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Introduction

> **The First Water Law of the West is the Law of Gravity. Water runs downhill. The initial uses of water in the West involved the use of gravity to tap rivers and divert their flows into canals for delivery to farms and mines. This is also known as Newton's Law.**
>
> **The Second Water Law of the West is the original law of Los Angeles…[and] states that 'water runs uphill to money.' The development of energy technologies to lift water against the pull of gravity is the basis for modern Western civilization. Los Angeles pioneered the effort to defy gravity with money in the early 1900s with its Owens Valley Aqueduct…Phoenix, San Francisco and Denver also utilize massive pumping and diversion systems to transport water from great distances in defiance of gravity to serve their growing urban populations.**
>
> **—Hugh Holub, 1999**

Societies throughout history have used laws to define, control, and sanction the use of natural resources for their benefit – water being no exception, and perhaps all the more so because of its absolute non-substitutability. Water, however, is a law-defying entity. As Holub's first two Water Laws of the West make clear, even Newton's Law, long used to the advantage of farmers, miners, and other water users, may be superceded when societal ambition and ingenuity dictate necessary (Lebel et al. 2005). Today, we are beginning to realise the limits of our legal measures to manage water. Holub's laws were written with reference to the water saga that has long endured in the American West (Reisner 1993), but apply with little modification to numerous societies that have made similar valiant attempts to support livelihoods, economies, and political regimes on arid landscapes, often with remarkable success, and as the historical record indicates, equally often with phenomenal failure (Tainter 1998, Diamond 2005).

Perhaps nowhere has the need to reform the way water is managed and even conceived been more apparent than in South Africa in the last decade. In a country where history has been so prominently shaped by unevenly distributed natural resources (Figure 1.1), the nation's leaders seized an opportunity at the close of the apartheid era to overhaul the previous water law and replace it with one of the most progressive pieces of water legislation in the world to date. The enactment of National Water Act No. 36 of 1998 signaled not only the end of an era of resource

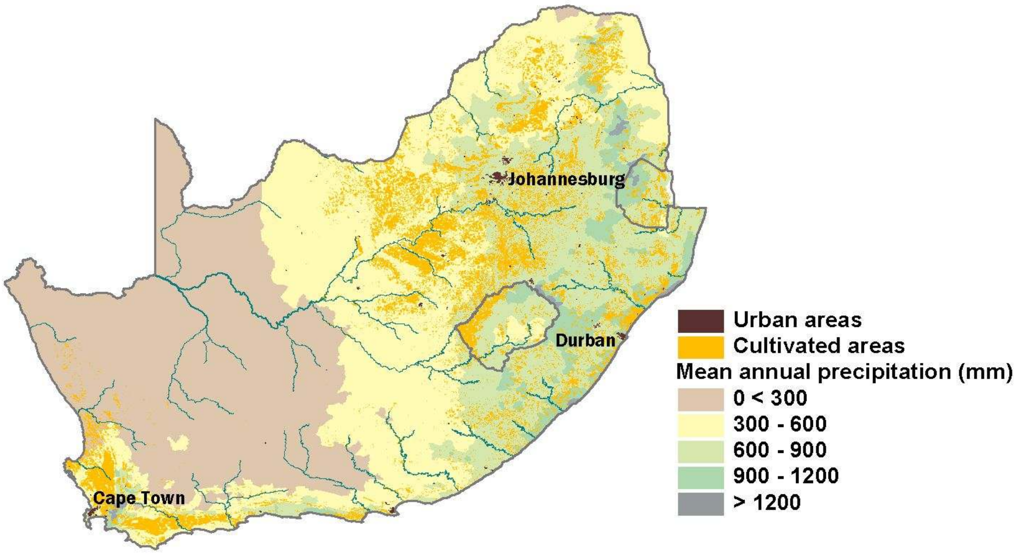

Figure 1.1. South Africa, with major rivers, cities, urban and cultivated areas, and mean annual precipitation.

management but the beginning of a commitment to ecological and social sustainability, abolishing all water rights except for two: the right of every citizen to an adequate, safe supply of water for domestic needs and the right of ecosystems to the water required for their continued functioning (DWAF 2004*a*). Together, these rights constitute the Reserve, the unconditional first priority in water allocation. The Act also strives for efficiency, so that scarce water resources beyond the Reserve are used for the collective benefit of the nation's present and future generations.

Four years after the Act was passed, the World Summit on Sustainable Development was held in Johannesburg. To showcase South African water policy for the benefit of international visitors, the Department of Water Affairs and Forestry took out a billboard ad in a prominent location. The ad showed the image of a smiling African child standing at a tap, while beneath the image ran the newly-adopted slogan of the department: "Some, for all, forever," a reference to the Water Act's three core principles of efficiency, equity, and sustainability. Here was a very appealing concept: the department's new law would serve the 'triple bottom line' of the people, the economy, and the environment. It was a concept that everyone could buy into, and few could argue against.

As of early 2006, major parts of the new water policy await implementation, and many questions about how to do it remain unanswered. Moving from legislation to action on the ground must extend beyond a paradigm shift in thinking to the establishment of new institutional arrangements, demonstrable progress on the significant backlog in service delivery especially in the rural population (DWAF 2004*b*), and an improved understanding of the complex relationships between hydrology, ecology, and society. This amounts to an enormous task, and while the new Water Act is a significant piece of legislation, concerns are expressed that an enabling environment for implementation of the law does not yet exist, necessary partnerships among and between institutions and communities are not being forged, and the Act's vision is not being effectively communicated (MacKay et al. 2003).

We now know that water cannot be governed by physics alone. Managing water sustainably is a question of biological and physical processes, but it is every bit as much a question of social ones (Pahl-Wostl 2002). In this thesis I propose that water management in South Africa – which encompasses its water resources, ecosystems and their services (Daily et al. 1997), people they support, and institutions that govern them – is a social-ecological system: a coupled, inseparable system of human beings and nature. However, social-ecological systems theory, increasingly embraced by those working at the interface of social and natural science problems, has not been fully brought to bear on the challenges that South African water management faces now and may encounter in the future. I then argue that a social-ecological systems perspective is needed to understand the true nature of these challenges. Below I elaborate on this perspective before outlining the thesis structure and the approach adopted in each chapter to support this argument.

A Social-Ecological Systems Perspective on Water Management

Science and broader society have traditionally treated social systems and ecosystems as distinct, according to one of two general views (Westley et al. 2002). One is that ecosystems are part of social systems – 'natural' patches within a human-dominated matrix. The other is that social systems are part of ecosystems, with ecosystems comprising all life, among which the human species has come to dominate. Each view tends to draw from a unique disciplinary paradigm, and each may be used to support different approaches to conservation and development problems (Norgaard 1994).

A growing volume of case studies and examples (e.g. Gunderson and Holling 2002, Janssen 2002, Berkes et al. 2003) suggests that each of these views has limits when called upon to provide sustainable solutions to such problems. The first view, that ecosystems are contained within social systems, may arrive at an assumption that managers can control ecosystems. Much management in industrialised nations has been based on a 'command-and-control' (Holling and Meffe 1996) approach that supports the idea that humans can and should dominate, tame, or triumph over nature. A counterargument is that all ecosystems, no matter how much humans influence them, are partially but inherently beyond human control. This is because ecosystems behave as complex adaptive systems (Walker et. al. 2002), which tend to be non-linear, uncertain, unpredictable, and adaptive to change. Their complexity emerges from simple rules (Lee 1993), the ability to self-organise (Holling 2001), and the interaction of slow variables – the governing structures and processes that drive system behavior – with rapidly changing ones (Gunderson and Holling 2002). Complex systems are able to shift between alternative states; state change is often characterised by thresholds that are difficult to predict (Scheffer and Carpenter 2003). When a critical threshold is passed, recovery to the previous system state is often extremely difficult (Scheffer et al 2001). Such dynamics explain the severe resource collapse or degradation that has been observed in large complex systems such as the Columbia River Basin (Lee 1993), the Everglades (Light et al. 1995), and the Western Australia agricultural region (Allison and Hobbes 2004), all of which have been guided by command-and-control management approaches.

The second view, that social systems, as a construct of the human species, are contained within ecosystems, may conclude that humans, though a remarkably successful species, are just like any other (Pinker 1997), and therefore, human control over and custody for ecosystems can be relinquished. The likeness of humans to other life forms is not debated here; the salient argument against this view is that the human species, though only one of many, has made an indelible and profound mark on global ecosystems and human well-being (MA 2005). Some liken the current scale of human domination to a new geologic era, the 'Anthropocene' (Meybeck 2003), in which the modern human species – *Homo economus* (O'Neill and Kahn 2000) – has appropriated primary production (Vitousek et al. 1997), freshwater (Vörösmarty and Sahagian

2000), and biodiversity (Pimm et al. 1995) as no other species has done before. The continuation of these activities, and the unprecedented scale of their effects, does not bode well for future human (or other) generations (MA 2005). Furthermore, some challenge the 'just another species' view on the grounds that nature has intrinsic value and a right to exist beyond any human needs or desires for it (Noss and Cooperrider 1994).

Where sustainability is concerned, a more meaningful position is likely to lie somewhere between the two views – one that suggests a more complex relationship between humans and ecosystems, appreciating that while humans are at least partially at the mercy of ecosystem complexity, they have tremendous impact on natural systems, and recognising this, are capable of better management. Such a relationship is not novel in human history; case studies show how recognition of the fundamentally coupled nature of social-ecological systems has allowed some societies to manage their resource bases sustainably, sometimes for centuries (Berkes et al. 2000, Dietz et al. 2003). At present, however, such a position does not feature prominently in the positivist tradition of Western science (Berkes et al. 1998) or conventional resource management (Holling and Meffe 1996).

In South Africa, water management has been dominated largely by the first view (Rogers et al. 2000), though elements of the second also persist. Undoubtedly, a more holistic perspective is required to achieve the efficiency, equity, and sustainability principles of the Water Act. This is a call echoed by water researchers and practitioners across the globe (Pahl-Wostl et al. 2002, Folke 2003), but it is often guided by incomplete understanding on the ground. For example, Integrated Water Resources Management, which focuses on coordinated management of water resources to achieve social, economic, and sustainability goals, is often an attempt at such holism, but at other times is a mere buzzword that obscures underlying perceptions about human-water relationships (Chikozho 2005, Moench 2005).

Water is an especially challenging resource to manage because of its tight links to other ecosystem components, land use, economies, culture, and fundamentally, ethics (Acreman 2001). The South African Water Act clearly acknowledges these links and trade-offs in a 'water and society' system context, but recent dialogue regarding the creation of new water institutions has suggested that this context is not always being appreciated in practice (Rogers et al. 2000). In academic and research circles, different aspects of social-ecological systems theory are reflected in the current water management discourse and analysis. These focus on the role of adaptive management (Rogers et al. 2000, MacKay et al. 2003), the incorporation of value systems in monitoring programmes (Rogers and Biggs 1999), limits of biophysical research (van Wyk et al. 2001), and governance mismatches (Pollard and du Toit 2005). Despite this, the theory needs continued development and application to the South African context, individual efforts need to be synthesised, and greater investment made in communication with those responsible for implementing water policies. This thesis is an attempt to respond to these needs by pushing social-ecological systems thinking in several new directions in an arena where its application has been limited thus far.

Thesis Structure: Hypothesis, Key Questions, and Approach

My hypothesis is that a social-ecological systems perspective makes a unique contribution to our understanding of water management in South Africa, and particularly to the current transition underway. To explore this, I identify five key questions that flow from this premise (Table 1.1), and use a variety of approaches and methods to address them in the next five chapters. Two chapters (2, 3) of this thesis draw on the experience of the Southern African Millennium Ecosystem Assessment (Biggs et al. 2004, Bohensky et al. 2004, van Jaarsveld et al. 2005 – see Appendix A), part of a global initiative to provide information to decision-makers about the relationships between ecosystem services and human well-being (MA 2003, MA 2005). To a large degree, the scientific basis of the Millennium Assessment is rooted in social-ecological systems theory, though in itself it was not a theoretical exercise intended to support or test this theory, an issue I return to in a later chapter (6).

Two chapters (4, 5) use an agent-based modelling approach that was developed for this thesis to explore the evolution of interactions between water resources and water users in a spatio-temporal environment that represents South Africa. Agent-based modeling has its origins in the arenas of artificial intelligence (Ferber 1999) and social science (Epstein and Axtell 1996) but is becoming widely applied to natural resource management research that adopts a social-ecological systems perspective (Bousquet and Le Page 2004).

Table 1.1. Thesis structure.

Chapter	**Key Question(s)**
1 Introduction	How can a social-ecological systems perspective contribute to our understanding of South African water management?
2 Evaluating responses in complex adaptive systems: insights for water management from the Southern African Millennium Ecosystem Assessment (SAfMA)	What factors characterise effective management responses - those that maintain ecological and social resilience - in complex systems?
3 Future ecosystem services in a southern African river basin: a scenario planning approach to uncertainty	How can scenarios of possible alternative futures aid our ability to deal with uncertainty in complex social-ecological systems?
4 Decentralisation and its discontents: redefining winners and losers on the South African 'waterscape'	Does the decentralisation of water management in South Africa lead to 'better' outcomes, or does it simply redefine winners and losers?
5 Learning dilemmas in a social-ecological system: an agent-based modelling exploration	How do certain social-ecological system conditions enable or constrain learning? Does the Water Act create optimal environments for learning?
6 Discovering resilient pathways for water management: two frameworks and a vision	Can existing social-ecological systems frameworks help to discover resilient pathways for South African water management and achieve the vision of the Water Act?
7 Synthesis	How can a social-ecological systems perspective contribute to our understanding of South African water management?

In order to understand why certain systems of water management in southern Africa have succeeded or failed in the past, and the likelihood of future successes and failures, water management responses need to be viewed in a complex adaptive systems context. In **Chapter 2**, I investigate whether certain factors characterise effective management responses – those that maintain ecological and social resilience – in complex systems. Water management in South Africa needs to be understood in light of the dominant paradigms of past and present that have enabled or constrained people’s options for managing water. I present a conceptual framework of responses in complex social-ecological systems to evaluate different interventions to manage water. The framework consists of three interconnected scopes or spatial and temporal domains: the scope of an impact, the scope of the awareness of the impact, and the scope of the power or influence to respond. I suggest that these scopes must be at least mostly congruent for a response to be effective. I then assess the validity of this suggestion by evaluating water management responses in the Gariep and Zambezi River basins that formed part of the Southern African Millennium Ecosystem Assessment. Fundamentally, this chapter seeks to gain a better understanding of past water management responses, and is a logical basis for the questions explored in the following chapters of the thesis which essentially focus on the future.

Many uncertainties influence the future of water management in South Africa, and are not easily controlled by actors in the system. In such situations, scenarios, as plausible narratives describing alternative futures, have shown great potential to stimulate thinking and debate. For this reason, scenarios have been used widely in business and political contexts, where they have frequently been instrumental in achieving major strategy changes and paradigm shifts. In **Chapter 3**, I review a scenario planning exercise as an approach for identifying social-ecological management decisions that are robust to high levels of uncertainty about future ecosystems and their services. I then discuss the objectives, approaches, and findings of a scenario analysis in the Gariep River basin in Southern Africa. I also look more closely at the key findings of this analysis, why they emerged from the scenarios, as well as the shortcomings of this exercise and how it could be improved for future use. Scenarios show greatest potential when designed to address a focal policy issue, and could therefore play an important role for dealing with uncertainty surrounding the South African water management transition.

The new water management paradigm in South Africa entails an unprecedented decentralisation process for this country. Social-ecological systems theory suggests that democratic decentralisation is an effective management response because it transfers decision-making authority to local actors who presumably have the most relevant information about their water resources, and it also minimises risk by promoting a diversity of water management strategies. Yet in reality, few examples exist of successful decentralisation experiments for natural resource management. In **Chapter 4** I ask if decentralisation leads to 'better' outcomes in social-ecological systems, or simply redefines winners and losers. I pursue this question with the use of an agent-based model of decision-making in the South African water sector called the WaterScape. I compare the outcomes of actors' decisions for achieving the three Water Act principles of efficiency, equity, and sustainability under three dominant water management paradigms and under a decentralised system that allows collective learning. Given that water management must occur at multiple scales, I explore to what extent decentralised decision-making is appropriate.

Learning is important in a social-ecological system so that actors can capture information and detect key patterns. Because social-ecological systems are dynamic, actors must be able to learn and adapt. While in Chapter 4 I ask whether the Water Act principles are more likely to be achieved when learning is allowed, in **Chapter 5** I extend this line of questioning and ask what causes agents to learn, and conversely, what prevents them from learning. I propose that water management in South Africa, as a social-ecological system, is challenged by 'learning dilemmas,' in which human perceptions combined with social-ecological conditions affect the capacity, understanding, and willingness required to learn. In South Africa, learning how to manage water has been affected by water's high temporal variability, scarcity, and lack of access to 'learning networks' through which relevant, timely information can be obtained. Learning is also affected by the indicators selected to measure the effectiveness of different management strategies. I use the WaterScape model presented in Chapter 4 to investigate social-ecological conditions that encourage or constrain learning by agents in the South African water sector. I explore how variability, water stress, and spatial heterogeneity, together with indicator selection affect learning ability. I then ask, given these conditions, what can be done to enhance learning, and how can management ensure that optimal conditions for learning are maintained or created?

In **Chapter 6** I investigate the concept of resilience in water management. Resilience – defined as the amount of change or disturbance a system can withstand and still maintain its essential structure, function, and identity (Rappaport 1968, Holling 1973, Levin 1999, Cumming et al. 2005) – as it applies to water management is poorly understood, yet it is a critical issue to the successful implementation of the South African Water Act over the long term. Because a social-ecological system undergoes continuous change, the concept of resilience needs to be viewed with respect to particular system configurations rather than to the system itself. It is therefore useful to identify resilient "pathways" for the system that can guide future management actions. A growing body of theory and associated frameworks exist to improve understanding of resilience, but its relevance to management, and specifically for the example in this thesis, is unclear. I evaluate the potential of two existing frameworks – the conceptual framework of the Millennium Assessment and the "panarchy model" of Holling that has played a pivotal role in current resilience theory – to help water managers discover resilient pathways that are likely to align with a common vision for the South African water sector. I then identify features of the framework that may require modification as well as gaps in the vision, with the practical example of South African water management ultimately serving to strengthen social-ecological systems understanding.

In **Chapter 7**, I revisit the hypothesis presented above: can a social-ecological systems perspective contribute to our understanding of water management in South Africa? I attempt to answer this in a synthesis of the arguments made in the five main thesis chapters. I then discuss some of the expected implications of this work for water management and research in the future.

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Evaluating responses in complex adaptive systems: Insights on water management from the Southern African Millennium Ecosystem Assessment (SAfMA)

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Keywords: responses, complex adaptive systems, ecosystem services, southern Africa, water management, impact, awareness, power

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Published in: *Ecology and Society*: 10(1): 11.
[online] URL: http://www.ecologyandsociety.org/vol10/iss1/art11/

Abstract

Ecosystem services are embedded in complex adaptive systems. These systems are riddled with non-linearities, uncertainties, and surprises, made increasingly complex by the many human responses to problems or changes arising within them. In this paper we ask whether certain factors characterize effective responses in complex systems. We construct a framework for response evaluation with three interconnected scopes – or spatial and temporal domains: the scope of an impact, the scope of the awareness of the impact, and the scope of the power or influence to respond. Drawing from the experience of the Southern African Millennium Ecosystem Assessment (SAfMA), we explore the applicability of this framework to the example of water management in southern Africa, where an ongoing paradigm shift in some areas has enabled a transition from supply-side to demand-side responses and the creation of new institutions to manage water across scales. We suggest that the most effective responses exhibit congruence between impact, awareness, and power scopes, distribute impacts across space and time, expand response options, enhance social memory, and depend on power-distributing mechanisms. We conclude by stressing the need for sufficient flexibility to adapt responses to the specific, ever-evolving contexts in which they are implemented. While our discussion focuses on water in southern Africa, we believe the framework has broad applicability to a range of complex systems and places.

INTRODUCTION

Ecosystems, the services they provide, and the people who use and manage them comprise complex adaptive systems. Complex systems are inherently non-linear, variable, and uncertain, and are hence seldom predictable; if anything, surprise is the norm (Costanza et al. 1993, Gunderson and Holling 2002). Part of their complexity lies in the fact that human responses to different situations are constantly occurring across different scales and levels of organization, playing out in multiple, uncoordinated, improvisational theatres in which actors are never quite sure what will happen next. Due to the great uncertainties in complex systems, we cannot predict the full range of a response's implications. All responses are, therefore, experiments.

This does not mean that the way complex systems work is beyond human comprehension. Complexity often emerges from simple rules (Lee 1993). Within the complex couplings of people and nature, experimentation, adaptation, and co-evolution have taken place for as long as humans have existed. A wealth of information exists from the long history of human experience with ecosystem change that can contribute to current understanding and ultimately foster sustainability.

In this paper we seek an answer to the following question: What factors characterize effective responses in complex adaptive systems? "Responses" are behavioral, institutional, or technical adaptations that people make to deal with (or in anticipation of) problems or changes in complex systems. Although ecosystems also respond to change, we limit our discussion to human responses.

The definition of an "effective" response in a complex adaptive system also needs some clarification. It is naïve to suggest that effectiveness means achieving objectives. Dams, in many cases, have been effective in stabilizing river flows and providing hydropower but have severely undermined downstream ecosystem service delivery and human livelihood systems (WCD 2000*a*). In essence, these responses have yielded benefits to some components of the system at a significant cost to other components. In the context of this paper we use the term "effective" to mean responses that maintain a system's social and ecological resilience. Resilience is used here to refer to the amount of change a system can withstand while retaining its structure and the variables and processes that control its behavior (Holling and Gunderson 2002). Resilient systems tend to be self-organizing (as opposed to controlled by external forces), and can build the capacity to learn and adapt (Carpenter et al. 2001).

We present a simple framework for evaluating responses, and explore it using the experiences and information generated by SAfMA, the southern African component of the Millennium Ecosystem Assessment. We focus our evaluation on responses for managing water in southern Africa, where recent change in the water sector makes it a particularly compelling case, though we believe the framework can be applied to other problems that involve complex systems of people and nature.

RESPONSES IN THE MILLENNIUM ECOSYSTEM ASSESSMENT

The Millennium Ecosystem Assessment (MA) is a four-year international process to provide decision-makers with scientific information about the relationships between ecosystems and human well-being. The MA marks a departure from other global assessments in several ways: it is multi-scale (in space and time), integrated (involving ecologists, social scientists, and economists), and user-driven (serving a range of information needs, from those of local communities to international environmental conventions). Central to the MA design is a common conceptual framework (MA 2003) that describes the relationships between ecosystems and their services, human well-being and poverty reduction, and direct and indirect drivers of ecosystem change. Within the framework there are opportunities for responses: strategies and interventions that can halt, reverse, or otherwise change these relationships. A critical aspect of the MA’s work is to identify features of responses that cause them to succeed or fail and to ultimately give guidance to decision-makers for choosing among response options.

The Southern African Millennium Ecosystem Assessment (SAfMA) is one of approximately 30 sub-global assessments linked to the MA. Using the MA framework, SAfMA evaluated southern African ecosystems and the ways in which they support human societies. SAfMA consists of the following partially-nested assessment components: a regional assessment of nineteen countries of mainland Africa south of the equator; two river basins, the Gariep and Zambezi; four local assessments located within the Gariep basin; and a local assessment of the Gorongosa-Marromeu, Mozambique region in the Zambezi basin (Figure 2.1).

The SAfMA teams generally used two approaches to assess responses: at coarser scales (regional and river basin) we reviewed past and present responses, and at local scales we used interactive processes with stakeholders to elicit information about responses used or likely to be used in alternative future worlds depicted by scenarios. Although many of us had expected response evaluation to be the simplest component of the MA's conceptual framework, we had difficulty distilling clear messages from the information available about what makes a response work.

We observed that responses may be proactive; that is, people anticipate some impact will occur and begin responding before the impact happens. Much policy falls in this category. Other responses are reactive, or those in which people begin responding only after an impact happens or is perceived, such as when a herder decides to move in response to shifts in rainfall. If people cannot affect drivers of change, they are more likely to adopt reactive response options. We focus on proactive responses in this paper. We believe that many of the suggestions we make will also hold true for reactive responses, but do not specifically explore these.

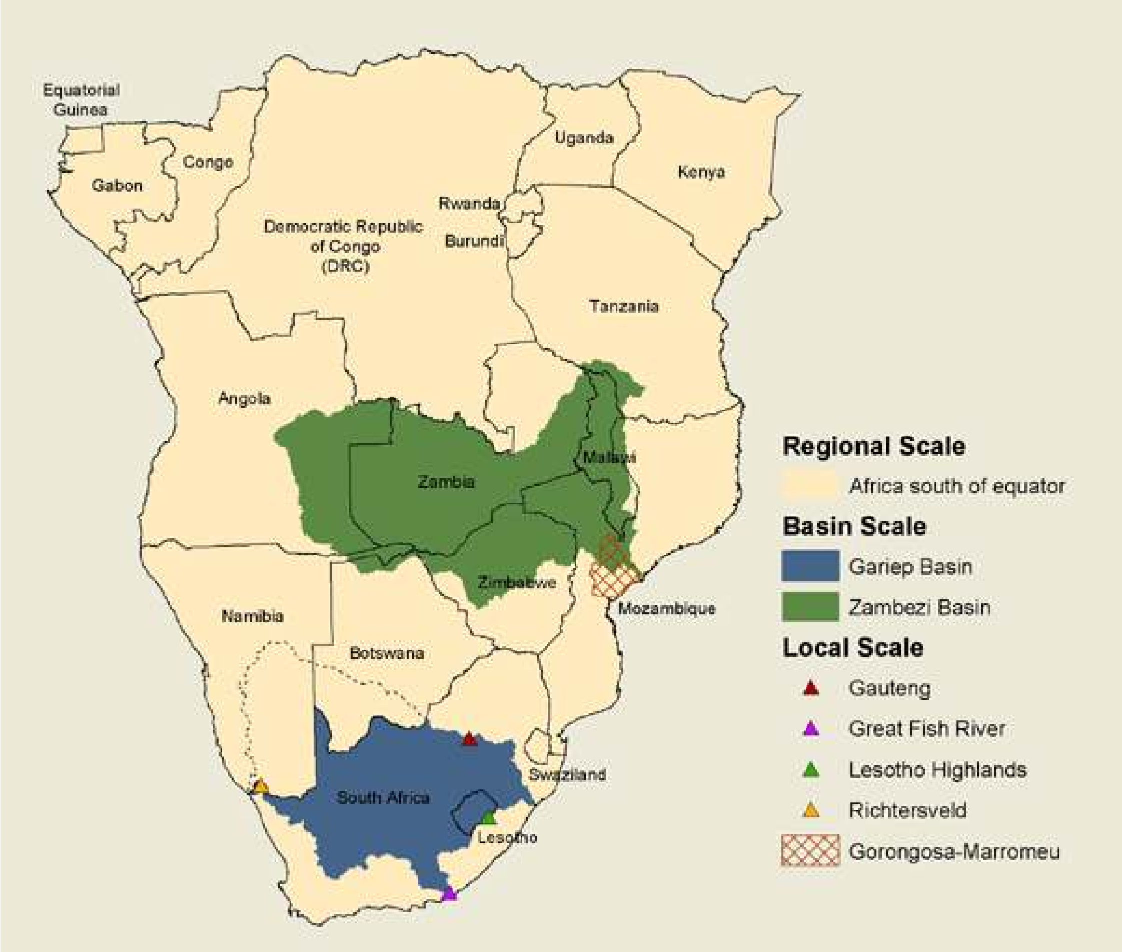

Figure 2.1. The SAfMA study area and its nested, multi-scale design. Note that the actual Gariep basin (indicated by a dashed line) extends beyond the area assessed.

We found it helpful to develop our own simple framework to address the focal question of what makes a response effective, which we then applied to the real-world example of water management based on the SAfMA experience. Below we describe the framework, demonstrate its utility by evaluating responses used to manage water in two southern African river basins, and then suggest simple guidelines for designing effective responses.

A FRAMEWORK FOR RESPONSE EVALUATION

We construct our framework for response evaluation with three inter-connected components, which we call scopes of impact, awareness, and power. The *impact* scope is the spatial and temporal domain in which an impact occurs - who or what is impacted, where, when, and for how long. The same impact situation can affect different groups or locations differently, either in space, in time, or both. Climate change, for example, is expected to make some areas of southern Africa better suited to grain production and other areas worse (Jones and Thornton 2003).

The second component of our framework for response evaluation is *awareness*. People respond to actual or perceived changes in some matter of consequence to them. They will not deliberately respond to a change unless they are aware of it. It must first register on their conscious or unconscious minds. We differentiate between two major elements of awareness. The first is awareness of the consequences or impacts of a change. This often encompasses awareness of a state, such as the amount of water in a stream, or trend, such as a decrease in this amount over time. The second element is an awareness of the direct and indirect drivers of the observed or expected change. Unless people are aware that increased anthropogenic CO_2 emissions cause changes in the global temperature, and that changes in temperature can change ecosystems that they depend on, they cannot understand why certain preventative actions are required to curtail these emissions. In both instances, we use the term awareness to reflect a reasonably true state of knowledge, characterized by useful degrees of accuracy and of precision. Inaccurate or imprecise awareness by this definition has little utility and is therefore at least as bad as being unaware, and possibly worse. Awareness in a complex system implies learning. As the system changes, new drivers and conditions emerge. Awareness must be sufficiently flexible to incorporate these changes through learning.

People will often seek to capture the benefits of a response while transferring the costs or disservices elsewhere in time or space. For example, a government’s decision to construct a dam to capture the benefits of cheap hydroelectric power transfers ecosystem disservices, such as reduced fisheries production or reduced alluvial deposition for riverbank agriculture, and consequent disruption of livelihood systems, to people living downstream or to future generations. Awareness is therefore a broader concept than we have initially portrayed it. For responses to be effective, there must also be an awareness of cross-sectoral and cross-scale (spatial and temporal) trade-offs. This requires a great deal of knowledge about, and sensitivity to, a response's implications for all sectors of society.

The third component of our framework is *power*. People may be aware of an impact, such as reduced streamflow, and be aware of its direct cause (a decrease in rainfall) and indirect cause (anthropogenic climate change). They may not be able to alter these factors, however. For example, responses identified by rural villagers in central Mozambique to two scenarios of the future were all reactive (Lynam et al. 2004). This is a key observation. Poor people perceive themselves to be largely powerless to influence the major processes that govern their livelihoods, and indeed they often are. Powerlessness is not unique to the poor, however; affluent people may be able to do little more than rural villagers to affect climatic processes. The resilience of livelihoods is enhanced by having a wide set of response options, both reactive and proactive. Choice counts and power expands choice.

Power, like impacts and awareness, is seldom symmetrically distributed in time or space or among actors. Power tends to accumulate upwards through hierarchical structures; hence, people can often only indirectly influence large-scale causal processes through cumulative expressions of individual wishes through political or economic mechanisms, such as elections or markets. These mechanisms can be slow or dominated by individuals and societies elsewhere with different problems and needs. Responses are often lagged, such that their effects are only felt long after the causal factors have been alleviated. This can result in system over- or undershoots as lagged responses try to correct historical deviations from desirable states. The asymmetry of power has an important implication: there will always be trade-offs between the different needs or desires of different social groups. Mechanisms that influence power distribute benefits and costs and hence define winners and losers. Future generations are often the losers (and sometimes the winners) by default, as they have virtually no control over current responses.

We suggest that when impacted people are fully aware of the consequences and causes of a change and they have the power to alter the processes driving these changes, they have a good chance of selecting and implementing effective responses. We refer to this situation as congruence, or overlap, among the impact, awareness, and power scopes (Figure 2.2a). When these components are incongruent or non-overlapping (Figure 2.2b), we suggest that the chances of effective responses being identified and implemented are reduced.

Identifying an effective response to a problem in complex adaptive systems can be difficult because impacts, awareness, and power are dynamic. Impacts are not uniformly and simultaneously experienced everywhere by everyone, and responses will emerge at different scales in space and time. A flood wave that inundates the Zambezi Valley is first experienced in the upper reaches, then the lower, and then is felt indirectly by the adjacent communities who absorb the refugees, and perhaps finally by the national government when budget lines are shifted to relief efforts. Local people alter their behaviour immediately by moving from the flood zone. District, provincial, national, and international administrators and relief agencies mobilize resources to support the affected people.

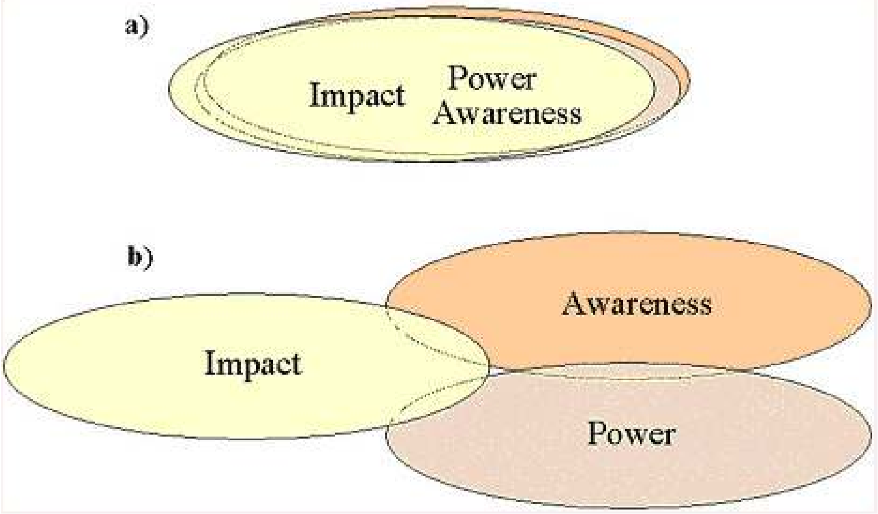

Figure 2.2. a) Impact, awareness and power scopes are nearly congruent. b) Impact, awareness and power scopes are highly incongruent.

Over time the impact continues, but becomes more like a ripple from a stone dropped in a pond. Once the immediate needs are addressed with reactive responses, policy makers begin to develop proactive responses, such as the design of new monitoring systems and agencies. Downstream, people seek assistance to rebuild houses and livelihood systems destroyed by the flood. New plans are formulated to improve the dam management so that the flood cannot happen again, new flood early warning systems are installed, and regional cooperative linkages are improved to better coordinate flood releases. There is new learning, both social and ecological (new channels are gouged from the river bed), resulting in new awareness, which institutions quickly try to capture. Then slowly the impact and its memories begin to fade as other priorities and concerns take center stage. Just as the impact ebbs and flows spatially and temporally in the wake of the flood event, so too do awareness and power. Power generally shifts much more slowly, if at all. As new agencies for cooperation are formed, new powers are created or old ones transformed. With each response, a new configuration of impacts, awareness, and power takes shape. The stage is set for another performance.

In what follows we apply the framework in an exploration of historical and current responses to manage water in the Gariep and Zambezi River basins, and seek lessons from this framework in understanding responses in complex adaptive systems.

WATER MANAGEMENT IN SOUTHERN AFRICA: RESPONSE THEATRE IN PROGRESS

Southern Africa is characterized by high climatic variability, an uneven spatial and temporal distribution of runoff, and a history of attempts, with varying success, to compensate for an unpredictable water supply. Water issues in this region are now being cast in a new light, illuminating the essential challenge to balance the preservation of ecological integrity and the achievement of social and economic development objectives. Several countries are reforming their water law, and are increasingly decentralizing management or forming new institutions, often across national boundaries. This shift has not been universal, however, and water-related problems are expected to persist in some areas, especially where competition for water is fierce and institutions are weak. The result is a temporal and spatial mosaic of water management systems that presents a unique case for evaluating responses across various temporal and spatial scales and socio-economic conditions.

The two river basins that SAfMA assessed are different pieces of this mosaic (Table 2.1). The Gariep is water-stressed (Falkenmark and Widstrand 1992), with the small mountainous region of Lesotho and South African Drakensberg highlands contributing significantly to the basin’s runoff through a series of ambitious diversions of water to the major South African demand centers. The Zambezi, by contrast, is endowed with a relative abundance of water. The Gariep basin contains one of the greatest concentrations of wealth

Table 2.1. Characteristics of the Gariep and Zambezi basins.

	Area (square kilometers)	Shared by:	Mean Annual Runoff (millions of cubic meters per annum)	Per Capita Water Availability (cubic meters per person per annum)	Human Development Index
Gariep	1,039,266	Botswana, Lesotho, Namibia, South Africa	15,957	1,125	All medium-development nations (rank 111th to 137th).
Zambezi	1,234,000	Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia, Zimbabwe	110,000	>10,000	All low-development nations except Botswana, Namibia, Zimbabwe (rank 124th to 170th).
Source: Watson, *pers. comm.* (Gariep); Snaddon et al. 2000 (Zambezi area, mean annual runoff); Revenga et al. 1998 (Zambezi per capita water availability).					

on the African continent, Gauteng Province (which includes the Johannesburg and Pretoria metropolitan areas), while the eight nations that share the Zambezi are among the poorest in the world. Human well-being as reflected by the human development index (UNDP 2003) is on average higher in the Gariep than the Zambezi. These characteristics are indicative of the enabling conditions and binding constraints for possible responses - the realities on the ground at a given moment that either allow or prohibit people from adopting responses that are sustainable.

Each societal response to the problem of water availability can generally be described as falling into one of three categories: supply augmentation, conservation, and allocation (Molle 2003). Supplies are augmented, for example, by constructing storage dams and reservoirs or diverting water from within or across basin boundaries. Conservation strives for increased efficiency of use of existing water resources. Allocation refers to the redistribution of water from one user or sector to another to alleviate some of the total pressure on water resources. As a consequence of the actual or perceived decreasing abundance of water resources over time, initial responses to water management are typically supply-side strategies (augmentation), followed, if possible, by a shift to demand-side strategies (conservation and allocation).

The development of water resources in the Gariep basin exemplifies the typical progression from supply-side to demand-side responses. By contrast, the Zambezi basin, which has more water and less demand for it, has not undergone the same progression, but still may. Whether a river basin progresses through this trajectory – essentially, how water-related problems are dealt with - depends on what Ohlsson and Turton (2000) call a "turning of the screw" between a first-order scarcity of water and a second-order scarcity of the social resources required to successfully adapt to the first-order scarcity. Within the Gariep basin, first-order scarcity is high, but second-order scarcity is relatively low, due to the management capacity that exists in South Africa, in which most of the basin lies. In the Zambezi, first-order scarcity is low but second-order scarcity is fairly high due to the limited social resources and therefore capacity to employ a range of responses to address water-related problems.

Despite these differences between the Gariep and Zambezi, the responses selected to manage water in these two basins were initially similar, and have only begun to diverge more recently.

The "get more water" era

Until the mid-1900s, the focus of water management in most southern African countries, apart from securing the relatively small amounts needed for municipal and domestic use, was on increasing or stabilizing supplies for irrigation. South Africa's shift in the middle of the last century from an irrigation-centered water policy to one based on a more diversified economy is reflected in its passage of its 1956 Water Act, which repealed its Irrigation and Conservation Act of 1912. While irrigation continues to consume the majority of total available runoff (currently more than 60% in the Gariep basin), in South Africa the contribution of agriculture to GNP is small (less than 5%) relative to the mining, manufacturing, and services sectors.

For the purposes of this paper we unite these two phases into a single era in which "getting more water" (Dent 2000) was of prime concern and was addressed through supply-side responses that tended to favor the agricultural and, later, industrial sectors. In South Africa, this was achieved through a centralized system of management, informed by science that resided largely in state departments, and with laws that put water-related decision-making in the hands of the state and private landowners. Throughout the region, variable and unpredictable river flows were dealt with largely through technical responses, leaving a legacy of imposing structures across the landscape as physical evidence of the prevailing mindset of the time.

In the Gariep basin, the Orange River Development Project (ORDP) commenced in 1962 and included South Africa's two largest dams and a major inter-basin transfer scheme. Built primarily to secure water supplies for the commercial agricultural sector, the power base of South Africa's then-ruling National Party, the ORDP was also intended to strengthen the party's apartheid regime as it faced increasing internal and international resistance. The Lesotho Highlands Water Project (LHWP), a joint undertaking by South Africa and Lesotho to supply water to the former and electricity to the latter, is the most recent of the region's major dam projects. Envisioned when initiated in 1986 to have five dams (second in size only to China's Three Gorges), the LHWP was eventually scaled down considerably at least in part due to the realization that initial water demand forecasts were too high and supplies too low (Klasen 2002). In the Zambezi, the World Bank-backed Kariba dam was completed in 1959 on the border between Zambia (then Northern Rhodesia) and Zimbabwe (then Southern Rhodesia) to supply power to the region's growing copper mines and manufacturing industries after World War II. Construction on the Cahora Bassa dam began in the 1960s; when completed in 1975 it enabled the Portuguese colonial government in Mozambique to produce hydropower for sale to South Africa.

This focus on augmenting water supplies or services such as hydropower succeeded in improving human well-being for some members of society. Improvements in the Gariep included significant economic and social benefits in the form of increased water supply, agricultural production, flood protection, hydropower, and employment (WCD 2000*b*). In the Zambezi, the Kariba dam encouraged tourism to the lake and a significant kapenta fishery, both providing employment. Reliance on coal-fired electricity was alleviated, and the cost of electricity in the area served by the Kariba and Kafue dams decreased by about 30% in the period 1961–1977, even as the average price for other commodities and services rose by more than 75% during the same time (Soils Incorporated 2000).

However, these responses also had several serious negative consequences. These include the social impacts such responses had on communities (especially but not exclusively poor ones), particularly the tens of thousands of individuals who were displaced or resettled to more marginal lands without consultation, and with little or no compensation (Isaacman and Sneddon 2000, Soils Incorporated 2000, Thabane 2000, WCD 2000*b*). This was particularly acute in projects executed under colonial or apartheid regimes due to the social and political acceptability of relocating people as the state saw necessary to achieve project objectives. As such practices had become internationally unpopular by the time the LHWP was built, affected people were compensated for losses, in a process that has begun to bring the realities of some of the social and environmental impacts, typically externalized, of large dam projects to bear on their overall economic viability. Despite these major investments in water resources, the distribution of benefits has remained highly skewed, accruing more to commercial farmers, distant cities and tourists than to the residents in the vicinities of these projects (Soils Incorporated 2000). Where rural people have lacked access to formal water services, they have relied on direct withdrawals from rivers for domestic use and livestock watering, putting undue pressure on rivers and riparian zones (Motteux 2002).

An additional problem with responses aimed at augmenting water supplies in the southern African region, as elsewhere, is that their potential effects on ecosystems were ignored in the planning and implementation processes. This resulted some time later in ecosystem degradation and transformation that reached disastrous proportions in some places. Along the lower Gariep River, a pest blackfly (*Simulium chutteri*) infestation erupted after the flow regime was changed by the ORDP (Chutter et al. 1996), costing the agriculture sector an annual R88 million (equivalent to 14.7 million 1998 US dollars) in livestock productivity losses and another R2 million (330,000 1998 US dollars) in annual control costs (WCD 2000*b*). The potential impacts of the project on water quality were overlooked at the onset despite warnings, causing an unexpected surprise when salinity levels suddenly increased after water began traveling through the Orange-Fish tunnel (Herold 1992). In the Zambezi, the Kariba and Cahora Bassa dams have had deleterious effects on downstream ecosystem services. These include morphological changes in the river and floodplain, disrupted sediment and nutrient flows, widespread encroachment of woody savanna onto the herbaceous floodplain in the Marromeu wetland complex, a 40% loss of mangroves and coastal erosion. Wetlands have been disconnected from the main channel of the Zambezi, disturbing bird and fish habitat, with a 60% reduction in prawn catch rates attributed to the decline in runoff between 1978 and 1995 (Davies et al. 2000).

The planning of large dams during this era was often flawed because of inadequate public participation and inappropriate project timelines. The political expediency of the ORDP's authorization made detailed planning impossible and even cursory impact assessments implausible; yet in fact, the project experienced unanticipated delays and cost three times more than its initial budget – rising from a projected US $571.3 million (in 1998 US dollars) in 1962/3 to US $2313.7 million when completed (WCD 2000*b*). In some projects, the laws and procedures in existence at a project's inception had changed, sometimes radically, by the time of its completion. In the LHWP, an environmental impact assessment for downstream effects was only conducted retroactively after the first dam was in operation (LHDA 2002).

Lastly, the focus on supply augmentation created an illusion of abundant water resources, and obscured the signs that the natural limits of the water supply were being rapidly approached, even as droughts devastated parts of southern Africa during the 1980s and 1990s. In 1995, such a drought led water managers in Gauteng Province to restrict water use unless major rain events occurred during the following summer. The rains came, and restrictions were lifted. By implementing a very localized, short-sighted response, a potential signal to curb water losses was ignored and an opportunity to better manage water demand was lost (Snaddon *et al*. 1998).

Cumulative storage dam capacity in South Africa increased steadily from 1900 to 1975 and then increased sharply between 1975 and 1990 (Figure 2.3), appropriating an ever larger share of the total freshwater supply. Only in the 1990s did growth slow significantly as a result of the saturation of available dam sites, along with the increasing acceptance by water managers that there was little water left to allocate, and that the actual cost-benefit ratios of large dam projects were rarely as low as originally projected.

The "get more water" era was characterized by high-cost, technical responses to problems of water scarcity in the Gariep and the supply of cheap energy in the Zambezi, and had similar effects despite the different characteristics of these river basins. These responses emerged in the age of "control thinking:" everything could be effectively controlled to achieve clearly defined objectives. The world was seen to be a linear, reducible system that could be fully understood, but in fact, awareness was highly limited in that the impacts of these responses on livelihoods and ecosystems were underestimated or simply ignored. Certain individuals recognized these problems, of course, but were unable to motivate the majority to act. Impact, awareness, and power were seldom, if ever, congruent. The result was that the water management responses of the time often created new problems by attempting to solve old ones without contemplating their possible effects across space and time.

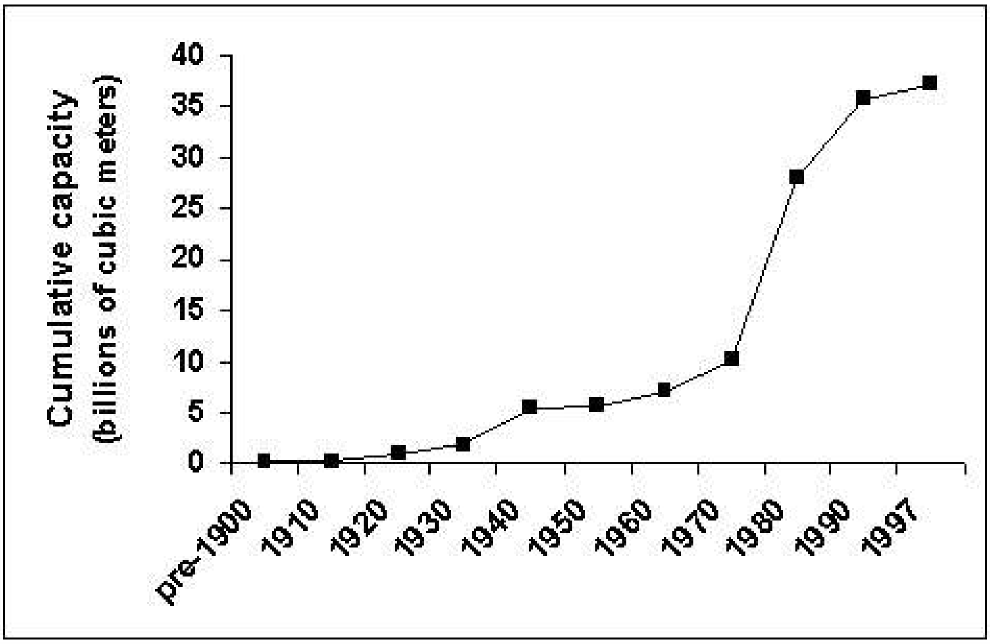

Figure 2.3. Water supply augmentation, illustrated by cumulative storage dam capacity in South Africa from pre-1900 until 1997 (ALCOM 1999).

We should not expect, in a complex system, to fully understand system functioning or to be able to predict system behavior with meaningful certainty. Responses need to be designed that are cognizant of this recognition. We can never have enough data (Johannes 1998), but awareness needs to be distributed across all scales and sectors of the system. In South Africa, the state's control of water-related research effectively obliterated the potential contributions to the collective knowledge base of local communities - often the first to detect a problem because they are closest to it. Communities in the Great Fish River valley of South Africa, for example, have been tacitly monitoring water quality during the past four decades as part of their daily use to determine whether silt levels in runoff from cattle dips are within acceptable limits (Shackleton et al. 2004). With no effective means for transmission of this information upward, however, local knowledge remains in the community and is unable to influence the causal processes operating at higher levels.

The "some, for all, forever" era

In the late 1980s and early 1990s, data became available from South African monitoring programs that revealed the long-term trend of deterioration of water resources and aquatic ecosystems (MacKay 2003). As the limits of the supply augmentation responses of the past were increasingly exposed, the need for a new approach to water allocation became urgent. In 1994, apartheid and minority rule ended in South Africa. The country's transition to democracy presented a unique opportunity to reform its 1956 water policy in order to better reconcile its resources with the needs of its people, environment, and economy. This marked the onset of a new paradigm in the water sector, in which the emphasis of water provision quite rapidly broadened to encompass the needs of society in its entirety and ecosystems. Financing for water management was to be achieved by full cost-recovery from users rather than from government subsidization. Decision-making moved from a technocratic to participatory arena where pertinent issues could be collectively addressed.

The paradigm shift that occurred as a result of democratic elections and the increased awareness of changes in water quality and quantity was marked by a realignment of the impact, awareness, and power scopes. The power and awareness scopes were brought into greater congruence with the impact scope, providing opportunities for developing effective responses.

The transition from the supply augmentation to the allocation phase has been most apparent in South Africa. Its 1998 Water Act, among the world's most progressive, is founded on the principles of equity, sustainability and efficiency – its overarching goal to provide "some, for all, forever" (MacKay 2003). Noting the needs to redress the inequality of access to water created by past discrimination as well as to provide for future generations, the law promotes equity by its definition of water as a basic human right and guarantees provision of 25 liters per day of safe water within 200 meters of the home to all South Africans. It promotes sustainability by protecting aquatic ecosystems through ecological reserve requirements, or environmental flows, and resource protection measures. Efficiency is promoted through licensing and pricing strategies designed to allow water to be allocated to the uses of highest value (DWAF 2002). The water designated for basic human needs and environmental needs define a legally recognized "Reserve" which has the highest allocation priority. Since its passage, equity has clearly improved: in 1998, 12 million people were without any access to formal water services and 21 million lacked sanitation (King and Louw 1998). Currently, these numbers have decreased to about five million and 16 million, respectively, and are steadily dropping (DWAF 2004).

The equity and sustainability issues highlighted in the South African legislation have also surfaced in the Zambezi, where several of the nations that share this basin are currently reforming their water policies or institutions to incorporate principles of environmental and social sustainability (Scholes and Biggs 2004). The deteriorating state of the Zambezi delta and its wetland ecosystems as a result of the changed flood regime from the two major dams and their implications for the livelihoods of delta inhabitants have led Mozambican and international scientists to negotiate for rehabilitation measures (Beilfuss and Davies 1998). The recent declaration of the delta's Marromeu complex as a Ramsar Site (a Wetland of International Importance as defined by the Ramsar Convention on Wetlands) may facilitate the process, though to a large degree the many governments managing this basin lack the institutional mechanisms at present to implement the necessary measures.

New institutions for water management

As water management moved into the allocation phase in South Africa, it became clear that the existing Department of Water Affairs and Forestry (DWAF) and its policies did not support public participation in decision-making. Rather, the new thinking about water management embraces the idea that natural resources are most effectively managed when responsibility is shared with democratic local institutions, which presumably have detailed and key information about the resources and are more easily held accountable to local populations (Ribot 2002).

The South African Water Act of 1998 mandates the establishment of nineteen statutory bodies called catchment management agencies (CMAs) to govern water resources in conjunction with locally-elected boards that represent a wide range of stakeholders (DWAF 2002). Each CMA is responsible for a water management area that corresponds with major catchment boundaries, for which it can license water users and establish charges for different uses of water, the revenues from which will fund the CMA's management activities. The CMA will also be responsible for implementing the appropriate resource protection measures in order to meet the requirements of the ecological reserve. This decentralizes decision-making in the water sector, and while the national agency, DWAF, remains the custodian of South Africa's water resources and oversees its national strategy, the authority to execute the strategy will increasingly lie with the CMAs and local institutions within the catchment.

It is uncertain at this time if the CMAs, which are to be fully functioning in the next five to ten years, will be able to successfully implement the new policies. Few areas within the Gariep basin are expected to have the capacity to carry out their functions in the near term. Of concern is that they are being charged with both the allocation of water and protection of the resource in their catchment, two not necessarily compatible tasks that were never before administered by a single authority (Rogers et al. 2000). In such a situation, more powerful interests within the CMA may be able to bring the impact and power scopes out of congruence, or, by manipulating information, may constrain the awareness of those in the impact scope.

Whether the CMAs will provide a successful mechanism within South Africa’s broader legal environment for contesting water use is also unknown. An independent Water Tribunal can hear and adjudicate appeals against certain decisions concerning water allocation, and further appeals can be made to the High Court, although the Reserve and some resource protection measures cannot be contested once established (MacKay 2003). The Water Act is designed so that in principle, a CMA cannot negatively impact the water resources of another, thus securing the needs of downstream catchments. However, the Water Act only gives CMAs the authority to manage surface and ground water, while activities that occur on land are the jurisdiction of other agencies (MacKay 2003). This may leave room for loopholes in the application of the law, and introduces a further source of incongruence between the impact and power scopes. What may be more likely is that power will revert to the centralized model if the CMAs are unable to carry out their functions successfully.

Regional cooperation

While some functions of water management are being devolved to a finer scale, others are evolving to address problems that pervade large river basins spanning international boundaries. These issues are frequently rooted in the complexities of hydropolitics (Turton 2002), and thus the co-management of international river basins usually requires the establishment of bi- or multi-lateral institutions. Previously, the water security of one nation was often assured by compromising that of another (usually downstream or institutionally weaker) nation. Today, regional river basin management institutions, or river basin organizations (RBO) are increasingly being established on the premise that water insecurity threatens the development capacity and hence political stability of the greater region. Turton (2003) observes that one function of an RBO is to create convergence of ideas around a common security and reduced uncertainty for all member states. This is largely achieved through the sharing of data, a common set of rules, and a formal agreement for conflict resolution - a broadening and sharing of awareness and power to collectively manage common impacts.

Several legal and institutional frameworks support regional cooperation. The SADC Protocol on Shared Water Course Systems, last revised in 2003 and ratified by all of the

Gariep and Zambezi states except Angola, is a legal instrument for achieving the development goals of the water sector. While the protocol requires that joint management mechanisms be established, it does not explicitly suggest how this should be done. Thus, a range of RBOs exists in southern Africa, with each operating under a unique set of rules. In the Gariep basin, the Orange-Senqu River Commission (ORASECOM) established in 2000 by South Africa, Lesotho, Botswana, and Namibia, is intended to provide a forum to discuss technical matters related to the mutually-shared resources of the basin states. It does not, however, take precedence over the national legislation of each country or existing bilateral protocols, and is not yet recognized as an established international water management body by the South African Water Act (DWAF 2002).

The Action Plan for the Environmental Management of the Common Zambezi River System (ZACPLAN) was initiated in 1987 with the support of donor governments, but was stalled when it was taken over in 1995 by SADC's new water sector, after which time confusion regarding ownership of the process delayed project preparation. A new plan, ZACPRO, has since been launched with the aim of achieving development objectives based on secure water supplies, but fundamentally needs to first establish an enabling environment and build capacity to execute the plan (Granit 2000), which is apt to further delay any real action. Despite years of discussion and meetings, the emphasis on cooperation of agencies managing the Zambezi River has had little apparent effect, even as many warnings of the ecological and social consequences of dam construction that were ignored over the past decades have now come to fruition (Davies et al. 2000).

The barriers faced by RBOs are in some ways similar to those the CMAs may confront. First, power among stakeholders is likely to be asymmetrical, due to the great diversity of socioeconomic characteristics and management systems among basin states. States with weak economies and limited capacities to manage water usually have less bargaining power. In addition, there is no guarantee of adherence to principles of SADC treaties that are not embedded in national laws (SARDC 2001). The latter are likely to differ, sometimes irreconcilably, between members. In these cases a mechanism for the impact scope to influence the power scope is absent and the power of the regional institutions is constrained.

The degree to which regional cooperation succeeds may depend on the extent to which a paradigm shift similar to that witnessed in South Africa emerges in the larger southern African region. The negative impacts of Kariba and Cahora Bassa dams on the delivery of ecosystem services predicted decades ago may eventually motivate a management change in the Zambezi basin that encompasses multiple objectives and stakeholders. What seems clear is that a sustainable course of water management in southern Africa will need to evolve against a backdrop of increasing regional integration. Water resources could potentially serve as an integrating link, through concepts such as “virtual water.” In this model, water-intensive commodities such as grain (approximately 1000 cubic meters of water are required to produce one ton of grain) are produced by countries with low water stress, such as Zambia or Angola, for export to a water-scarce country such as South Africa or Namibia, freeing it to allocate its water resources to higher-efficiency uses. Virtual water trade has significant economic benefits for the importer, as seen in other areas of the world where it occurs (Allan 2002). This model is not yet viable for southern Africa as a region, however, due to many countries’ current lack of technical capacity and political stability and their reluctance to relinquish self-sufficiency and national security to a regional body. The idea of regional cooperation should be to foster a collective security while simultaneously giving each member state sufficient flexibility in determining its goals and how to achieve them, thus preserving the variability, and hence resilience, of the regional water mosaic. This highlights the need for certain elements of regional management to be agreed upon at a regional scale but others to be tailored to unique conditions at as local a scale as appropriate and possible.

As lessons learned from other systems reveal, crises in social-ecological systems often occur at the intersection of large-scale processes and changing local variability, as local problems cascade up to higher levels (Gunderson et al. 2002). This is why institutions at different scales such as those we describe here need to communicate and exchange information with one another, especially as southern African people and institutions find themselves responding increasingly to novel regional changes in climate, global markets, and political initiatives, but which affect them locally. Information needs to flow not only from the top to the bottom, but also in the reverse direction. The monitoring routinely done by communities can provide important early-warning data, but the exchange of information between local and higher-level institutions cannot happen if they operate independently as they have traditionally done. The institutional arrangements that are apt to produce the most effective responses may entail multi-subsidiarity, whereby local organizations, CMAs, RBOs, and national ministries collectively work towards a common end.

Integrated responses

Increasingly, the sectoral approach to natural resources management of the past is being replaced by the adoption of responses that are integrated across ecosystem service sectors. Integrated Water Resources Management (IWRM) is an internationally recognized framework in which policies and practices address the linkages between water, land, and environmental resources though the hydrological cycle (DWAF 2002).

One of the most notable integrated responses in the region is the Working for Water Programme in South Africa, a multi-agency intervention to combat the spread of invasive alien plants, which consume approximately 3300 million cubic meters (seven percent) of the country's total mean annual runoff and are expected to become an increasing threat in the future (Le Maitre et al. 2000). By hiring previously unemployed individuals to clear and eradicate invasive alien plants, Working for Water addresses the multiple objectives of water conservation, ecosystem rehabilitation, and poverty relief through job creation and the development of secondary industries from products made from the cleared alien species. Through its high visibility and public campaigns, the program has raised awareness about alien plants and water conservation among its employees, their communities, and a broad spectrum of society, and has stimulated research on invasive alien plants in the scientific and engineering communities (Görgens and van Wilgen 2004).

The Working for Water program had an initial budget of R25 million in 1995/6, which increased to R442 million in 2003/4 due to the program's success over the years (Marais et al. 2004). It is currently funded through special poverty relief funds, but eventually these costs are to be recovered from the water resources management charges imposed on users as specified by the Water Act. By the end of 2003, the clearing of almost 1.2 million hectares of alien vegetation by the 24,000 people employed by the program was estimated to yield water benefits of between 50-130 million cubic meters a year (Görgens and van Wilgen 2004). Several cost-benefit analyses in South Africa suggest that clearing is a cost-effective approach to eradicating invasive alien plants in terms of water resources (Görgens and van Wilgen 2004), though costs tend to be overestimated and benefits underestimated and highly discounted because they often emerge only in the long term (Turpie 2004).

The Working for Water program is probably the best example of an effective response according to our framework: it empowers and increases the awareness of the impacted population. It also fits our original definition of "effective": the program's mechanisms for maintaining social and ecological resilience are mutually reinforcing, because a synergy is created between social development (job creation/poverty relief) and preservation of ecological integrity (alien eradication, restoration of hydrological flows, and improved production potential of land). By freeing water resources for other uses, the initiative also has the potential to yield significant economic benefits over the longer term.

DISCUSSION

The congruence of impacts, awareness, and power is at the heart of the "some, for all, forever" concept. This concept is realized through an awareness based on widely-distributed (cross-sectoral and cross-scale) information, power decentralization and cooperation through the development of new institutions, and effective mechanisms for influencing power at different scales. While our framework suggests that this is indeed the situation most conducive to developing effective responses, our application of the framework to water management in southern Africa reveals several caveats.

First, ecological, economic, and even social processes (which relate to impact) rarely conform to administrative structures or scales (which relate to power). Some southern African experiments in distributing power, such as Community Based Natural Resource Management (CBNRM), have failed when power is maintained at specific scales (Fabricius et al. 2001). Cross-scale and cross-sectoral institutional interactions come with high transaction costs – line ministries and managers are accountable to their ministers and agencies first; cooperation is an afterthought. We have noted that the new water management institutions may encounter similar problems.

Second, in some instances, responses of previous eras severely constrain the response options available for the current era. The hydrological flow regime created by the Cahora Bassa dam over the past few decades has been one of controlled and constant low-level flows. Gone are the huge floods of the past. One consequence of this has been that people have moved into areas of the Zambezi Delta floodplain that formerly would have only been safe for temporary house construction or limited agricultural development. Recent attempts to restore a more natural flood regime for the Zambezi (Beilfuss and Davies 1998) are constrained by the developments on the floodplain which would require expensive movements of people and infrastructure and could even result in loss of life. In the Gariep basin, operating costs of infrastructure built by previous governments deplete funds that could have been invested in demand-side initiatives and basic service provision. The list of foregone opportunities is long.

Third, a distribution of power does not necessarily mean a distribution of awareness, although we suspect the latter would follow from the former. Awareness, in a multi-scaled system created through power devolution, means a distributed capacity to learn as well as mechanisms to transfer lessons, knowledge, or information across scales. The development of these mechanisms is likely to lag significantly behind power transfers, which tend to follow political time scales. Consequently, responses made in the initial period after a redistribution of power may yield a great range of results, from the great successes to the abysmal failures. What is most worrying about this is the high turnover in human expertise that now characterizes southern African management agencies. A continued loss of expertise from these agencies, which are a major repository of social memory, could mean long periods of ineffective responses and possibly considerable pressure to revert to centralized controls as a consequence – in a decentralization backlash (Ribot 2002).

We thus note a limitation in the application of our framework to complex systems in the real world: it can be extremely difficult to achieve congruence between impact, awareness, and power, because it goes against the grain of social-ecological system design. The scales at which impact, awareness, and power operate are mismatched in space and time. Bearing this in mind, however, the framework points to several features of responses that are likely to increase their effectiveness if incorporated into their design.

Designing effective responses

Our analysis suggests that effective responses in complex adaptive systems are characterized by the following factors:

1. Congruence between scopes of impacts, awareness, and power. We acknowledge that this may be difficult and is beyond people's control in many situations. In cases where people cannot affect the indirect drivers of an impact, they may still be able to adopt proactive response options. For example, local livelihood diversification is a coping strategy to deal with uncertainty (Shackleton et al. 2004). At national scales, governments often cannot affect drivers of global processes like climate change; however, they can be proactive by preparing for uncertainty and managing ecosystem services with the possible range of extreme conditions in mind. Often, a response is both a consequence of responses that came before and a driver of responses that will come after. When and where congruence already exists, it

needs to be maintained through the continued implementation of effective responses. New responses must try to establish the best conditions for future responses to take shape.

2. Distribution of impacts, awareness, and power across locations in space and time that are most resilient to negative change, or most in need of positive change. Different social groups or ecological groups or locations are differentially vulnerable to change. The most effective responses will be those that differentiate between these groups, or where this cannot be done, provide different response options for them. Suggested flow regime changes for the Zambezi River downstream of Cahora Bassa dam, for example, seek to do this with releases from the dam geared to continued hydro-electricity generation as well as the maintenance of downstream ecosystem services on which local livelihoods are dependent. Awareness, too, needs to be effectively distributed, by feeding cross-sectoral and cross-scale information and knowledge into decision-making processes.

3. Expansion of response options at and across all scales. The ability to respond meaningfully to change is greatly enhanced if we have a large set of responses to choose from. Effective responses may be generated more successfully by expanding people's response options rather than direct interventions. If we accept that we can never know enough about any complex system to fully control it, then the wisest course of action may be to let the impacted themselves make choices from the widest possible set of options. The process of involving a wide range of stakeholders in the ecological reserve determinations as suggested by the South African Water Act is an example of how this can be done.

4. Enhanced or stabilized social memory. One of the gravest problems of management and policy in southern Africa is the constant loss of human capital from the agencies most intimately involved in implementing responses. Long-term experts are lost to the private sector, to international non-governmental organisations, and to distant continents. Local ecological knowledge is lost as rural people move to cities and become disconnected from the cultures in which the knowledge is embedded. Moving with many of these people are their experiences in response experimentation; key bits of social memory. There does not seem to be a simple solution to this problem other than to create stronger incentives for them to stay. Orderly documentation of their experiences does not always seem to work. Loss of documents and records or the inability to accept recommendations because of a lack of experience means that important lessons that should have been learnt are sometimes not. This may be an area

that requires special research attention: how do we maintain social memory in the face of very fluid human capital?

CONCLUSIONS

What factors characterize effective responses in complex adaptive systems? We have defined "effective" responses as those that maintain a complex system's social and ecological resilience, or its ability to withstand change. Drawing on the experience of SAfMA, we crafted a simple framework to evaluate responses consisting of three components: impact, awareness, and power. We have suggested that effective responses are those in which the scopes of impact, awareness, and power are congruent; impact, awareness and power are distributed across the system; broad response options are available; and social memory is preserved. In applying this framework to a range of responses for managing water in southern Africa, we observed that it may be extremely difficult to achieve or maintain congruence.

Responses are adaptive reflections of prevailing social, economic, political, and ecological conditions. This explains in part the SAfMA team's difficulty in assessing and extracting meaningful lessons from the responses of the past. Responses are constructed and implemented in specific contexts. When these contexts change, as they invariably do, we should expect responses to change, too, possibly rendering the responses that are effective now useless in the future. No two situations are ever the same and we should therefore be surprised if they elicit the same responses. A government's response to the construction of a major dam when it approaches an election may be entirely different than it would be when it has a major drought on its hands. Not only are responses and their contexts dynamic; the particular lens through which we view and evaluate the world is dynamic because of changing social objectives. Responses in the era of "get more water" were consistent with a defined set of social objectives. This set has now been swept offstage and replaced with an updated version.

By examining the two different trajectories of the Gariep and Zambezi with our framework, we can apply our learning about responses from one to the other, though with an understanding that water management is operating within a different context now than it was during the early development phases of these basins. Water is increasingly being seen in southern Africa as a regional resource, presenting opportunities for a redefinition of impact, awareness, and power scopes. As the region becomes more interconnected through its water resources, opportunities for learning are expanded.

Responses to changing relationships between ecosystem services and human well-being require constant adjustment and adaptation. We adapt our responses to the prevailing circumstances and add the experience to our memory. We learn. Responses to changes in complex adaptive systems are complex adaptive systems themselves. Given that we cannot predict what a complex system will do, we are unlikely to be able to design responses that will steer the system to where we want it to be. At best, effective responses should provide incentives for a complex system to remain within desirable configurations.

The framework provides a useful tool for exploring the problem of responding in complex systems and could be used in other applications beyond those discussed here. While we looked "backward" in this paper by evaluating the historical trajectory of water management responses in southern Africa, our evaluation would be likely to benefit from further development in conjunction with scenario analysis. Scenarios provide a wind tunnel for envisioning alternative future worlds, and can help people to identify the response options that are most likely to be robust (i.e. enhance resilience) in different futures that may unfold.

Acknowledgements

We thank the Gariep Basin and Gorongosa-Marromeu User Advisory Groups for providing data and insights for the assessments. Members of SAfMA, particularly R. Biggs, contributed ideas for this paper, an early version of which was presented at "Bridging Scales and Epistemologies: Linking Local Knowledge with Global Science in Multi-Scale Assessments," in Alexandria, Egypt in March 2004. D. Biggs and J. Jones read the manuscript and made helpful suggestions. Funding for SAfMA was provided by the Millennium Ecosystem Assessment through a grant from the government of Norway, administered by United Nations Environment Programme.

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Future ecosystem services in a Southern African river basin: A scenario planning approach to uncertainty

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Keywords: conservation decision making, ecological processes, ecosystem services, Millennium Ecosystem Assessment, possible futures, social processes

In press: *Conservation Biology*

Abstract

Scenario planning is a promising tool for dealing with uncertainty surrounding the future but has been underutilized in ecology and conservation. The use of scenarios to explore ecological dynamics of alternative futures has been given a major boost by the recently completed Millennium Ecosystem Assessment, a 4-year initiative to investigate relationships between ecosystem services and human well-being at multiple scales. Scenarios, as descriptive narratives of pathways to the future, are a mechanism for improving the understanding and management of ecological and social processes by scientists and decision makers with greater flexibility than conventional techniques afford. We used scenarios in one of the Millennium Ecosystem Assessment's subglobal components to explore four possible futures in a Southern African river basin. Because of its ability to capture spatial and temporal dynamics, the scenario exercise revealed key trade-offs in ecosystem services in space and time, and the importance of a multiple-scale scenario design. At subglobal scales, scenarios are a powerful vehicle for communication and engagement of decision makers, especially when designed to identify responses to specific problems. Scenario planning has the potential to be a critical ingredient in conservation, as calls are increasingly made for the field to help define and achieve sustainable visions of the future.

Introduction

The future is inherently laden with uncertainty and surprise. In many cases, science and technology have reduced fundamental uncertainties about how the world works, vastly improving our ability to anticipate change, but the elusiveness and unpredictability of numerous aspects of the future remain. This makes the practice of conservation a challenging prospect, and despite our best efforts, all the data, information, and technology we have are unlikely to save us from some unpleasant surprises (McDaniel et al. 2003). There is a need to better embrace the future's uncertainty and to develop mechanisms to elucidate aspects that are difficult to contemplate. This uncertainty is also likely to require a different approach to conservation, taking it beyond its roots in crisis and an "atmosphere of loss and blame" (Redford & Sanjayan 2003) to an expanded view of humans and nature as coupled, coevolved components of social-ecological systems (Westley et al. 2002). Ultimately, we must recognize that we will never know "all" and must therefore design approaches to conservation that are robust under a wide range of possible outcomes.

Fortunately, the focus of scientific assessment is beginning to expand beyond the gathering, analyzing, and synthesizing of information to helping decision makers deal with and respond to uncertainty (Salzman 2005). This shift does not obviate the need for further specific scientific knowledge, rather it recognizes that stocktaking efforts need to ask both scientists and decision makers to identify key system processes, drivers, and interactions that are most likely to result in surprise. It is in this spirit that scenarios, as narratives that describe alternative pathways to the future, offer a promising collaborative approach for building resilience to the future's unpredictability. The recently completed Millennium Ecosystem Assessment (MA 2003) provided an unprecedented opportunity to develop scenarios of future ecosystem services and their relationships to human well-being at global, regional, and local scales. In this paper we discuss the experience, findings, and lessons learned from a scenario analysis of a multi-national river basin that formed part of the subglobal Southern African Millennium Ecosystem Assessment (Biggs et al. 2004). We suggest that scenarios deserve more prominence in scientific efforts to understand and manage uncertainty in ecological and conservation decision making.

Scenarios in the Millennium Ecosystem Assessment

The Millennium Ecosystem Assessment was a 4-year program launched in 2001 to meet the needs of decision makers for scientific information about the relationships between ecosystem change and human well-being (MA 2003). In addition to a global analysis, it included 33 subglobal assessments, ranging in size from village to sub-continent, to provide a more detailed picture of ecosystem services and human well-being, build capacity to conduct ecosystem assessments, and strengthen user involvement across the globe. Guided by a user-driven process, it sought to engage ecosystem users and managers and to incorporate their knowledge and perceptions into the assessment. The global assessment served three international environmental conventions, national governments, and the private sector, whereas subglobal assessments addressed the concerns of specific user advisory groups.

Scenarios formed a major component of the Millennium Assessment's work. We define *scenarios* as a set of plausible narratives that depict alternative pathways to the future. Scenario planning is the creation and use of such scenarios in a structured way to stimulate thinking and evaluate assumptions about future events or trends, and to make uncertainties about these explicit. It is important to make a distinction between scenarios in this sense and projections, forecasts, and predictions, all of which relate more to the probability than possibility of future outcomes (Peterson et al. 2003). Projections and forecasts – which typically place an estimate on the likelihood of an event's occurrence – work best for short-term forecasting in well-understood systems (Bennett et al. 2003). This is an appropriate way to deal with uncertainty when the objective is risk management, which requires at least an intuitive probability to be placed on the occurrence of a rare event, such as a space shuttle accident (Seife 2003). Ecosystem services and human well-being, on the other hand, are part of social-ecological systems, in which unexpected outcomes are common (Gunderson & Holling 2002).

Scenario planning is most useful for dealing with uncertainty when we lack sufficient information about the probabilities that different events will occur. In the business world, scenarios helped Royal Dutch/Shell to navigate unpredictable market shocks in the 1970s and 1980s by envisioning and preparing for a future that no one thought would happen (Wack 1985*a*; 1985*b*). Scenario planning also offers a platform for engaging stakeholders with divergent viewpoints and competing objectives, and has succeeded in smoothing potentially contentious situations, such as South Africa's transition to democracy in the early 1990s (Kahane 1992). Although the virtues of scenario planning have long been appreciated in business and other fields, it has not been used widely in ecology or conservation (Peterson et al. 2003). Scenarios with an environmental dimension exist, but these generally have several limitations. Most tend to focus on the impacts of drivers on the environment (European Commission 1999; UNEP 2002) or biodiversity (Sala et al. 2000; Bombard et al. 2005), and do not incorporate ecological feedbacks or human responses. In addition, existing environmental scenarios have usually ignored cross-scale processes – interactions between global climate, national policies, and local population dynamics, for example. Major ecological problems in recent times have resulted from misunderstanding how these processes work (Wilson et al. 1999; Gunderson et al. 2002), making a third common shortcoming of scenario exercises especially pertinent: they often exclude regional and local decision makers, despite recent advances in participatory scenario planning methodology (Wollenberg et al. 2000; Waltner-Toews & Kay 2005).

The Millennium Assessment took scenario planning to a new level. A Scenarios Working Group, comprised of ecologists, economists, and social scientists representing academia, research institutes, non-governmental organizations, businesses, and indigenous groups from around the world developed participatory, policy-relevant global scenarios to describe the evolution of ecosystem services, human well-being, and their interactions over the next century. In a departure from previous efforts, they focused specifically on the ways in which decisions may drive future ecosystem change, ecosystem change may constrain future decisions, and ecological feedbacks may lead to surprise (MA 2005). A second defining feature was the multiple-scale nature of the effort, with subglobal scenarios developed concurrently by regional and local assessment teams.

The global scenario analysis entailed a review of existing scenarios, interviews of decision-makers, visionaries, and other leaders about their key concerns and hopes for the future, and identification of the major ecological management dilemmas that the scenarios could address (Bennett et al. 2005). The Scenarios Working Group ultimately chose to develop new scenarios that would be consistent with assumptions about ecosystem resilience, unlike most existing scenarios (Cumming et al. 2005). Four scenarios, focused on uncertainties related to the extent of globalization or regionalism, and a proactive or reactive approach to environmental problems, evolved from this process. Global Orchestration depicts a globalized and reactive world, driven by a desire to bring the world's poor out of poverty as quickly as possible. In Order from Strength, the world is regionalized, reactive, and driven by a desire for security. Adapting Mosaic is characterized by a regionalized but proactive society, and increasingly relies on local institutions and learning to improve ecosystem management. TechnoGarden describes a globalized, proactive world, driven by a pursuit of eco-technologies (MA 2005).

At the subglobal scale, each assessment team was free to develop any number of scenarios thought to be plausible in the medium term. This resulted in multiple scenario sets for the subglobal assessments, some related to the global scenarios and some completely different (Lebel et al. 2005). Typically created in a participatory fashion, subglobal scenarios were driven by specific assessment issues, world views, and the role of the user group in the assessment process. A distinguishing feature of some subglobal scenario exercises was their use of creative forms of expression such as dramatic performance, often more effective than conventional methods for conveying complex issues to stakeholders (Burt & Copteros 2004).

Building Southern African Scenarios: the Gariep Basin Experience

The Gariep River basin

The Gariep River basin (665,000 km^2), which we define as the area of South Africa and Lesotho drained by the Senqu-Gariep-Vaal river system, contains one of the greatest concentrations of wealth on the African continent, Gauteng Province (the Johannesburg-Pretoria metropolitan area). The basin is a region in transition, owing in large part to South Africa's shift to democratic governance in 1994. This political change was a catalyst for accelerating economic growth, redressing inequitable access to resources under the former Apartheid regime, promoting human well-being, and passing progressive legislation on biodiversity, the environment, and water. Current policy trends in the region such as decentralization, multinational resource management, and the establishment of pan-African initiatives such as the New Partnership for Africa's Development all have far-reaching implications for ecosystem services.

The Gariep is the most modified river basin in Southern Africa, with massive undertakings such as the Lesotho Highlands Water Project, the largest transfer scheme in African history, impounding and diverting water to serve the Gariep River's competing uses: irrigation of its agricultural heartland, urban and industrial demands, and people and ecosystems. The basin encompasses South Africa's major cereal production area, the bulk of its mining and coal industries, and two international biodiversity hotspots (Succulent Karoo and Maputaland-Pondoland-Albany). The Gariep basin is home to nearly 40% of the South African population and all of Lesotho's, who range from destitute rural communities that are tightly bound to ecosystem services to highly developed industrialized societies.

The Gariep basin assessment was conducted by a team of scientists with guidance from a user advisory group, consisting of policy makers from agriculture, water, tourism, and conservation departments of national and provincial government, and researchers working on environmental or conservation policy issues. The team and group met five times over two years, initially to discuss the assessment objectives, design, and expected outcomes, and proceeding to tackle increasingly complex issues of trade-offs, scenarios, and interventions. Between workshops, the assessment team undertook more extensive analysis of the focal issues identified with the group, with whom it communicated regularly.

The initial assessment task was to identify major ecosystem services in the Gariep basin and threats to their continued delivery. The group identified food production, water, and energy from various sources as provisioning services - products obtained from ecosystems - and biodiversity as an essential source of many other services (MA 2003). In a departure from the global Millennium Assessment, the user group argued for the inclusion of mineral services due to their importance as a natural resource in the economy and livelihoods of the Gariep basin. The group cited land-use practices – notably urbanization, industrial and mining developments, agriculture, and forestry – and abstraction and diversion of water resources as the major threats to ecosystem services in the basin (Bohensky et al. 2004). Paradoxically, most of these threatening practices have intended to secure ecosystem services and human well-being, but within the context of a narrow, sectoral approach to natural resource management. Group members cited numerous cases of ecological surprise; for example, massive dams built in the 1960s and 70s to stabilize the Gariep River's flow regime enabled a pest blackfly (*Simulium chutteri*) to proliferate and affect livestock operations along the river, imposing severe costs on the precise industry intended to benefit from the dams (Myburgh & Nevill 2003).

Scenarios were intended to explore possible futures for ecosystem services and human well-being in the basin during the years 2000 to 2030. The user advisory group indicated that the major uncertainties associated with the future of the basin's ecosystems and human well-being are the strength of national governance and civil society. Because these uncertainties resemble those of four well-known global scenario archetypes (Gallopín et al. 1997), we decided to test the applicability of these archetypes to the Gariep basin, retaining some elements while adapting others to the finer scale of analysis. The initial scenarios were developed by the assessment team and refined in follow-up workshops with the group. To better understand regional dynamics, we also interacted with a team developing two scenarios for the broader Southern African region (Scholes & Biggs 2004).

The four global scenarios are based on clusters of driving forces such as economic and geopolitical forces and social issues: Market Forces and Policy Reform both see a continuation of current trends, but the former is driven by economic growth and the latter by social and environmental sustainability. Fortress World and Breakdown (also called Local Resources) describe a world driven by a global economy, but in the former there is an increasing preoccupation with national security and in the latter a reliance on local institutions. In our interpretation for the Gariep basin, Market Forces becomes a situation where national governance and the economy are strong, but civil society plays a minor role. Fortress World is a scenario about a collapse of national governance structures, a faltering economy, and a fragmented civil society. In Local Resources, a strong, self-reliant civil society emerges at local levels in the absence of strong national governance. Policy Reform describes a strong, globally-linked economy within a sound governance framework, balanced by an active civil society (Bohensky et al. 2004). Adapting these global scenario archetypes to the circumstances in the basin had two major advantages: it increased the validity of the scenarios in the eyes of the users, and enabled a comparison of similarities and differences between scenarios at the two scales.

In addition to the two main uncertainties, we identified bifurcations of drivers that we believed would distinguish the four scenarios in the Gariep basin (Table 3.1): (1) national economic growth, (2) wealth distribution, (3) national social and environmental (including climate) policy, (4) management of HIV/AIDS, (5) birth rate, (6) mortality rate, and (7) urbanization. The user group acknowledged the significance of HIV/AIDS and climate change in future ecosystem services and human well-being in the Gariep basin. To keep the number of uncertainties manageable, however, we chose to focus only on differences in the management of these issues under the different scenarios and did not consider different HIV/AIDS and climate projections. We assumed for all scenarios that the current high HIV/AIDS prevalence rate in South Africa, among the highest in the world (UNAIDS/WHO 2004), will continue to decrease human capital, divert government resources, and increase dependency burdens (Goldblatt et al. 2002). We assumed for all scenarios that between 1990 and 2050, climate change will raise temperatures by as much as 2°C (IPCC 2001), and will decrease runoff in South Africa by up to 10%, moving progressively from west to east (DWAF 2004). This is likely to threaten water availability, food production, and biodiversity in the more arid parts of the basin, although certain crops and species may thrive in other parts (van Jaarsveld & Chown 2001).

Table 3.1. Key bifurcations in drivers of change that distinguish four scenarios of future ecosystem services and human well-being (adapted from Bohensky et al. 2004).

Driver	Market Forces[a]	Policy Reform	Fortress World	Local Resources
Political, economic, and social environment				
National governance Structures	+	++	-	-
Civil society	-	+	-	+
National economic growth	++	+	-	-
Distribution of wealth	-	+	-	-
National social and environmental policy	-	+	-	-
HIV Management	+	++	-	-
Demographic trends				
Birth rate	Medium	Low	High	High
Mortality rate	Medium	Low	High	High
Urbanization	Increasing	Increasing	Increasing	Constant

[1] *Symbols: ++, Exceptionally strong; +, Strong; -, Weak or non-existent*

We expected the scenarios to manifest differently within the basin, and therefore defined four zones based on biophysical and socioeconomic characteristics: (1) urban areas, notably Gauteng Province, which depend to a large degree on ecosystem services from other regions; (2) the "Grain Basket," the agriculturally productive grasslands and water-rich highlands; (3) the densely populated, largely rural, and poor Great Fish River; and (4) the "Arid West," a low-rainfall, sparsely populated, mostly rural expanse of land where many mining operations are concentrated.

We experimented with several approaches to describe the implications of the scenario bifurcations for ecosystem services. We first used an integrated dynamic systems model (Erasmus & van Jaarsveld 2002) to generate results, but the user group felt the model – which they had no part in creating - was too complex to elucidate important relationships. We then tried an interactive approach, and asked users to draw arrows to indicate direction and magnitude of change in ecosystem services and human well-being under each scenario relative to current condition. Users struggled to reach agreement, arguing that in attempting to summarize change we were oversimplifying it. Users appreciated the division of the basin into zones, but noted important fine-scale differences within zones – for example, food production in South Africa's Grain Basket is significantly more commercialized than in Lesotho's. Essentially, the users' dissatisfaction lay in the inability of these methods and categorizations to tell the whole story. Users were much more accepting of short narratives of change which had greater flexibility to capture important differences. Later, we used spider diagrams to illustrate trends in these narratives.

Below we summarize the scenario storylines that resulted from our initial translation of the global scenarios, the scenario workshops, and subsequent consultation with members of the user advisory group. For each scenario, key drivers are identified, followed by a description of their consequences for five ecosystem service categories: biodiversity, energy, food, freshwater, and mineral services (Bohensky et al. 2004). We explore these dynamics in the four regions of the basin defined above, and consider how they may differ in Lesotho. We also describe conservation attitudes, opportunities, and constrains in these alternative futures.

Market Forces

Gauteng continues to expand as the commercial and industrial heartland of the basin. Average income rises, but so do income disparities between rich and poor. The urban poor benefit marginally from the trickle-down effects of a growing economy. As rural living conditions deteriorate, the rural poor flock to the rapidly expanding periurban areas to find employment.

Mining activities expand wherever possible, and agricultural land in Gauteng is rapidly converted to urban or industrial use. Unregulated coal power generation and increased industrial effluent cause water and air pollution and lead to a higher prevalence of water-borne diseases in poor urban populations. South Africa's entry into free trade agreements pushes agricultural production toward exports, such as grapes and citrus along the Gariep River. While food production increases in some regions, the lack of a clear policy framework for climate change decreases household food security for subsistence farmers and the rural poor. Farming on increasingly marginal lands promotes soil erosion. Water is increasingly impounded and diverted for use by cities, industry, and commercial irrigation.

Societal values largely favor development over conservation, and poor enforcement of environmental legislation negatively affects biodiversity, though conservation does benefit in some places from private investment. In Lesotho, siltation that results from the large dams ignites conflict between farmers who are affected and industries that champion economic growth. Those with an interest in preserving the region's threatened species form an unexpected alliance with the affected farmers to demand compensation for lost ecosystem services.

Policy Reform

Amid socially and environmentally sound governance and regional peace and security, the region sustains high foreign investment. A fair trade environment promotes its global competitiveness, and a vibrant technology sector supports improvements in infrastructure, health, education, and service delivery.

However, some of the new policies have mixed consequences for ecosystem services. Increased trade encourages intensified agricultural practices and the rapid adoption of genetically modified organisms, pesticides, irrigation technology, and fertilizers, but also creates access to organic farming markets. Increased wealth drives the agricultural sector towards intensive livestock production, with a positive conservation spin-off: game farming operations expand in the basin, and are far more compatible with protected areas than the livestock farms they replace. Reduced pressure for land means a favorable outlook for conservation in general. Biodiversity conservation and environmental education are high on the agenda of policy makers. People recognize that climate change is causing more frequent droughts and floods that affect a range of ecosystem services that they value. Water withdrawals and treatment costs increase with economic growth, but the establishment of catchment management agencies and market instruments ensure accountability for water use. Policies on environmental flows and freshwater biodiversity become models for other regions to follow. Coal still dominates the energy sector, but a growing proportion of the basin's urban and wealthy populations power their households with renewable sources – solar power projects flourish in the Arid West.

Lesotho becomes an attractive ecotourism destination, owing in part to a successful marketing campaign for the Drakensberg-Maloti Transfrontier Conservation Area and the rise of prolific community-run lodges. Yet the rapid influx of tourists challenges the capacity of park managers, while some local residents feel that they do not benefit from these initiatives.

Fortress World

The Gariep basin becomes visibly divided: The wealthy live in security enclaves and rely on imports, while the poor become increasingly impoverished. Lack of access to water, land, and mining rights ignites local tension and conflict across the basin, allowing corporations and the political elite to take advantage of the unregulated and chaotic environment.

The ability of the rural poor to survive in a variable and arid climate is compromised, and many seek employment in cities, where competition for limited jobs is fierce. Others resort to poaching and harvesting of resources in reserves, where cash-strapped conservation departments are unable to enforce legislation, and the region's tourism appeal rapidly plummets. Reduced industrial activity and pollution retards degradation of ecosystem services somewhat, but most gains are offset by government failures to extend electricity and water services to people forcing them to exploit the limited biofuels and water supplies within their reach.

South Africa defaults on its royalty payments for the Lesotho Highlands Water Project, eroding the financial and energy benefits once provided to Lesotho. Water supplies in Gauteng and beyond become highly stressed. Reductions of water and sediment inflow to the Orange River Mouth Wetland, a Ramsar Site and Important Bird Area, cause declines in its migratory bird populations, raising concerns among conservationists and hinting at other ecological changes that have not been monitored. This seems to draw little attention from politicians, however, who seem to believe that environmental problems will somehow dissipate on their own.

Local Resources

Despite ineffective national governance, corruption, and economic mismanagement, strong civil society networks form across the basin and encourage local infrastructure development, with community-driven service provision. The rural population, growing steadily and faced with a declining resource base for subsistence farming, becomes increasingly self-reliant.

The remnants of commercial agricultural are sufficient to feed the urban markets but are expanded onto increasingly marginal lands, exacerbating soil erosion. Agricultural diversity provides some resistance to pest outbreaks though crop failures are common, as droughts occur more frequently due to climate change. Local conservation initiatives spring up in places, and garner the support of international NGOs. With a few exceptions, most local authorities are unable to make the promises of the free basic water and electricity programs a reality. Rainwater harvesting becomes common in many areas, new wells are dug, and community woodlots supply household energy needs. However, national environmental standards are poorly enforced, allowing waste products to be dumped on poor communities across the basin. Water quality deteriorates, sewage is untreated, and mortalities from water-borne disease rise.

Lesotho, in an effort to decrease its economic dependence on South Africa, secures international assistance to increase its agricultural productivity. In a botanical reserve created as part of the Lesotho water project, a local team of biologists discovers an endemic plant with high pharmaceutical value. Residents lobby for more formal conservation of this biome, as well as stronger legislation to protect intellectual property rights.

Key Findings

The expected direction and magnitude of change in ecosystem services in each scenario and region are depicted with spider diagrams (Fig. 1a-b). Change is described as a sharp increase (+2), a slight increase (+1), no change (0), a slight decrease (-1), or a sharp decrease (-2) in the availability of ecosystem services. We make a distinction between provisioning services, such as food, in which an increase signifies higher levels of service production, and regulating and supporting services, such as biodiversity, in which an increase means an improvement in the condition of the service. Freshwater provides both types of services, but we focused on its regulating services in line with the expanded definition of water resources under the South African Water Act of 1998 (Mackay 2003).

The scenario analysis highlighted several key findings of significance to the assessment, which we discuss below. One is that trade-offs of several types are ubiquitous in all scenarios and regions. A second is that some, but not all, findings converge with those of the global scenarios, underscoring the importance of a multiple-scale design.

Trade-offs

Trade-offs, as well as synergies, between ecosystem services and biodiversity are a major conservation concern. The maintenance of some services, such as nature-based tourism, medicinal plants, and crop pollination, has a clear link to biodiversity, and provides a strong economic argument for conservation (Ricketts 2004). Biodiversity also has fundamental link to human well-being in that it enables people, especially the rural poor, to maintain diverse livelihoods based on ecosystem services (Tengö & Belfrage 2004). However, the relationship between biodiversity and many services is often an uneasy one, and poorly understood. Our difficulty in deciphering these relationships under the scenarios made this clear, and stressed the need for better information on thresholds.

Under most scenarios, a common trade-off is the increase in provisioning services at the expense of regulating and supporting services and biodiversity. This is essentially a trade-off between current and future generations: people can derive benefits from provisioning services now, but this choice may eventually result in a loss of services. This is especially prominent

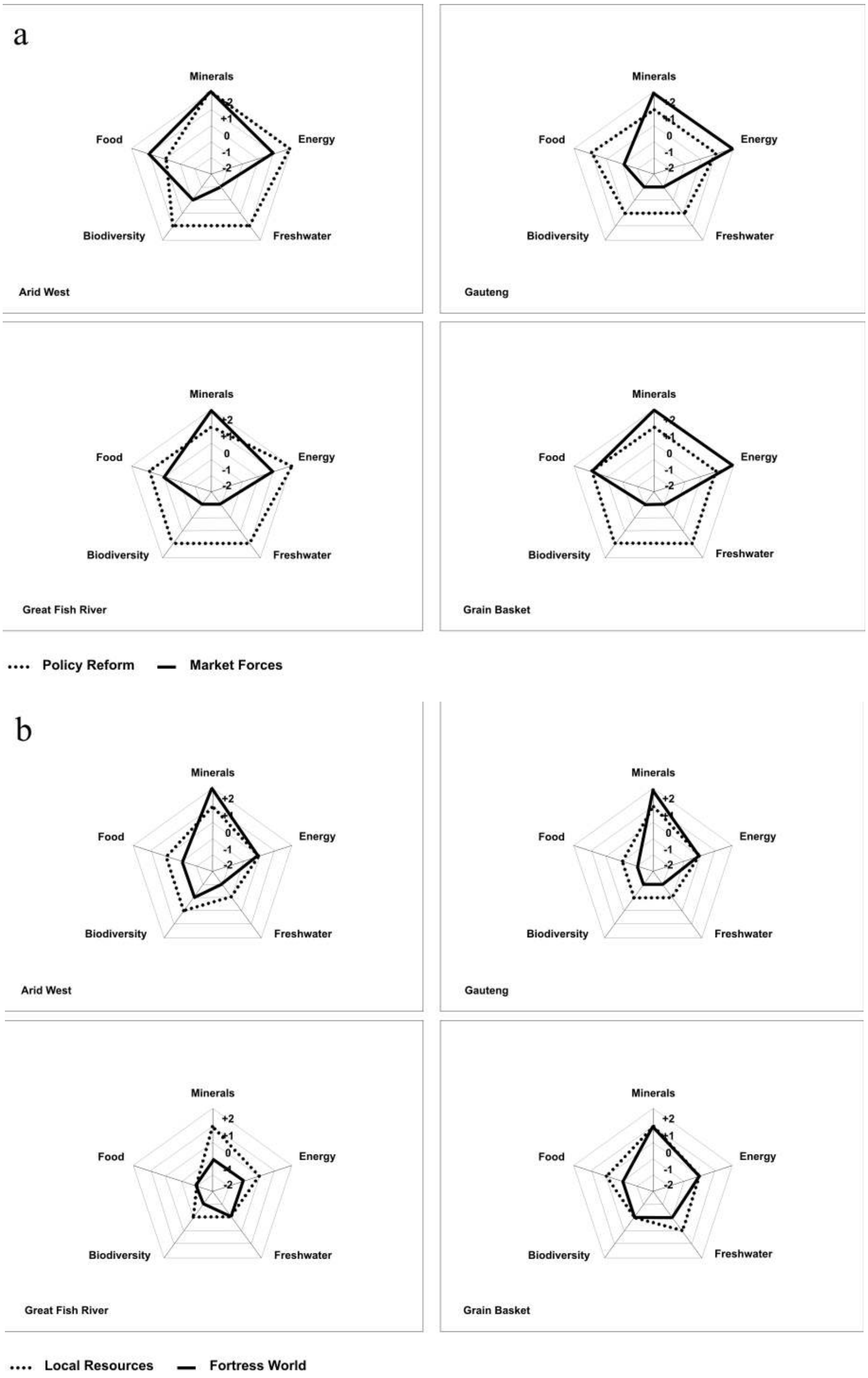

Figure 3.1. Change in production or condition of ecosystem services in the four regions of the Gariep basin from 2000 to 2030 under (*a*) Policy Reform and Market Forces scenarios, and under (*b*) Local Resources and Fortress World scenarios. The amount of change in each service is described as a sharp increase (+2), slight increase (+1), no change (0), slight decrease (-1), or sharp decrease (–2).

in Market Forces, while in Policy Reform, provisioning services increase but synergistic management across the basin strives to balance the use of these services with the maintenance of regulating and supporting services. Yet Policy Reform is not a panacea. Policies to intensify agriculture, for example, may embody a command-and-control mentality aimed at maximizing returns rather than maintaining a variety of ecosystem services, and possibly reducing critical system variability over the longer term (Rogers et al. 2000).

Trade-offs may occur between services in space. Freshwater flows and transfers create important interdependencies between regions, and only under Policy Reform, where water use is effectively regulated by national policy, does it improve throughout the basin. In addition, supply and demand of each ecosystem service have a unique spatial distribution. Trade-offs may occur in areas that have multiple competing services (Grain Basket); in areas which produce services (Grain Basket) which are consumed elsewhere (Gauteng); or where ecosystem service use outstrips the capacity of the region to produce it (Arid West).

We also observed trade-offs in the ways that societies deal with ecosystem service deficiencies. Affluent and urban populations tend to buffer themselves from shocks and disturbances by using manufactured capital or technology, or consuming ecosystem services from distant places (Lambin et al. 2001). However, over time, a society’s dependence on such buffers can increase its vulnerability to change if the buffer is removed (Gunderson et al. 1995). By contrast, poor populations often must be adaptive, adopting coping strategies that enable survival in difficult times, which may help to build their resilience (Berkes et al. 2000). An example is temporary migration between urban and rural areas with the ebb and flow of economic opportunities. Yet as urban densities increase, urban quality of life for the poor may decline, eventually drawing people back to their rural homes (Potts & Mutambirwa 1998). This creates an important spatiotemporal dynamic in the demand for ecosystem services that many analyses do not capture.

These different types of trade-offs tend to transfer costs from one individual or society to another. This may be easy when the transferring party is not accountable, such as when the affected party is far away or powerless to intervene – future generations are therefore common victims (Bohensky & Lynam 2005). Yet sometimes the effects of trade-offs are felt closer and sooner than expected, such as the “surprise” blackfly outbreak noted above. For this reason, scenarios can be effective for illustrating how such surprises might happen and eliciting users' reactions.

Cross-scale convergence

While there was little true cross-scale integration or nesting of the Millennium Assessment scenarios, some findings of the global and basin scenarios agree; the trade-off between provisioning services and other services is endemic in all scenarios at both scales, for example. Another similarity between the global and basin scenarios is the finding that a high-level governing authority is not always needed to manage all ecosystem services, but the ability to solve problems without it depends critically on the scale of the ecosystem process in question. Local Resources contradicts the "tragedy of the commons," suggesting that in the absence of strong central government control, some ecosystem degradation can be avoided through self-governing local institutions (Dietz et al. 2003). However, we see in this scenario that basin-scale measures are needed to protect downstream water resources from upstream impacts, and in Adapting Mosaic that global interventions are required to govern the global commons (MA 2005). Policy Reform, like TechnoGarden, works in part because people begin to understand the links at all scales between ecosystem services, biodiversity, and human well-being, and coordination between institutions at multiple scales reflects this understanding.

The global and basin scenarios diverge where concepts do not translate meaningfully from one scale to another because of differences in objectives and values. The most significant differences emerge because the Gariep is largely a developing-world basin, where much debate abounds about where environment and conservation fit on an agenda to promote economic growth and improve social services. While a Policy Reform scenario may be possible in parts of Southern Africa, a TechnoGarden type of scenario may be premature, as the user group conveyed early in the process. Such "ground truthing" with stakeholders needs to be done to ensure that scenarios are realistic and consistent (Peterson et al. 2003).

Reflections on a Learning Experience

While our assessment of current conditions and trends in ecosystem services and human well-being in the Gariep basin drew on information from past studies, the scenario analysis ventured into more unknown terrain – yet many of the assessment's key findings emerged precisely from peering into the future. This may be because the scenario analysis was the only aspect of the assessment in which space and time were fundamentally integrated. Space and time clearly matter: dynamic issues such as proximity to resources, connectedness to markets, position in the basin, buffer effects, and migration trends all shape these different futures. Tellingly, the uncertainty surrounding the future provoked the most reaction in our user advisory group workshops. Users were usually in agreement about the condition and trends of ecosystem services and current response options, but there was considerably more divergence in their opinions on the "big unknowns" of the future. This lack of consensus challenged us to rethink some assumptions of the assessment and its preliminary findings.

We sensed a limitation of the exercise in that it was not intended to inform a focal policy issue or decision. Scenarios are likely to be most beneficial to conservation if developed with the intent of identifying or solving specific problems (Wollenberg et al. 2000). There are numerous examples of issues in the Gariep basin that would benefit from scenarios. One is the ecological reserve, or environmental flows, determination under South Africa's National Water Act. This process entails a stakeholder-defined classification of water resources in each catchment according to ecosystem services that they consider to be of value (Mackay 2003). The use of scenarios would allow stakeholders to explore consequences of managing water along alternative pathways to the future. The Gariep scenarios approach is also being explored to better understand and manage invasive alien species in the region, an issue in critical need of a more integrated spatial and temporal frame (Duke & Mooney 1999; Chapman et al. 2001).

Despite its shortcomings, the scenario exercise exposed a range of individuals and organizations in the region to a new approach to problem solving, and several indicated interest in using the results or approach in their own conservation and environmental initiatives. For the longer term, it has contributed to the knowledge base for scenario planning in an ecological context in the Southern African region. We note that even though scenarios provoked debate among the user advisory group, some participants stated they were the most exciting and informative part of the assessment because they imparted a sense of ownership, rather than mere spectatorship, of a process that might influence the future (GBN 1998). Scenarios also encouraged them to mentally transcend the boundaries that typically constrain decision making to a narrow range of expectations. Finally, scenarios have a tremendous ability to illustrate and communicate important messages that scientists sometimes take for granted to a decision-making audience, which is often not accustomed to dealing with uncertainty over long time horizons.

Conclusion: Preparing for a Range of Futures

Based on the Gariep basin scenario experience, we believe that scenarios are a powerful tool for ecology and conservation, but cannot understate the need for future scenario exercises to place added emphasis on engagement of and communication with decision makers, and at appropriate scales for addressing the problems in question (Reid & Mace 2003). At subglobal scales, we recommend that scenario planners strive to involve and excite people through creative methods, and suggest that qualitative storylines may be more accessible than quantitative models and graphics.

Calls are increasingly made for the science and practice of conservation biology to help define and achieve sustainable visions of the future. Although scenarios offer a promising mechanism, we need to continue to hone our tools for the task. Uncertainty frequently results in crises, but mostly because - inherent though it may be - we are ill-prepared to respond. Through scenarios, scientists and decision makers can collectively embrace uncertainty, prepare for a range of potential futures, and turn would-be crises into opportunities for positive change.

Acknowledgements

We thank the Gariep Basin User Advisory Group for its contributions to the scenario analysis and J. Jones and two anonymous reviewers for helpful comments on the manuscript. SAfMA was funded by the Millennium Ecosystem Assessment through a grant from the government of Norway, administered by the United Nations Environment Programme.

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Decentralisation and its discontents: redefining winners and losers on the South African 'waterscape'

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In review: South African Journal of Science

Abstract

The decentralisation of natural resource management is an increasingly common trend across the globe, but many of the social and ecological consequences of these decentralisation processes remain uncertain. Decentralisation is intended to distribute power broadly among local, accountable actors and increase management efficiency, equity, and sustainability. Yet effective decentralisation can be difficult to achieve for numerous reasons, in part because natural resources and people comprise social-ecological systems that are characterised by non-linearity, variability, and unpredictability. Such challenges are anticipated in the South African water sector, which is embarking on a decentralisation process in the wake of a major paradigm shift and drafting of new legislation. In this paper I explore this process in a social-ecological systems context: will decentralised decision-making produce better overall outcomes, or simply redefine winners and losers? I use an agent-based model to simulate the behavior of water users across the South African 'waterscape' under alternative scenarios of centralised and decentralised management and examine the role of learning from collective experiences. The model reveals that 1) no scenario is likely to achieve improvements in the legislation's three central principles at the national scale, though some come closer than others; 2) patterns of winners and losers change at a finer management scale and sectoral level; 3) learning tends to achieve more middle-of-the-road outcomes which are slightly better than average because water use is diversified. These results suggest that although decentralisation will always create winners and losers, it promotes diversity and allows local experimentation, which tends to enhance resilience. Because individual agents often sacrifice sustainability to achieve social and economic goals, however, decentralised decision-making is likely to yield the greatest benefits if embedded within a broader policy framework to ensure sustainability.

Introduction

The decentralisation of natural resource management has become increasingly popular in many developing nations in the quest for improved efficiency, equity, and sustainability. Since the mid-1980s, many such decentralisation processes have been initiated (Larson and Ribot 2004). Decentralisation is defined as the formal transfer of power from a central government to actors and institutions at lower levels in a political-administrative and territorial hierarchy (Ribot 2002*a*). The rationale for decentralisation is that, when done correctly, it bestows decision-making powers on local and accountable actors who have the most relevant information about natural resources (Pritchard and Sanderson 2002, Ribot 2002*b*) and appropriate incentives to manage them (Wilson 2002).

The concept of democratic decentralisation and the empowerment of local actors is consistent with the notion advanced by social-ecological systems theory that resilience is more likely to be maintained in situations where actors are fully aware of and capable of controlling the impacts that affect them (Gallopín 2002, Bohensky and Lynam 2005). I define a social-ecological system (SES) as a coupled system of people and nature and their interactions across multiple scales of time and space (Walker et al. 2002), in a distinct departure from the view that 'ecosystems' and 'social systems' are separate entities (Westley et al. 2002). SES are complex, variable, non-linear and unpredictable, but are often governed by simple rules (Lee 1993) and self-organizing feedbacks (Holling 2001). Decentralisation, ideally, is one way of maintaining these rules and feedbacks for the benefit of both society and the environment.

The appropriateness of decentralisation, among other forms of management, for governing natural resources is the subject of a growing literature, much of which suggests an important relationship between institutional success or failure and social-ecological system dynamics (Pahl-Wostl 2002, Dietz et al. 2003, Anderies et al. 2004). Fisheries in New England (Wilson 2002) and Brazil (Kalikoski et al. 2002) provide classic examples of management failures that result from a lack of information about or understanding of what are fundamentally social-ecological system dynamics – in these cases, the interactions between fish population structure and fisher behavior. From these misunderstandings, inappropriate rules emerge, usually conceived by 'outsiders' such as central governments and large commissions. Conversely, successful institutions tend to appreciate spatial and temporal scale, uncertainty, variability, non-linearity, and feedbacks, and encourage learning by allowing actors to respond using local information and experience. Dietz et al. (2003)

distinguish the outcomes in two Maine fisheries that were managed by different sets of rules: one subjected to a top-down approach crashed, while one governed by local rules survived. The authors explain the difference in part by the ability of the latter to be guided by a knowledge base of recorded successes and failures over a long temporal scale. Ultimately, institutions may fail when they are informed by science and management philosophies that prevent the detection of important signals in the system. The potential advantage of decentralised resource management is that, by promoting diversity in the system, it may minimise the risk of missing some key signals and adopting maladaptive practices (Wilson 2002). On the other hand, devolving too much decision-making power to the local level can result in 'signal-missing' at the other end of the spectrum, where large- (or cross-) scale problems may emerge (Gunderson et al. 2002, Diamond 2005).

While social-ecological systems theory offers some of the most convincing arguments for decentralisation, it also explains some of its greatest obstacles. Apart from the difficulty of aligning scales of ecosystem processes and institutions (Pritchard and Sanderson 2002), perhaps the most contentious challenge of decentralisation stems from its inherent shifting of the balance of power in a social-ecological system. This makes decentralisation a fundamentally political process, replete with struggles for control (Galvin and Habib 2003). The creation of winners and losers is inevitable, but its potential to undermine decentralisation's intended objectives is not a trivial concern. Any assessment of the decentralisation experiments in the natural resource management field to date is likely to be inconclusive, as most processes remain in their infancy, or have been largely superficial (Larson and Ribot 2004). Little attention has been given to the consequences of decentralisation for social and ecological resilience, or system ability to recover from shocks and disturbances (Holling and Gunderson 2002): what is the capacity of the system to absorb the loss inherent in a redistribution of power?

These challenges are now of great relevance to the South African water sector, where a decentralisation process is beginning. This process entails the radical overhaul of past water legislation and a redesign of the decision-making structures for the allocation and conservation of the country's scarce water resources. The proposed institutional arrangements are anticipated with great hope, but also caution, by water users, managers, and scientists (MacKay et al. 2003). In this paper I use an agent-based model to explore water management in South Africa in a social-ecological systems context: does decentralisation lead to better outcomes for society and ecosystems, or does it simply redefine winners and losers? The model simulates actor behavior on the South African 'waterscape' and contrasts the outcomes under alternative scenarios of centralised and decentralised systems of water management. The latter allows agents to choose between strategies based on learning from collective experience. By illuminating some of the emergent dynamics in space and time, the model stimulates thought about the degree of decentralisation most appropriate for South African water management.

South African water management in transition

The decentralisation of water management in South African is part of a major transition away from the past command-and-control approach of water management by bureaucracy and technology, highly inequitable policies, and frequent disregard for the substantial hydrological, ecological, and social variability in the system (Rogers et al. 2000). Where previous water management favored farms and industries and required increasingly complex and costly technical interventions, the end of minority rule under the apartheid regime created an opportunity to reform water legislation and introduce a dramatically different vision in line with the new democratic system of governance. The Water Act of 1998 – among the most progressive water policies in the world (MacKay et al. 2003) – is founded on three fundamental principles of economic efficiency, social equity, and ecological sustainability. While the environment and poor communities were frequently 'losers' under the previous regime, the Act guarantees fundamental minimum levels of water for basic domestic and ecological needs before authorization may be made for any other purpose. All other water use must ensure efficiency and economy of operations. This combination of social, ecological, and economic priorities, viewed by some as serving the 'triple-bottom-line,' has some potentially negative repercussions, however, particularly for the notoriously inefficient agricultural water sector, which consumes some 65% of the country's water and contributes less than 5% to the GDP (DWAF 2004*a*), but has played an important role in the national economy, livelihoods, and drive for self-sufficiency (WCD 2000).

The institutional arrangements by which the Water Act's principles are to be achieved involve numerous actors, including the national ministry, the Department of Water Affairs and Forestry (DWAF), and nineteen new statutory bodies called Catchment Management Agencies (CMAs), each of which corresponds to a Water Management Area (WMA), roughly defined by large catchment boundaries. Once operational, CMAs, working with local stakeholder organisations, will assume some of the decision-making powers formerly held by DWAF, an arrangement that will allow stakeholders within each catchment to decide the desired balance between protection and utilisation of water resources and to establish a course of action to achieve it, within the limits of the national legislation. Concerns are expressed among water managers and scientists about the capacity of the CMAs to carry out and oversee these potentially momentous tasks (MacKay et al. 2003). By some accounts, the new decentralised institutions are in danger of becoming simply the regional extensions of the national water ministry (Rogers et al. 2000, Dent 2005) rather than autonomous, participatory entities. In addition, whether the decentralisation of decision-making will lead actors to manage water in a way that is consistent with the Water Act principles remains unknown.

Any prognosis for the future of water management in South Africa is necessarily speculative. The Water Act of 1998 and subsequent strategies mark a major transition in the relationship between people and water in South Africa, yet the transition creates some novel conditions, the outcomes of which are difficult to predict. Agent-based modelling is a particularly well-suited tool for elucidating situations of high uncertainty, and for comparing alternative future visions, options, and trajectories. In the following I describe how an agent-based model is used to simulate and compare some of the consequences of top-down (centralised) and bottom-up (decentralised) decision-making for meeting the goals of the South African Water Act.

The WaterScape: An agent-based water management model

Agent-based models investigate dynamics that emerge in complex systems from the interaction of agents, an environment, and rules. Agent-based modeling has been used to explore emergent system dynamics that emanate from decisions made by individual actors (Epstein and Axtell 1996, Goldstone and Janssen 2005), issues of control, communication, and coordination in ecosystem management (Bousquet and Le Page 2004), and sustainability and resilience over the broad scales of time and space at which social-ecological dynamics occur (Janssen and Carpenter 1999, Erasmus et al. 2002, Carpenter and Brock 2004). Several agent-based models have been used to explore aspects of water management (Lansing and Kremer 1993, Barreteau et al. 2003, Becu et al. 2003), including the new policy environment in South Africa and trade-offs between socio-economic options in particular catchments (Farolfi et al. 2004). The model described in this paper differs from previous efforts in the region in its broader spatial and temporal extent, which I suggest is fundamental to understanding the decentralisation process. Furthermore, this model adopts a unique social-ecological perspective on the South African water management transition that incorporates alternative management paradigms and the role of learning.

I used the CORMAS (Common-pool Resources and Multiagent Systems) simulation platform (Bousquet et al. 1998) to develop the WaterScape, an agent-based model of human responses for managing water in a simulated environment that approximates the hydrological landscape of South Africa (A class diagram and description of the model entities are included in Appendix B and C; the full model code is available upon request from the author at erin@sun.ac.za). Alternative scenarios define distinct agent world views about the use of water and strategies that correspond to these world views. Collectively, agents must fulfill both short-term needs for water, such as daily domestic use, livelihoods, and economic growth, and long-term needs, such as the continued delivery of ecosystem services. They must also balance fine-scale and broad-scale water interests, within the constraints of the environment and overarching rules that govern agent behavior, described below.

Eco-hydrological environment

The WaterScape is a simplistic representation of the social-ecological system of South African water resources and the people that they support. This system has several key characteristics. First, water resources in South Africa are unevenly distributed in both space and time. This variability has to some degree been averaged out by the construction of dams and water transfer schemes (Basson et al. 1997). Secondly, as the country's many large engineering works testify, great effort has been expended to harness and stabilise the variability of nature, with the skewed sectoral distribution of water use reflecting the historical control of resources.

The collective surface water resources of South Africa, Lesotho and Swaziland, a volume of approximately 49,000 million m³/a, constitute the WaterScape environment; the latter two countries are included because of their contributions to South Africa's runoff (4 800 million m³/a and 700 million m³/a, respectively). The total area (1268 km^2) is divided into 1946 quaternary catchments. The WaterScape is made up of quarter-degree-square (50 km^2) grid cells, each of which is approximately equal to an average-sized quaternary catchment. Each quaternary catchment that falls entirely or partially within South Africa belongs to one of nineteen contiguous Water Management Areas (WMA).

The model operates at a temporal resolution of a year, which corresponds to DWAF's National Water Resources Strategy and the principal hydrologic model of the region, the

Water Situation Assessment Model (WSAM) version 3.0 used to support broad national water resources planning (Watson, *pers. comm.*). Initial runoff values are obtained from this model. Each year, runoff in a catchment is replenished at a rate that reflects inter-annual variation, based on a normally-distributed random function and the catchment's hydrological index value, a measure of flow variability (Hughes and Hannart 2003). Runoff is also affected by climate change, which is likely to lead to pronounced decreases in runoff that will move progressively from west to east. In the model I assume a 10% decrease in runoff by 2015 in the western part of the country and a 10% decrease in runoff by 2060 in the eastern part of the country, with increases in some catchments along the eastern seaboard, in the northeast, and isolated areas in the west during the same period (Schulze 2005). Water that is not withdrawn for consumption flows to downstream catchments. Water may also be transferred from WMAs with a surplus of water to WMAs with a deficit, according to scenario-specific rules described below. In the WaterScape model, water transferred into a catchment is always immediately allocated according to the scenario currently in operation in that catchment.

Additional factors that may potentially alter the future water balance, but that are thought to have minimal impact or are not well understood, were not incorporated into the analysis. These include the effects of return flows (i.e. industrial effluent) to rivers, which may significantly augment the current water supply but often require treatment (DWAF 2004*a*), the reduction of streamflow by invasive alien plant species (Görgens and van Wilgen 2004), and the contribution of groundwater to total yield. While groundwater is an increasingly important component of the water balance in some parts of the country, its utilisation is limited at present and reliable groundwater data for the region are scarce (Haupt 2001).

Agents

Each type of agent operates at a specified spatial scale (Figure 4.1). DWAF, the national water ministry, sets the 'rules of the game' according to the prevailing water management paradigm, described below. The Catchment Management Agency (CMA) is responsible for the reconciliation of demand and supply in the WMA over which it presides. Sectoral agents represent a category of water use in a quaternary catchment. Five sectors are distinguished: commercial agriculture, commercial afforestation, mines and industry, rural (including domestic use and livestock watering), and urban (including domestic and municipal use), based roughly on the definitions of the National Water Resource Strategy

(DWAF 2004*a*). Each sector has a distinctive pattern of water use, based on various biophysical (e.g. land-cover, geology, climate) and socioeconomic (e.g. demographics, infrastructure) factors. Initial demand values for the model are obtained from the WSAM. These amounts change from year to year based on two water usage projections of high (4% annual GDP increase) and low (1.5%) growth (DWAF 2004*a*) and in accordance with scenario assumptions, described below. I assume that an increase in a sector's demand may only occur in catchments where the sector already consumes water. The advantage of this restriction is that it prevents agricultural growth from occurring in areas that are not viable for agriculture; the disadvantage is that it also prevents some potentially realistic growth, such as urban development in presently rural areas. However, in order to keep model complexity manageable it was decided not to explore land use changes, which to a large extent (i.e. agriculture, forestry) have stabilised for the foreseeable future in South Africa (Biggs and Scholes 2002).

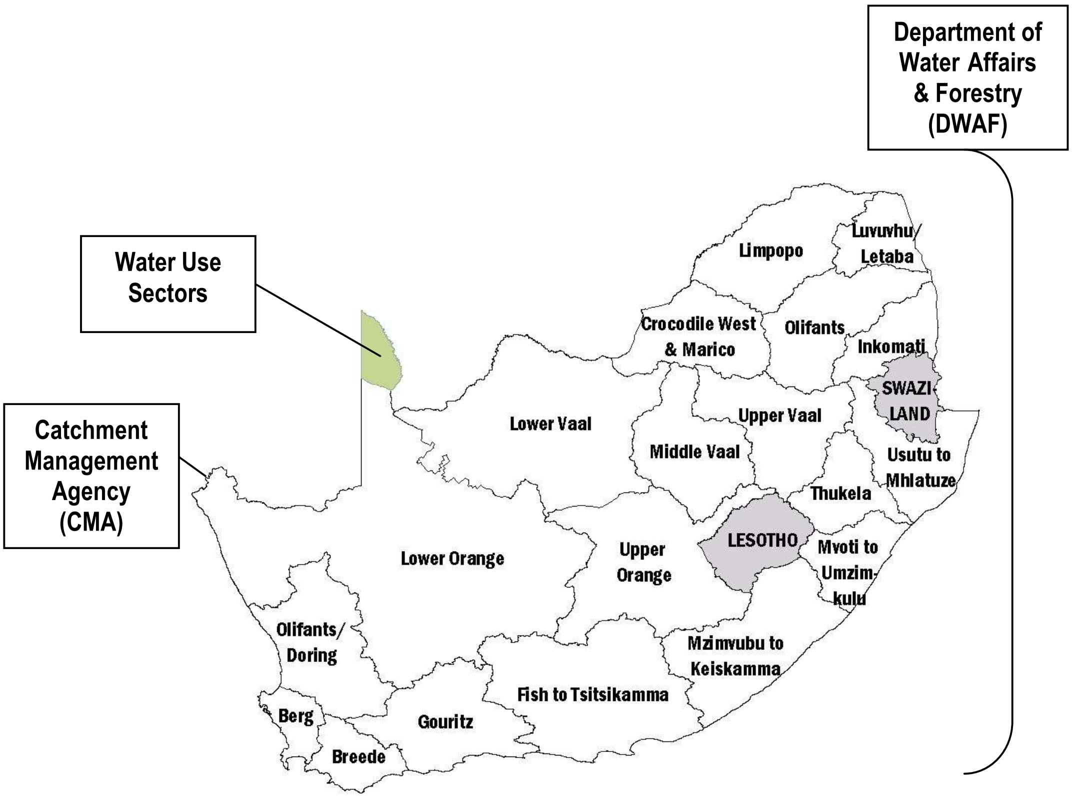

Figure 4.1. Spatial and social entities in the WaterScape model. The national ministry, DWAF, presides over decision-making at the national scale. Each Catchment Management Agency (CMA) is responsible for decision-making in its corresponding Water Management Area. In each quaternary catchment, five agents representing water use sectors make decisions about water management at the finest scale.

The productivity of water use (i.e. contribution to GDP per unit of water consumed) by these sectors varies greatly, with industry generating more than 50 times the GDP of agriculture for a given quantity of water (DBSA 2000). The following sectoral multipliers were used to derive value generated in South African Rands per cubic meter, based on estimates of DBSA 2000: 1.4 for agriculture, 73.6 for forestry and mining and industrial, 30 for urban and 10 for rural. As these multipliers are averages for the country, they do not reflect the variation within sectors or between regions. For example, some areas support the production of very high-value agricultural crops such as citrus and grapes, where the multiplier would be much higher than the average value. The productivity of industrial water use is also highly varied (Hassan 2003).

With the passage of the 1998 Water Act, the allocation of water to meet sectoral demands must take into account a legally-defined Reserve, which has two components. The human reserve is a mandated minimum of 25 litres per person per day from a source within 200 meters of the home (DWAF 2004*a*). The ecological reserve refers to the quantity, quality, pattern, timing, water level, and assurance of water that must remain in a natural body of water in order to ensure its ecological functioning (DWAF 2002). The ecological reserve requirement is to be set by DWAF for each quaternary catchment based on a desired ecological management class, in turn based on objectives for the water resources (Palmer et al. 2004). Class values range from A for a pristine water resource to F for a critically modified one. Where conservation and ecotourism are viewed as important objectives for the water resource, for example, the desired class would be designated as an A and a higher ecological reserve requirement would be set, while the desired class would be designated as a C or D and the reserve requirement would be lower if the primary objective of the resource was to provide water for waste disposal. Desktop estimates of the present ecological management class for each quaternary catchment (Kleynhans 2000) are used in the model.

Environment-agent feedbacks

Numerous types of feedbacks influence dynamics between water resources, their users, and ecosystems. The model focuses on one in particular between water withdrawal in a catchment and the ecological management class, which in turn may affect future water availability (Figure 4.2). This feedback is a function of the ratio of water withdrawal to availability, whereby a value of 0.4 or higher indicates severe water stress (Alcamo et al. 2000 and 2003, Cosgrove and Rijsberman 2000, Vörösmarty et al. 2000). I assume that when this ratio is exceeded, a reclassification is required such that the catchment is assigned to a lower (i.e. more modified) ecological management class. The reclassification depends on the extent the ratio is exceeded and the sensitivity of the catchment to water withdrawal, and is calculated by multiplying the withdrawal-to-availability ratio and the catchment's importance and sensitivity category (DWAF 1999, Kleynhans 2000). An impact on the ecological management class value in a given catchment similarly affects all downstream catchments in which the withdrawal-to-availability threshold is exceeded. It is assumed that an ecological management class value of D or worse (i.e. D-F) denotes a transformed catchment (Nel et al. 2004), for which actions to improve the ecological management class will not normally be undertaken. In transformed catchments, the amount of water available for withdrawal is likewise impacted, on the basis that fitness for use of the water resource is compromised. The decline in available water due to transformation is also a function of the ecological importance and sensitivity category. Admittedly, the modelled relationships between the importance and sensitivity category, the ecological management class, and runoff available for withdrawal represent a best guess about generally poorly understood relationships between hydrology and ecological integrity (Hughes and Hannart 2003).

Scenarios: Water management paradigms

Water management at a given point of time is driven by a prevailing discourse that shapes a paradigm regarding the relationship between society and water resources (Turton and Meissner 2002). Given the high uncertainty associated with the new era of water management in South Africa, scenarios that represent alternative paradigms are a useful mechanism for exploring possible future pathways and their implications. The scenarios used in this model are based on those developed for the Gariep Basin Millennium Ecosystem Assessment (Bohensky et al. 2004, Bohensky et al. *in press*), in turn based on the archetypes of Gallopín et al. (1997), but with a focus on water (Appendix D).

Under the *Efficiency First* scenario, water management is driven by the Water Act's efficiency principle and DWAF's view of water as an economic resource that can be managed through markets, price signals, and consumer preferences. Priority in allocation is given to sectors that are able to generate the highest economic returns; this is typically the urban, mining and industrial, and commercial forestry sectors. The agriculture and rural sectors, which generate relatively low returns per unit of water, are not irrelevant in the *Efficiency*

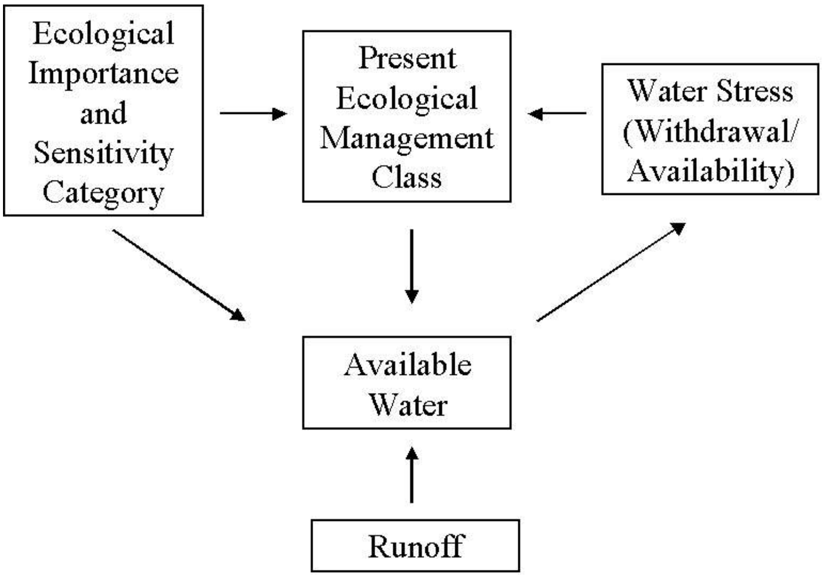

Figure 4.2. Ecological feedbacks in the WaterScape model. Ecological condition, indicated by the present ecological management class value, deteriorates when water stress, determined by the withdrawal-to-availability ratio, exceeds a threshold value of 0.4. The extent of deterioration depends on both the ecological importance and sensitivity category of the catchment and the extent of water stress. A present ecological management class value of 'D' or worse, indicating a transformed catchment, impacts the amount of available water that may be withdrawn from runoff.

First scenario, as they have strong links to the more efficient sectors and create employment, but spatially optimal water use in all sectors is strongly encouraged. Management is guided by a 'trickle down' philosophy, which assumes that economic growth and prosperity will create incentives for the fulfillment of basic human and ecological needs.

Under the *Hydraulic Mission* (Turton and Meissner 2002) scenario, DWAF pursues a command-and-control approach to maintain a constant supply of provisioning freshwater services – the tangible goods provided by water – but often at the cost of maintaining a wider array of regulating, supporting, and cultural freshwater services (MA 2003). Management is top-down, driven by government-controlled science, and emphasises the efficiency of operations in order to preserve the status quo. Little attention is given to monitoring, so institutions are reactive rather than proactive. Change is resisted until a crisis occurs that usually yields a call for tighter control instead of a critical, holistic analysis of the actions that precipitated the crisis (Holling and Meffe 1996). *Hydraulic Mission* essentially describes the past era of water management in South Africa. While the new Water Act reflects a significant departure from this paradigm, it has been suggested that management may revert to its previous style, either inadvertently, for example, if the focus of decentralisation is on form rather than function (Rogers et al. 2000), or deliberately if the pursuit of the Water Act principles lead to unsustainable water use (Turton and Meissner 2002).

Under the *Some, for All, Forever* scenario, DWAF explicitly embraces the Water Act's efficiency, equity, sustainability principles. At the core of this scenario is a belief that a vision of the desired state of the country's water resources must be defined, which determines the allocation for the human and ecological reserve, before any allocation proceeds. All remaining water is allocated as economically efficiently as possible, as under the *Efficiency First* rule. The vision, vis-à-vis ecological management classes, guides decisions about which management actions to introduce. However, there is a particular tension in this scenario between the Water Act's equity and sustainability objectives, which are not always seen as compatible (Turton and Meissner 2002).

Rules of the Game

The game as perceived by agents is to satisfy demand in accordance with scenario-specific rules. Of interest is whether the way agents play the game enables the three Water Act principles of efficiency, equity, and sustainability to be met. Efficiency of water use for the WaterScape and the WMAs is measured in Rand value generated per cubic meter of water use. Equity has multiple dimensions, and numerous indicators have been devised to measure equity in water allocation and access, such as the Water Poverty Index (Sullivan 2002). However, such measures are most easily applied within small areas and where socio-economic data related to water usage at household level are available. The WaterScape model does not operate at a resolution finer than the sectoral divisions of a quaternary catchment, requiring the use of an alternative equity measure. For this purpose, an index of relative dissatisfaction was developed, which measures the difference between the largest and smallest ratios of water allocated to water demanded in a catchment, on the assumption that large differences in satisfaction levels within a catchment are indicative of inequity. Index values range from 1 to 10; a value of 1 represents a difference in allocation-demand ratios of less than 0.1, and a value of 10 represents a difference greater than 0.9. Sustainability is measured by the extent of ecological transformation, defined as a present ecological management class value of ‘D’ or worse.

A different set of indicators was required to evaluate the five sectors because they do not correspond to spatially explicit areas; thus, the total value that the sector adds to the economy in millions of Rands was calculated. In addition, a Gini coefficient (Taylor 1977) was calculated to measure dissimilarity between the amounts of water allocated to the five sectors in a catchment. However, this cannot be considered a true measure of equity between sectors because opportunities for consumption differ greatly among sectors and catchments (i.e. forestry is only viable where climatic conditions allow for it).

As the central decision-making agent, DWAF sets the rules under each scenario which the CMAs and water users must adhere to. Within the constraints of these rules, water is distributed among the sectoral agents in their catchment each year, and management interventions are introduced by the CMAs to reconcile demand and supply (Table 4.1). In addition, each scenario includes assumptions about changes in sectoral demand in each WMA, based on a high and base growth projection to 2025 of the National Water Resources Strategy (DWAF 2004*a*), which I assume hold for the 100-year period of the simulations.

In *Efficiency First*, if available water equals or exceeds the total demand of all agents in the catchment, all agents get as much water as they need. If there is not sufficient water, water is allocated in preferential order to the mines and industry, forestry, urban, rural, and agricultural sectors respectively, until either all water is allocated or all demands are fulfilled. Spatial reallocation is also used to achieve greater efficiency; for example, in catchments that still have a deficit, water users may ‘offload’ their demand by relocating their businesses and residences to catchments in the WMA who have surplus water, or by trading water use licenses within their sector, serving to shift water use to water-rich areas. In WMAs where a deficit remains, water may be transferred from the catchment with the largest surplus to the catchment with the largest demand, on two conditions: water must travel over the shortest distance possible, and only an amount equal to or less than the amount of the recipient’s deficit may be transferred (i.e. the recipient gets only what it needs).

In *Hydraulic Mission*, the same rule used in *Efficiency First* applies if there is sufficient water to meet all agents’ needs. If available water is less than the total demand, each sector receives an amount proportional to its demand, serving to preserve the current sectoral

Table 4.1. Scenario assumptions and rules.

Scenario	*Efficiency First*	*Hydraulic Mission*	*Some, for All, Forever*
Allocation Strategy	Prioritises high-value sectors, then the Reserve	Allocates proportionally based on demand	Prioritises the Reserve, then high-value sectors
Interventions	Spatial redistribution of demand (i.e. relocation, license trading); high efficiency transfers with preference given to high-value sectors	Maximum volume transfers to largest consumers	Enforces demand management for large consumers; increase the ecological Reserve; restores untransformed catchments; high-efficiency transfers to areas in greatest need
Growth in sectoral demand	According to high projections[a] for urban, mining and industry, forestry; base projection for rural; no growth for agriculture	According to high projections[a] for agriculture, mining and industry, forestry, rural; base projection for urban	According to base projections[a] for urban, mining and industry, forestry, rural; no growth for agriculture

[a] National Water Resources Strategy projections to 2025 (DWAF 2004*a*). High projections are based on an annual GDP growth rate of 4%, and low projections on a growth rate of 1.5%.

ratios of water use. If a WMA has a deficit, water may be transferred from the catchment with the largest surplus to the catchment with the largest demand, serving to give preference to catchments with high levels of consumption. The conditions specified above do not apply under this scenario; thus a recipient can receive all of a donor's available water, from any location on the WaterScape.

In *Some, for All, Forever*, CMAs are required by the Water Act to satisfy the human and ecological components of the Reserve, respectively. Remaining water is then allocated according to the strategy used in *Efficiency First*. Water can then be transferred between WMAs under the same conditions that apply to *Efficiency First*, but in this case priority is given to the catchment with the largest deficit, irrespective of its demand. Under this scenario, CMAs take several active measures in the catchments that they manage to improve sustainability and equity. First, restoration efforts are undertaken as long as the level of transformation and the withdrawal-to-availability ratio in the catchment are below the threshold values. Second, if the difference between the allocation-demand ratios of the most and least satisfied users in the catchment exceeds 0.5 for five consecutive years (i.e. the most satisfied user's ratio is more than 50% greater than the least satisfied user's), a CMA can require the largest consumer in the catchment to reduce its demand by five percent; this could be done, for example, through demand management practices that allow current productivity to be maintained with less water. The CMA can also intervene if the ecological management class deteriorates by five percent or more within a period of five years. When this happens, a CMA may increase the ecological reserve requirement for the catchment by five percent, provided that the requirement can currently be met.

The three scenarios above represent different forms of centralised decision-making for the management of water, where sectoral agents have little autonomy. In reality, a combination of these scenario-specific approaches for reconciling demand and supply is likely to be adopted. To explore this, I introduce a learning scenario, which grants agents the ability to choose between the three scenarios above based on collective experience. I assume that a decentralised water management system selects elements of these three scenarios, depending on whether control and continuity of water provision (*Hydraulic Mission*), market incentives (*Efficiency First*), or social and environmental regulation (*Some, for All, Forever*) best meet agent objectives.

In the model, learning is necessarily simplistic. The water management strategy of one of the three scenarios is initially assigned at random to each catchment. In each subsequent year, the catchment's agents evaluate their collective success, as defined below, in the previous year. If the agents unanimously consider themselves successful, they continue with their previous strategy; if not, they evaluate the success of other catchments in their WMA and adopt the strategy that they deem most successful, on the assumption that catchments within a WMA are relatively similar and imitation is therefore rational behaviour (Jager et al. 2002). They are unable to make decisions beyond the confines of the three scenarios.

Two variants of learning are explored which represent alternative decision-making approaches, one based on maximising returns, and one on minimising risk. In the first variant, 'Learning by Maximum Allocation,' agents strive to maximise the total allocation of water to their catchment. If a catchment's total allocation is less than 75% of the total demand of all agents in the catchment, the agents consider this a failure and adopt the strategy used by the catchment that received the largest allocation of water in the previous year. In the second variant, 'Learning by Proportion Satisfied,' agents opt for the strategy that has the best chance of being successful for the average catchment. If less than 75% of a catchment's demand is able to be satisfied, agents in the catchment choose the strategy that satisfied (i.e. met 75% or more of demand) the highest proportion of catchments in the WMA in the previous year.

Simulation Results

Each simulation was run for 100 years to allow a sufficiently long time interval for a range of social-ecological system dynamics to emerge on the WaterScape, and was run 20 times to account for stochasticity; mean values are reported in all results below. The achievement of the three Water Act principles is compared under each of the scenarios. Results for quaternary catchments are aggregated at three levels: the whole WaterScape, the WMAs, and the five sectors.

WaterScape

For the WaterScape as a whole, the prospect of achieving all three principles under any single scenario appears unlikely (Table 4.2). Of the three paradigm scenarios, *Efficiency First* is indeed the most efficient, achieving the highest value added to the economy per cubic meter of water use at the end of the simulation. *Hydraulic Mission* is the most equitable based on its mean dissatisfaction index value, while *Some, for All, Forever* is the most sustainable in terms of ecological transformation. Both learning scenarios perform relatively well in terms of efficiency and equity, and outperform all other scenarios for sustainability, with the second-highest level of efficiency achieved under *Learning by Proportion Satisfied* and second-highest level of equity occuring under *Learning by Maximum Allocation,* also the most sustainable scenario.

Water Management Areas

When the WaterScape results are aggregated to the finer WMA scale, more complex dynamics are observed. Similarly to the WaterScape as a whole, relatively high efficiency can be attained in the WMAs without substantial increases in inequity, such as in the Crocodile West and Marico and Upper Vaal WMAs under *Efficiency First* (Figures 4.3 and 4.4). Yet high efficiency can come at significant cost to sustainability, as it does in the Upper Vaal, Olifants, Mvoti to Umzimkulu, and Berg WMAs under the same scenario (Figure 4.5). On the

Table 4.2. Efficiency, equity, and sustainability of water use on WaterScape at beginning and end of 100 years under five scenarios, expressed respectively as value added, mean satisfaction index value, and proportion of transformation. All figures are mean values from 20 simulations. EF = Efficiency First, HM = Hydraulic Mission, SFAF = Some, for all, Forever, LMA = Learning by Maximum Allocation, LPS = Learning by Proportion Satisfied. Numbers in bold indicate the maximum values for efficiency, equity, and sustainability achieved after 100 years.

	EF	HM	SFAF	LMA	LPS
Value added (Rands/m^3)					
Year 1	17.96	15.19	16.66	16.65	16.61
Year 100	**31.25**	12.80	17.81	22.65	24.85
Mean satisfaction index value					
Year 1	3.16	1.85	3.34	2.81	2.82
Year 100	2.28	**1.85**	2.45	1.99	2.01
Proportion of WaterScape transformed					
Year 1	0.22	0.22	0.19	0.22	0.22
Year 100	0.50	0.48	0.33	**0.29**	0.31

other hand, compared to the WaterScape as a whole, some of the trade-offs between the three principles in some WMAs are much more modest. Examples can be found under each scenario: in the Usutu to Mhlatuze WMA under *Efficiency First*, and the Mzimvubu to Keiskamma under *Hydraulic Mission* and *Some, for All, Forever*. It is thus possible to strike a balance between all three principles under all of these scenarios, but it should be noted that these WMAs benefit from their location in the well-watered eastern part of the country with relatively low water stress. However, the Lower Orange WMA, though the most water-stressed in the country, remains at roughly constant levels of efficiency, equity, and sustainability under *Some, for All, Forever*.

Some WMAs show little sensitivity to scenario selection. The Lower Orange and Olifants/Doring WMAs (as well as Swaziland and Lesotho) achieve about the same low levels of efficiency under all five scenarios, for example (Figure 4.3). A likely explanation is that water use by the Lower Orange and Olifants/Doring WMAs is largely for agricultural purposes, and as runoff in these WMAs is relatively low, their efficiency cannot easily rise above 0-10 Rands/m^3. The level of transformation of the Usutu to Mhlatuze WMA is likewise insensitive to scenario selection, and remains relatively low under all situations (Figure 4.5).

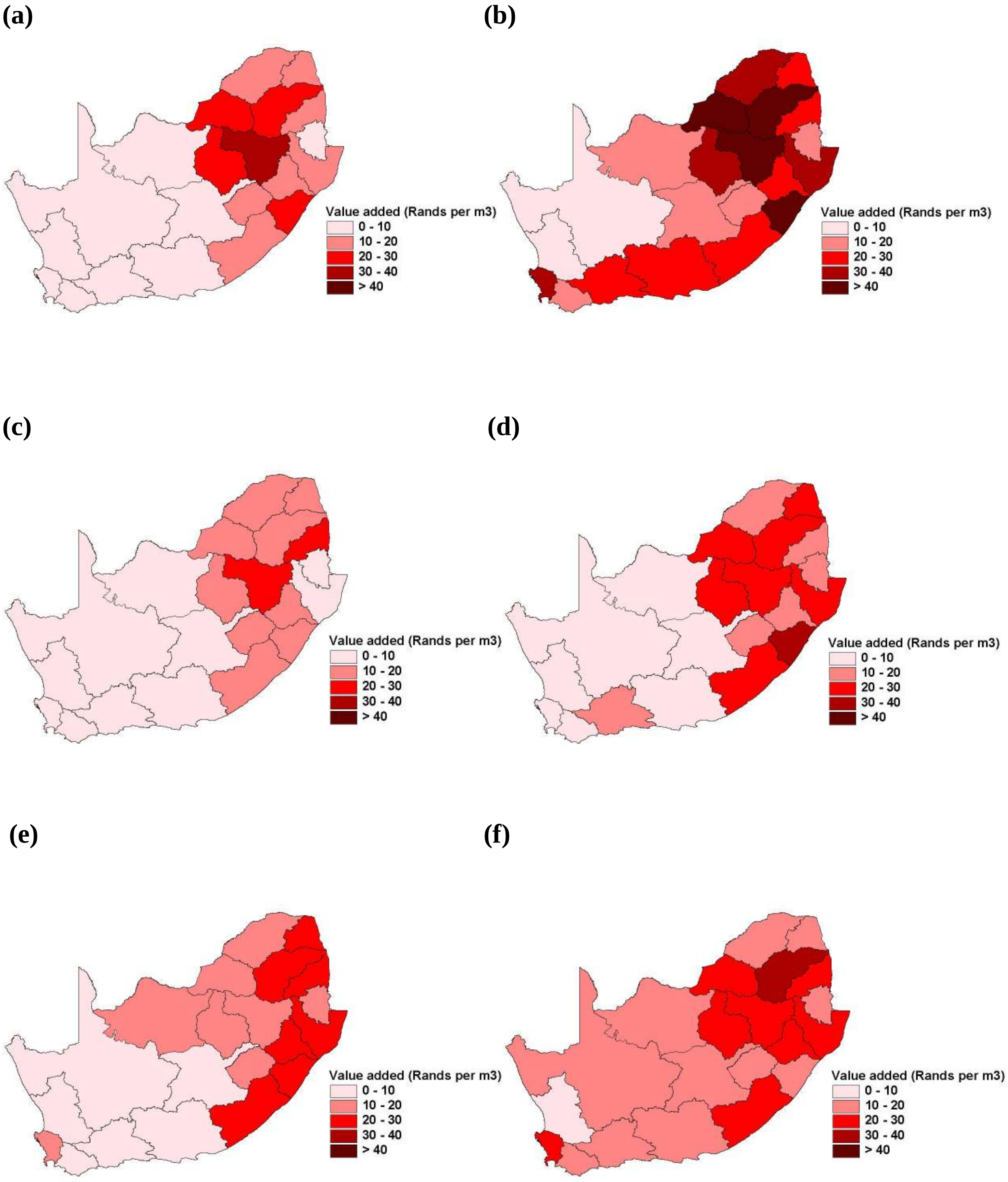

Figure 4.3. Value added in Rands per m^3 (a) at initialisation, and after 100 years under five scenarios: (b) Efficiency First (c) Hydraulic Mission (d) Some, for all, Forever (e) Learning by Maximum Allocation and (f) Learning by Proportion Satisfied. Values shown are means of 20 simulations.

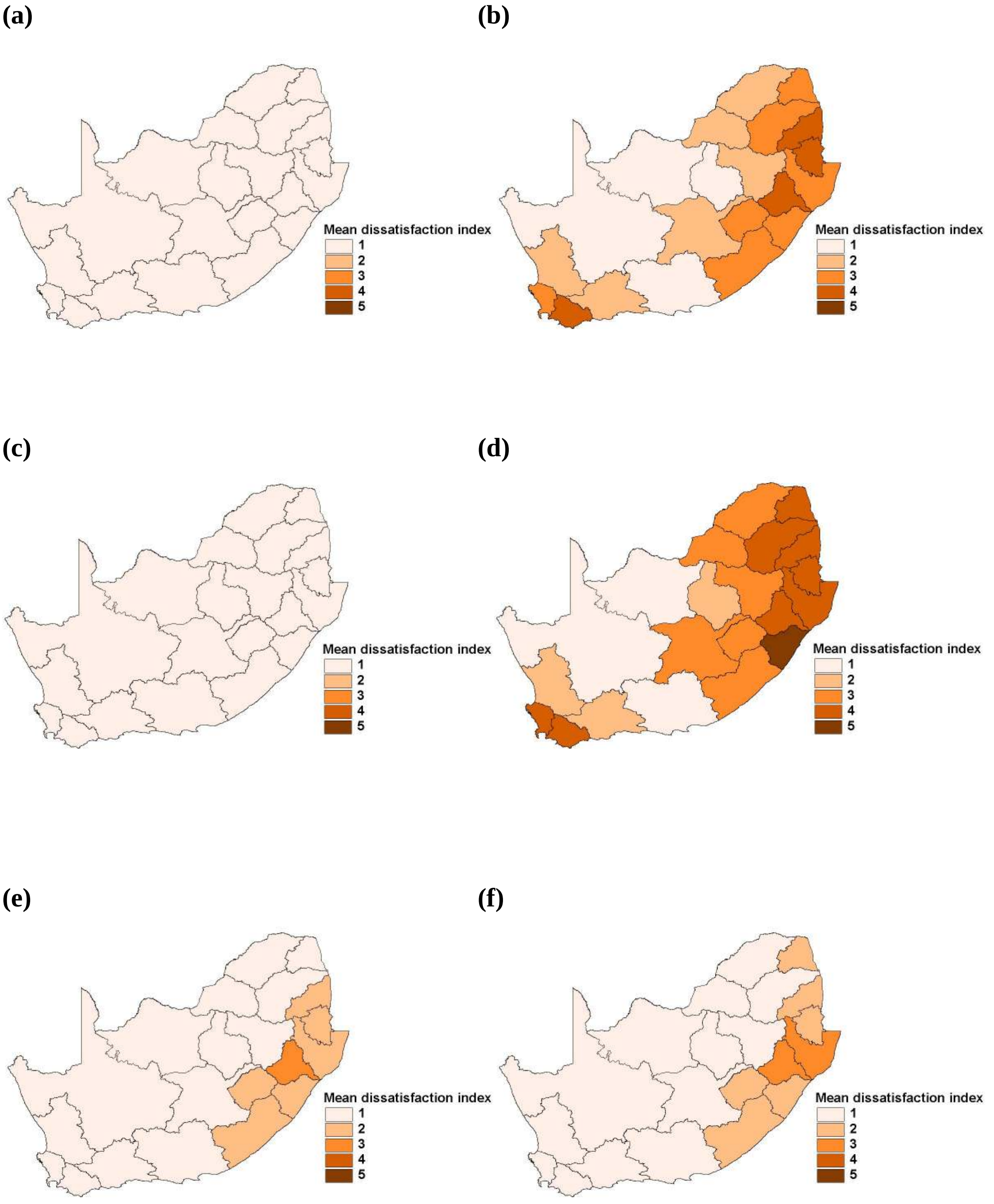

Figure 4.4. Mean dissatisfaction index value (a) at initialisation, and after 100 years under five scenarios: (b) Efficiency First (c) Hydraulic Mission (d) Some, for all, Forever (e) Learning by Maximum Allocation and (f) Learning by Proportion Satisfied. Values shown are means of 20 simulations.

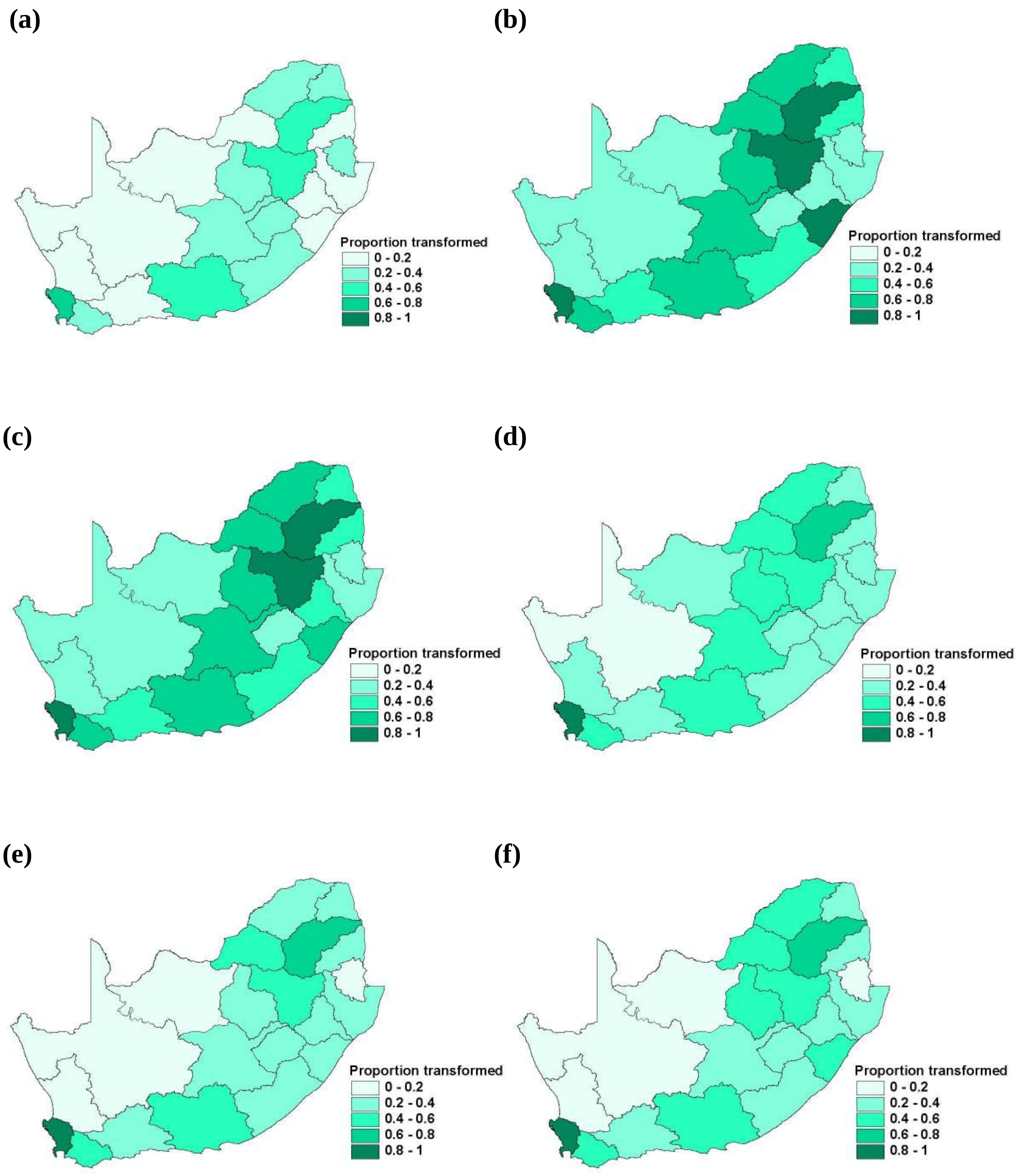

Figure 4.5. Proportion of catchments in WMA that are ecologically transformed (a) at initialisation, and after 100 years under five scenarios: (b) Efficiency First (c) Hydraulic Mission (d) Some, for all, Forever (e) Learning by Maximum Allocation and (f) Learning by Proportion Satisfied. Values shown are means of 20 simulations.

Conversely, WMAs with more diversified water use or higher water stress appear to be more sensitive to the nature of decision-making.

Role of Learning

The ability to learn enables agents to search for a water management approach that satisfies their demands for water given their particular environmental constraints. Under both learning algorithms, scenario selection is patchily distributed, but *Hydraulic Mission* is clearly dominant at the end of the simulation under *Learning by Maximum Allocation*, while the majority of WMAs select *Efficiency First* at the end of the 100-year period (Figure 4.6). Comparing these maps to those of the achievement of the three Water Act principles, it becomes clear why water use is more sustainable under *Learning by Maximum Allocation* than under any other scenario. Consider that CMAs can intervene in the water supply under *Hydraulic Mission* by negotiating water transfers from surplus to deficit WMAs, and moving all of the donor catchments' available water between any two points on the WaterScape. As water becomes increasingly scarce, this is probably the most aggressive way to access more, and more available water relative to demand decreases the withdrawal-to-availability ratio and hence transformation (despite the numerous risks associated with water transfers, which the model ignores). Meanwhile, the success threshold (satisfaction of 75% or more of demand) becomes increasingly difficult to meet, and agents who are unable to reap the merits of *Hydraulic Mission* switch scenarios with increasing frequency as they search for the most

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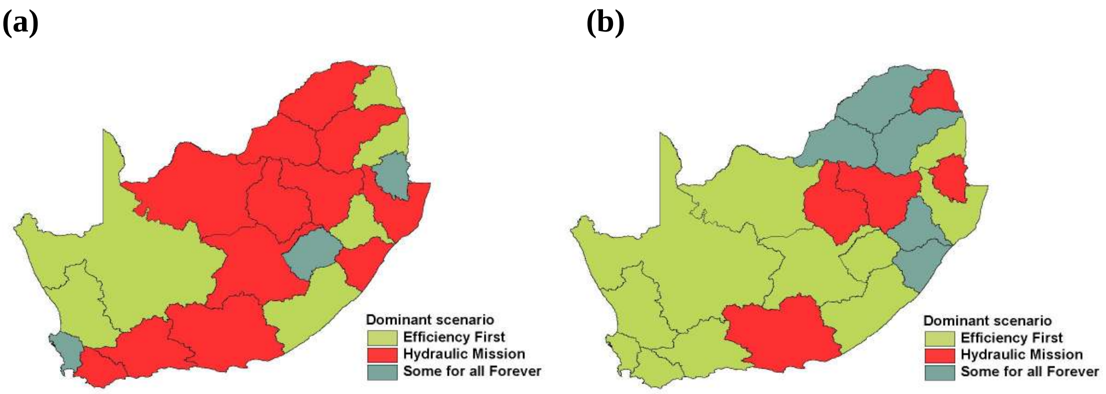

Figure 4.6. Dominant scenario selected after 100 years under (a) Learning by Maximum Allocation; (b) Learning by Proportion Satisfied. Values shown are means of 20 simulations**.**

successful one. The effect is to maintain a diversity of strategies over the WaterScape and thereby avoid dominance by a single strategy that becomes too successful at achieving one principle at the expense of others In several WMAs the principles are achieved to a greater degree under the learning algorithms than they are under any of the three scenarios, even though these algorithms merely represent different ways of selecting from the three scenarios. For example, the Lower Orange WMA achieves its highest efficiency under *Learning by Proportion Satisfied*. Figure 4.6b shows that *Efficiency First* is indeed the dominant scenario selected by the Lower Orange WMA at the end of the simulation. However, when *Efficiency First* is used exclusively across the WaterScape, withdrawals by upstream WMAs do not leave enough water for downstream WMAs to achieve their maximum efficiency. Similarly, the Lower Vaal and Olifants/Doring WMAs, as well as Swaziland, all achieve their highest levels of sustainability under *Learning by Maximum Allocation* and *Learning by Proportion Satisfied* rather than under *Some, for All, Forever,* again possibly due to dynamics between upstream and downstream water use.

Sectoral Outlook

Among the five sectors, who wins and loses? Are there trade-offs between maximising value and minimising inequity? On the WaterScape as a whole, agriculture is the most notable loser in terms of total value generated, which declines under all scenarios as water availability decreases, but least so under *Hydraulic Mission* because of the status-quo rule (Table 4.3), whereas priorities shift to higher-value water uses under all other scenarios. The forestry, mining and industry, and urban sectors do best economically under *Efficiency First*. The rural sector becomes increasingly important to the economy under *Hydraulic Mission* and also under *Learning by Proportion Satisfied*; in the latter case, this reflects the emphasis on satisfying the maximum number of water users, which benefits the rural sector because of the broad spatial distribution of rural water use (i.e. rural use occurs in most catchments). The most pronounced differences in value between scenarios are evident in the urban sector; high urban growth is unique to the *Efficiency First* scenario, while it is drastically reduced under all others.

Gini coefficients illustrate the dissimilarity in water consumption between the five sectors (Table 4.4). *Learning by Proportion Satisfied* has the most even distribution, while *Hydraulic Mission* has the least. Of note is that sectoral dissimilarity decreases during the 100-year period under all scenarios except *Hydraulic Mission*.

Table 4.3. Valued added (millions of Rands) by each sector at beginning and end of 100 years under five scenarios. Each value is the mean from 20 simulations; numbers in bold indicate the maximum values achieved.

Scenario	EF	HM	SFAF	LMA	LPS
Year 1					
Agriculture	7677	**7920**	7258	7621	7670
Forestry	**19504**	19482	19480	19481	19485
Mines & Industry	**76710**	58258	65151	62738	66906
Rural	**8963**	6702	8089	7909	7916
Urban	**62921**	40048	42800	47519	48667
Total	**175774**	132410	142779	149768	150644
Year 100					
Agriculture	2268	**6944**	3138	2493	2370
Forestry	**38879**	24205	19770	27704	24286
Mines & Industry	**80446**	39545	25063	32225	47081
Rural	7405	**8821**	5879	6690	8678
Urban	**109153**	10825	18131	20552	36862
Total	**238152**	90341	71981	89665	119277

Table 4.4. Gini coefficients for sectoral consumption at beginning and end of 100 years under five scenarios. Each value is the mean from 20 simulations. Numbers in bold indicate the minimum dissimilarity between sectors.

	EF	HM	SFAF	LMA	LPS
Year 1	**0.37**	0.45	0.40	0.41	0.40
Year 100	0.29	0.50	0.35	0.25	**0.21**

Discussion

With the model results, I revisit two questions: first, which scenario(s) best achieve the Water Act principles? Second, does decentralisation of decision-making and the ability to learn indeed select for these principles, or are these best achieved through a centralised, top-down planning approach? The model results suggest some answers to these questions. I then discuss some implications of these findings for management, model limitations, and suggested directions for further work.

On the whole WaterScape, *Efficiency First* is most efficient, *Hydraulic Mission* is most equitable based on the dissatisfaction index, *Learning by Proportion Satisfied* is the most equitable based on sectoral consumption, and *Some, for All, Forever* is best poised for sustainability. The difference in the outcome of these scenarios represents the fundamental tension between fulfilling societal needs for water and achieving economic growth and sharing its benefits on the one hand, and sustaining resources in order to benefit future societies and ecosystems on the other. Because water consumption at *Efficiency First* levels is not likely to be sustainable, the high level of efficiency and possibly the moderate level of equity attained at the end of the 100-year period are also unlikely to be sustained. However, the *Efficiency First* scenario may win popular support in the short term, particularly in light of the severe backlog in access to adequate water services for a large fraction of the population (DWAF 2004*b*). By contrast, the *Some, for All, Forever* scenario is likely to bring about only modest improvements in equity and efficiency compared to current levels. Thus the relatively small gains it forecasts for sustainability over the next century may not provide a sufficiently convincing argument for worrying about ‘forever’ now. What seems clear is that *Hydraulic Mission*, despite its success in some WMAs, is unlikely to meaningfully achieve any of the Water Act principles at the national level. The inconsistency between the mean dissatisfaction index value and sectoral Gini coefficients under this scenario is noteworthy. While the index value remains constant, sectoral dissimilarity increases, which is likely due to the agricultural sector’s sustained high growth rate, enabling it to access increasingly larger volumes of water even though its proportional share remains the same.

Does decentralisation of decision-making and the ability to learn help to achieve the Water Act goals? Simulations where learning is allowed tend to achieve a more middle-of-the-road position and strike a better balance between the three principles than simulations where a single scenario prevails. Furthermore, decentralisation allows diversification of strategy use in space or time, which tends to increase sustainability (Capenter and Brock 2004, Tengö and Belfrage 2004). This explains why the riskier maximum allocation scenario, by forcing a higher proportion of users to change strategies, is the most sustainable for the WaterScape and for some WMAs, though not the explicit goal of this scenario. Where learning is allowed, variability within the system is maintained and provides insurance in times of crisis (Holling and Meffe 1996); the system’s heterogeneity is its emergency support system. Variability also enables the identification of more successful practices. The learning scenarios can essentially be seen as adaptive management, which promote a heterogeneous, ‘patchy’ waterscape (Palmer and van Wyk, unpublished).

While decentralisation seems to achieve somewhat better outcomes for the system as a whole than the three centralised water management paradigms, does it create more 'discontents' at the WMA or catchment level? The model suggests that in some cases it does, evident in the ability of many WMAs to achieve one or more of the Water Act principles best under the paradigm scenarios. However, because it appears impossible for all WMAs to simultaneously achieve all three principles under a single scenario, decentralisation provides the opportunity for agents to experiment and learn rather than sink into any one particular 'basin of attraction,' that may be maladaptive and difficult to escape (Redman and Kinzig 2003).

The WaterScape's sectoral water users are designed to be fundamentally self-interested agents with a single purpose: to secure water for themselves. While this representation may be partially accurate, to suggest that all agents are driven purely by the same narrow, short-term goals is an admitted oversimplification. As the Water Act, the result of an extensive participatory process, makes clear, a growing awareness of the importance of sustainability is shared by many individual, communal, private, and other water users in South Africa. At the same time, the increasing competition for water suggested by the model simulations and elsewhere (Hirji et al. 2002, Kabat et al. 2002) may make longer-term thinking and planning in water management incredibly difficult for many water users to achieve, possibly even if sustainability is the first priority, and almost certainly if efficiency or equity is.

Given the above, what are the implications for management? Any management response in a complex social-ecological system will involve trade-offs, but the consequences of decentralising South African water management for overall system resilience depend on whether detrimental impacts occur where the system is able to absorb them (Bohensky and Lynam 2005). While the WaterScape model does not indicate precisely what this absorption capacity is, it does offer some practical insights. The inefficient agricultural sector is an obvious place to direct negative impacts, for example, but this may not be socially acceptable. The best solution for achieving the principles is likely to be embedded in a *Some, for All, Forever* framework, but which adapts *Efficiency First* elements to allow incentives for the agriculture sector to improve irrigation efficiency (DWAF 2004a), switch to other forms of land-use e.g. ecotourism, or engage in virtual water trade which encourages a shift toward higher-value crop production through import of lower-value water-intensive crops like cereals (Allan 2002).

Because the situation on the WaterScape is not always mirrored at the WMA scale or sectoral level, and the definition of winners and losers may differ in space and time, a policy framework that recognises social-ecological system diversity is likely to enhance resilience more than a 'one-size-fits-all' one (Carpenter and Brock 2004). The unexpected sustainability of the *Learning by Maximum Allocation* scenario as a result of frequently changing water management strategies illustrates this point. The outcome is essentially the collective product of individual agent decisions in response to their changing environment. Understanding how these individual actions lead to emergent system properties is key for anticipating the future of water management at the broader scale. In this respect, coupled learning by DWAF, the CMAs, and local actors is essential (Palmer and van Wyk, unpublished). Thus the framework suggested above also must accommodate and provide incentives for local (WMA or finer-scale) diversification and experimentation to adjust to specific conditions. Some decisions, such as those related to the long-term planning horizon and the Reserve requirement, need to be made at the higher level of the national ministry, but the decentralisation of other decision-making within the national framework offers a system of checks and balances for ensuring a sustainable future.

The model has some clear limitations. As this is a broad-scale model of potential water resource situations in South Africa, it is necessarily lacking in certain details, reflecting a common trade-off in agent-based modeling (Goldstone and Janssen 2005). The primary focus of this paper is on spatial rather than temporal dynamics, which are given closer attention elsewhere (Bohensky, *in prep*.). In addition, learning in the model is quite simple: agents use arbitrary, fixed thresholds in their determination of success, lack the ability to fully evaluate cause and effect, and do not consider trends or remember events that happened long ago. More realistic, complex learning, more intelligent agents, and the introduction of economic behaviour would make for a richer model.

Conclusion

While the South African water sector has a tremendous opportunity for positive innovation and change, this analysis reveals possible challenges related to decentralisation and achievement of the Water Act principles from a social-ecological systems perspective. Much of the current dialogue surrounding the implementation of the CMAs focuses on form and nature of participation and contestation of water (Chikozho 2005) without considering some of the fundamental social-ecological dynamics that will determine to what extent they will succeed or fail. A counterpoint to this dialogue is that CMAs, together with their constituents, can be thought of and designed as learning organisations (MacKay et al. 2003) that capture and put into practice lessons from past experience. Where information is widespread and shared among all actors, the boundaries that define winners and losers may become less distinct.

Learning has a paramount role in effective management of social-ecological systems (Fazey et al. 2005) and should not be underestimated. The WaterScape model is an initial step in what will hopefully become a broader investigation of the social-ecological dynamics that are so tightly linked to the water management transition in South Africa. Further research should address how water users learn, what motivates or inhibits their learning, and what enables the translation from learning to action.

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Learning dilemmas in a social-ecological system: an agent-based modelling exploration

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For submission to: *Ecological Modelling*

Abstract

The process of learning in social-ecological systems is an emerging area of research, but little attention has been given to how social and ecological interactions motivate or inhibit learning. This is of great relevance to the South African water sector, where a major policy transition is occurring that will give local water users and managers new opportunities to engage in adaptive learning about how to balance human and ecological needs for water. In this paper, an agent-based model is used to explore South African water management’s potential ‘learning dilemmas,’ or barriers to learning, whereby human perceptions combined with social-ecological conditions affect the capacity, understanding, and willingness required to learn. Agents manage water according to one of three management strategies and use various indicators to evaluate their success. The model shows that in areas with highly variable hydrological regimes, agents may be less able to learn because conditions change too rapidly for them to benefit from past experience. Because of this rapid change, however, agents are more likely to try new water management strategies, promoting a greater diversity of experience in the system for agents to learn from in the future. Similarly, in water-stressed areas, where agents tend to have greater difficulty fulfilling demand for water than in areas with abundant water supplies, they are more apt to try new strategies. When learning is restricted to small areas, agents may learn more quickly but based on a more narrow range of experience than in larger or more heterogeneous areas. These results suggest a need for specific monitoring to enhance learning that take into account the impacts of interacting hydrological, ecological, and social dynamics on learning. Although this is only a preliminary exploration of the challenges to learning, more analysis of this kind can eventually help to reverse the past trend of poor understanding of social-ecological dynamics as they relate to water management.

1. Introduction

Sustainable management of complex social-ecological systems is based on an understanding and maintenance of system function and structure, amid situations of change and uncertainty (Walker et al. 2002). In particular, the ability of decision makers to capture system information so that important patterns can be detected is essential to achieving sustainability (Wilson 2002). Social-ecological systems, however, are inherently dynamic, requiring decision makers to not only detect patterns, but also to constantly 'keep up' with change in these patterns through reflection and adaptive learning. More often than not, however, institutions are disadvantageously positioned, first to capture and process appropriate information, and secondly to use it to guide management, serving to explain numerous resource management failures (Carpenter et al. 2002).

Historically, both types of barriers - to learning and integrating learning into management - have plagued South African water management, the example discussed in this paper. I do not explicitly address the challenge of incorporating learning into management, which is addressed elsewhere (Rogers and Biggs 1999, Lynam and Stafford Smith 2004, Fazey et al. 2005). Improving learning has been recognized as a high priority for the individuals and organizations responsible for implementing the South African Water Act of 1998 (Rogers et al. 2000, van Wyk et al. 2001, MacKay et al. 2003) and its accompanying set of institutional reforms. This will require management of water resources at a catchment scale, marking a significant transition in information and power flows (Dent 2001) and an opportunity for further learning by actors across all scales. However, numerous barriers to learning will need to be overcome. Many of these arise from human perceptions of water resources that have been based on, and further contribute to, a flawed understanding (MacKay 2003). Meanwhile, these perceptions are confounded by social-ecological dynamics such as water stress, water variability, and ability of actors to access relevant information through learning networks. In this paper an agent-based modelling approach is used to investigate some of the major barriers to learning, which I call 'learning dilemmas,' confronting South African water management. This is followed by an examination of the implications of these outcomes for future water management and monitoring.

1.1. Learning how to learn

The problem of 'learning how to learn' is garnering increasing attention from researchers in the natural and social sciences, as well as natural resource managers and practitioners (Gunderson et al. 1995, Pahl-Wostl 2002, Berkes and Folke 2003, Fazey et al. 2005). Learning in social-ecological systems is important for several reasons. This is a time of dynamic change: we are inundated – if not overwhelmed – by information, data, and computational power, exert tremendous pressure on resources, and have forged greater interconnectedness among disparate parts of global systems than possibly ever before in the history of the human enterprise (Holling et al. 2002). While most modern societies seem to embrace and indeed invest in this complexity (Tainter 2000), it can be difficult to filter crucial signals from noise.

As change and complexity increase, so does awareness of the limits of scientific knowledge and understanding for solving integrated problems in the real world (Holling et al. 2002). Active adaptive management, which integrates research and action (Salafsky et al. 2001, Fazey et al. 2005), is commonly advocated as an approach based on this awareness. Learning becomes especially pertinent in the modern era of natural resource management, in which involvement of local resource users through participatory processes and management guided by alternative epistemologies (i.e. cosmologies, taboos) that depart from Western positivist science is becoming commonplace (Berkes and Folke 1998, Berkes et al. 2000, Wollenberg et al. 2000). In this paper, the definition of learning is not restricted to the expansion of a formal body of knowledge about the natural environment, but includes varied individual and societal perceptions of this environment (Adams et al. 2003) as well as needs and aspirations in relation to it (Sen 1999). Learning is also understood to be a dynamic process, in which the interpretation of feedbacks is a key element. This includes the ability to read cues from the environment as well as to respond to them appropriately (Berkes and Folke 1998, Tengö and Belfrage 2004).

1.2. 'Learning dilemmas'

Gallopín (2002) suggests that decision-making for sustainable development rests on three 'pillars': capacity, understanding, and willingness. This metaphor is extended to the analysis of learning in the South African water sector. 'Learning dilemmas' – akin to cracks in the pillars – form when human perceptions combined with social-ecological conditions produce a deficiency of capacity, understanding, or willingness to learn. Understanding in learning terms means perceiving a problem in relation to learning; knowing what and how to learn. Willingness to learn depends on confidence in learning; belief that learning will help solve problems, as well as the acceptance of some level of risk, or tolerance of change. The ability to learn depends on reliable access to a 'learning network' from which information can be obtained. This may include other actors, media, or experimentation that allows for recording and evaluation of past experiences. Naturally, capacity, understanding, and willingness are all related, so may sometimes function as a 'package' as well as individual pillars.

In resource management, such dilemmas are common. Human and natural systems are linked social-ecological systems (Berkes et al. 2003); thus, an impact on one system component invariably affects the other. Human societies have a long history of learning how to manage these systems sustainably (Berkes et al. 2000), but the very nature of social-ecological systems can cause challenges to learning. For example, natural environmental variability may obscure signals and make it difficult to relate cause and effect (Fazey et al. 2005). Anthropogenic changes to the environment can also convolute understanding of natural processes. Ironically, it has been common practice to reduce natural ecosystem variability to increase productivity of a resource, although this may compromise learning ability and decrease adaptability over the longer term (Holling and Meffe 1996). For example, when dams reduce natural variability by stabilizing river flows (Hughes et al. 2005), people become accustomed to distortions in the hydrological system, and respond in ways that would be unlikely in the absence of such interventions, such as using water-consumptive devices in the home. Learning may be stalled by differences in opinion about what learning priorities are and how they should be achieved; although managers and leaders may want to encourage learning, they may diverge on priorities or the way to achieve them. In other cases, leaders may limit public acquisition of new information because it is perceived as a threat to their power (Pritchard and Sanderson 2002).

Learning in the South African water sector, while affected by most of these problems, has been particularly influenced by three significant characteristics of South African water resources: high temporal variability, spatial heterogeneity (Basson 1997), and water stress that is expected to intensify during the next 20 years (Seckler 1998). These conditions are likely to have even more impact in the future, due to the effects of climate change (Schulze 2005) and increasing demand for limited resources. Although these three characteristics are not the only ones that contribute to learning dilemmas, they are among the most important and are the focus of this paper.

2. Change in the South African water sector

In the South African water sector, understanding of social-ecological dynamics has been poor and information has not historically been collected with such understanding in mind. South Africa shares the water management trajectory of many nations, where an initial focus on supply-side solutions is giving way to more integrated demand-side management as water stress increases (van Wyk et al. 2001). During the 20th century, learning was based on science and knowledge that was generated and controlled by the state (Dent 2001). This top-down style of water resources isolated itself from much of the knowledge that existed on the ground and had been amassed through observations and research by communities and civil society organizations.

The value of learning was also obscured by the prevailing worldview of the relationship between water and society. Water resources – and all of nature for that matter – were seen as guided by linear processes with predictable, controllable outcomes, though in fact, water resource dynamics throughout southern Africa are highly variable and non-linear. In the previous era, it was believed that most problems that arose could be solved through already proven technical means (Turton and Meissner 2002) – water shortages could be averted by building large storage dams, for example. The need to monitor was rarely recognised, because it was believed all of the necessary information already existed and any problems that arose could be dealt with in the same way as before. Within this environment, resistance to change grew. Because change was not encouraged, it was very costly to attempt to deviate from the 'sanctioned discourse' of water management (Turton and Meissner 2002). Trying new approaches was synonymous with abandoning accepted views and long-held traditions, admitting flaws in current practices, and jeopardizing one's job or career, and as such, little investment was made in the construction of a broad knowledge base (Dent 2001). Locally, access to information was hampered by poor infrastructure, low levels of education and literacy, livelihood demands, poverty, and limited opportunities for interaction with a broad range of actors (Motteux 2002).

The situation of the past is in stark contrast to the vision outlined in the country's current legislation, the Water Act of 1998, and its basis on three principles: efficiency, equity, and sustainability. By this law, some of the powers formerly held by the state will be devolved to large catchment-scale institutions called catchment management agencies (CMAs), which together with their constituents will each prepare a catchment management strategy for the water management area (WMA) over which it presides. Currently, the biggest learning challenge faced in this arena revolves around implementation of the Act, which represents a major cognitive and institutional shift from the previous system of water management. Meeting its three principles is expected to require an adaptive approach (Rogers et al. 2000, MacKay et al. 2003), because a uniform management regime cannot accommodate the vast range of variation and unpredictability in the country's water resources and water use.

3. An agent-based model of learning

To better understand how people learn how to manage social-ecological systems over large scales, models have been used to investigate social and environmental conditions that motivate or inhibit learning in ecosystem management. Many of these efforts have used an agent-based modelling approach, which allows the observation of dynamics that emerge from individual decisions over large scales of space and time (Epstein and Axtell 1996, Bousquet and Le Page 2004). These models have explored, for example, learning under alternative institutional regimes for managing rangelands (Janssen et al. 2000), perceptions of actors in a Swiss water supply system (Pahl-Wostl 2002), the effect of uncertainty on overharvesting (Jager et al. 2003), learning trajectories of lake managers when confronted with surprise (Peterson et al. 2003), and the prevalence of 'sunk cost effects' that lead to irrational decision making in groups of rational agents (Janssen and Scheffer 2004).

Much of the modelling of South Africa's water resources to date has not included social processes (Dent 2000). An agent-based model, called the WaterScape, is used in this paper to ask whether agents in a simplified version of the situation described above exhibit unique patterns of learning. Developed with CORMAS (Common-pool Resources and Multiagent Systems), an object-oriented programming platform (Bousquet et al. 1998), the WaterScape has been used in related work to explore the ability of water users to meet the South African Water Act principles by adopting different strategies and using different methods of learning (Bohensky, *submitted*). Here, a series of learning experiments is conducted to explore two aspects of learning dilemmas: 1) how different social-ecological conditions and 2) agents' selection of different indicators to evaluate their actions affect capacity to learn, willingness to learn, and understanding of how and what to learn.

3.1. Spatial environment

The learning 'game' is played on a spatial environment representing the collective surface water resources of South Africa, and upstream neighbours Lesotho and Swaziland (Figure 5.1). Namibia, which lies partially downstream of South Africa, is not included in the modelled environment consists of quarter-degree-square (50 km^2) grid cells, each of which represents approximately one quaternary catchment. Each quaternary catchment that falls entirely or partially within South Africa belongs to one of nineteen contiguous Water Management Areas (WMA).

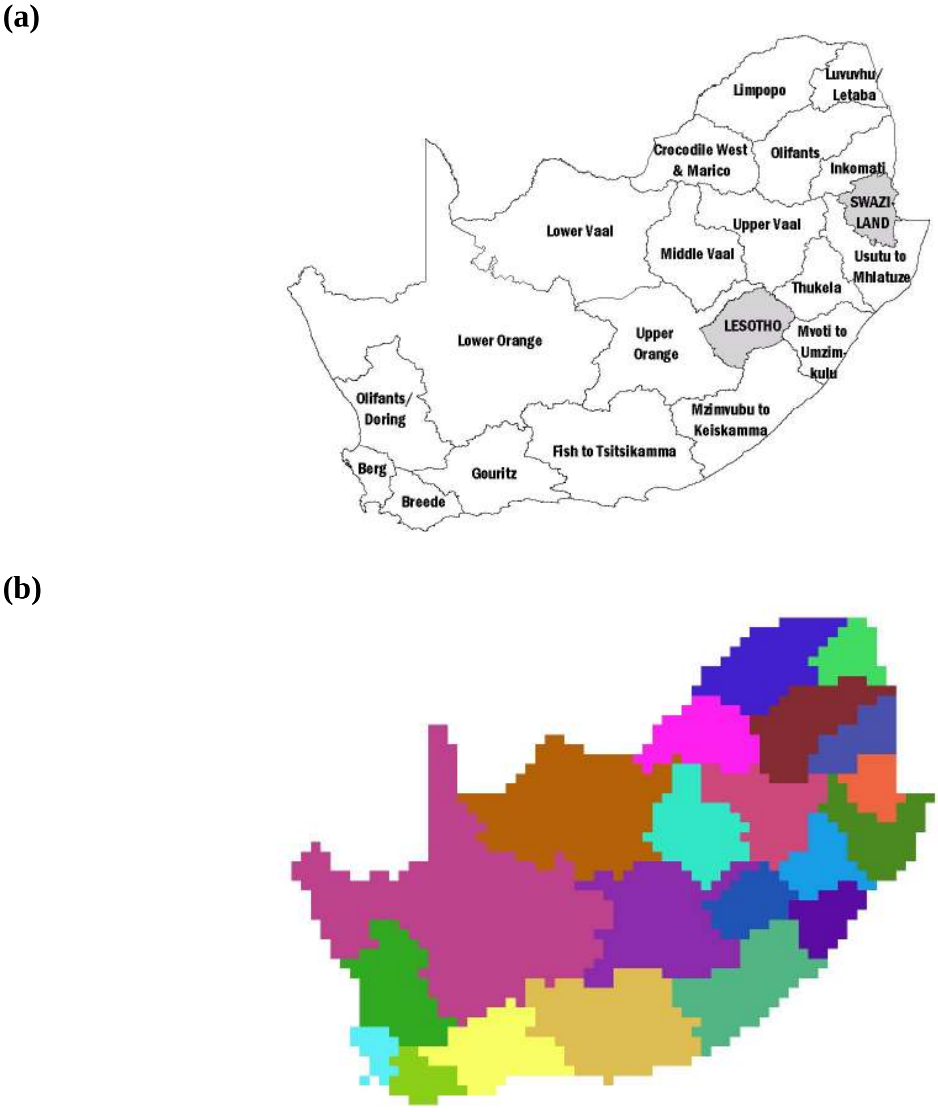

Figure 5.1. (a) Map of South Africa depicting international boundaries and Water Management Areas (WMAs). (b) Visual representation of WMAs in the CORMAS program.

model, although the Water Act makes provision for water-sharing with neighbouring countries. The total area (1268 km^2) is divided into 1946 quaternary catchments. The Initial runoff values are obtained from a hydrologic model of the region, the Water Situation Assessment Model (WSAM) version 3.0 (Watson, *personal communication*). At each time step, equivalent to one year, runoff in a catchment is replenished at a rate that reflects inter-annual variation, based on a normally-distributed random function and the catchment's hydrological index value, a measure of flow variability (Hughes and Hannart 2003). Runoff is also affected by climate change, which is likely to lead to pronounced decreases in runoff that will move progressively from west to east. In the model I assume a 10% decrease in runoff by 2015 in the western part of the country and a 10% decrease in runoff by 2060 in the eastern part of the country, with increases in some catchments along the eastern seaboard, in the northeast, and isolated areas in the west during the same period (Schulze 2005). Water that is not withdrawn for consumption flows to downstream catchments.

3. 2. Agent decision-making

Water management decisions are based on information about the environment that is socially-constructed, and tend to be framed by a prevailing discourse on the relationship between water resources and society (Turton and Meissner 2002). However, this discourse is mediated by individual agent worldviews regarding the 'real' world (Janssen and de Vries 1998). These social and individual perceptions of the WaterScape environment manifest in the selection of measures or indicators used by agents to make decisions (Figure 5.2). The effectiveness of a water management strategy may be judged very differently when it is based on an indicator of economic value that can be obtained from a catchment and an indicator of ecological transformation in the catchment.

3.2.1. Agents

In this model there are two types of agents, each of which represents a level of decision-making. The first type represents a water use sector, of which there are five: agriculture, forestry, mining and industry, rural and urban. The CMA is the second type of agent in the model, whose purpose is to enforce rules to balance demand and supply in its Water Management Area (WMA). The sectoral agents' objective is to meet their demand with

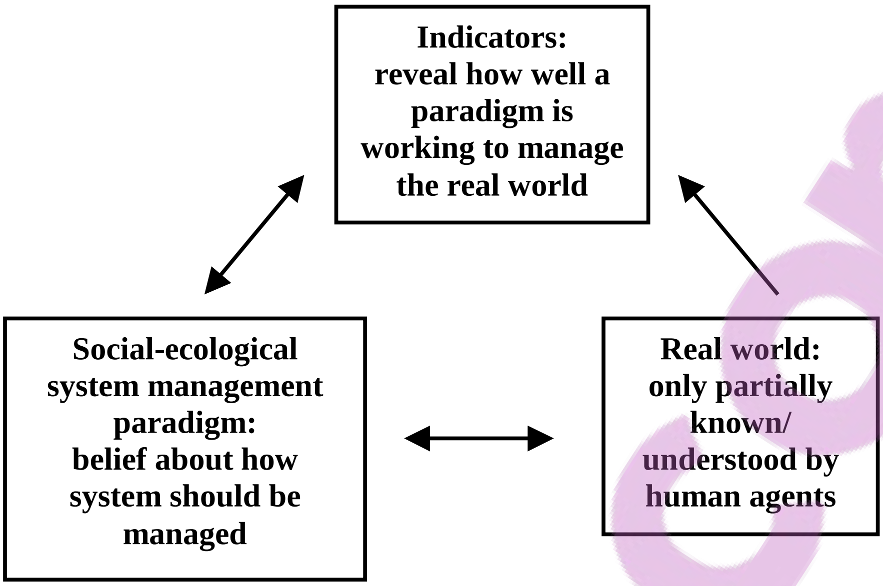

Figure 5.2. Schematic of major relationships governing an actual and perceived environment in a social-ecological system. Indicators are a link between management paradigms and the 'real' world. The selection of indicators may be refined with changes in the paradigm or observations of the real world; the paradigm may change with information from the indicator or real world experience. The real world can likewise be changed through actions driven by the paradigm. Changes in the real world can influence both the information provided by the indicator and the choice of management paradigm.

existing supplies in their quaternary catchment. Each sector has a distinctive pattern of water use, based on various biophysical (e.g. land-cover, geology, climate) and socioeconomic (e.g. demographics, infrastructure) factors. Initial demand values for the model are obtained from the WSAM, as above. These amounts change from year to year in accordance with assumptions of each paradigm, and are estimated from a high or base growth projection for each sector and each WMA (DWAF 2004).

3.2.2. Demand projections

Growth in sectoral demand is constrained to catchments in which the sector already consumes water; this constraint prevents agricultural growth, for example, from occurring in areas that are not viable for agriculture, but also prevents some potentially realistic growth, such as urban development in a presently rural area. To a large degree, areas that are suitable and available for agriculture and forestry in South Africa are already in use, and thus little further expansion is expected (Biggs and Scholes 2002). Urbanisation, while expected to have prolific implications for water resources in South Africa (DWAF 2004), were not explored in order to keep model complexity manageable.

3.2.4. Water productivity

The productivity of water use (i.e. contribution to GDP per unit of water consumed) by these sectors varies greatly, with industry generating more than 50 times the GDP of agriculture for a given quantity of water (DBSA 2000). I use the following sectoral multipliers to derive value generated in South African Rands per cubic meter, based on estimates of DBSA (2000): 1.4 for agriculture, 73.6 for forestry and mining and industrial, 30 for urban and 10 for rural water use. As more detailed data on water productivity is limited, these average multipliers for the country only provide a rough indication of the relative value of water use by different sectors. These multipliers do not reflect variation within sectors or between regions, nor possible change over the 100-year period, all of which may be significant.

3.2.5. Human and Ecological Reserve

Under the 1998 Water Act, the allocation of water to meet sectoral demands must take into account a legally-defined Reserve, which has two components (DWAF 2004). The human reserve is a mandated minimum of 25 litres per person per day from a source within 200 meters of the home. The ecological reserve refers to the quantity, quality, pattern, timing, water level, and assurance of water that must remain in a river in order to ensure its ecological functioning. The ecological reserve requirement is to be set by DWAF for each quaternary catchment based on a desired ecological management class, in turn based on objectives for the water resources (Palmer et al. 2004). Class values range from A for a pristine water resource to F for a critically modified one. Where conservation and ecotourism are viewed as important objectives for the water resource, for example, the desired class would be designated as an A and a higher ecological reserve requirement would be set, while the desired class would be designated as a C or D and the reserve requirement would be lower if the primary objective of the resource was to provide water for waste disposal. Desktop estimates of the present ecological management class for each quaternary catchment (Kleynhans 2000) are used in the model, where each class corresponds to a range of numerical values, which increase with increasing modification.

3.2.6. Ecological feedbacks

A water resource must be reclassified, and its ecological management class adjusted, when water withdrawal increases beyond a certain threshold, which in turn may affect future water availability (Figure 5.3). I assume that this occurs when the ratio of water withdrawal to availability exceeds 0.4, indicating severe water stress (Alcamo et al. 2000 and 2003, Cosgrove and Rijsberman 2000, Vörösmarty et al. 2000). The level of reclassification depends on the extent the ratio is exceeded and the sensitivity of the catchment to water withdrawal, and is calculated by multiplying the withdrawal-to-availability ratio and the catchment's importance and sensitivity index value (DWAF 1999, Kleynhans 2000). An impact on the ecological management class value in a given catchment similarly affects all downstream catchments in which the withdrawal-to-availability threshold is exceeded. It is assumed that an ecological management class value of D or worse (i.e. D-F) denotes a transformed catchment (Nel et al. 2004), for which the ecological management class value is not allowed to improve.

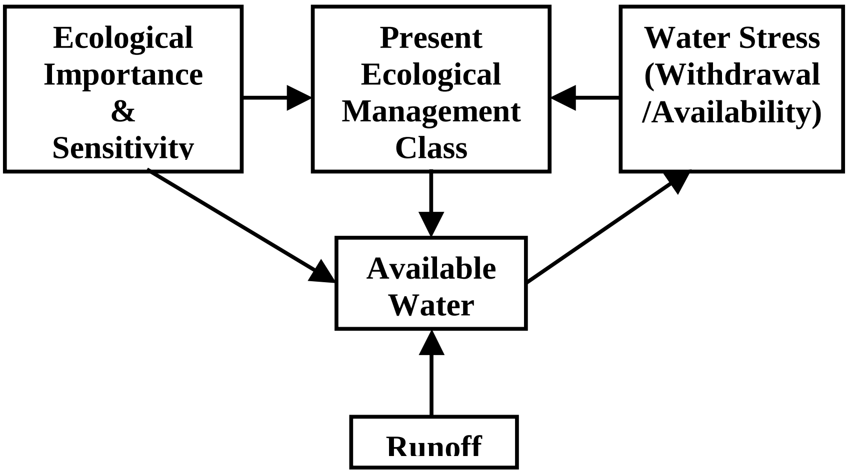

Figure 5.3. Ecological feedbacks in the WaterScape model. Ecological condition, indicated by the present ecological management class value, deteriorates when water stress, determined by the withdrawal-to-availability ratio, exceeds a threshold value of 0.4. The extent of deterioration depends on both the ecological importance and sensitivity category of the catchment and the extent of water stress. A present ecological management class value of 'D' or worse, indicating a transformed catchment, impacts the amount of available water that may be withdrawn from runoff.

In transformed catchments, the amount of water available for withdrawal is likewise impacted by an increase in the ecological management class value, on the basis that fitness for use of the water resource is compromised. The decline in available water is also a function of the ecological importance and sensitivity index value. The modelled relationships between the importance and sensitivity index, the ecological management class, and runoff available for withdrawal are necessarily somewhat arbitrary, as the precise relationships between hydrology and ecological integrity are not well known (Hughes and Hannart 2003).

3. 3. Water management paradigms

I assume, for the sake of minimising model uncertainty, that water use is influenced by three broad water management paradigms (see Appendix D): one based on maximising efficiency (*Efficiency First*), one rooted in a command-and-control approach (*Hydraulic Mission*), and one that strives for a balance of the three Water Act principles of efficiency, equity, and sustainability (*Some, for All, Forever*). Agents' decision-making is limited to choosing among these. These paradigms define the rules by which water is distributed among the sectoral agents in their catchment each year, management interventions that the CMAs can use to reconcile demand and supply, and different rates of growth for the five sectors.

3.3.1. *Efficiency First*

Under this scenario, if available water equals or exceeds the total demand of all agents in the catchment, all agents get as much water as they need. If there is not sufficient water, water is allocated preferentially, based on a sector's economic efficiency (Rand value generated per m^3 of water use) in each catchment. Water is allocated in this way until either all water is allocated or all demands are fulfilled. In catchments that still have a deficit, demand can be 'offloaded' from deficit catchments in the WMA to catchments that have surplus water. The mechanism for such a shift might be the relocation of businesses and residences, or trading of water use licenses within a sector, for example. Once this process is complete, any existing water shortages in a WMA can be alleviated through water transfers between WMAs. Under this scenario, water may be transferred from the catchment with the maximum surplus to the catchment with the maximum demand, on two conditions: water must travel over the shortest distance possible, and the amount transferred cannot exceed the recipient's deficit. Transferred water is immediately allocated according to the preferential rule described above.

3.3.2. *Hydraulic Mission*

Here, the same rule used in *Efficiency First* applies if there is sufficient water to meet all agents' needs. If available water is less than the total demanded, each sector receives an amount proportional to its demand, serving to preserve the current sectoral ratios of water use. If a WMA has a deficit, water may be transferred from a surplus WMA. Transfers are made from catchments with the maximum available surplus to catchments with the maximum demand, which favours the agricultural and mining and industrial sectors. There are no limits in the model on the distance over which water can be transferred. Transferred water is immediately allocated according to the proportional rule described above.

3.3.3. *Some, for All, Forever*

Under this scenario, CMAs are required by the Water Act to first satisfy the human and ecological components of the Reserve, respectively. Remaining water is then allocated according to the strategy used in *Efficiency First*. Water can then be transferred between WMAs under the same conditions that apply to *Efficiency First*, but in this case priority is given to the catchment with the largest deficit, irrespective of its demand. Under this scenario, CMAs take several active measures to improve sustainability and equity. First, restoration efforts are undertaken to improve the ecological management class so long as the level of ecological transformation and the withdrawal-to-availability ratio in the catchment are below the threshold values given above. Second, if the ecological management class deteriorates by five percent or more from initial conditions within a period of five years, a CMA may increase the ecological reserve requirement for the catchment by five percent, so long as the Reserve is currently met. Third, to improve equity, a CMA may intervene in catchments where the difference between the largest and smallest ratios of water allocated to water demanded exceeds 0.5 for five consecutive years (i.e. the most satisfied user's ratio is more than 50% greater than the least satisfied user's). Here, CMAs enforce water demand management practices for the largest consumer in the catchment such that a five percent reduction in demand is achieved – in other words, the consumer is able to maintain current productivity with five percent less water and the 'freed up' water can be allocated to other sectors.

3.4. Indicators

As an important area of learning on the WaterScape concerns the meeting of the three Water Act principles, agents use indicators that relate to these principles to guide their decision-making. Agents can change their water use strategy when the value of their indicator exceeds a certain threshold. For simplicity, I assume in the model that each agent uses only one indicator at any given point in time. The first indicator is the economic value generated per cubic meter of water use, a measure of efficiency. Agents change strategies when this value falls below 10 South African Rands/m^3, equivalent to one-half the average water use value across all sectors (DBSA 2000). The second indicator is the ability to fulfil the human reserve requirement with available water; agents change strategies when there is a human reserve deficit. This indicator provides a broad measure of equity, in that the inability of the human reserve requirement to be met implies that either 1) the distribution of water within a catchment is skewed or 2) the distribution of water between different catchments is skewed (or both). A third indicator is the extent of change in the present ecological management class value, a measure of sustainability; agents may change strategies when the ecological management class declines from its initial value by five percent or more.

The learning process is modeled as follows (Figure 5.4): Each year, agents use their indicator to evaluate whether their strategy in the previous year was successful. As agents assume conditions in the coming year will be similar to those in the previous year, a successful agent will continue using its previous strategy. An unsuccessful agent will imitate the most successful water user in its water management area, on the assumption that agents in relatively close proximity face reasonably similar conditions and should thus achieve similar results. An agent considers experience in the previous year only, believing memory and older information to be outdated or too costly to obtain. Learning occurs when the outcome of an agent's decision to change or persist with its strategy matches its expectation of success.

In an initial experiment, agents cannot change their indicator during the simulation. A second experiment is then conducted, in which agents may change their indicator after five successive years of failing to meet their success threshold. After five years there is a reasonable chance that an unsuccessful agent has tried all three water management strategies and may thus wish to revisit its paradigm and subsequently, the indicator by which it measures success. Indicator change follows a prescribed sequence (Figure 5.5). First, agents who use the efficiency indicator and fail to meet the success threshold are likely to be situated in catchments dominated by low-efficiency water use (i.e. agriculture and rural). Although in reality measures may exist to improve efficiency in these catchments, this is not possible in the model. These agents believe that the onus is on other catchments to improve efficiency, while the best they can do is to ensure that all water users get a reasonable share of the resource; thus they switch to the equity indicator. Second, agents who use the sustainability

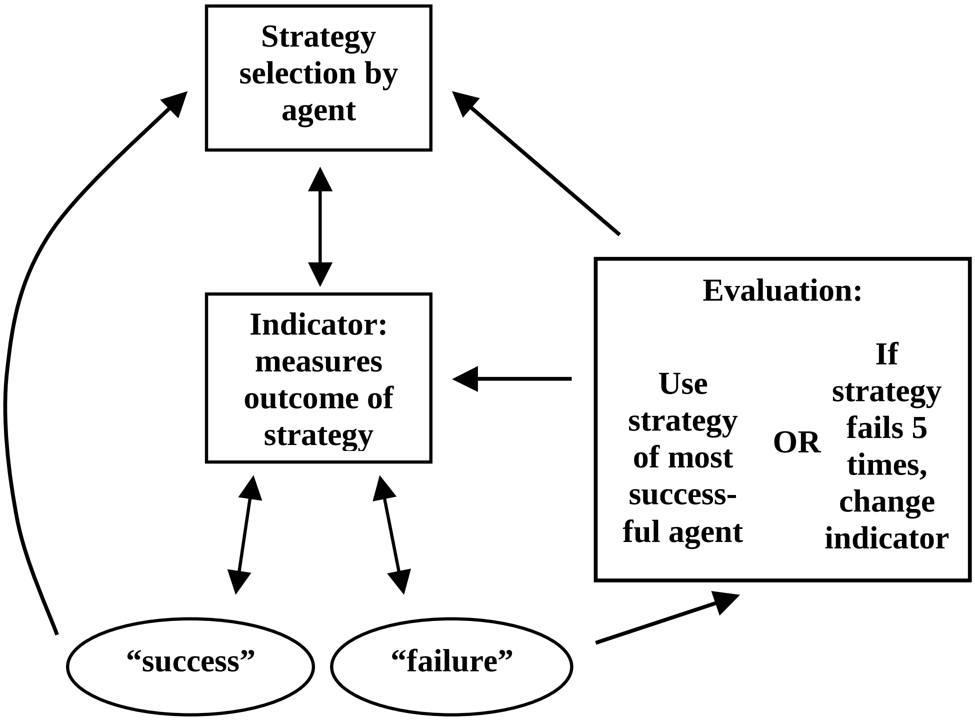

Figure 5.4. The mechanics of learning as represented in the WaterScape model.

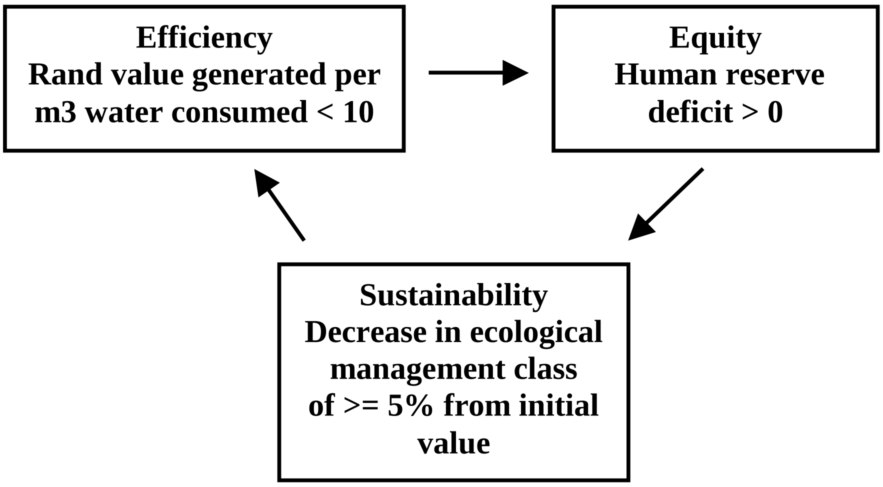

Figure 5.5. Sequence of indicator change. Agents who are unable to succeed using the efficiency indicator switch to more equitable water use; those who are unable to achieve equitable water use switch to sustainability; those who are unable to succeed using the sustainability indicator switch to efficiency.

indicator and fail switch to the efficiency indicator, believing that higher efficiency will reduce water consumption and thus slow the decline in ecological condition. Third, agents who use the equity indicator and fail are likely to be witnessing a water supply crisis: equity cannot be improved simply by increasing the amount allocated to each user. This drives these agents to adopt a more conservation-oriented approach and switch to the sustainability indicator.

The sequence of model activities is illustrated in Figure 5.6 (see also Appendix B and C for a description of model entities and attributes; the full model code is available upon request from the author at erin@sun.ac.za).

4. Results of learning experiments

Each model experiment was run for 100 time steps to observe medium- to long-term learning dynamics, and was run 20 times to account for random variation between simulations.

4.1. Use of indicators

If all agents share a perception of the WaterScape, how do they choose to manage it? When the total population of agents uses the efficiency indicator, the vast majority (80%) select the *Efficiency First* strategy at the end of the 100-year period (Figure 5.7). When the equity indicator is used by all agents, strategy selection is more erratic, but *Efficiency First* is the slightly preferred strategy for most of the simulation (Figure 5.8). When all agents use the sustainability indicator, more than 40% select *Some, for All, Forever*, with an approximately equal preference for the other two (Figure 5.9). When the three indicators are randomly distributed among agents, but are fixed, agents increasingly select the *Efficiency First* strategy, while the selection of the other two strategies declines over time (Figure 5.10), a trend that is mirrored when agents are allowed to change indicators (Figure 5.11).

Figure 5.12 shows the proportions of agents who change strategies. Agents change strategies when they fail to meet their success threshold; thus an increase in this measure signifies either increasing difficulty for agents to meet the threshold, decreasing ability to learn from other agents in the water management area, or both. About 80% of the efficiency indicator users change strategies (i.e. adopt the most successful strategy in their water management area), while about 40% of the equity and sustainability indicator users do at the end of the simulation. When the three indicators are used together, but are fixed, the proportion of strategy changers drops to about 30%, and to less than 20% when agents can

Time Step	**WaterUnit**	**WaterUser**	**CMA (Efficiency First)**	**CMA (Hydraulic Mission)**	**CMA (Some, for All, Forever)**
1	Reset variables for next step				
	Replenish runoff, as follows: 1) Adjust runoff for climate change; 2) Replenish runoff by a normally-distributed random function; 3) Adjust runoff for change in ecological management class				
			For all CMA's WaterUnits: 1) Allocate water using randomly-selected strategy; 2) Randomly assign indicator		
		'Offload' demand to other water users in sector (*EF* only)			
			Transfer water from surplus to deficit WMAs, according to rule		
					Restore degraded catchments
	Adjust ecological management class for degradation				
	Release unallocated water to downstream cells				
2	Evaluate indicator				
			For all CMA's WaterUnits: 1) Calculate or adjust for Reserve; 2) Adjust demand; 3) Allocate water based on success in previous timestep		
5	Change indicator if failure occurs for 5 consecutive timesteps				Reduce demand of largest consumer by 5% if equity threshold is exceeded for 5 consecutive timesteps; increase Reserve if sustainability threshold is exceeded for 5 consecutive timesteps

Figure 5.6. Sequence of activities in the model. All activities are repeated each timestep unless noted otherwise.

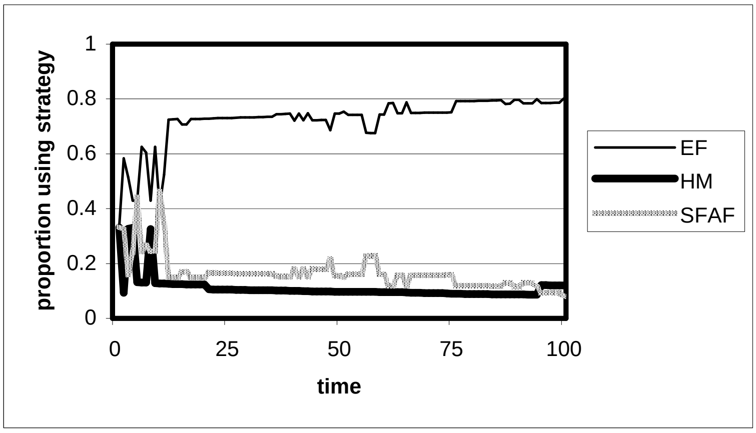

Figure 5.7. Strategy selection when all agents use the efficiency indicator (Rand value per cubic meter of water use). EF = Efficiency First, HM = Hydraulic Mission, SFAF = Some, for All, Forever.

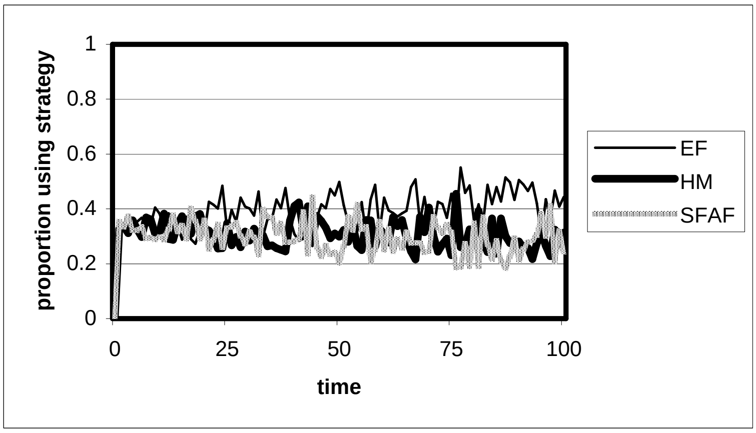

Figure 5.8. Strategy selection when all agents use the equity indicator (human reserve deficit).

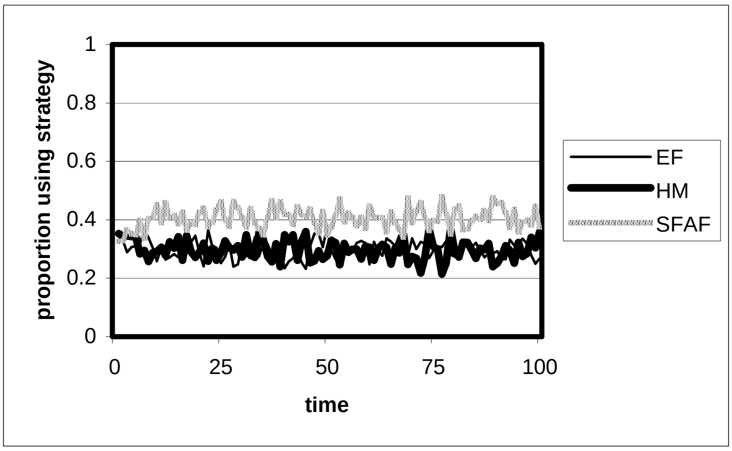

Figure 5.9. Strategy selection when all agents use the sustainability indicator (decline in present ecological management class from initial value).

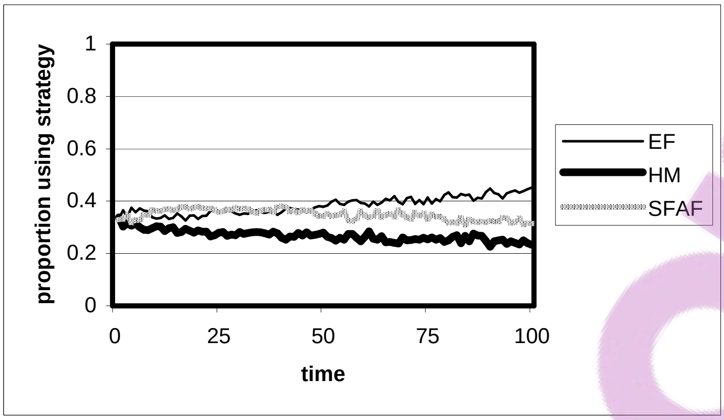

Figure 5.10. Strategy selection by agents when indicators are randomly assigned and fixed.

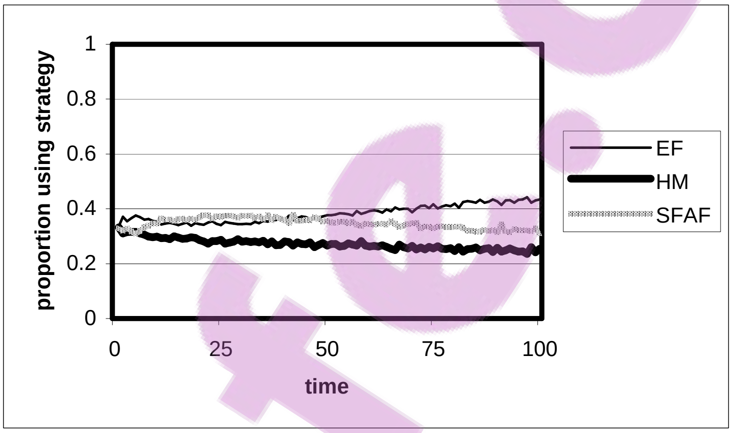

Figure 5.11. Strategy selection by agents when agents are allowed to change indicators.

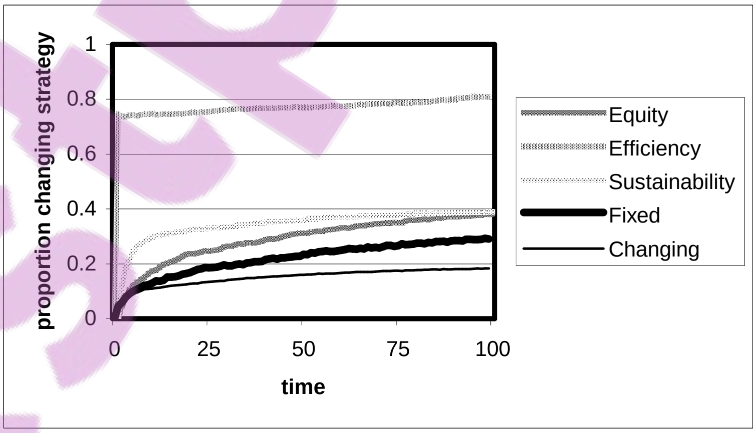

Figure 5.12. Strategy change when agents use the three single indicators, randomly-assigned fixed indicators, and changing indicators.

change indicators. In all cases, the proportion of agents that change strategies increases during the 100 years.

Given a choice of indicators, nearly half of the agents use the sustainability indicator, nearly 40% use the equity indicator, and less than 20% use the efficiency indicator by the end of the 100 years (Figure 5.13). The proportions of agents using the sustainability and efficiency indicator decline over time, however, while the proportion using the equity indicator increases.

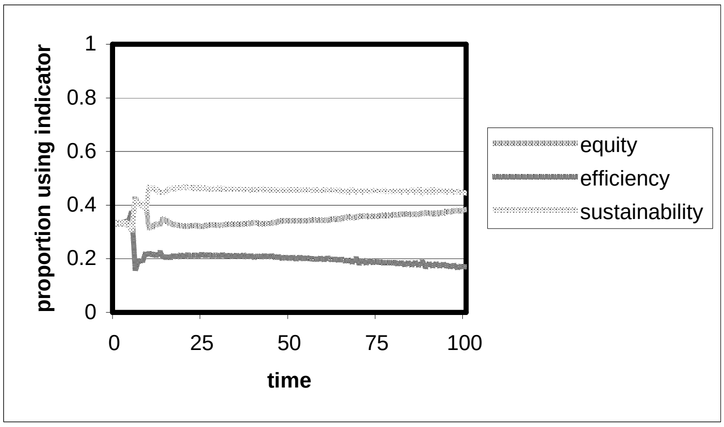

Figure 5.13. Indicator selection by agents with changing indicators.

4.2. Water Management Area (WMA) comparison

Perceptions of the WaterScape are not influenced only by agents' water management paradigms, but by the environmental conditions they experience or observe. Because many future water management decisions in South Africa will be made at the WMA level, results are compared in five WMAs which differ in hydrological variability, water stress, and size (Figure 5.14).

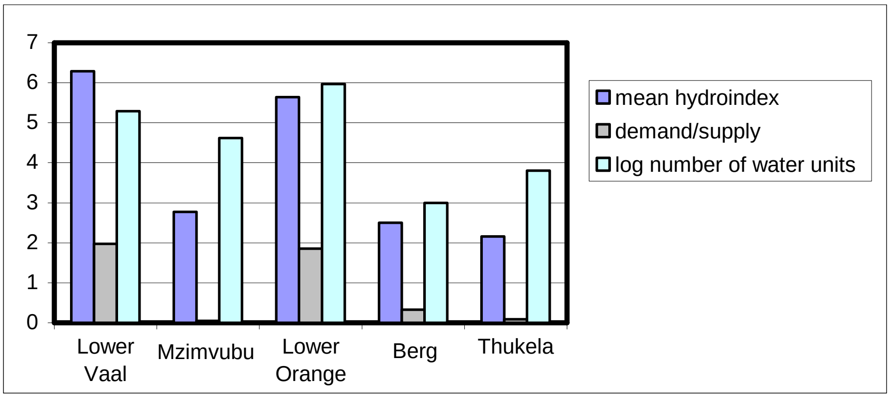

Figure 5.14. Hydrological variability (mean hydrological index value), water stress (ratio of demand to supply) and size (log number of water units) of five water management areas.

When indicators are randomly-assigned, agents slightly prefer *Efficiency First* where water stress and variability are high (e.g. Lower Vaal and Lower Orange WMAs, Figures 5.15a, c) and *Some, for All, Forever* where water stress and variability are relatively lower (e.g. Thukela and Mzimvubu, Figures 5.15b, e). Strategy preferences tend to be clearer in the least variable WMA, the Thukela, while they are most dynamic in the smallest WMA, the Berg, where a strategy selection ‘switch’ occurs at about 60 years, where *Efficiency First* overtakes *Some, for All, Forever*, and again at about 87 years, surpasses *Hydraulic Mission*.

When agents can change indicators, *Some, for All, Forever* is slightly less preferred in the Lower Vaal and Lower Orange, and *Efficiency First* is slightly more dominant in the latter (Figure 5.16a, c). *Efficiency First* prevails in the Berg (d) while in the Thukela (b) and Mzimvubu WMAs (e), *Some, for All, Forever* is strongly preferred.

When agents cannot change indicators, strategy change is more prevalent in the Lower Orange, Lower Vaal, and Berg WMAs, but increases in all over time (Figure 5.17). When they can change indicators, the proportions of agents changing strategies decreases significantly in all WMAs except the Thukela, where the majority of agents use their previous strategies regardless of whether they can change indicators. More agents continue to change strategies in the Lower Orange and Lower Vaal WMAs than in the three others (Figure 5.18).

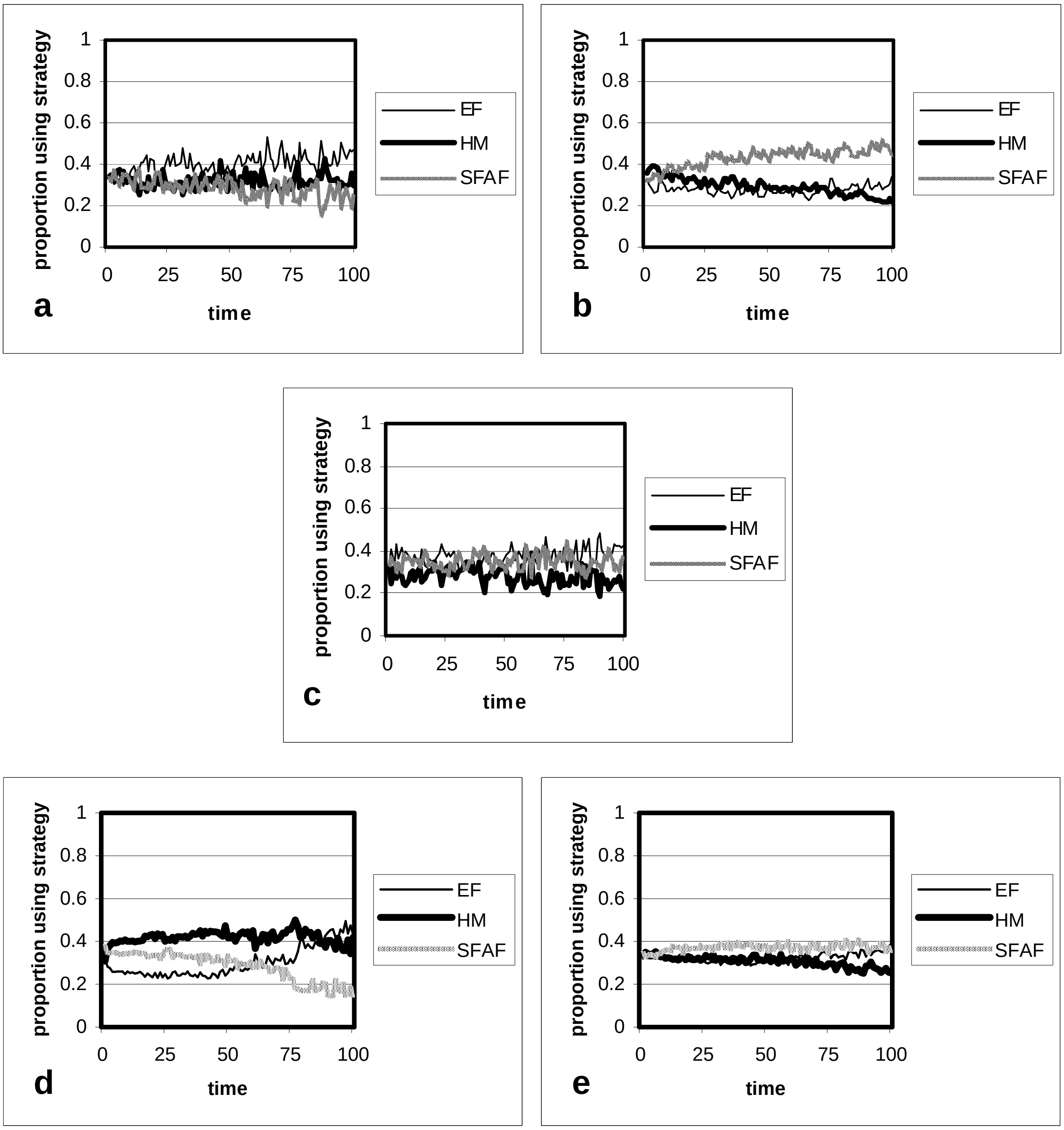

Figure 5.15. Strategy selection by agents in: a) most variable and water-stressed (Lower Vaal); b) least variable (Thukela); c) largest (Lower Orange); d) smallest (Berg); and e) least water-stressed (Mzimvubu) WMAs using randomly-assigned fixed indicators. EF = Efficiency First, HM Hydraulic Mission, SFAF = Some, for All, Forever.

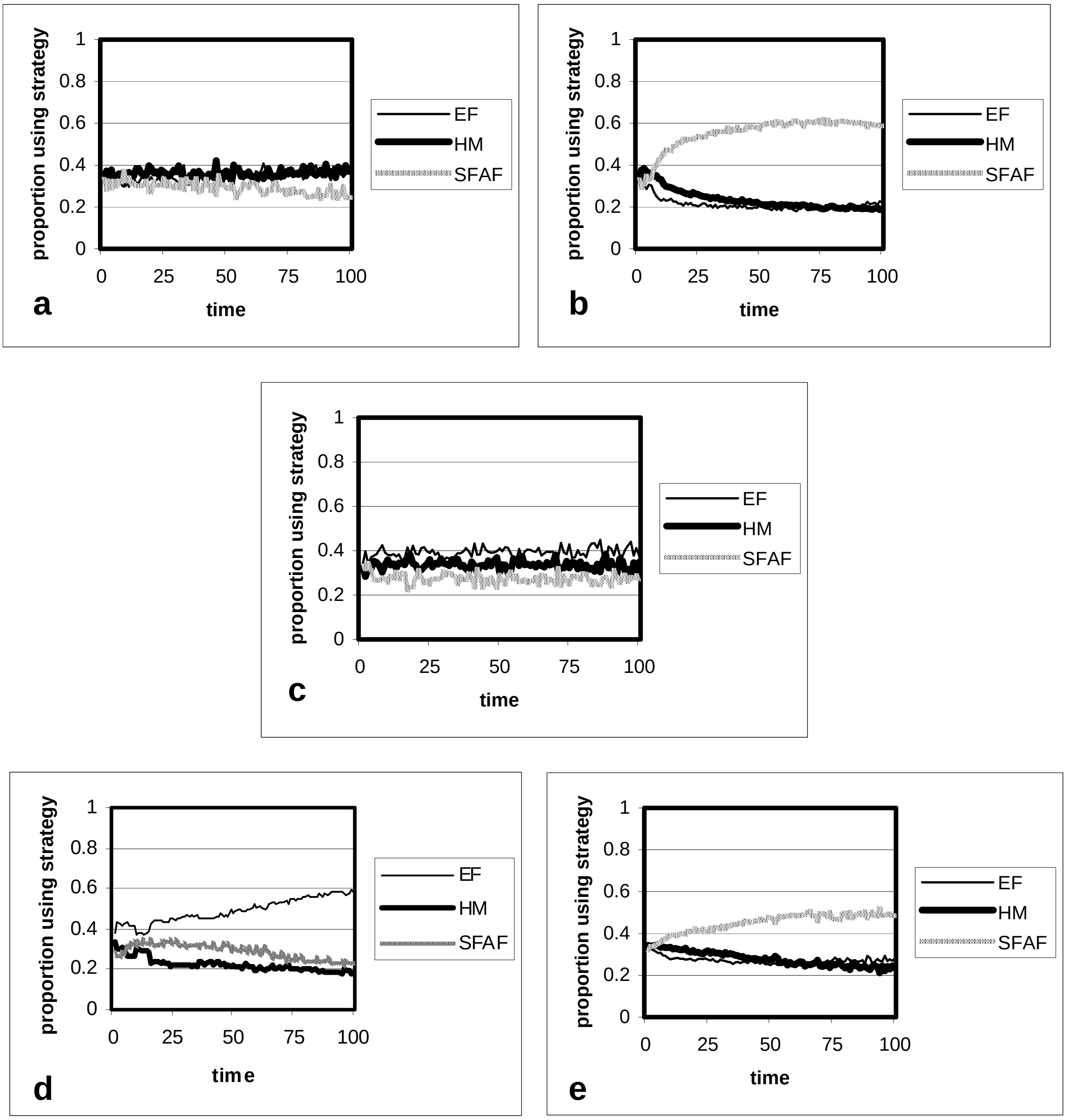

Figure 5.16. Strategy selection by agents in: a) most variable and water-stressed (Lower Vaal); b) least variable (Thukela); c) largest (Lower Orange); d) smallest (Berg); and e) least water-stressed (Mzimvubu) WMAs using changing indicators. EF = Efficiency First, HM Hydraulic Mission, SFAF = Some, for All, Forever.

The equity indicator is most strongly favoured by the Berg WMA, although at least 30% of agents use it in each WMA (Figure 5.19). The efficiency indicator is initially strongly favoured by the Berg, but preference declines over time; use of this indicator increases slightly in the Thukela (Figure 5.20). The sustainability indicator dominates most clearly in the Lower Orange and Lower Vaal WMAs, while use decreases steadily in the Berg during the first 50 years of the simulation (Figure 5.21).

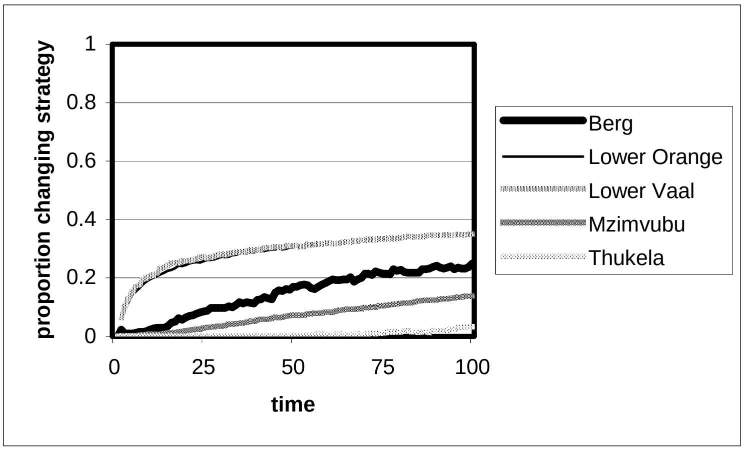

Figure 5.17. Strategy change by agents in five WMAs using randomly-assigned fixed indicators.

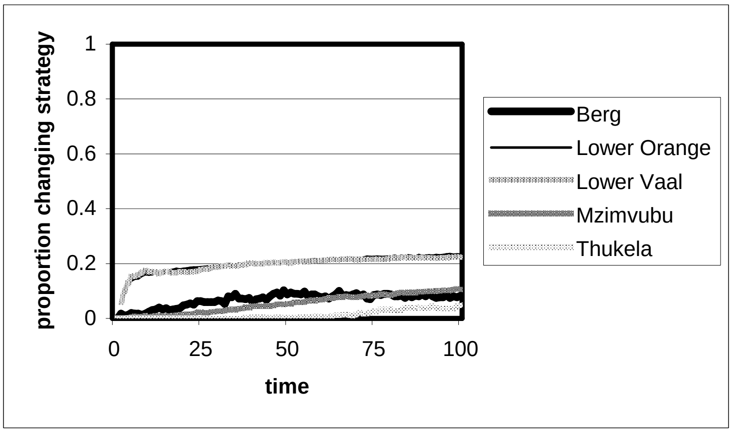

Figure 5.18. Strategy change by agents in five WMAs with changing indicators.

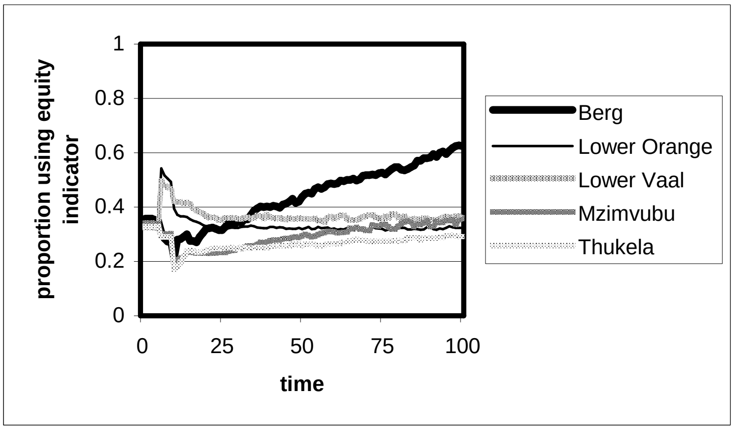

Figure 5.19. Selection of equity indicator by agents in five WMAs.

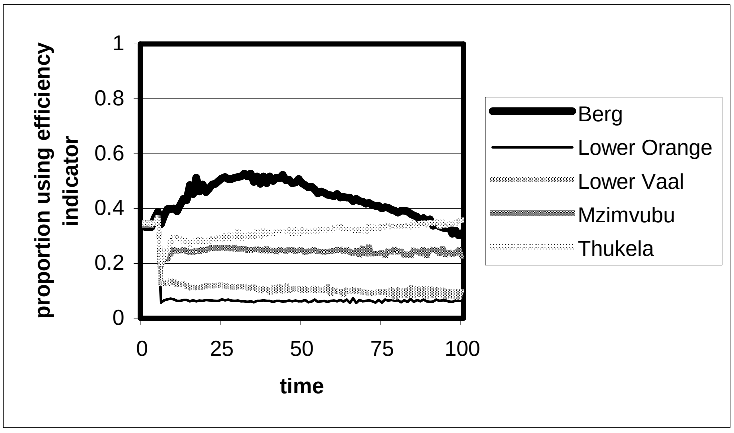

Figure 5.20. Selection of efficiency indicator by agents in five WMAs.

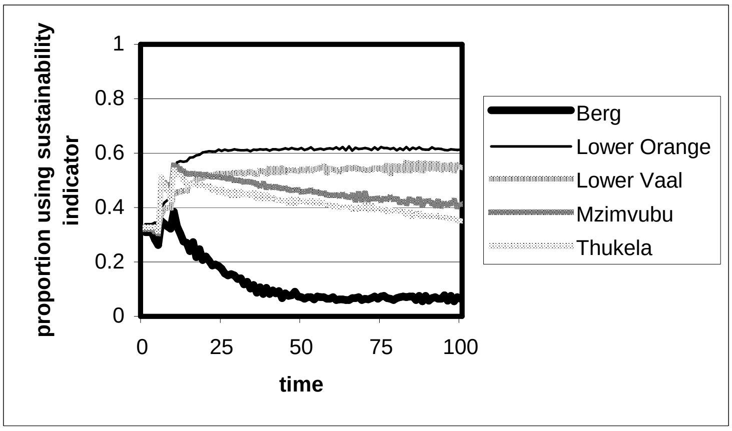

Figure 5.21. Selection of sustainability indicator by agents in five WMAs.

5. Discussion

These learning experiments investigated 1) how different social-ecological conditions and 2) agents' selection of different indicators to evaluate their actions affect capacity to learn, willingness to learn, and understanding of how and what to learn.

5.1. Social-ecological conditions

By comparing agent decisions at the WaterScape level with those made in five different WMAs, some of the ways in which conditions such as hydrological variability, water stress, and size may affect learning in the model become evident. Among the clearest preferences for a particular strategy are those shown when agents can change indicators in the Thukela WMA, which has the lowest hydrological variability and where agent experience in a given year thus has a greater change of being relevant in the following year. Agents in highly variable environments, however, may be unable to benefit from their or others' experience in the previous year, because conditions change too rapidly for them to process and respond appropriately to the change. In the Lower Vaal and Lower Orange WMAs, which have the most variable runoff and highest water stress in the country, agents' strategy choice is less erratic when they can change their indicator than when they can only change their strategy based on the success of other agents in the previous year, which may be irrelevant. In this case, high variability may challenge agents' ability to detect patterns, as observed elsewhere in resource management systems (Wilson 2002). On the other hand, where agents have difficulty achieving success, they may have more incentive to keep trying to learn from their experimentation. Thus, variability may have mixed effects: it may negatively affect agent capacity to learn or decrease confidence in learning, but may increase willingness to learn and understanding of what learning is needed.

In WMAs with lower water stress, agents are better able to stick with their current strategies, and have less 'incentive' to learn. In areas affected by higher water stress, by contrast, there is a greater need to try new strategies, a situation which may therefore increase willingness to learn. In fact, agents in water-stressed areas have an advantage over those in more water-rich ones who are simply required by the model algorithm to 'pass the test' in order to continue using their existing strategies, though these may be sub-optimal. Water-stressed agents, by failing the success test, must try new strategies, and are more likely to locate optimal ones. However, high levels of variability and water stress tend to co-occur, amplifying the opportunity to learn but also a dilemma: agents are more likely to fail to meet a success threshold because of high stress but are also more likely to fail to learn because variability makes learning difficult.

The role that size – and a related issue, the range of spatial variation in an area – plays is not entirely clear. Divergence in strategy selection clearly occurs in the Berg WMA, with about 60% of agents choosing *Efficiency First* when indicators can change. In addition to being the smallest WMA in the country, the Berg is also among the most transformed and urbanised. The high transformation discourages agents from using the sustainability indicator, while the high level of urbanisation enables a majority of agents to first use the efficiency indicator while water stress is lower and increasingly adopt the equity indicator, which the *Efficiency First* strategy serves best. Yet the small size of the Berg WMA also suggests that agents may have fewer options available for learning, so most options are identified quickly. Thus, the learning process may be more efficient than in larger or more spatially heterogeneous WMAs, but also draws on a more narrow range of experience.

It is apparent that there are ‘different strokes for different folks’: a variety of indicator-strategy combinations emerge. For variable, water-stressed WMAs, the sustainability indicator is favoured, but together with a combination of strategies. This suggests that a diversity of strategies is often most compatible with the objective of sustainability, particularly where water is less abundant. At the opposite end of the variability and water stress spectrum, a combination of the *Some, for All, Forever* strategy and the equity or efficiency indicator prevails, but this changes over time, presumably a result of the decreasing abundance of water relative to demand. The Berg WMA does not fit either profile: it begins favouring efficiency, briefly pursues sustainability, and lastly adopts the efficiency indicator. All three scenarios are roughly in equal use in the beginning of the simulation but *Efficiency First* ultimately takes over.

5. 2. Indicator selection

The use of multiple indicators frees agents from using only collective learning to identify the most successful strategy, and allows them to better evaluate individual success in combination with the success of others. Furthermore, the ability to change indicators gives agents greater power to act on their evaluations. Nevertheless, the indicators and their use in the model are clearly simplistic. Naturally water users and managers employ numerous indicators to monitor the environment and evaluate their actions. In the model, agents can use three at most – and no agent can use all simultaneously. Furthermore, in reality, water users and managers usually have access to other information that is not incorporated into indicators but provides context for decision-making, over the longer term as well as from year to year. In addition, success in achieving one's goal must be measured in a way that is consistent with the broader management goals for the system.

5. 3. Overcoming dilemmas

The results presented above suggest that the WaterScape agents may sometimes fall afoul of the learning dilemmas of challenged capacity, willingness, or understanding. This modelling exercise offers a few insights for overcoming these dilemmas to allow for more effective learning in future monitoring and management. The major indication is this: to ensure that the three pillars of learning are upheld, the focus of learning and use of indicators sometimes needs to be tailored to specific environmental conditions. For example, in high-variability areas, management may benefit in particular from a better understanding of long term trends, and the extent to which maintaining a diversity of management options that can be readily adopted as conditions change has been a successful practice in the past (Tengö and Belfrage 2004). The focus of monitoring in these areas should be on slow variables that operate in the background, such as changes in climate, that tend to occur over long time scales and coarse spatial scales, and on interactions between fast and slow variables (Wilson 2002, Lynam and Stafford-Smith 2004).

The model results suggest that agents in water-stressed WMAs may have a greater drive to learn, and be more active in formulating water allocation, conservation, and demand management strategies than water-rich WMAs. However, the new water legislation in South Africa requires water resources to be managed as a national asset, and the burden of water stress may shift to the more water-rich areas in the future as they absorb growing demands for water (DWAF 2004). Where water stress is high, learning may need to focus on efficiency of water use and demand management, as well as reallocation within and also between WMAs. Here there will be especially numerous opportunities to learn about the sensitivity to water stress of ecological parameters such as change in the ecological management class and the ecological reserve.

The size and spatial heterogeneity of an agent's 'learning network' needs to be considered: Do all agents have access to information that may help them to manage better? Can experience be broadened and shared where needed? At the same time, a bigger network may not always be better; there is a need to avoid information overload. Small or homogeneous catchments are often well-suited to learning, where they enable a high level of interaction between agents and quick building of trust (Dietz et al. 2003). Such learning environments should be supported but learning should also be extended and broadened to encompass larger-scale problems and cross-comparison where similar challenges are experienced. Databases and information exchanges to capture and share information and experiences between WMAs will be beneficial.

6. Conclusion

Learning processes in South African water management have much to gain from an agent-based modelling approach. First, the approach treats water management in the integrated social-ecological context that the subject demands, rather than treating human behaviour and water resources as distinct components. Second, implementation of the new water policy has barely begun, so there will be a much to learn and vast uncertainty that cannot be explored in any way but through visions and models of the future. The great advantage of agent-based models is that they do not intend to predict future outcomes but stimulate thinking and initiate dialogue, critical to addressing the challenges that are faced in this arena.

Only a few of the many learning dilemmas that can arise in social-ecological systems are explored here, and many cannot be solved with modelling approaches alone but will demand attention in multi-stakeholder fora. Yet such models may soon play a role in informing water-related negotiations in South Africa; in fact, they already do at smaller scales (Farolfi et al. 2004). The greatest contributions to the current era of South African water management stand to be made from an improved understanding of precisely how and why alternative water use decisions achieve efficient, equitable, and sustainable outcomes or not. Greater illumination now needs to be cast on the question of whether, under the new institutional arrangements, opportunities for learning in this dynamic environment.

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Discovering resilient pathways for water management: two frameworks and a vision

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For submission to: *Ecology and Society*

Abstract

Resilience is the amount of change or disturbance a system can withstand and still maintain its essential structure, function, and identity. Because social-ecological systems (SES) undergo constant change, managers of SES must recognize and focus on resilient 'pathways,' in which learning about and maintaining resilience is a dynamic process; a journey to a more desirable and achievable future based on a long-term perspective of the system. Several compelling frameworks and models now exist to better understand resilience from this perspective and to improve management of practical problems. In this paper, I compare the ability of two frameworks to discover resilient pathways, using the case of water management in South Africa as a focal example. These are: 1) the conceptual framework of the Millennium Ecosystem Assessment and 2) the "panarchy" model of the adaptive cycle described by Holling and elaborated by numerous others. Current South African water policy is guided by an overarching vision to balance efficiency, equity, and sustainability, but as of yet, the concept of resilience has not been fully incorporated into plans to achieve this vision. While both frameworks yield insights in this arena, each has limitations that may reduce its usefulness to managers, especially in regard to the representation of dynamics across space and time, changes in perception, and trade-offs. Improving these or other frameworks so that they are more useful to management should be a top priority, in order to more rigorously incorporate the concept of resilience into the water management discourse in South Africa, particularly at this critical time of change and opportunity.

Resilience in social-ecological systems: the temporal dimension

The view of humans and nature as coupled complex systems is gaining currency in ecological and social science, and with it, theory is proliferating to understand how these systems work and how management can consciously make them more robust (Walker et al 2002, Allison and Hobbes 2004). Increasingly, the ability to understand why management regimes for social-ecological systems (Berkes et al. 2003) succeed or fail is seen to hinge on the crucial property of resilience (Allison and Hobbes 2004, Ludwig and Stafford-Smith 2005). Resilience has multiple meanings, but is used here to refer to the ability of a system to retain its essential structure and function in the face of disturbance or change (Rappaport 1968, Holling 1973, Levin 1999). This may be expressed in terms of identity, meaning the system's critical components, their relationships in space and time, and the innovation and/or self-organization that maintain them (Cumming et al. 2005), or the ecosystem services the system provides (Walker et al. 2002). Resilient systems tend to be flexible, self-organizing (rather than controlled by external forces), and can build the capacity to learn and adapt (Carpenter et al. 2001). Though seminal work on resilience has addressed mainly its ecological dimensions (Holling 1973), there is an increasing recognition of the need to better understand social aspects of resilience (Gunderson and Folke 2005), as well as relationships between the two (Adger 2000, Cumming et al. 2005). This accompanies recent developments in resilience theory that focus on fostering sustainability by embracing change and transformation (Gunderson and Holling 2002, Walker et al. 2004).

Resilience has an important temporal dimension in that social-ecological systems tend to shift over time (and correspondingly, space) between alternative configurations. It may therefore be more useful to view resilience as a property of a particular configuration of a system than of a system itself (Carpenter et al. 2001). These alternative system configurations provide different combinations of ecosystem services; a lake in a eutrophic state may offer nearby communities the service of waste disposal for agricultural runoff, while an oligotrophic lake may offer the services of recreation and a domestic water supply that requires little treatment (Carpenter et al. 2001). This is not to say that these services are tied exclusively to these configurations; instead, the same services may be derived from ecosystems under different management regimes and degrees of conversion (Balmford et al. 2002). However, disturbance and change can result in abrupt, non-linear shifts that move the system past a threshold, beyond which services can no longer be provided as they were previously (MA 2005). In this case, configuration *x* of a social-ecological system can be said to lack resilience to disturbance *y*, and is forced to transform, or flip, into another configuration – in what may appear to be the collapse of the system as it is presently known. Such a collapse, however, does not usually affect the entire system, but rather a particular configuration and associated ecosystem services. Numerous empirical studies exist that demonstrate this in a range of ecosystems under different management regimes, such as the lakes described above (see Scheffer et al. 2001 for a review).

Because such changes may be driven by slow variables (Carpenter and Turner 2001) and are often not observable within the average human lifetime, studies of resilience that appropriate a 'deep time' perspective that incorporates a system's past, present, and future are of interest in social-ecological systems research (van der Leeuw and Aschan-Leygonie 2000, Redman and Kinzig 2003). Understanding of resilience has benefited in particular from the study of ancient societies, from which rich social-ecological histories can be reconstructed (Janssen et al. 2003, Redman and Kinzig 2003). In addition, a long-term perspective encapsulates the changing social contexts for managing social-ecological systems (Bohensky and Lynam 2005); definitions of what is socially desirable are always anchored to a temporal reference point. The ecological contexts for management also change. As Scheffer et al. (2001) observe on the challenge of ecosystem restoration: "resilient approaches acknowledge that recovery of systems from one regime to another must acknowledge that the path back is likely to be very different from the one forward."

Given the dynamic properties of resilience, the concept of "resilient pathways" (Walker et al. 2002) offers an appropriate frame for understanding resilience in social-ecological systems and managing to enhance resilience. The identification of these pathways can be seen as a process of discovery, a journey that involves learning from the past, along with the recognition that the future may be quite different from anything experienced before, and the acceptance of uncertainty (Redman and Kinzig 2003). Discovering resilient pathways is about learning by doing – improving understanding through management, and vice versa (Lee 1993).

Resilience is becoming an integral concept in water management worldwide (Falkenmark 2003, Folke 2003, Moench 2005) and has particular relevance to South Africa, where much change in its water sector is now occurring (Mackay et al. 2003). However, the potential benefits of resilience theory sit precariously alongside the danger of overwhelming policymakers with confusing, conflicting, or - because it is not arrived at through consensus - mistrusted information (Dent 2000), leading to inappropriate or limited interpretation (Cumming et al. 2005). Mechanisms are thus needed that allow stakeholders to develop a shared understanding of past trajectories, and be able to link theory to practice so that they are able to identify and navigate water management along more resilient pathways. A number of frameworks exist, but their ability to contribute to the real-world problem of water management in South Africa is not clear.

In this paper I evaluate the potential of two existing conceptual frameworks to assist the discovery of resilient pathways for South African water management. The first is the conceptual framework of the Millennium Ecosystem Assessment, an effort to provide decision-makers with information about relationships between ecosystems and human well-being (MA 2003). The second is the "panarchy model" of linked adaptive cycles described by Holling (1986, 1987, 2001) and central to the work of the Resilience Alliance (http://www.resalliance.org), which seeks to understand the source and role of transforming change in social-ecological systems (Gunderson and Holling 2002). Both are to some extent already informing water policy and policy-relevant research in South Africa (see Rogers and Biggs 1999, Rogers et al. 2000, Turton and Henwood 2002, Nel et al. 2004, Turton et al. 2005), and both enable long-term perspectives on resilience or closely related concepts. Only the panarchy model deals explicitly with resilience, but the Millennium Assessment framework addresses it implicitly. Below I describe the evolution of water management in South Africa to date, and the Water Act's fundamental vision of an efficient, equitable, and sustainable water management future. I then explore these frameworks and how they may help to inform this vision.

Evolution of water management in South Africa

Water management in South Africa has historically been challenged by a semi-arid climate and the distance of mineral deposits from large rivers, which encouraged settlement far from major water sources (Basson et al. 1997). From the mid-19th century until the present day, water management has become increasingly complex as the relationship between people and water changed (Turton and Meissner 2003) and human populations and their aspirations for water use grew (Table 6.1). For much of this period, the sector's focus was on getting water to farms and industries, with increasingly costly technical interventions such as dams and diversions assuring supplies and subsidies for commercial agriculture that discouraged sustainability (WCD 2000). Until 1994, which saw the end of minority rule under the apartheid system, water management in South Africa was rooted in highly inequitable policies that favored White individuals and the support base of the ruling political parties of the day.

Table 6.1. Water management in South Africa: a timeline of events

Year(s)	**Event**
1800s	Korana people farm on Gariep (Orange) River banks; Europeans build irrigation scheme at Upington
1820-1870	A large influx of settlers from around the world introduces 11 of the 12 invasive species that now cause the greatest problems in fynbos biome
1872	First dam constructed in Gariep basin
1880	Gold discovered in Johannesburg; water demands rise throughout surrounding Witwatersrand region
1880s-1890s	Botanists begin to note the spread of nonnative plants over mountain slopes and losses of endemic species in fynbos vegetation, while foresters promote mountain plantations of non-native trees
1895	All major Witwatersrand aquifers tapped; Johannesburg experiences water shortages
1903	Rand Water Board established
1912	Passage of South Africa's Irrigation and Conservation of Water Act lays foundation for future water allocation, reserving surplus water for private property owners and establishing irrigation boards
1920s	Controversy about effects of forest plantations on water supplies begins; demand for commercial timber products will drive high rates of afforestation with non-native hardwoods for next 60 years
1928	Department of Irrigation conceives idea of Orange River Development Project, but considered too costly
1937	Passage of the Weeds Act; poor enforcement due to lack of field staff and resources
1935	Salinity levels in Vaal Dam begin to increase due to increasing industrial activities
1943	Annual flow of Gariep River reaches 62-year high of 25,472 million cubic metres[†]
1949	Purification works built to clean or divert highly saline water in the Vaal catchment
1940s-1970s	Hydrological studies show that plantations have a negative effect on streamflow; efforts to control invasives are launched, but are uncoordinated, erratic, and hampered by limited follow-up clearing
1950s	First survey of Basutoland (now Lesotho)'s water resources undertaken to assess viability of water exportation to South Africa
1956	South Africa passes Water Act no. 54 to accommodate needs of industrial expansion
1962-3	Political climate enables Orange River Development Project to win approval; poor planning results in delays and a quadrupling of initial budget
1965	Marked acceleration of Vaal Dam salinity problem
1970s	Blackfly (*Simulium chutteri*) acquires pest status along Vaal, Gariep and Great Fish Rivers after completion of Bloemhof, Gariep, Van der Kloof Dams and Orange-Fish Tunnel.
1970	Mountain Catchment Act passed, giving responsibility for high-lying catchments to Department of Forestry; alien plants are cleared from tens of thousands of hectares
1971	Gariep Dam completed; storage capacity (5341 million cubic metres) equal to roughly one-third of Gariep basin's total runoff
1971	Water Research Commission created to initiate and fund research projects related to water management
1975	Orange-Fish Tunnel begins delivering water from Gariep River to Eastern Cape Province
1978	Vanderkloof Dam completed, the highest (108m) in South Africa
1986	Treaty signed to implement Lesotho Highlands Water Project (LHWP) after 8 years of negotiations
Late-1980s	Mountain catchment management responsibility passed from Department of Forestry to provinces; lack of funding hampers integrated invasive plant control programs and plants re-invade cleared areas
1992	Annual flow of Gariep River reaches 62-year low of 818 million cubic metres[†]
1995	DWAF minister Kader Asmal founds Working for Water Programme, which hires 7,000 people and clears 33,000 ha in its first 8 months
1995	Katse Dam – at 185 metres, the highest in Africa - completed in Lesotho's Maloti Mountains
1998	South Africa's Water Act no. 36 declares adequate water a basic human and environmental right
1998	LHWP completed; first LHWP water is released
2004	National Water Resources Strategy completed, paving the way for Water Act implementation; first proposals to establish Catchment Management Agencies completed
2005	Olifants River stops flowing into lower reaches for first time in recorded history, threatening biodiversity in downstream Kruger National Park

Sources: Herold et al. 1992; Chutter et al. 1996; World Commission on Dams 2000; WRI 2000; Thompson et al. 2001; Turton and Meissner 2002; DWAF 2003; Metsi Consultants 2002; Myburgh and Nevill 2003.

[†] Based on annual flow records from 1935-1997; mean flow for period was 6980 million cubic metres.

Non-White individuals were restricted to certain areas, typically of higher aridity, lower productivity, and lacking in formal water services (Turton and Meissner 2003).

In the years that followed South Africa's democratic elections in 1994, the National Water Act No. 36 of 1998 was penned to set the course for dramatic change in the management of water. Founded on the principles of efficiency, equity, and sustainability, the act defines water for basic human needs and for the maintenance of environmental sustainability as a right, and promotes economic efficiency of water use through charges for the financial costs of providing water to users (DWAF 2004*a*). The Act enforces a "Reserve" that sets water aside for the purposes of meeting basic human and ecosystem needs. Critically, the law devolves management of water to new institutions at the catchment level, called Catchment Management Agencies (CMAs). While the CMAs are the pivotal institutional entity in the new water management framework, they will work with local Catchment Management Committees and stakeholder organizations, which will guide the process within each catchment to decide the desired balance between protection and utilization of water resources and to establish a course of action to achieve this. They will also be subordinate to the national ministry, who will retain certain functions. Thus, there will be three tiers of water management: operational (catchment), strategic (catchment or Water Management Area (WMA)), and policy (national or regional) (MacKay et al. 2003), each operating on a different spatial as well as temporal scale.

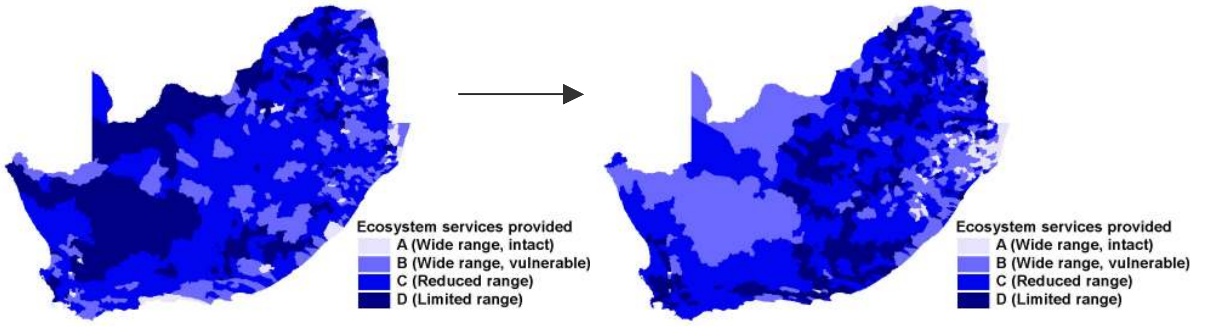
The discovery of resilient pathways takes on critical importance at this time of change. Because of large-scale interventions in South Africa's water supply and investments in expensive water quality treatment schemes (Herold et al. 1992), the capacity of what are actually highly transformed freshwater systems to deliver provisioning ecosystem services (water for people, farms, and industry) may appear to be highly resilient particularly to the many water users who are unaware of the great distances over which their water has travelled to reach them (Snaddon et al. 1998). However, the generation of runoff is only one function of these systems, and other ecosystem services have not fared as well. Water managers, like other natural resource managers, have had a tendency to trade off ecosystem services in space or time, often optimizing for a certain output and disregarding others (Gunderson 2000). In South Africa as elsewhere, most past responses improved provisioning ecosystem services and some regulating services (protection against drought and floods, and dilution of pollutants), with benefits flowing to many, but certainly not the whole of society (WCD 2000, MA 2005). These improvements have often come at the expense of supporting services (in-stream flows for aquatic biota), and cultural services (recreation, nature-based tourism, preservation of sacred sites, and cultural appreciation and use of water), and sometimes the provisioning and regulating services that they were originally intended to secure. The building of the Orange River Development Project in the 1960s, for example, improved water availability for the commercial farming sector, but altered river flows so drastically that a prolific pest blackfly (*Simulium chutteri*) invaded a large section of river used by livestock farmers, and has required significant investments in mitigation ever since (Myburgh and Nevill 2003).

At present, South African water management sits on the brink of a major transformation. The new policies enable water users and managers to collectively decide how to reap the multiple benefits of water, asking them to carefully define their objectives for the systems in which they live and the pathways they will follow to get there. However, they are faced with the formidable task of striking a balance between social equity and ecological sustainability: How to derive benefits for all – including some 5 million South Africans who still lack access to a safe and reliable water supply and another 16 million without sanitation (DWAF 2004*b*) – without taxing the ecosystems that produce them? The pathway forward depends to a large degree on the capacity of water users, managers, and institutions to plot a sustainable course to govern resources in the coming years, based on a mutual vision of the future (Rogers and Biggs 1999).

A vision for water management

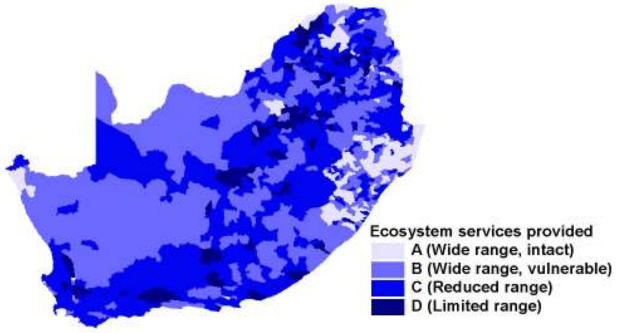
A vision in terms of the South African Water Act refers to a universally-accepted conceptualization of how water will be managed in the future and the ecosystem services that will be maintained, so that the three Water Act principles of efficiency, equity, and sustainability are upheld. Such a vision is expected to be achieved through the integration of social values, scientific knowledge, and management experience in a multi-party system (Rogers and Bestbier 1997, Rogers and Biggs 1999).

Defining a desired trajectory for water management requires a sound and shared understanding of the biophysical processes that govern water resources and the array of ecosystem services that they provide; it also demands an understanding of the human (individual, social, and cultural) dependence and impacts on these services (MA 2003). To date, more progress has probably made on the first aspect in South Africa (van Wyk et al. 2001). Initiatives such as the National Spatial Biodiversity Assessment (Driver et al. 2005), which have analyzed the spatial distribution of freshwater biodiversity and the level of threat imposed by current land use, water abstraction, and other human activities, provide a reasonably good basis for understanding ecological integrity and vulnerability (Nel et al. 2004). Efforts to actually map the full range of ecosystem services provided by freshwater in South Africa are only beginning (Bohensky et al. 2004, Reyers et al. 2005) and must currently be inferred from an water resources classification system (Palmer et al. 2004) that indicate the extent of modification of each water resource in the country. As the classification process is still being refined, only desktop estimates are presently available (Kleynhans 2000) based on data collected in 1998 and 1999 and regional expert knowledge, but allow for a rudimentary comparison of present, suggested, and default ecological management classes, and the plotting of various pathways of future water management. Figure 6.1 illustrates such a pathway, revealing how past actions have increased the range of ecosystem services in some areas but have reduced it in others. This also suggests one possible vision for the future, and identifies areas to target for restoration.



Past (default, prior to modification)

Present



Future: possible attainable vision

Figure 6.1. A possible pathway of water use, based on past, present and suggested future ecological management classes (Kleynhans 2000).

Little work has dealt with the other side of the equation – the extent to which these services actually reach people, growing human demands for water, and trade-offs between services and human well-being. In moving from the present to the future of water management, sacrifices will be made: which ones will be considered acceptable, and where will the power to make such decisions reside? Such questions are rooted in the social dimension of resilience. One avenue of research related to social resilience in South African water management is Ohlsson and Turton (2000)'s exploration of social adaptive capacity. Social adaptive capacity is defined as the ability of society to manage water scarcity (what the authors call "first order scarcity"), usually through economic ("second order scarcity") means. More recent work by Turton et al. (2005) proposes a model of water governance, which unites government, society, and science in an integrated view of the water scarcity concept. This model shows promise as a mechanism for linking social aspects of water management to those related to ecological resilience.

Two frameworks

Millennium Ecosystem Assessment

The Millennium Ecosystem Assessment (MA) was a four-year international work program to bring scientific information about the relationships between ecosystems and human well-being to decision-makers in government, institutions, communities, and private industry (MA 2005). The program was designed around a conceptual framework that identifies the relationships between indirect and direct drivers of ecosystem change, ecosystem services, and human well-being (Figure 6.2). Indirect drivers include demographics, economy, institutions, technology, and culture and religion which influence human behaviour. These can affect human well-being directly or indirectly via direct drivers, which include environmental processes such as climate change, land use change, hydrological change, which in turn affect ecosystem services. Human well-being may have feedbacks on indirect drivers. Within the framework there are opportunities for responses, or strategies and interventions that can halt, reverse, or otherwise change a process in order to enhance human well-being and conserve ecosystems. The interactions depicted by the framework occur at and across various spatial and temporal scales. The Millennium Ecosystem Assessment did not focus explicitly on resilience, but acknowledges both ecological and social aspects of

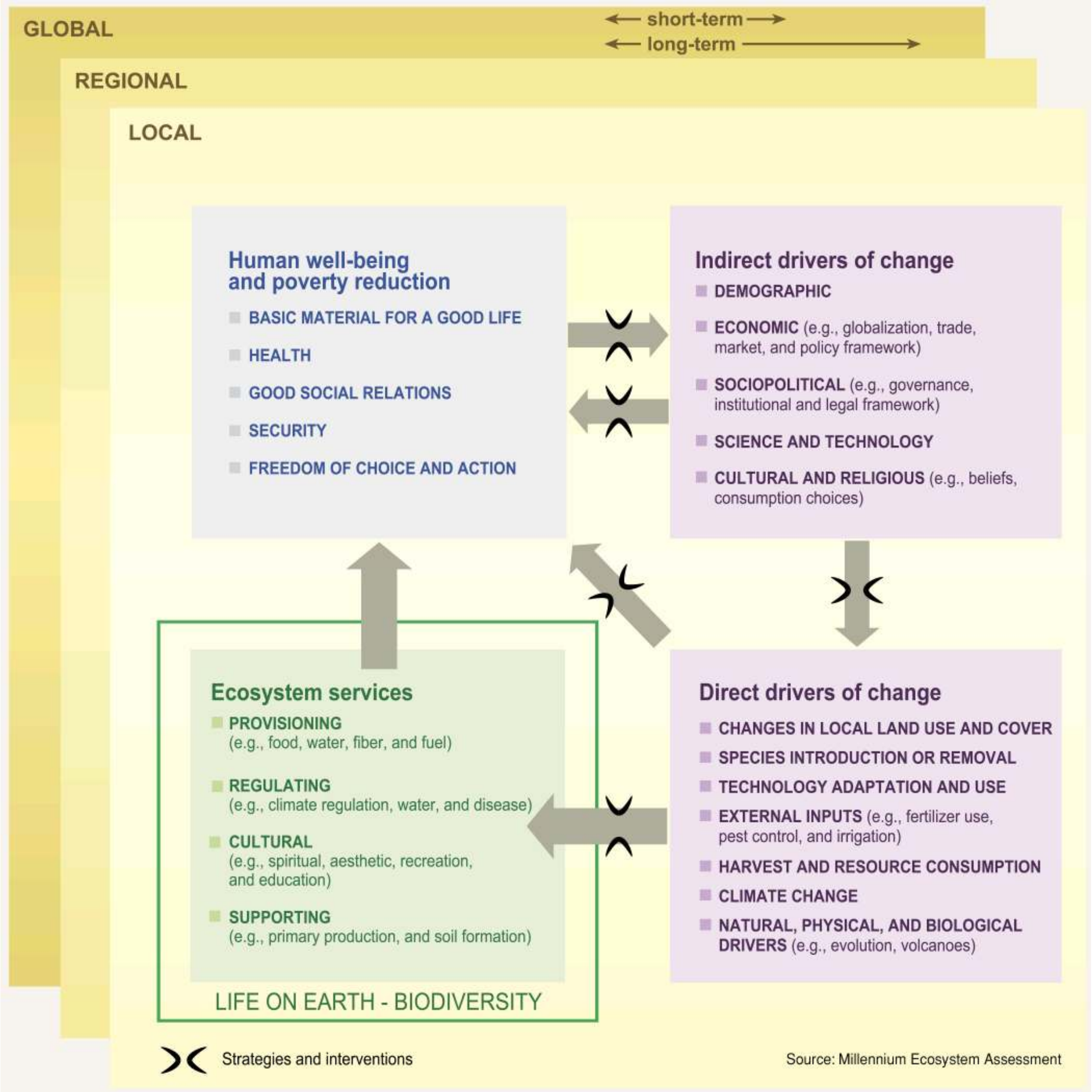
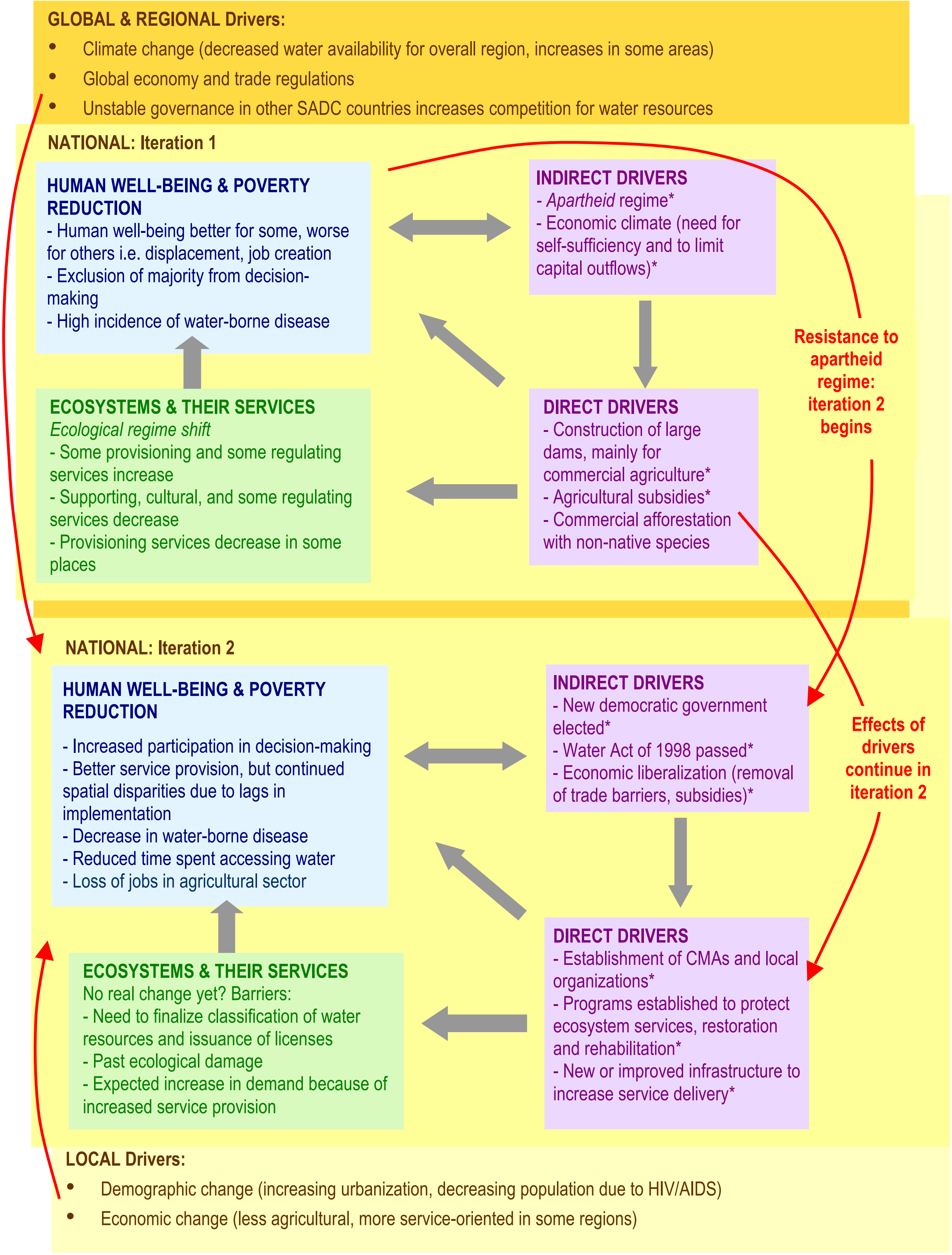


Figure 6.2. Conceptual framework of the Millennium Ecosystem Assessment (MA 2005). Key components of the framework are indirect drivers, direct drivers, ecosystem services, and human well-being and poverty reduction, and the relationships between components. Note that there are no interventions in the relationship between ecosystem services and human well-being, which is assumed to be unalterable, although it is possible to alter this relationship through the drivers that act on ecosystem services and human well-being.



GLOBAL & REGIONAL Drivers:

- Climate change (decreased water availability for overall region, increases in some areas)
- Global economy and trade regulations
- Unstable governance in other SADC countries increases competition for water resources

NATIONAL: Iteration 1

HUMAN WELL-BEING & POVERTY REDUCTION
- Human well-being better for some, worse for others i.e. displacement, job creation
- Exclusion of majority from decision-making
- High incidence of water-borne disease

INDIRECT DRIVERS
- *Apartheid* regime*
- Economic climate (need for self-sufficiency and to limit capital outflows)*

ECOSYSTEMS & THEIR SERVICES
Ecological regime shift
- Some provisioning and some regulating services increase
- Supporting, cultural, and some regulating services decrease
- Provisioning services decrease in some places

DIRECT DRIVERS
- Construction of large dams, mainly for commercial agriculture*
- Agricultural subsidies*
- Commercial afforestation with non-native species

NATIONAL: Iteration 2

HUMAN WELL-BEING & POVERTY REDUCTION

- Increased participation in decision-making
- Better service provision, but continued spatial disparities due to lags in implementation
- Decrease in water-borne disease
- Reduced time spent accessing water
- Loss of jobs in agricultural sector

INDIRECT DRIVERS
- New democratic government elected*
- Water Act of 1998 passed*
- Economic liberalization (removal of trade barriers, subsidies)*

ECOSYSTEMS & THEIR SERVICES
No real change yet? Barriers:
- Need to finalize classification of water resources and issuance of licenses
- Past ecological damage
- Expected increase in demand because of increased service provision

DIRECT DRIVERS
- Establishment of CMAs and local organizations*
- Programs established to protect ecosystem services, restoration and rehabilitation*
- New or improved infrastructure to increase service delivery*

LOCAL Drivers:

- Demographic change (increasing urbanization, decreasing population due to HIV/AIDS)
- Economic change (less agricultural, more service-oriented in some regions)

Figure 6.3. Adaptation of the MA conceptual framework to depict two iterations of South African water management. An asterisk (*) denotes features that are both drivers and (direct and indirect) responses for managing water.

resilience in line with the definition above (MA 2005).

In Figure 6.3, the generic components of the framework shown in Figure 6.2 are populated with the South African water example. For the sake of simplicity and clarity, only the dynamics that are thought to be most relevant to social-ecological system resilience are included. Because water management today is significantly shaped by numerous events and processes that have dominated the past century, two iterations of the framework are shown, each of which depicts an era of water management. In addition, because water management at the national scale is linked to processes at global, regional, and local scales, two boxes are added to Figure 6.3. in which some of the main higher- and lower-level drivers are listed.

In the first iteration, the apartheid regime and its policies (indirect drivers of change) encourage the building of large dams and other infrastructure in support of commercial agriculture (direct drivers of change). These effect an ecological regime shift in the most modified catchments of the country, whereby highly altered flow regimes cause large changes in aquatic chemistry and biota (Chutter et al. 1996). There are adverse effects on human well-being but also beneficial ones; the dam projects displace some communities but commercial farms are a major source of employment (MacKay 2003). During this time, commercial forestry plantations of non-native species in mountain catchments proliferate and reduce streamflow (Görgens and van Wilgen 2004); they also facilitate the spread of non-commercial invasive alien plant species (Le Maitre et al. 2004).

The transition from the first to second era comes about as part of the growing internal and external resistance to apartheid and its economic, social, and environmental consequences (MacKay 2003). In the second iteration, the nature of drivers shifts to some degree from technical responses aimed at supporting commercial agriculture and industry to a broader, integrative approach that makes legal provision for the satisfaction of basic human and ecological needs. Since this era is still in progress, few of the effects of this new approach on ecosystems and their services are observable at present, although efforts such as the Working for Water Programme to restore ecosystems through invasive plant eradication have demonstrated substantial benefits for water resources (Görgens and van Wilgen 2004). Human well-being is expected to improve in time from the policy changes, particularly through increased access to water supplies (DWAF 2004*b*) and participatory decision-making, but there is limited evidence of improvement at present. Gains may also be offset by the past erosion of ecological integrity and detrimental feedbacks on current and future human well-being, though thus far not well documented or understood. Additionally, the new water management policies eliminate subsidies for commercial agriculture with the aim of internalizing some of the high costs of agriculture that were previously passed on to society and ecosystems, but to some extent compromising the economic viability of this sector (MacKay 2003).

To indicate the continuation of the cycle over time, the framework is amended with the addition of an arrow from the human-well being box in the first iteration to the indirect drivers box in the second iteration. While indirect drivers change from the first era to the second, some of the direct drivers that operate in the first era, such as investment in infrastructure to support supply-side water management, continue to operate in the present and are expected to form part of the national water supply strategy for the foreseeable future (DWAF 2004*a*). A second arrow is inserted to show the continued influence of the first-iteration direct drivers in the second iteration. Arrows are also drawn from the “global and regional drivers” and “local drivers” boxes to the second iteration of the national-scale dynamics, where these cross-scale links become apparent.

In populating the framework with this example, one observes that some elements can be categorized as drivers and responses, depending on the reference point in space and time. In fact, one can argue that all of the anthropogenic drivers of change in ecosystems and their services are human responses in one form or another. Indeed, the categorization of such elements may depend on the use of the framework: an assessment intended to identify or improve policies may prefer to consider these as responses, whereas an assessment focused on understanding processes may opt to label these as drivers. For the purposes of this paper, in which the intent is closer to the latter, these elements are identified as drivers in Figure 6.3, but are noted with an asterisk, while possible interventions in the relationships between components are not shown.

Panarchy

The panarchy model is a theory of complex system dynamics, of which the adaptive cycle is a central feature (Holling 1986, 1987, 2001, Holling and Gunderson 2002). The cycle describes four phases or ecosystem functions: growth or exploitation, denoted by *r*, in which recently disturbed areas are rapidly colonized; conservation (*K*), in which energy and material are slowly accumulated and stored; release (*Ω*), in which the tightly bound accumulation of biomass becomes increasingly fragile until it is suddenly released by external agents; and reorganization (*α*), in which resources are reconfigured to take advantage of new opportunities. While this description refers to ecosystems, it also applies to social or social-ecological systems, which likewise progress through phases of growth, conservation, release, and reorganization (Redman and Kinzig 2003).

The cycle can be illustrated as a heuristic model best represented as a "figure of eight" in two-dimensional space, with connectedness on the *x* axis and potential or capital on the *y* axis (Holling and Gunderson 2002; Figure 6.4). *Connectedness* refers to the strength of internal links or relationships that mediate external variability. A certain amount of connectedness has advantages, but it is possible for a system to become overconnected, which reduces external variability and increases system rigidity. *Potential* means the capability for change through accumulated resources, whether ecological, social, or economic. The length of the arrows between the phases indicates the speed of transition; the model suggests that the system moves quickly from exploitation to conservation, and more slowly from conservation to release and from release to reorganization. At this point, the system may exit from the cycle and enter a second iteration as an alternatively configured system (Holling 1986). The cycle then begins again. "Panarchy" refers to a series of linked and often nested cycles that evolve through space and time (Holling et al. 2002).

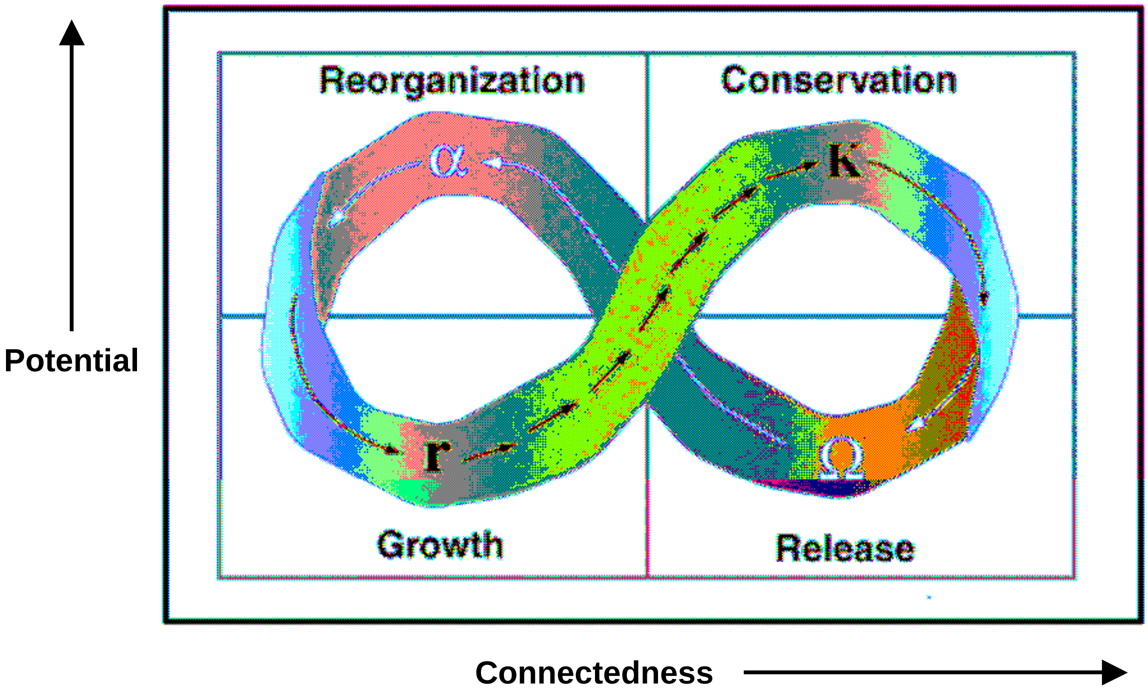


Figure 6.4. The panarchy model (Holling 2001) is comprised of four ecosystem phases (r, K, Ω, and α) and the flow of events between them. Figure adapted from Moench (2005).

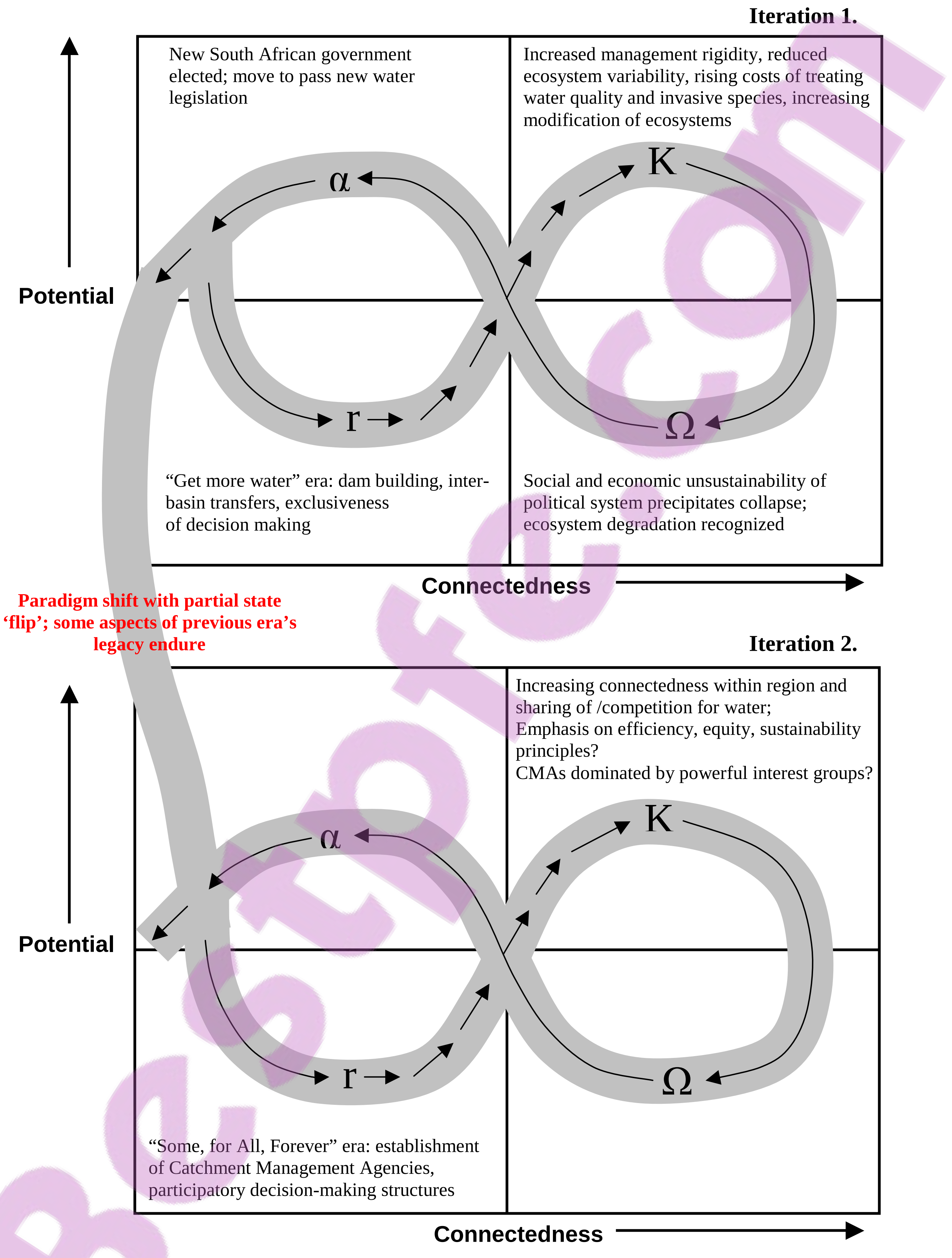


Figure 6.5. The panarchy model of the adaptive cycle is used to depict the dynamics in South African water management during the previous (iteration 1) and current (iteration 2) eras.

In Figure 6.5, the South African water management example is worked through the panarchy model. As with the MA framework, two iterations are shown. The first depicts the previous “get more water” era of management (Dent 2000), which has completed one full phase of the adaptive cycle. During the exploitation phase, increasing investment is made in large infrastructure as potential and connectedness both increase. This leads to greater management rigidity, and through reduced ecosystem variability, increasing degradation, though the ecosystem services of water and food production increase. Forces largely external to the water management system, in the form of social discontent, economic decline, and political pressure, eventually leads to the collapse of the apartheid government. As the system reorganizes, old water laws are repealed and an extensive consultation process commences to draft new laws.

The second iteration of the cycle begins. At this point in time, the overall system undergoes a paradigm shift but only a partial change in configuration. The Water Act marks a phase of reorganization, but the system is saddled with the legacy of the past era’s high-cost responses that severely limit flexibility in achieving the Act’s efficiency, equity, and sustainability principles: large dams, interbasin transfers, and treatment of invasive species and pollution. The system has endured some partial crises and collapses, but none that have overwhelmed it entirely because there has been sufficient ecological and social resilience overall to buffer the effects of disturbance. This does not preclude the future occurrence of a larger-scale crisis, however. Past actions have compromised many future options; freshwater biodiversity is considered transformed in 26% of the country’s mainstem rivers to the point that rehabilitation is no longer possible (Nel et al. 2004).

As water management moves into the second iteration, there is increasing connectedness within the social-ecological system. The South African economy is highly dependent on inter-basin transfers. In Gauteng Province, which generates the majority of South Africa’s wealth, all economically-productive water is transferred from catchments outside the province (Basson et al. 1997). South Africa is now highly reliant on the water resources of Lesotho through a multi-billion dollar water project (Metsi Consultants 2002). Water resources are shared with four additional neighboring countries, all with growing demands.

Connectedness extends beyond links between surface water resources; there are interactions between surface and ground water, for example, with groundwater becoming an increasingly important resource in many areas, over-abstraction may deplete surface water (Haupt 2001). There are also increasing water-atmosphere connections; in the Vaal catchment, salinity, already a substantial problem, is believed to have increased due to atmospheric deposition from the area's power plants and other industries (Herold et al. 1992).

The effect of the new Catchment Management Agencies (CMA)s on this connectedness is unclear; in theory; the devolution of water management functions to CMAs provides insurance against over-connectedness, as each develops its own system and style of governance in its Water Management Area. However, there is a danger that some CMAs may be dominated by powerful interests (Chikozho 2005), lack capacity to carry out their functions (Pollard and du Toit 2005), or revert to the old practices of the Department of Water Affairs and Forestry – simply becoming regional extensions of the national department rather than reasonably autonomous entities (Dent 2005).

Analysis of frameworks

A framework should be used to understand the past or guide the future; the resilient pathways concept suggests that it needs to do both. Bearing this is mind, can these frameworks help to clarify the vision of the South African Water Act and ultimately achieve it?

It is possible to trace the past era of water management through a full cycle of the MA framework and the panarchy model. The previous era appears to be traceable through the direct drivers box in the MA framework; many of the effects of these drivers on ecosystem services and human well-being remain uncertain at present. The current era of water management is traceable through the very early exploitation and growth phase in the panarchy model; some elements are more likely to remain in the reorganization phase, while other elements have not actually exited from the previous iteration of the cycle. Beyond these points, only inferences may be made and possible scenarios sketched about the future course of events.

From this exercise, several findings emerge about water management dynamics and the application of these frameworks. The first is that cross-scale connectedness has increased over time. In the system's first iteration, during the "get more water" era, there is little need to include regional or local processes in either illustration of the example. During the second iteration, increasing awareness of global and regional change (e.g. climate, trade), and increasing involvement of local institutions and communities in decision making, create a need to expand upon the illustration with links to these processes. This emphasizes a particular limitation encountered in using the MA framework that arises from the static relationship that the framework implies (Zermoglio et al. 2006). As noted above, the distinction between drivers and responses can be somewhat ambiguous. In addition, issues of temporal scale are difficult to capture with the generic framework. Links between scales may change over time (Gunderson et al. 2002); in the example, they become more relevant in the second iteration, where connectedness to global and regional processes increases in the post-apartheid environment, while sensitivity to local processes increases with the decentralization of decision-making.

These limitations, however, underscore an important finding about the changing dynamics of water management: a fundamental change from the first to second iteration is one in the managers' *understanding* and acceptance of connectedness (Gunderson et al. 2002). Regional and local processes have always influenced water resource dynamics in South Africa, but were previously ignored by managers who treated the system as closed (Bohensky and Lynam 2005). While the MA framework does treat human behavior and perception as an indirect driver, neither of these two frameworks seem to cater for a distinction between "actual" and perceived dynamics, with the latter often being equally if not more important than any physical system change.

Secondly, managers rarely have a clean slate to work upon at the beginning of a new iteration because of the legacy effects of past management actions. Consequences of the past still linger now, as remnants from management decisions taken today will linger in the future. The adaptation of the panarchy model to the South African water situation suggests that some options have been eliminated or constrained, and even as a new iteration of the cycle begins after a partial release, the system may be too overconnected.

A third finding relates to trade-offs, which are inherent in social-ecological systems. The MA framework suggests that improvements in ecosystem services and human well-being are not always synergistic; more often there are trade-offs. One may be inclined to conclude - though never implied by the framework - that 'good' drivers will lead to 'better' ecosystem services and then to 'better' human well-being, but this is in fact a gross simplification. Interestingly, the MA invested great efforts in assessing trade-offs (MA 2005), and that the framework does not more explicitly accommodate their representation is somewhat surprising. The panarchy model, by contrast, does capture an important trade-off of a different nature, between connectedness and potential. This may manifest, for example, in the decision to manage for productivity or to manage for sustainability (Walker et al. 2002). Note that a system in the upper-right quadrant (high potential and connectedness) is unlikely to persist in its current configuration.

The emphasis of current work on ecological aspects of the vision for South African water management suggests that the social aspects of the vision need more development. Both frameworks, and indeed the broader study of resilience, may contribute in this regard, in that they begin to break down the barriers that have traditionally separated the study of human and natural systems. They do this in quite different ways, however. The MA framework includes the crucial feedback from human well-being to drivers of ecosystem change. This is an aspect of natural resource management and decision-making that is typically ignored and generally very poorly understood, though so often at the center of a debate on whether impoverished (in all senses of the word) people cause more environmental destruction than their more well-off counterparts (MA 2003). The panarchy model, on the other hand, does not use a compartmentalization that distinguishes ecological and human components of the system, but rather treats them as one. The MA framework, which treats ecosystem services and human well-being as distinct boxes or arrows, describes the elements of the system - though this may pose a challenge for elements which may not be neatly categorized, as noted above. The panarchy model describes its processes, fluxes, and transitions – how the relationships captured in the framework may change over time.

It is important to note the different intentions of these frameworks; the MA framework was developed to assist decision-makers in understanding the relationships between ecosystems and human well-being, while the panarchy effort sought to develop an integrative theory of adaptive change that applies to some, if not all, social-ecological systems. The MA framework may be more accessible as a tool for identifying management responses, whereas the panarchy model is somewhat vague as a mechanism for guiding action. Alternatively, the two could be used together, where researchers and managers use the MA framework to define the elements and their relationships to one another at a particular scale of space and time, and then use the panarchy model to see how these relationships may change or gain or lose relevance as the system evolves.

Both frameworks run the risk of being too general, but this does not make them useless where sufficient flexibility is allowed. The Millennium Assessment framework, for example, was considered too abstract and inaccessible to a sub-global assessment team in Peru who worked closely with local Quechua communities, so it was modified to better reflect their cosmologies (Zermoglio et al. 2006). The adaptive cycle and panarchy concepts have been replicated, elaborated upon, and adapted widely by contributors to Gunderson and Holling’s edited volume *Panarchy* (2002) and the journal *Ecology & Society* (see Redman and Kinzig 2003, Allison and Hobbes 2004, Cumming and Collier 2005), among others (e.g.

Peterson 2000). Such innovations are likely to strengthen both the framework and understanding of the real-world examples studied.

Conclusion

The two frameworks explored in this paper appear able to help clarify the vision of the South African Water Act and challenges faced in achieving it. This is an essential starting point. Sizeable efforts are still needed to bring the understanding of resilience into sharper focus and to unite disparate strands of resilience-related research in the South African water sector. Thus far, most research appears to be limited to one or another part of the resilience equation rather than the whole: resilience is discussed either in an ecological and ecosystem services sense (MacKay 2000), or in a socio-political sense, though the word “resilience” may not actually be used (Ohlsson and Turton 2000, Pollard and du Toit 2005, Turton et al. 2005). In isolation, neither approach may prove to be extremely useful for moving water management forward, with convergence of the two required somewhere in the middle, as some of these contributions appear to recognize.

South Africa’s water sector is currently in the midst of an unprecedented transformation, with a unique history serving as an excellent opportunity to test and contribute to resilience theory and application from a long-term perspective. The exploration of existing frameworks can assist managers in the discovery of resilience and clarification of a vision, though the process of discovering resilient pathways – the journey itself – may be as important as the outcome. Further development of such frameworks could provide stakeholders with diverse interests a forum in which to interact around often difficult and contentious issues, where they may finally arrive at a desirable road map for the future.

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Synthesis

> **The Law of Vanishing Civilizations: The Tenth Water Law of the West should be called the Hohokam Law of Water and Gravity. Under this law, if there is no rain, there is no water to flow down hill. What went up—the buildings and the civilization—may crumble to dust if Mother Nature decides to hold a long drought. Lying beneath the streets of Phoenix are the ruins of the ancient Hohokam Indian metropolis that vanished prior to 1400 AD. Phoenix is the second city to be built on the same site in reliance on the erratic flows of the Salt River. Californians prayed for rain for the last six years (apparently successfully) because they didn't have enough water to flush their toilets. Many Southern Californians had been heard to ask 'What do you mean this used to be a desert?'**
>
> **—Hugh Holub, 1999**

At the end of 2005 a southern African river, the Olifants, stopped flowing into its downstream reaches for the first time in recorded history. Unlike the Salt River of Phoenix, the downstream reaches of the Olifants do not support an urban metropolis, but a major reservoir of biodiversity and an ecotourism flagship, the Kruger National Park. Park managers, tracking rainfall and upstream withdrawals, foresaw this outcome months - even years - prior to its occurrence, but believed the problem would be easily solved by the usual means whenever river flows fell below a certain threshold of potential concern (Rogers and Biggs 1999): a negotiated release from a dam upstream. This time, however, the dam manager refused the request, an unexpected outcome (H. C. Biggs, *pers. comm.*). Because the South African Water Act is not yet fully implemented, the park was without any clear legal recourse to persuade higher levels of authority to intervene on its behalf in what had become a battle for water between multiple government departments, each trying to fulfill its mandate (Macleod 2006). In the no-man's-land in which South African water law now finds itself, praying for rain may be as good an option as any.

Why, when today's scientific and technological capabilities are presumably advanced far beyond the knowledge base on which the Hohokam civilisation relied, does modern society still resort to myopic management responses – or no responses at all? This question, of much philosophical interest to scholars across disciplines (Tainter 1998, Janssen et al. 2003, Redman and Kinzig 2003, Diamond 2005), is closely linked to the central question explored in the previous five chapters of this thesis: why is sound management so elusive, and how can social-ecological systems thinking improve management? Here I explore some potential answers to this question, synthesising the findings of the five chapters and the considering the contribution each makes to our current understanding of water from a social-ecological systems perspective.

Chapter 2 presents a framework for understanding why management responses in complex systems may succeed or fail based on congruence of impact, awareness, and power scopes. While congruence of impact, awareness, and power is more likely to accompany effective responses, it can never be complete. Decentralisation and devolution of power to Catchment Management Agencies (CMAs) will not achieve perfect congruence, for example, because CMAs will inevitably be affected by processes operating at other scales. A concern emerging now is the scale mismatch between broader water management by the CMAs, and the responsibility for water supply, which is given to municipalities under the Water Services Act of 1997 (Pollard and du Toit 2005). Water managers must recognise that institutional structures of any type may be inadequate to deal with the full suite of social-ecological system dynamics in operation, many beyond their control (Wilson 2006). They must instead be prepared to respond adaptively, to improvise in the so-called theatre of water management. A further crucial aspect of management is also highlighted: the changing context within which societal responses to problems arising in complex adaptive systems must be developed. Maintaining flexibility – though this may contradict elements of the historical command-and-control approach to water management – is therefore the fundamental 'effective' response for water managers to adopt. Managers should also consider where the negative impacts of responses can best be absorbed within the system, where there is both awareness and power to respond effectively – in other words, where both ecological and social resilience are highest. The absorption capacity of the lower Olifants River in the Kruger Park, for example, needs to be weighed up against the resilience of mining interests upstream and that of downstream communities in Mozambique.

One way to enhance congruence and enable more effective management responses is through the use of scenarios, which allows stakeholders to develop a common understanding of a problem that impacts them - often the first step required to influence power. In **Chapter 3**, the utility of scenarios is demonstrated for dealing with situations of uncertainty encountered in resource management and conservation. Scenario analysis for the Gariep basin illuminated spatio-temporal trade-offs between ecosystem services and human well-being that were not so apparent otherwise, demonstrating the importance of designing a scenario analysis so that it captures the cross-scale processes and links of interest to decision makers (Biggs et al. 2006). While scenarios are often used in situations of uncontrollable uncertainty (Peterson et al. 2003), the Gariep experience suggests that scenarios are apt to yield the greatest benefits to social-ecological systems management when they are designed to inform a focal policy issue that stakeholders have some power to change. The great virtue of scenarios lies in their ability to impart a sense of ownership in stakeholders of the processes they believe will shape the future. The scenario development process ultimately underscores the necessity of considering the future in a social-ecological systems context, because it is in the complex interactions between people and nature that uncertainty in ecology and conservation has its roots.

A major area of uncertainty in South African water management revolves around the decentralisation of functions from the national department to CMAs. **Chapter 4**'s exploration of the decentralisation of water management through an agent-based modeling approach shows that decentralised decision-making almost always shifts the balance of winners and losers. Of the three dominant 'centralised' water management paradigms that are explored in the model, none does particularly well in balancing the Water Act principles at the national level or in all water management areas. In both cases, trade-offs among efficiency, equity, and sustainability are made except in areas where water resources are abundant. On the other hand, the ability of water users to learn and employ a diversity of management systems tends to yield the most sustainable outcomes. This finding is in agreement with other examples from the literature (Holling and Meffe 1995), yet of particular interest is that ecological sustainability is best achieved in the model when sectoral water users have difficulty fulfilling their demands, suggesting either that restraints on use are needed to maintain ecosystems in good condition or that severe reallocation measures need to be put in place. The most promising solution to ensure that sustainability is prioritised appears to be a national-level *Some, for All, Forever* framework, within which learning is able to take place. Rather than adopt a 'one-size-fits-all' policy, Catchment Management Agencies and local organisations must approach their specific problems with unique perspectives and fresh insight, appropriate for specific conditions in the Water Management Area (WMA).

If learning is such an important prerequisite for a robust water management system, how do agents learn, and what needs to be done to enhance learning? Extending the use of the model used in the previous chapter, the subject of 'learning dilemmas' - social-ecological system properties and human perceptions that challenge learning's three pillars of capacity, understanding, and willingness - is pursued in **Chapter 5**. What agents learn also depends on the measures that they select to provide information about the real world, and their ability to update or change these measures when conditions change. The model experiments show that mismatches are commonplace between social-ecological system properties and human cognitive abilities to process information about these properties. These social-ecological system properties need to be kept in mind in efforts to increase learning. Where learning is difficult due to social-ecological system conditions, monitoring systems must be designed so that they capture key patterns in these conditions. This may also require a redesign of existing institutional structures (Wilson 2006).

In **Chapter 6**, the immense challenge of linking theory to action is addressed. Resilience is identified as an intriguing theoretical concept for South African water management, but existing frameworks to analyse resilience are not yet adequate for taking the South African Water Act forward. The usefulness of two frameworks is examined for the implementation of the act and its vision of a future in balance: the Millennium Ecosystem Assessment's conceptual framework and the adaptive cycle. While these frameworks both have limitations, their exploration by South African water managers as part of a broader study of resilience could provide a mechanism for breaking down the traditional social science-natural science divide in water management. The two frameworks are in many ways complementary; managers that use these frameworks, however, should be prepared to modify them as needed to handle specific management challenges or questions (van Wyk et al. 2001). In this sense, the practical challenges encountered in implementing the Water Act may help to put resilience theory to the test. The Olifants River incident suggests nothing flawed about the Water Act itself, but points to a weakness in the overarching South African water management system in which the Water Act is only a single, albeit central, component. Its significance notwithstanding, additional checks and balances need to be in place (MacKay 2003); unwavering dependence on the Water Act to do its job, and the expectation that it will never fail, does not promote discovery of resilient pathways.

In short, the answer to the question raised at the beginning of this chapter is that the problems experienced in the Salt and Olifants Rivers are essentially both management failures rooted in a lack of understanding of linked social and ecological dynamics. Experience shows that some objectives have been served quite well by misinterpreting or disregarding these dynamics (Wilson 2002, Allison and Hobbes 2004) – in a world where natural resources appear limitless, impacts can be transferred elsewhere in space and time, and competition and conflict are minimal, the consideration of the social and ecological implications of one's actions is often counterproductive for meeting one's immediate goals. Water in South Africa has definite physical limits; however, societies are not typically doomed by such a limitation alone, but rather by perceptions of the limitation and options available for overcoming these limits (Tainter 1998, Diamond 2005).

It is also arguable that in both examples, a lack of understanding was closely coupled with a deeply-entrenched disconnect between science and management that hampered the emergence of an adaptive learning environment. Even in simpler, traditional systems, such a disconnect – typically between those with information and those with decision-making power – could have profound implications for the long-term welfare of the society and its resource base (Redman and Kinzig 2003). In present times, there is a call to move from "knowledge transfer," which tends to impart knowledge of scientists to managers in a unidirectional fashion, and is often contested or ignored, to "knowledge interfacing and sharing," whereby both parties take ownership of knowledge and use it to pursue common objectives (Roux et al. 2006).

Recommendations for water management and future research

Human behaviour is a great obstacle to change, but also a positive mechanism for it. While suggestions for modifying human behaviour are beyond the scope of this thesis, confronting it is a critical first step for changing water management (Folke 2003). Several recommendations follow from the analysis presented herein, which the South African water sector and researchers can begin implementing immediately:

1) Foster information sharing and exchange - within WMAs, between WMAs, across sectors, and internationally. There are numerous ways this may be done, which include both physical and virtual fora (MacKay et al. 2003), and need not be limited to national boundaries. There is a great deal to be learned from information sharing and exchange with countries such as France, for example, that have devolved management to

catchment-scale agencies (Buller 1996; Perret et al. *in press*) as well as other middle-income countries such as Mexico that have begun similar decentralisation processes (Wester et al. 2003). Certain challenges faced by South Africa in particular do need to be considered, as the greater focus on participation requires that stakeholder views are adequately captured in decision-making and research (van Wyk et al. 2001). As Chikozho (2005) notes in describing the process of CMA establishment in the Inkomati WMA, disadvantaged communities often have much less developed networks than the organised commercial sectors, for example, and thus the difficulty of getting genuine and legitimate representation from disadvantaged communities should not be understated. In addition, 'participation fatigue' may thwart progress on this front, and may be especially acute in WMAs like the Inkomati, in which the process has been ongoing for more than seven years. In such cases, participant turnover is likely to be high, which poses another challenge to moving forward. Stakeholder engagement will need to be approached in innovative, novel ways that are able to capture participants' imaginations and retain their active involvement in the process (scenarios, discussed below, are one such possibility).

2) Conduct participatory scenario planning exercises with water users at national, CMA, and local levels. Because of the multi-tiered, nested structure of the new institutional arrangements for the South African water sector, a simple, but multiple-scale scenario analysis involving key representatives of the national ministry, one or two neighbouring CMAs, and local catchment management committees and water user associations representing all sectors would be a highly useful exercise (Biggs et al. 2006). The first CMAs that are established should seize the opportunity to implement a scenario activity that can serve as a 'pilot' for the whole country, which subsequently-established CMAs can then learn from and refine.

3) Evaluation and redesign of monitoring systems. Monitoring must be spatially aligned with major processes and institutions. Spatially, it should be undertaken collectively by the Department of Water Affairs and Forestry (DWAF), CMAs, local institutions, as well as regional and international institutions. Monitoring must also be temporally aligned with these processes. A shift in emphasis is needed to slow variables or driving forces and

governing structures that determine system outcomes (Carpenter and Turner 2001, Lynam and Stafford-Smith 2004). While the River Health Programme is commended for its contribution in the area of monitoring ecological integrity, the need to monitor social aspects of water and drivers of change in water resources such as land use has been identified as a gap (van Wyk et al. 2001). Indicator development, which has been aligned with State of the Environment reporting initiatives in the past, also needs to shift to an integrated catchment management framework that involves institutions across scales (Walmsley et al. 2002).

4) Raise awareness of and train water managers and users in social-ecological systems and resilience thinking and approaches. The ideas of social-ecological systems and resilience theory are not always readily accessible to those with training in a traditional discipline or the public at large, due to the relatively abstract concepts and the lack of a tangible icon to represent these ideas. Thus, a creative infusion on how to approach this will be needed. One possible insertion point for communicating ideas about social-ecological systems may be the Working for Water Programme, whose public education efforts have begun to make a positive impact on people's awareness of invasive alien plants (Le Maitre et al. 2004). In simplest terms, water managers and users need to be envision the 'big picture' of water resources and not simply their small sub-area of the WMA (Chikozho 2005).

5) Encourage higher efficiency in the agricultural sector, the most consumptive water use and relatively unproductive in economic terms. This is a frequently-heard recommendation for achieving the Water Act principles, but until the problem of agricultural inefficiency is addressed in a more holistic way little progress is likely to be realised. The social implications of a reduction in agricultural water use (i.e. employment) are not trivial (MacKay 2003) and do need to be dealt with in an integrated fashion. Job creation will need to be supported in other sectors, such as tourism, and more funding allocated for poverty reduction programs which also emphasise ecological sustainability, like Working for Water (van Wilgen et al. 2005). Government agencies with overlapping, and especially those with conflicting mandates, including the Department of

Environmental Affairs and Tourism and Department of Agriculture, will need to work together with DWAF to ensure synergy in this area.

6) Maintain legal flexibility. For all the merits of the South African Water Act, it is not without flaws. Amendments may be needed as experience is gained, and the act should be seen as a living document with limits. Furthermore, potential conflicts between the Water Act and other laws, such as the Water Services Act (Pollard and du Toit 2005), and those pertaining to land reform, may need to be reconciled. However, the creation of a Water Tribunal to hear appeals is a promising step (MacKay 2003).

Conclusion

The view that the human and natural worlds are interdependent is clearly encapsulated by the South African Water Act, but the implications of this are not always completely understood. My attempt in this thesis has been to dig deeper into the social-ecological system 'well' of thought to identify and explain how this perspective may assist the water sector during this current transitional era in several specific ways. Certainly the ideas, approaches, and recommendations discussed here also apply to other challenges in ecosystem management and other parts of the world, and cross-comparison might prove fruitful.

"All the world's cultures, past and present, are to some degree available to us," Wilbur (2000) observes. Modern society now has the advantage of instantaneous communication across much of the globe. We also have hindsight, including a greater awareness of the past, and a good deal of foresight, thanks to advances in technology and cognitive tools like scenarios and modeling. The Hohokam, and even recent past generations of South Africans, have not had the same fortune. Of course, hindsight has limits in a rapidly-changing world, but meticulously and thoughtfully applied, stands to greatly enrich the knowledge base for current decision making.

Every society eventually succumbs to Holub's Tenth Law in one way or another – it collapses, disperses, or transforms (Tainter 1998). One day, future societies will read about South Africa in the early 21st century and its pivotal water policy. Will they read a story of success or failure, and what will it teach them about the future still to come?

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Appendix A.

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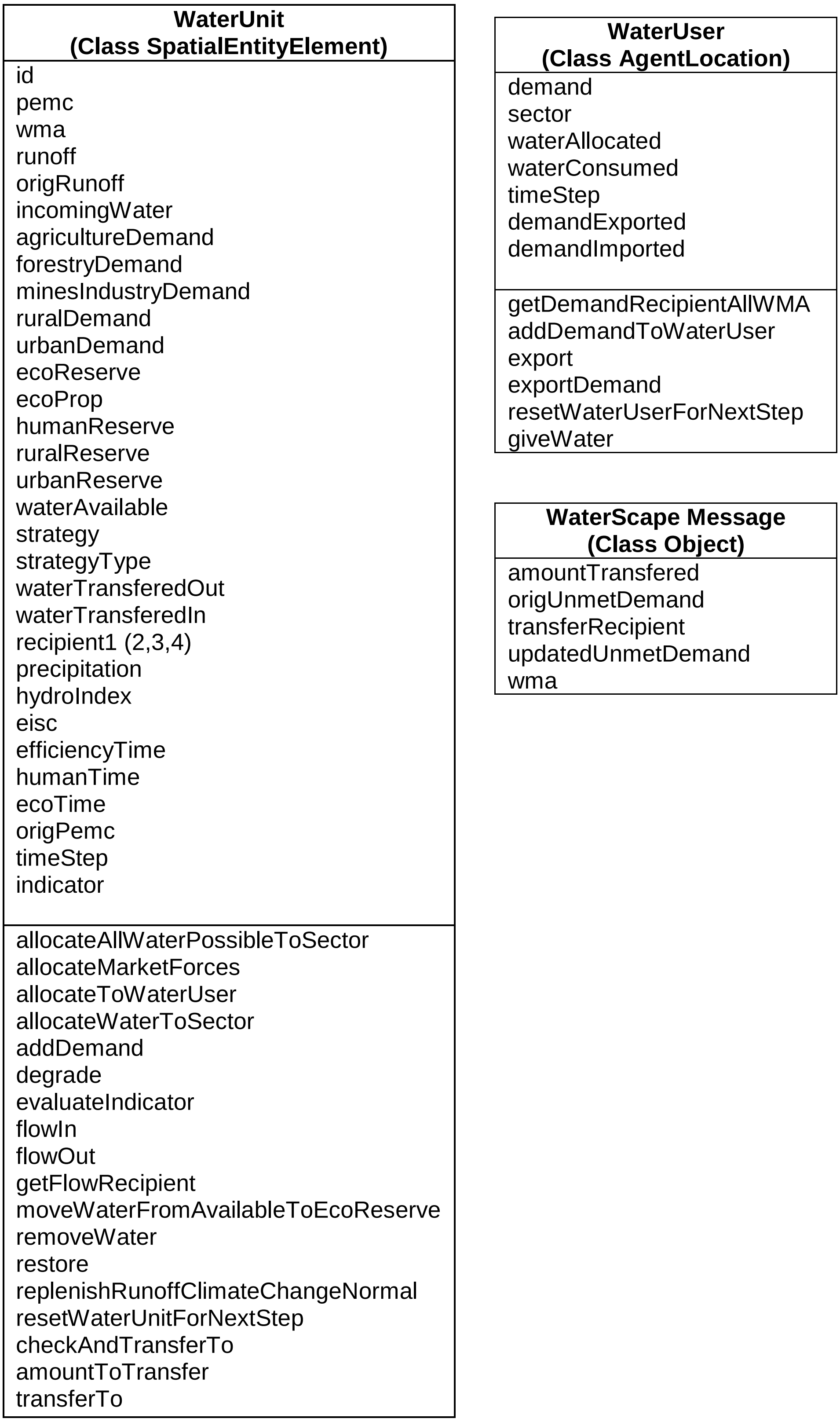
Appendix B. Class diagram depicting agent classes of the WaterScape model, with attributes in top box and methods in bottom box.



WaterUnit
(Class SpatialEntityElement)

id
pemc
wma
runoff
origRunoff
incomingWater
agricultureDemand
forestryDemand
minesIndustryDemand
ruralDemand
urbanDemand
ecoReserve
ecoProp
humanReserve
ruralReserve
urbanReserve
waterAvailable
strategy
strategyType
waterTransferedOut
waterTransferedIn
recipient1 (2,3,4)
precipitation
hydroIndex
eisc
efficiencyTime
humanTime
ecoTime
origPemc
timeStep
indicator

allocateAllWaterPossibleToSector
allocateMarketForces
allocateToWaterUser
allocateWaterToSector
addDemand
degrade
evaluateIndicator
flowIn
flowOut
getFlowRecipient
moveWaterFromAvailableToEcoReserve
removeWater
restore
replenishRunoffClimateChangeNormal
resetWaterUnitForNextStep
checkAndTransferTo
amountToTransfer
transferTo

WaterUser
(Class AgentLocation)

demand
sector
waterAllocated
waterConsumed
timeStep
demandExported
demandImported

getDemandRecipientAllWMA
addDemandToWaterUser
export
exportDemand
resetWaterUserForNextStep
giveWater

WaterScape Message
(Class Object)

amountTransfered
origUnmetDemand
transferRecipient
updatedUnmetDemand
wma

CMA
(Class AgentComm)

wma
waterUnits
allocationStrategy
firstTimeStep
timeStep
status

adjustDemandAgricultureBase
adjustDemandForestryBase
adjustDemandMinesIndustryBase
adjustDemandRuralBase
adjustDemandUrbanBase
adjustDemandAgricultureHigh
adjustDemandForestryHigh
adjustDemandMinesIndustryHigh
adjustDemandRuralHigh
adjustDemandUrbanHigh
allocateCollectiveLearningEfficiency
allocateCollectiveLearningEfficiencyIndicator
allocateCollectiveLearningEquity
allocateCollectiveLearningEquityIndicator
allocateCollectiveLearningSustainability
allocateCollectiveLearningSustainabilityIndicator
allocateCollectiveLearningIndicator
allocateFortressWorld
allocateMarketForces
allocateToWaterUser
allWaterUnitsGetFortressWorldAllocation
allWaterUnitsGetMarketForcesAllocation
allWaterUnitsUsePolicyReform
waterUnitsGetRandomStrategy
getTransferDonor
getTransferDonorNearest
getTransferRecipientMaxDemand
getTransferRecipientMaxUnmetDemand
resetCMAForNextStep
applyStrategy
fortressWorldStrategy
getStrategy
learningStrategy
marketForcesStrategy
policyReformStrategy
deficitAlertFortressWorld
deficitAlertMarketForces
deficitAlertPolicyReform
recipientsSendMessageFortressWorld
recipientsSendMessageLearning
recipientsSendMessageMarketForces
recipientsSendMessagePolicyReform
transferMaxAvailable
transferToNearest
transferToNearestMaxAvailable

APPENDIX C. Description of attributes of entities in the WaterScape model.

Entity	Attribute	Method	Description
WaterUnit	id		Unique value for each water unit
	pemc		Present ecological management class
	wma		Identification number of Water Management Area (WMA)
	runoff		Natural mean annual runoff
	origRunoff		Runoff value at initialisation
	incomingWater		Water from upstream water units
	agricultureDemand		Water requirement of agricultural sector
	forestryDemand		Water requirement of forestry sector
	minesIndustryDemand		Water requirement of mining and industrial sector
	ruralDemand		Water requirement of rural sector
	urbanDemand		Water requirement of urban sector
	ecoReserve		Ecological reserve requirement
	ecoProp		Proportion of total runoff designated for ecological reserve requirement
	humanReserve		Human reserve requirement
	ruralReserve		Human reserve requirement of rural population
	urbanReserve		Human reserve requirement of urban population
	waterAvailable		Component of runoff that is available for use
	strategy		Water management strategy (i.e. scenario)
	strategyType		Strategy type (i.e. previous or most successful strategy)
	waterTransferedOut		Water transferred out of water unit
	waterTransferedIn		Water transferred into water unit
	recipient1 (2,3,4)		Downstream water unit that receives water from this water unit
	precipitation		Mean annual precipitation
	hydroIndex		Hydrological index value
	eisc		Ecological importance and sensitivity value
	efficiencyTime		Consecutive number of times water unit exceeds efficiency indicator threshold value
	humanTime		Consecutive number of times water unit exceeds human indicator threshold value
	ecoTime		Consecutive number of times water unit exceeds ecological indicator threshold value

	origPemc		PEMC value at initialisation
	timeStep		Number of time steps (years) since initialisation
	indicator		Indicator by which success of strategy is measured
		allocateAllPossibleWaterToSector	Gives all water needed to satisfy demand; if demand is more than water available, gives all water available.
		allocateMarketForces	Allocates water to each of the sectors in turn according to 'Market Forces' rule (i.e. in order of average economic productivity).
		allocateToWaterUser	Allocates an amount to water user proportional to its demand.
		allocateWaterToSector	Gives water to the WaterUser of the specified sector; if not enough water is available, gives all available.
		addDemand	Increases demand of a WaterUser.
		degrade	Adjusts ecological management class (PEMC) for degradation, based on withdrawal-to-availability ratio and ecological importance and sensitivity index, for water unit and recipient (downstream) water units.
		evaluateIndicator	Evaluates success of indicator and changes if it fails for 5 successive timesteps.
		flowIn	Releases water into water unit from donor (upstream) water units.
		flowOut	Releases water out of this water unit into recipient water units.
		getFlowRecipient	Finds recipient to which water flows downstream from this water unit. If there is more than one, selects the nearest of these.
		moveWaterFromAvailableToEcoReserve	Sets aside water for ecological reserve. If the amount required is greater than the actual water available, moves all available.
		removeWater	Takes an amount of water away from the available water pool. If the requested amount is more than the amount available, takes it all.
		restore	Adjusts ecological management class (PEMC) for restoration, based on withdrawal-to-availability ratio and ecological importance and sensitivity index, for water unit and recipient (downstream) water units.
		replenishRunoffClimateChangeNormal	Sets runoff equal to the greater of 0 and the change projected to occur due to climate change, multiplied by a random positive number drawn from a normal distribution around the mean.
		resetWaterUnitForNextStep	Resets variables at the beginning of the timestep.
		checkAndTransferTo	Before water is transferred to water unit, checks unmet demand of transfer recipient to see if it has changed since requesting transfer. Compares the updated unmet demand to the amount designated for transfer and transfers the lesser of the two.
		transferTo	Transfers requested amount of water to transfer recipient.
WaterUser	demand		Water requirement of water user

	sector		Water use sector
	waterAllocated		Water allocated to water user
	timeStep		Number of time steps (years) since initialisation
	demandExported		Demand exported by water user
	demandImported		Demand imported by water user
	waterConsumed		Water consumed by water user
		getDemandRecipientAllWMA	Finds recipient water unit within WMA to which water user can export excess demand.
		addDemandToWaterUser	Increases demand by amount that has been exported to this water user; water user immediately consumes this amount of water from the WaterUnit.
		export	WaterUser with excess demand exports demand to WaterUnit with available water.
		exportDemand	Adds amount of exported demand to recipient's demand, and subtracts same amount from donor water user’s demand.
		resetWaterUserForNextStep	Resets variables at the beginning of the timestep.
		giveWater	Adds amount of exported water to water user’s available water and water consumed.
WaterScape Message	amountTransfered		Amount of water transferred from donor to recipient
	origUnmetDemand		Unmet demand of recipient at time of transfer request
	transferRecipient		Water unit that receives transfer
	updatedUnmetDemand		Unmet demand of recipient at time of transfer
	wma		Identification number of water management area requesting transfer
CMA	wma		Identification number of water management area
	waterUnits		Water units within water management area of CMA’s jurisdiction
	firstTimeStep		First time step (true or false)
	timeStep		Number of time steps (years) since initialisation
	status		Status of water availability (i.e. surplus or deficit)
		adjustDemandAgricultureBase	Adjusts demand of agricultural sector in each of its WaterUnits according to base growth projections.
		adjustDemandForestryBase	Adjusts demand of forestry sector in each of its WaterUnits according to base growth projections.
		adjustDemandMinesIndustryBase	Adjusts demand of mining and industry sector in each of its WaterUnits according to base growth projections.
		adjustDemandRuralBase	Adjusts demand of rural sector in each of its WaterUnits according to

			base growth projections.
		adjustDemandUrbanBase	Adjusts demand of urban sector in each of its WaterUnits according to base growth projections.
		adjustDemandAgricultureHigh	Adjusts demand of agricultural sector in each of its WaterUnits according to high growth projections.
		adjustDemandForestryHigh	Adjusts demand of forestry sector in each of its WaterUnits according to base growth projections.
		adjustDemandMinesIndustryHigh	Adjusts demand of mining and industrial sector in each of its WaterUnits according to high growth projections.
		adjustDemandRuralHigh	Adjusts demand of rural sector in each of its WaterUnits according to high growth projections.
		adjustDemandUrbanHigh	Adjusts demand of urban sector in each of its WaterUnits according to high growth projections.
		allocateCollectiveLearningEfficiency	Allocates water randomly, then allows agents to use efficiency indicator to choose allocation strategy in subsequent timesteps.
		allocateCollectiveLearningEfficiencyIndicator	Allocates water randomly, then allows agents to use efficiency indicator to choose allocation strategy in subsequent timesteps (used when all three indicators are distributed among agents).
		allocateCollectiveLearningEquity	Allocates water randomly, then allows agents to use equity indicator to choose allocation strategy in subsequent timesteps.
		allocateCollectiveLearningEquityIndicator	Allocates water randomly, then allows agents to use equity indicator to choose allocation strategy in subsequent timesteps (used when all three indicators are distributed among agents).
		allocateCollectiveLearningSustainability	Allocates water randomly, then allows agents to use sustainability indicator to choose allocation strategy in subsequent timesteps.
		allocateCollectiveLearningSustainabilityIndicator	Allocates water randomly, then allows agents to use sustainability indicator to choose allocation strategy in subsequent timesteps (used when all three indicators are distributed among agents).
		allocateCollectiveLearningIndicator	Allocates water randomly, then allows agents to use efficiency, equity, and sustainability indicators.
		allocateFortressWorld	Allocates water using Fortress World rule (proportional allocation).
		allocateMarketForces	Allocates water using Market Forces rule (preferential allocation, then to human and ecological Reserve).
		allWaterUnitsUsePolicyReform	Allocates water using Policy Reform rule (allocation to human and ecological Reserve, then preferential allocation).
		waterUnitsGetRandomStrategy	Randomly assigns allocation strategies to water units.
		getTransferDonor	Selects a surplus water unit from which to transfer water.

		getTransferDonorNearest	Selects the surplus water unit from which to transfer water with sufficient water available to meet recipient's unmet demand and that is nearest to the recipient.
		getTransferRecipientMaxDemand	Selects the water unit with the greatest demand from which to transfer water.
		getTransferRecipientMaxUnmetDemand	selects the water unit with the greatest unmet demand from which to transfer water.
		resetCMAForNextStep	Resets variables at the beginning of the timestep.
		deficitAlertFortressWorld	Sends a message to all other CMAs containing wma number and selected transfer recipient (water unit with maximum demand). The messages are delivered and processed asynchronously (as soon as received).
		deficitAlertMarketForces	Sends a message to all other CMAs containing wma number, selected transfer recipient (water unit with maximum demand), and amount requested (recipient’s unmet demand). The messages are delivered and processed synchronously (at end of timestep).
		deficitAlertPolicyReform	Sends a message to all other CMAs containing wma number, selected transfer recipient (water unit with maximum unmet demand), and amount requested (recipient’s unmet demand). The messages are delivered and processed synchronously (at end of timestep).
		transferMaxAvailable	Transfers all available water from the donor water unit, regardless of the requested amount, to selected recipient.
		transferToNearest	Transfers the lesser of the amount requested and the donor's available water to selected recipient.
		transferToNearestMaxAvailable	Transfers all available water from the donor water unit, regardless of the requested amount, to nearest of selected recipients.

Appendix D. Translation of scenario archetypes of Gallopín et al. (1997) to the South African water management context. Adapted from Bohensky, E. and A.S. van Jaarsveld. "Water management and conservation in a southern African river basin: A scenario planning approach to uncertainty." Poster presentation, Annual Meeting of the Society for Conservation Biology, New York, 30 July–2 August, 2004.

Scenario archetype	**WaterScape name**	**Key elements**
Market Forces	***Efficiency First***	Strong economy facilitated by national governance framework; poor wealth distribution; weak local governance; weak social and environmental policies. Economic efficiency of water allocation is achieved, with urban and industrial users in Gauteng Province paying high prices for water. This impacts the ability to fulfill ecological reserve requirements downstream. Human reserve requirements are met where spin-offs occur from economic development, but not in some rural areas.
Policy Reform	***Some, for All, Forever***	Effective democratic governance; strong, globally-linked economy in a balanced trade regime; significant poverty reduction; substantial investments in health, education, and technology sectors. Ecological reserve requirements are met through strict enforcement of both resource protection measures and demand management. Human reserve requirements are met due to large investments in service delivery to rural areas. This comes at a cost to short-term economic efficiency in some areas where this results in decreased water availability for agricultural and industrial use.
Fortress World	***Hydraulic Mission***	Weak and ineffective governance; economic collapse; weak civil society; increasing gap between wealthy and poor, who live, respectively, inside and outside the "fortress."Water management reverts to the pre-1994 system; agriculture commandeers resources and government subsidies are re-introduced. None of the economic, social, or environmental goals is met; however, a decline in industrial activity means ecological conditions are better in catchments downstream from industries than they would be under *Market Forces*.
Local Learning	Learning variants (Chapter 4: Learning by Maximum Allocation, Learning by Proportion Satisfied; Chapter 5: Learning by use of indicators)	Weak national governance; weak economy; strong civil society; community-driven resource management; strong reliance on informal sector. Overall, the situation remains the same as at present, with improvement in conditions in some catchments and increased degradation in others. However, these "varied experiments" can teach water managers about what works and what does not, and function as an adaptive management strategy if the lessons learned from these experiments can be implemented.