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

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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 m^3/a, constitute the WaterScape environment; the latter two countries are included because of their contributions to South Africa's runoff (4 800 million m^3/a and 700 million m^3/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).

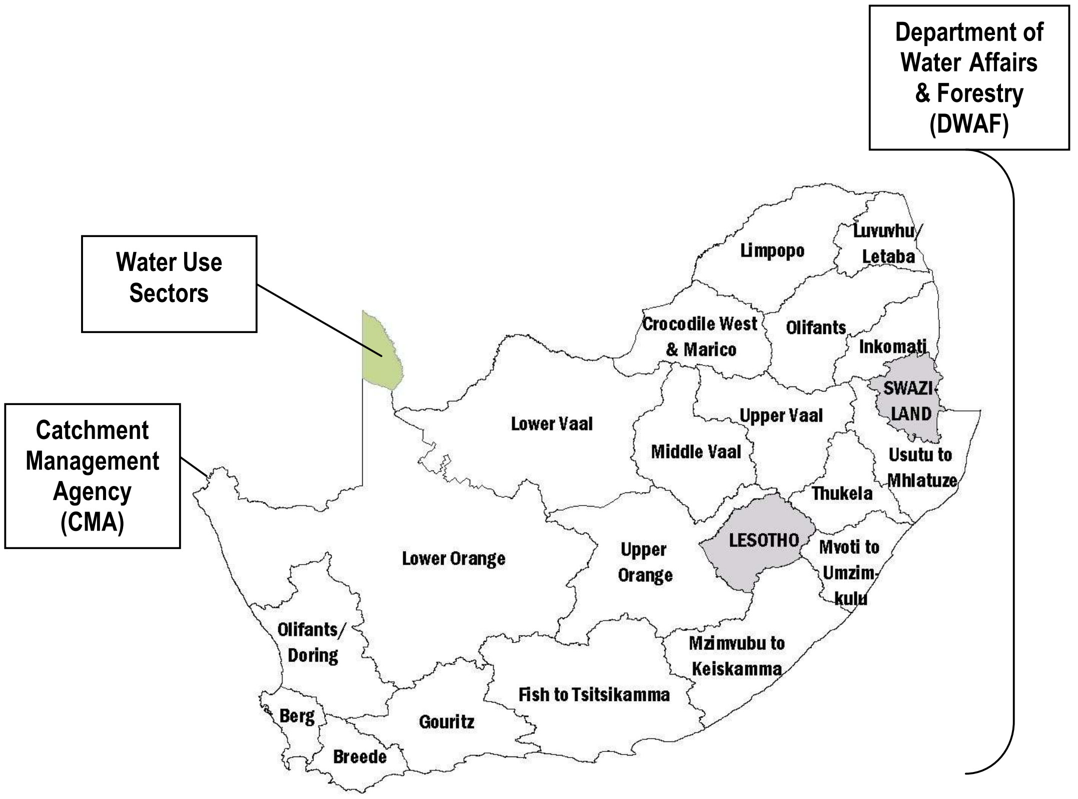

Figure 4.1. Spatial and social entities in the WaterScape model. The national ministry, DWAF, presides over decision-making at the national scale. Each Catchment Management Agency (CMA) is responsible for decision-making in its corresponding Water Management Area. In each quaternary catchment, five agents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

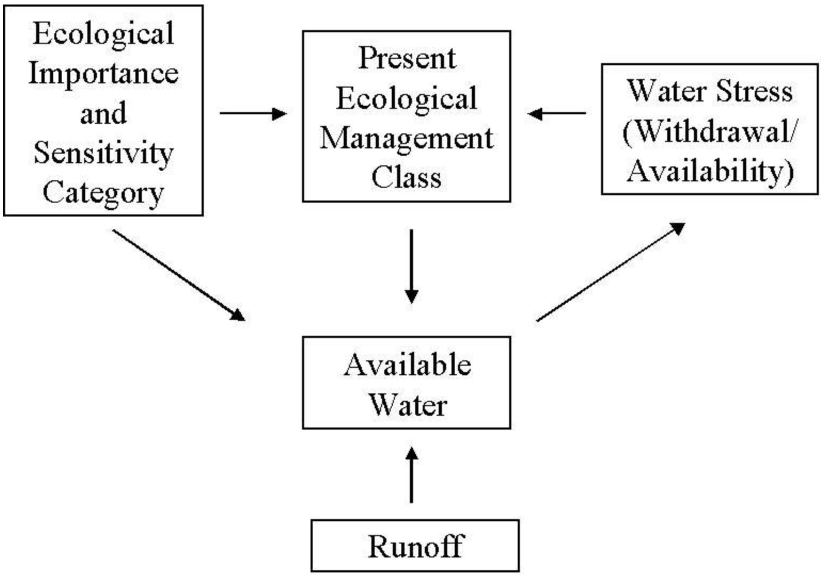

Figure 4.2. Ecological feedbacks in the WaterScape model. Ecological condition, indicated by the present ecological management class value, deteriorates when water stress, determined by the withdrawal-to-availability ratio, exceeds a threshold value of 0.4. The extent of deterioration depends on both 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).

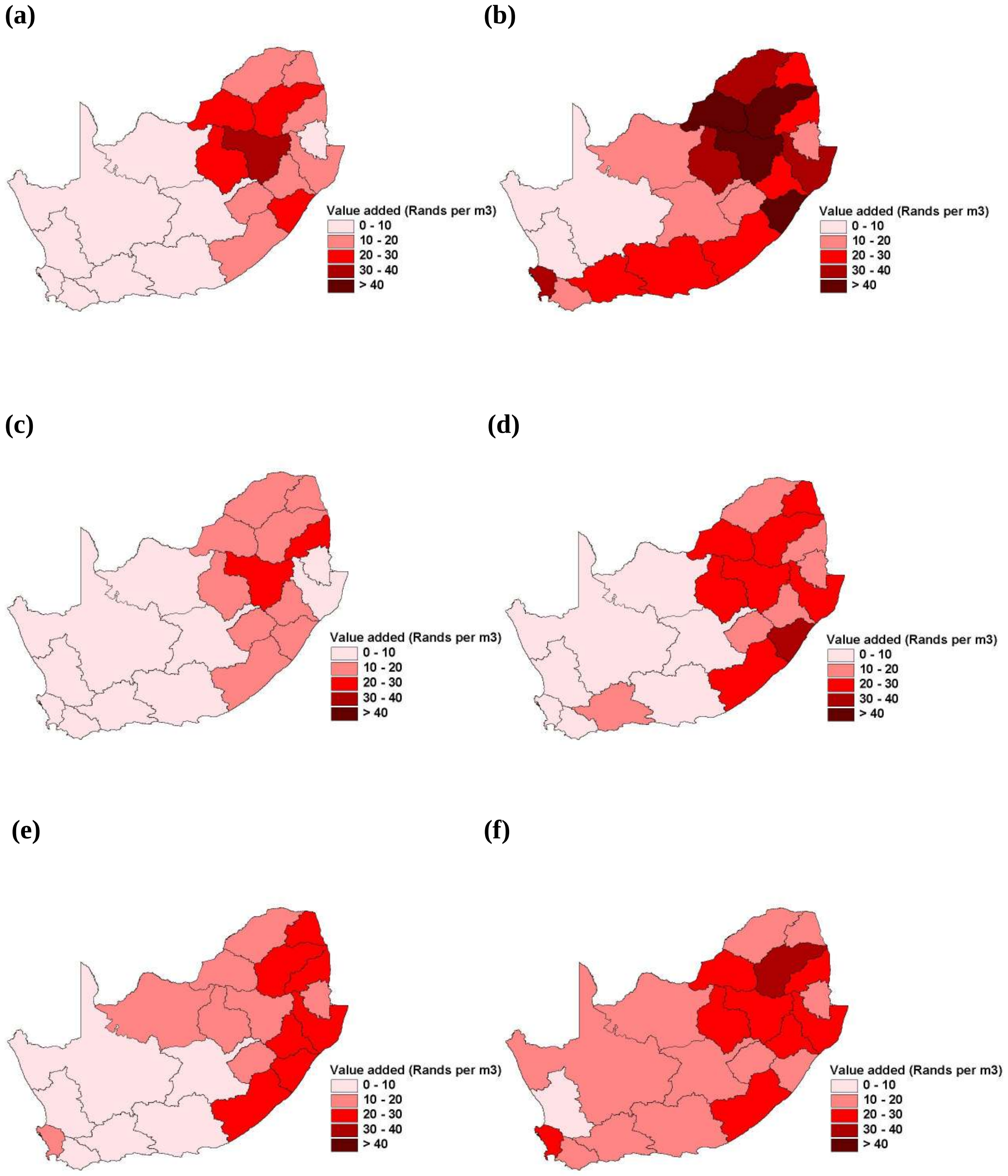

Figure 4.3. Value added in Rands per m^3 (a) at initialisation, and after 100 years under five scenarios: (b) Efficiency First (c) Hydraulic Mission (d) Some, for all, Forever (e) Learning by Maximum Allocation and (f) Learning by Proportion Satisfied. Values shown are means of 20 simulations.

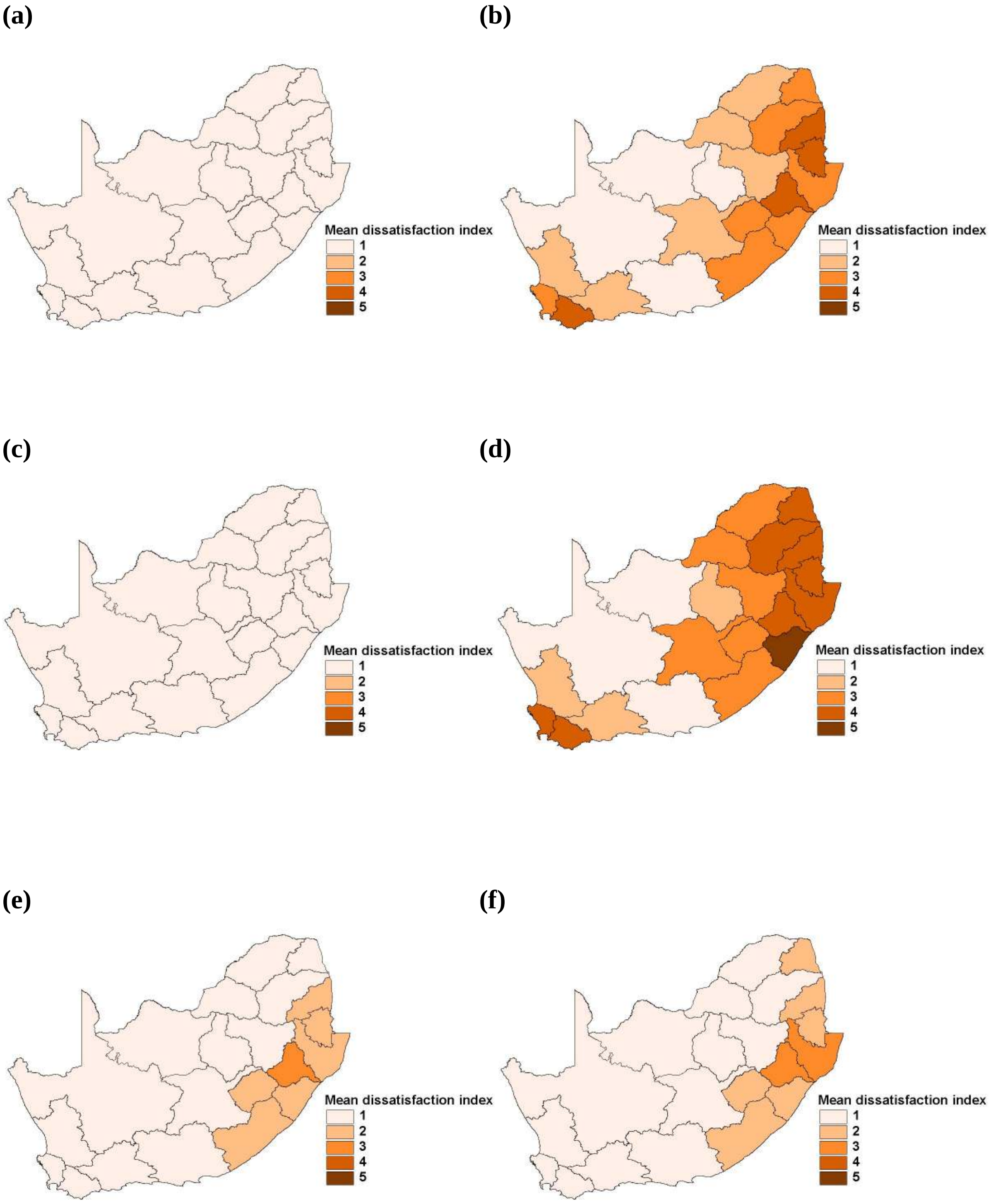

Figure 4.4. Mean dissatisfaction index value (a) at initialisation, and after 100 years under five scenarios: (b) Efficiency First (c) Hydraulic Mission (d) Some, for all, Forever (e) Learning by Maximum Allocation and (f) Learning by Proportion Satisfied. Values shown are means of 20 simulations.

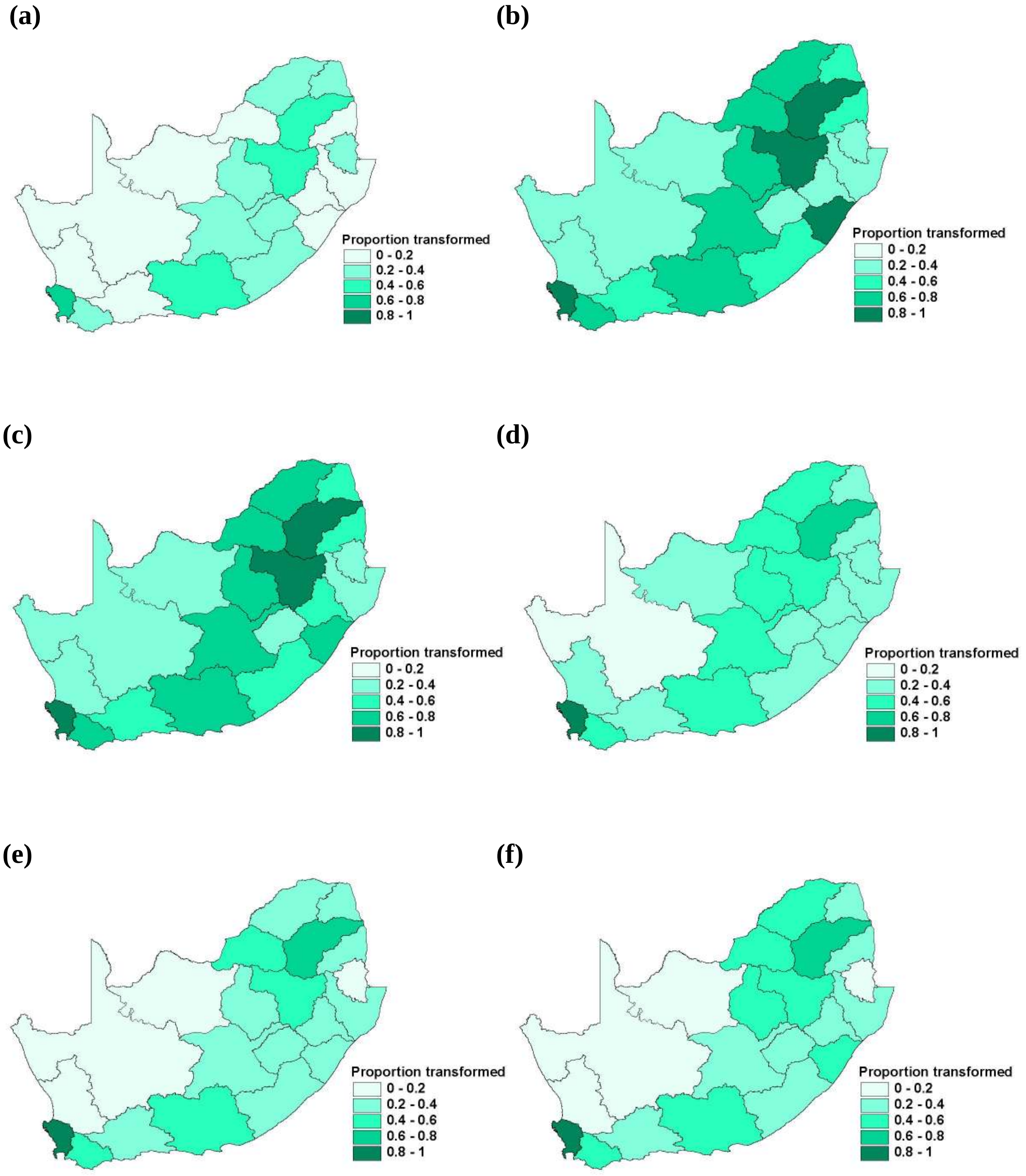

Figure 4.5. Proportion of catchments in WMA that are ecologically transformed (a) at initialisation, and after 100 years under five scenarios: (b) Efficiency First (c) Hydraulic Mission (d) Some, for all, Forever (e) Learning by Maximum Allocation and (f) Learning by Proportion Satisfied. Values shown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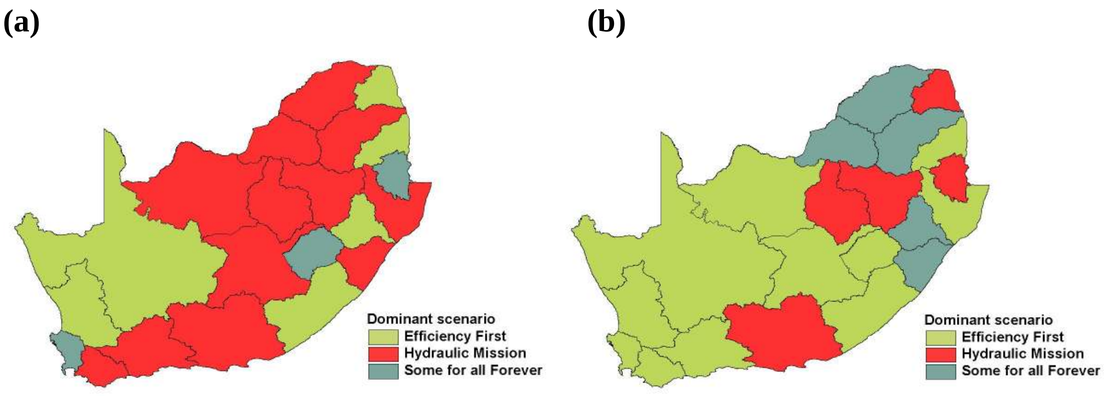

Figure 4.6. Dominant scenario selected after 100 years under (a) Learning by Maximum Allocation; (b) Learning by Proportion Satisfied. Values shown are means of 20 simulations**.**

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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