understanding and embeddedness of concepts of sustainability and the Reserve in water management practices

i. Change and lags:
ii. Integration of WRM and water supply:
iii. Unlawful use:
iv. Skills, capacity and ability to monitor and enforce:
v. Adaptive capacity and change:
vi. Feedback loops and self organisation:
vii. Learning within changing contexts:

This was followed by an analysis of case studies which sought to elucidate what lay behind the successes or constraints.

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[15] diversity, innovation, polycentric and overlapping governance, social capital, ecological variability, openness, and reserves. Additionally, insight into slow-acting variables and the suite of ecosystem goods and services adds to an understanding of the resilience of a system

The two cases examined include the Letaba (Luvuvhu/ Letaba WMA) and the Crocodile rivers (Inkomati WMA). Their histories and context as well as water resources management experiences are sufficiently different to provide useful; lessons and reflections.

6.3.2. Groot Letaba Catchment: Overview of biophysical and socio-economic characteristics

The Letaba River Catchment with an area of 13,500 km^2, comprises the Groot Letaba sub-catchment in the south and the Klein Letaba in the north (Figure 9). The Middle Letaba River which flows in a north-easterly direction drains into the Klein Letaba just downstream of the Middle Letaba Dam. The confluence of the Groot and Middle Letaba Rivers is at the KNP border and that with the Olifants River is 7 km upstream of the Mozambique border. The topography varies from a zone of high mountains in the west through to low mountains and foothills in the central part of the WMA to the low lying plains in the east. Rainfall is strongly influenced by the topography the mean annual precipitation varying from more than 1500 mm in the mountainous west strongly seasonal to less than 450 mm on the low lying plains. Rainfall occurs mainly during the summer months (i.e. October to March). Temperature also displays a gradient from a mean annual temperature of 18°C in the mountainous areas to more than 28°C in the east and a maximum temperature in January and minimum in July.

Intensive commercial, irrigated agriculture is practiced in the upper parts of the Klein Letaba Catchment, upstream and downstream of the Middle Letaba Dam, and along the Groot Letaba and Letsitele Rivers. Citrus, tropical fruit and vegetables (including the largest tomato production area in the country) are grown. Large areas of the high rainfall Drakensberg Escarpment are under commercial forestry. Land and water resources available for agriculture are already highly utilised, particularly with respect to irrigation and afforestation.

The population of the Luvuvhu/Letaba WMA was estimated at some 1.535,000 people (1995 population) of which over 90% reside in the rural areas (DWAF 2004b). A large proportion of these people are regarded as poor and live in the densely-populated areas that constituted the former apartheid bantustans of Lebowa and Gazankulu. These areas are also characterized by major socio-economic problems (poor education standards, high unemployment (formal – estimated at 49% of the workforce), and high level of HIV-Aids). According to the ISP (DWAF 2003), based on figures from nearly 10 years ago, the largest economic sectors in the WMA are government, trade and agriculture. Most of the economic activity is centred in the Tzaneen area with the surrounding activities in irrigation and afforestation (agriculture, trade). Tourism, associated with the KNP, is also an important sector.

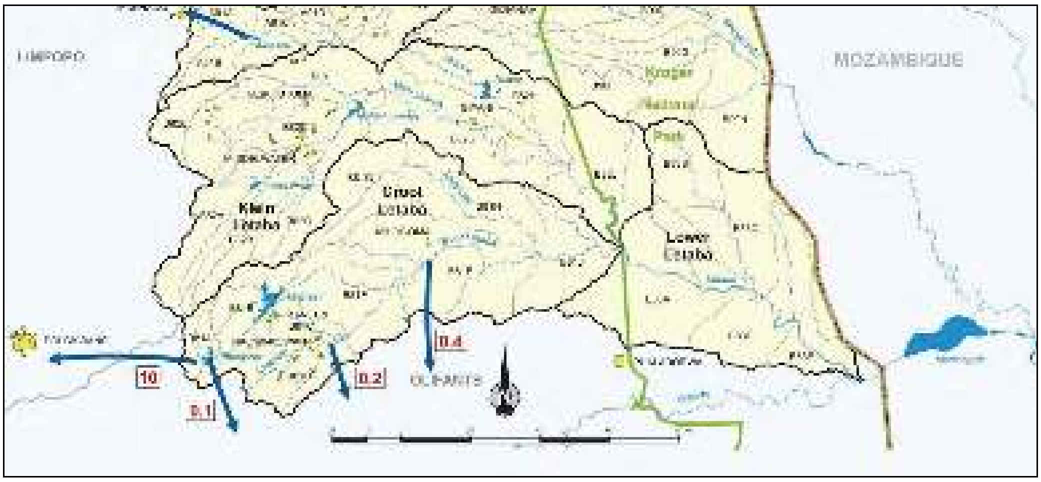

Figure 9 Map of the Letaba River Catchment showing the main towns, the boundaries of the Groot , Klein and Lower Letaba, major dams, the border of the Kruger National Park and Mozambique, and the interbasin transfers (source: Letaba ISP, 2004)

Water resources

Table 1 indicates that both the Groot and Klein Letaba catchments are in water deficit. The surface water resources are extensively developed with a large number of small to major dams constructed to meet domestic (urban and rural), irrigation and industrial water needs ((DWAF 2004b)). The water supply schemes generally consist of dams for storage, bulk water pipelines and extensive conveyance canals. The largest water user is irrigation followed by forestry.

6.3.3. Crocodile River Catchment: Overview of biophysical and socio-economic characteristics

The Crocodile River, together with the Sabie-Sand and Komati rivers, is part of the Inkomati WMA (WMA 5) which covers an area of approximately 28,757 km^2 (Figure 10). The confluence of the Crocodile and Komati rivers lies just upstream of the Mozambique border at Ressano Garcia where after the river is known as the Inkomati River. The Sabie flows into the Inkomati below Corumana Dam near the town of Moamba. These rivers are all part of the Inkomati **international watercourse** which is shared between the Republic of Mozambique, the Kingdom of Swaziland and the Republic of South Africa.

As with the other WMAs the topography strongly influences the rainfall. The mean annual rainfall varies from as high as 1445 mm/a in the escarpment and mountainous areas of the catchment (near Swaziland), to as low as 470 mm/a in the lowveld region. The other climatic characteristics are similar to those given for the Letaba Catchment.

The Crocodile catchment is approximately 10 400 km^2 stretching from the highveld in the west to the Kruger National Park and Mozambique border in the east. The main land uses are irrigation (42,300 ha) and forestry (1,775 km^2 of exotic forests)(DWAF 2004a). These two activities are also the major water users. Industrial water use in the catchment is limited and consists mostly of the Sappi paper mill at

Ngodwana and the sugar mills at Malelane and Komatipoort and mining industries in the upper and middle catchment.

In terms of water infrastructure the catchment has one major dam, the Kwena Dam, in the upper catchment and a number of smaller dams in the central portion (Witklip, Primkop, Klipkoppie/Longmere). Kwena is used mainly to augment low flows.

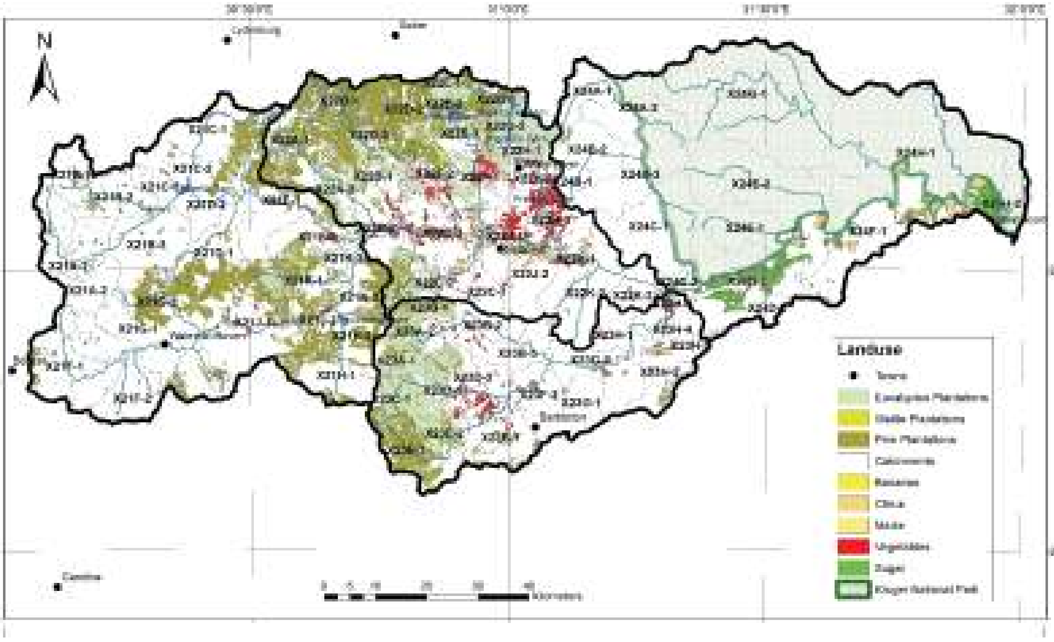

Figure 10 Map of Crocodile Catchment showing the EWR sites and Reserve Assessment Units (map from IWAAS 2009)

Water resources

The greatest demand for water is from irrigated agriculture and forestry. In terms of water infrastructure the catchment has one major dam, the Kwena Dam, in the upper catchment (which augments low flows) and a number of smaller dams in the central portion.

The water requirements exceed the available resource, and the catchment is considered to be **highly stressed**. The IWAAS conclusion is that the irrigation demands have been increasing since the 1990's up to their current levels. DWA's current policy for many years has been not to issue any more water use licences to irrigation but there is probably still some unlawful development. In the last 50 years there is increasing incidence of failure to meet the EWRs (see Table 3). This suggests that the international flows are also not met at times.

The Crocodile catchment is severely stressed and has experienced a reversal in flow seasonality as a result of the operation of Kwena Dam.

6.3.4. Compliance with the Ecological Reserve

An overview of non-compliance with the ecological Reserve is given in Table 1. In the Letaba, the estimated natural flow at the border to the park is 557 Mm^3/a (includes Middle Letaba) while the combined Reserve (Groot + Klein) at the border of the Kruger Park required only 96 Mm^3/a.
The low-flow requirements are only a very small fraction of what naturally flowed in the river. For example, the absolute minimum flow of the Reserve is 0.14 m^3/s in September while naturally this is estimated to be 2 m^3/s. The 'old' operating rule was to ensure a minimum flow of 600 l/s at the border to Kruger. The approved Reserve allows even lower flows than this. Compliance in the Groot Letaba has been improving over the last decade.

In the Crocodile, the ER has not be used as a goal per se. Rather the flows under the international water-sharing arrangements (see later) are loosely referred to as the ER although this minimum flow of 2 m^3/s is only to fulfil the requirements of the Pigg's Peak Agreement. Table 3 indicates that in the Crocodile last 50 years there is increasing incidence of failure to meet the EWRs. The likely reasons for the high levels of non-compliance with the ER are as follows.

- There has been an increase in irrigated agriculture and the last decade has seen an increasing demand for urban consumption associated with expanding development in the Nelspruit area as well as a demand for improved levels of domestic services.
- The current abstraction regimes can reduce flows to near zero on a daily basis during the course of the day. Irrigators have an agreement with Eskom to pump in off-peak times (rate can double causing huge fluctuations)

Table 3 Summary of incidence of non-compliance with the quality component of the Ecological Reserve for the case studies (from Pollard et al. 2010)

River	**Months of non-compliance**	**Non-compliance (% time)- Pre policy change**	**Non-compliance (% time)- Post policy change**	**Non-compliance (% time) based on daily data for last period**	**Worst month (do final check)**
Groot Letaba[1]	All months except January	41	22	48	February
Klein Letaba	All months	N/A	88	N/A	September
Crocodile[2]	All months	14	46	54	September
[1] Groot Letaba 1960–1993 1994 2008 [2]Croc. 1960-1983 1984-2010					

6.4. The emergence of self-organisation and feedback loops in water resources use and management in the lowveld rivers

6.4.1. The Letaba Catchment

As noted above the Groot Letaba River is in water deficit although users upstream of the Tzaneen Dam enjoy a relatively high level of assurance while those downstream experience shortages. The above discussion pointed to a high degree of non-compliance with the ecological reserve in two periods examined (pre and post-1994). However the results also suggest that there is increased compliance since 1994 in comparison to the preceding period. At about that time (1991) a new manager had taken responsibility for the management of water resources from Magoebaskloof, Ebenezer[16] and Tzaneen dams and started to monitor dam levels, flows and climate data and hence to develop operating rules for each dam. These – together with the required restrictions – were communicated to water users, mainly through the Groot Letaba Water User Association (or the former irrigation board) in the case of Ebenezer and Tzaneen Dam. Normally the planning is undertaken together with representatives at the start of the water year and taking into account crop types (J. Venter 2008, pers. comm.). Already the experience of financial losses incurred during droughts had resulted in high efficient water use by irrigators who often operated on 50% of their allocation.

In the late 199os the Kruger National Park started to voice concerns about the flows of the Letaba and Olifants rivers (state where this happens) and a minimum flow was agreed on as an interim arrangement until a comprehensive Reserve was undertaken. At present the operator of the system attempts to maintain a flow of 600 l/s into the Kruger Park. The need to meet these flows was therefore another stakeholder requirement that was built into the operating rules for water resources management. What had happened by this time however was that the irrigation of mostly perennial high-value crops has expanded to fully utilise the water resources prior to any allowance for the Ecological Reserve. This required further management and discussion between the Kruger and the water resources manager as well as the GLWUA.

6.4.2. Feedbacks, self-organisation and self-regulation

In the Groot Letaba Catchment a number of key self-organised feedbacks are evident and these have provided the basis for self-regulation and learning (Figure 11; (Pollard and Du Toit 2011). A number of actors are key: the local DWA manager (actually NWRIA), the Groot Letaba Water Users Association (GLWUA) and its various members and the Kruger National Park. As noted, the DWA manager monitors and manages the water resources- and particularly inflows and dam releases. He plans annual allocations communicates with and responds to concerns from stakeholders – mainly in the form of the GLWUA and the KNP.

The GLWUA manages some 520 registered water users (although not all of these might be active) and confine management to their area of operation which is the government water-controlled area from Ebenezer dam down to KNP Kruger National Park. They note that most of tributaries are outside of area

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[16] Already the water is over-subscribed from all dams: For example with a 17 Mm^3 transfer to Polokwane from Ebenezer Dam , the allocation is 12 Mm^3 is greatly exceeded

of control (GLWUA, February 2008, pers. comm.). In theory they represent all water users (e.g. municipalities) but in reality are plagued by non-attendance at meetings and actively therefore comprise commercial farmers. Once they have received their annual water allocation they distribute it across the users and months. They have a system of bailiffs who monitor water flows and use- for the area under their scheme. Transgressions such as over-abstraction are dealt with first as a warning after which charges are laid with the police.

The KNP monitors the flow at the entrance to the Park against a minimum flow requirement (albeit static in that it does not reflect rainfall)). If problems are noted[17] the Tzaneen area office manager (who manages the Tzaneen Dam) is alerted, who then alerts the GLWUA to reduce use. Internally the GLWUA informs users with instructions for use and monitors this.

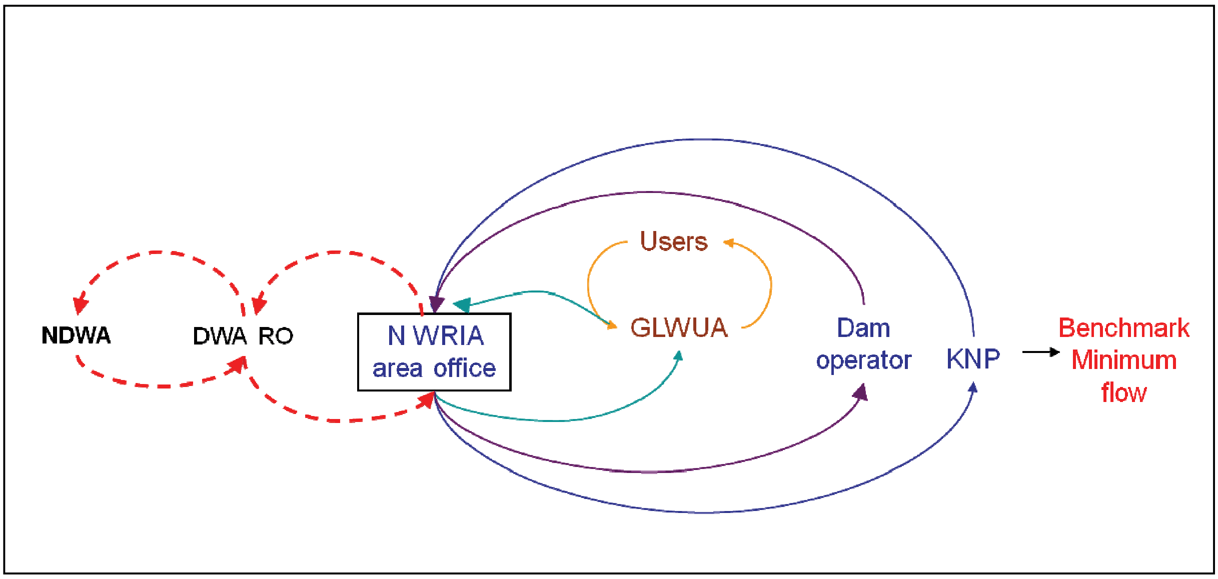

Figure 11 Functional feedback loops in the Letaba Catchment (from Pollard and du Toit 2011). Note the weak linkages to the regional and national DWA. NWRIA = National Water Resources Infrastructure Agency, KNP = Kruger National Park, GLWUA = Groot Letaba Water User

Thus in the Groot Letaba the feedbacks, although fragile, are functional at a certain scale (below Tzaneen Dam see Figure 9). The system displays inherent self organisation between the regulator, the watch-dog and the users, and the operation of the dam releases to mitigate low-flows. Leadership is undertaken by a manger that is trusted. Moreover, the capacity for self-regulation amongst long-standing WUA members (users) is high – although bringing new, emerging farmers on board has proved more difficult. (In contrast the same manager is involved in operational systems in the Klein Letaba system but here feedbacks are virtually non-existent and the system is in an almost permanent state of crisis and water deficit. This is because feedbacks at a wider scale are needed to secure lawful use through an integrated approach. Despite repetitive attempts to secure action through the regulator little meaningful action has transpired).

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[17] The Park identifies Thresholds of Potential Concern and responds accordingly**: Low Worry Level:** KNP Technician contact DWAF Tzaneen via phone call; **Medium Worry Level:** KNP River Manager contact DWAF & WUA via email & phone call; **High Worry Level** Meeting between KNP, DWAF and WUA.

There are a number of factors that lie behind the success of these two loops including the requirements of the law (the Reserve), the availability of benchmarks against which to monitor (the Reserve), the presence of a 'watchdog', the responsiveness of the manager and users and the ability to self-organise which we return to in Section 7.

However, the system is fragile in other respects. Firstly, Pollard and Du Toit (2009) note that one of these feedbacks is potentially quite fragile in that it depends on one key person – the area manager. Were he not to undertake this role, the question arises as to who would do this and whether or not they have the capacity and trust of the users. Secondly, the feedbacks are confined to a local scale and lack linkages to wider scales that would confer strength and resilience. There is little support from or interaction with the national or regional offices despite repeated attempts from local stakeholders.

As with self organization, self regulation has an important role to play in management within complex systems. The general sense from the interviews is that regulatory functions are perceived to reside with DWA and only on a few occasions did respondents recognise that they have a collaborative regulatory role to play when it comes to sustainability issues and the Reserve. No such regulation occurs on the Middle or Klein Letaba with the consequences that such responsibilities fall to DWA (who lacks the capacity to regulate).

6.4.3. Crocodile River

Key issues

As noted above, the water requirements the Crocodile River exceed the available resource, and the catchment is considered to be **highly stressed** and has experienced seasonal flow regime reversals. Pressures on the system are high and increasing and as pointed out below, include the need to meet the demands of emerging farmers, the Reserve and international agreements.

Improved technical and management systems since 2008, together with greater collaborative efforts between the Inkomati CMA and the irrigators give reason to believe that the situation will improve in the foreseeable future. Firstly the ICMA has developed its first draft of the catchment management strategy which attempts to deal with a wide range of socio-economic, political, technical and environmental issues based on adaptation and learning, as suggested in the DWAF guidelines (see DWAF 2007; Pollard & Du Toit 2008). Moreover, the Crocodile River is a focus of the PRIMA project designed to realise international water sharing agreements. Currently there is a real time study underway to address key problems east of the Kwena Dam. The objectives of this study – known as the *Real Time Operating Decision Support System for the Crocodile East River System* – are to assist with water distribution (run of river) and water releases (dams), to ensure compliance with the Reserve and with international obligations (Crocodile East RTOS meeting Nov 2007). The DSS must be capable of determining operational plans and should include a water allocation and utilisation management and monitoring system (DSS Team pers. comm.).

Feedbacks, self-organisation and self-regulation

In the Crocodile River a number of irrigation boards have assumed responsibly for regulating use by monitoring flows and controlling abstraction for irrigation in much the same way as that described for the Groot Letaba WUA, above. However prior to about 2005 the management of water by these irrigation boards was concerned only with the internal arrangements for distributing their own water allocation. Since then, the establishment of the ICMA together with a stronger and growing emphasis on IWRM for the catchment as a whole has slowly required that stakeholders look beyond their own individual needs to the wider context. Part of this context is the need to ensure that water is shared with sectors of the population that were denied access to water during Apartheid based on their race. Today there are a large number of emerging farmers (i.e. black farmers) especially in the lower Crocodile and Komati catchments that must be included in equitable water-sharing arrangements. Two important additional drivers are also evident. Firstly, the requirements for the Reserve have now been established through a Comprehensive Reserve Determination (RDM office, pers. comm.) and progressive compliance with the Reserve must be demonstrated. To date the history of compliance with the ecological Reserve – as a benchmark for ensuring the sustainability of the system – has been particularly weak (see Table 3). Secondly a key driver of the system is the obligation to meet cross-border international flows negotiated as part of the Interim Inco-Maputo Agreement or IIMA[18] (signed in 2002). Although this has been in place for nearly a decade the quantity is likely to change under the comprehensive agreement which is currently being developed and is also likely to be more closely monitored by each of the sovereign states.

The imperatives of equity and sustainability, not just at a national but also at an international scale, have meant that water-sharing arrangements together with the increasing pressure on the water resources are under much closer scrutiny. The role of self-organisation and feedbacks therefore is critical.

In terms of international water-sharing arrangements, the feedback is interesting in that it requires the collaboration between South Africa and Mozambique – and with Swaziland in the case of the Komati River – to monitor flows (KOBWA (along with the Komati Irrigation Board, the ICMA, DWA and Ara-Sul). Although communication is evident interviewees agreed that there was a need to improve this aspect, the responsibility of which falls to national DWA in South Africa.

Currently meeting all of the demands on water resources focuses on the management of the Kwena Dam in the upper Crocodile Catchment and of course on water user allocations (Figure 12). It is generally accepted that in order to meet the demands above (of emerging farmers, current users, the Reserve and international agreements) further water storage is necessary and a transfer of water use licences (through compulsory licencing) is likely.

In the meantime there are a number of more feedback loops that are being strengthened to keep the management process responsive to contextual changes. Probably the most clearly defined feedback system was established and is maintained by the Crocodile Major Irrigation Board (MIB). In their attempt to remain responsive to managing water allocations they have assembled a highly functional network of

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[18] This agreement between Mozambique, Swaziland and South Africa was signed in 2002 sets new limitations on water use in each of the countries, target flows to be maintained to sustain the riverine ecology and water quality standards. It has not yet been fully implemented and will be superseded by a comprehensive agreement. The intention of this interim agreement is partly to fulfil the requirements of the Pigg's Peak Agreement where 2 m^3/s.

water managers and users that interface with the current infrastructure, policies and regulation. Transformation has introduced changes and additions to these feedbacks specifically in terms of scale and stakeholder participation. Firstly the KNP has taken a much more active role as 'watchdog' in the Crocodile River so that reduction in flows to different levels elicits different management responses. The communication is to the dam bailiff (Kwena dam) and the ICMA. Secondly, in all cases regulation and feedback is only for specific river sections rather than for the system as a whole. In this regard, the ICMA water resources manager is currently in the process of establishing a river flow management system for the Crocodile River as a whole, including real-time operation for better management. This will be an integrated system and in addition to international obligations, it will include the Reserve requirements as drivers. Thus in addition to international obligations the requirements of the Reserve will be formally included as well as the ultimate incorporation of all users on the system and not just agriculture.

The leadership role of co-ordinating stakeholders and ensuring a reasonable flow of information has been assumed by the water resources manager of the ICMA. Equally, enforcement is an important component of the success of these systems in which the role of bailiffs and good monitoring systems are central (see Box 5 below). However this is still strongest within the remit of the users that fall under the irrigation boards. Interviews with various stakeholders indicated widespread lack of enforcement of transgressions especially by municipalities and the mining and in some cases, industrial sectors (Pollard & Du Toit 2011).

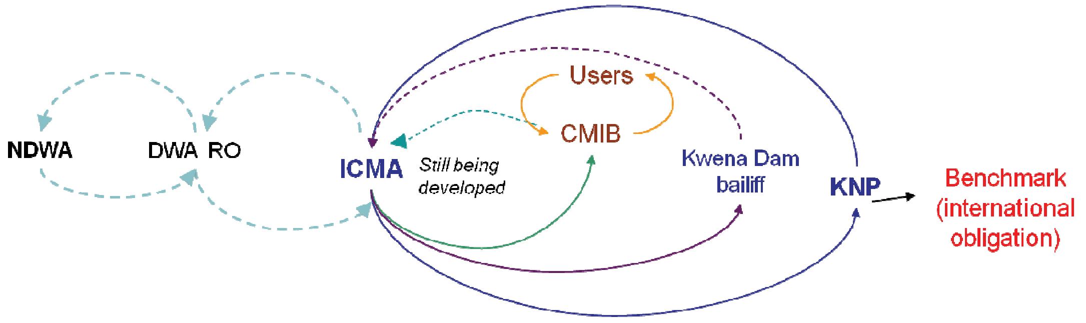

Figure 12 Feedback loops in the Crocodile Catchment (From Pollard & du Toit 2011).

Dashed lines indicate linkages that are still to be established. Note that the international linkages currently happen through NDWA. CMIB = Crocodile Major Irrigation Board; KNP = Kruger National Park, GLWUA = Groot Letaba Water User Association

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The details of self-organisation internal to the Crocodile MIB are outlined in Box 5; the components of which are central to the effective management of the river and for maintaining compliance. In setting up this network a sophisticated flow of information is maintained in order for responsivity and resilience to be built into the system. Each component needs to function effectively with interactions and feedback remaining focused. The flow of information is highlighted as an important part of the process with blockages and bottlenecks presenting a problem for the management process. In this regard it was noted that the DWA website is not always reliable with hydrological data sometimes missing [this can happen if weirs and monitoring gauges are broken]. It was highlighted that a planned 60% cut in Hydrometry budget at DWA will have serious consequences for monitoring and management.

Box 5:
An example of sectoral self-organisation for resource sharing along the Crocodile River (from Pollard & Du Toit 2011)

A detailed analysis of this network is beyond the scope of this profile. However, we have identified key areas that have been part of their attention to the management process and networking:

- Within the MIB there is a technical management committee. The committee develops and defines a strategy that is fed through to an operational manager who implements the operating rules;
- There is a chairperson (of the Technical Committee) who is knowledgeable of the system and the management processes, from both a technical and social perspective. During dry cycles when special management measures need to be put in place, special management committees are set up – comprising MIB chairperson, ICMA, DWA;
- A "mini- forum" is being established between the Irrigation Boards and the ICMA to deal with issues that are of direct interest to these parties
- There is attention to medium and longer term planning not just response to current issues and crises. Strategic planning is an important focus of the network;
- There is a designated person/s responsible for the day-to-day management
- The last (downstream) farmers to receive water are usually involved in the monitoring and reporting;
- Adequate and operational monitoring weirs: specifically key or critical weirs are identified. For example, management is largely dependent on the Van Graan Weir;
- Real time data is critical for the management process. Day-to-day management involves visiting the real time DWA website to see what volumes are crossing the weirs.

Finally it is notable that there are other instances self-regulation in individual sectors focusing on practices that will enable them to meet with the kinds of conditions and standards that the Reserve and IWRM require. For example, in terms of water conservation and demand management, one member of the industrial sector is aiming to devise closed water systems and improve water recycling, and one bulk supplier mentioned that it was busy conducting research in water leakages and wastages in the catchment. Unfortunately no comprehensive plan for dealing with water conservation and demand management was articulated by the municipality directly.

7. Factors constraining and enabling the emergence of self-organisation and feedbacks

Interest has grown over the course of this work in what makes feedbacks work and Pollard and Toit (2008)) traced the success of feedbacks to a number of factors (Box 6). These include an understanding of the legal requirements on the part of the regulator and stakeholders (the WUA and the KNP); the availability of benchmarks against which to monitor (the Reserve, albeit a minimum static value); the presence of a 'watchdog'; the role of leadership with authority (a champion), responsiveness of the manager and users; the ability to self- organise; the development of trust and collaboration over a decade between the role-players; the internal mechanisms for monitoring and action; and the development of a flexible management system that is understood and respected by the users.

The trusted point of contact – the manager – can and does respond appropriately whilst considering the risk that this may pose to other users (in this case agriculture). Enforcement is an important component of success and bailiffs (as another example of 'watchdogs') – are imperative. Self-organisation and regulation are key features and are elaborated below. In terms of leadership, Kotter ((1996)) cautions against conflating the two (leaders and managers), asserting that leadership produces change. However the managers in both of the cases examined display leadership qualities and certainly the process underway in the Crocodile River to introduce a real-time systems approach is transformative in nature complying more with Kotter's definition of leadership. Unlike the feedbacks that exist in the primary rivers of the Inkomati and Letaba catchments, other catchments such as the Olifants, Sand and Klein Letaba are characterised by weak or non-existent feedbacks. Pollard & Du Toit (2011) note that amongst other factors, a critical issue is that of leadership and authority. In all of these cases there is no single individual ***with authority*** (i.e. within DWA) *tasked with the overall governance of water resources* ***highlighting the critical role of leadership and appropriate and effective governance.*** In effect any issues that may be raised by stakeholders 'fall on deaf ears' in the sense that the leadership role and function is absent or is shared (and lost) between a number of departments and individuals. Returning to the discussion on feedbacks, the communication and action *loops between stakeholders and authority are weak or non-existent*.

The above cases illustrate that an important element of these loops is the ***ability for self-organisation*** in that the elements of a system have the potential to organise themselves within a complex system so that it need not tend towards disorder. Over time the users of the WUA or irrigation boards have developed and organised themselves into a system that is responsive to – although not always supportive of – the needs of downstream users. An important driver of these loops has been the need to share a scarce resource internally. This is a well-recognised determinant of co-operative management around natural resources (e.g. (Alchian and Demsetz 1973), cited in (Murphree 2004, Meinzen-Dick and Nkonya 2005, Pollard and Cousins 2008)). Thus the driver is primarily one of self-interest (in a non-pejorative sense) that has allowed wider interests (the Reserve) to be served. Most importantly, the locally-developed operating system that responds to conditions of resource scarcity is sufficiently flexible to accommodate change and surprise. Nonetheless, transformation has introduced changes to feedbacks specifically in terms of scale and stakeholder participation. For example, the role of the KNP as 'watchdog' is not only more active but is more widely recognised than it was 15 years ago. Also, although regulation and feedback is only for specific sections of the river rather than for the system as a whole, this is changing in some areas, notably in the Crocodile River as described above.

Box 6:
Key elements necessary for feedback loops

- the requirements of the law (supportive legal and institutional milieu (the Reserve*)
- the availability of benchmarks against which to monitor (the IFR*/ Reserve),
- the presence of a 'watchdog' (* although intermittent),
- the buy-in of users (also assume that they are getting a share)
- accountable leadership together with effective governance
- the responsiveness of the manager and users;
- the ability to act (staff, skills, capacity, tenable Reserve statements; infrastructure and so on)
- the ability to self regulate (bailiffs*, incentives to comply, authority to act*)
- the ability to self organise, and thus
- the ability to reflect and learn

We suggest that functional, responsive multi-scale feedbacks are essential for management in complex systems like catchments since they provide the basis for learning, reflection and response to an evolving context. However, the existence of these is variable from non-existent to emergent in the lowveld rivers.

8. Conclusions

As we move into these relatively unchartered waters, an important feedback loop requiring attention is that between academics, practitioners and managers and in particular the need to develop tenable methodologies (even if not perfect). Failure to do so adequately will simply frustrate turning one-time supporters into critics – thus breaking the loop of learning and action.

As water resources in the lowveld come under increasing pressure, regulators and users will need to find 'solutions' to oversubscribing the resource. The challenge will be to develop appropriate practices that address directly unsustainable use – this, arguably, can only be done with a certain level of self organization within and between the various sectors. In addition the need for learning as a key component for organisation and innovation is critical. *Support needs to be given to developing and strengthening leadership and coherent, robust and multi-scale feedbacks that provide the basis for action and learning*. Attention must be paid to strengthening linkages at higher scales (e.g. to DWA), monitoring and enforcement and delegation of duties if needed. However as Cilliers (1998) points out that local narratives only make sense in terms of their contrasts and to surrounding narratives – what we have is a self-organising process (in the Letaba for example) where meaning is generated through a dynamic process not a passive reflection of an autonomous agent. Thus collective action through stakeholder participation is an essential component for robust feedbacks. Equally, if we accept that learning has a vital role to play in ensuring that feedback loops have an impact on self-regulation and self-organization then it becomes a critical process in the support for, or hindrance of, establishing resilient, sustainable systems. In this regard, learning is taken to be a social process where engagement, communication and dialogue provide the basis for reflecting on and responding to feedback in a way that is open to change and that encourages creative and innovative responses to an ever evolving context.

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