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).

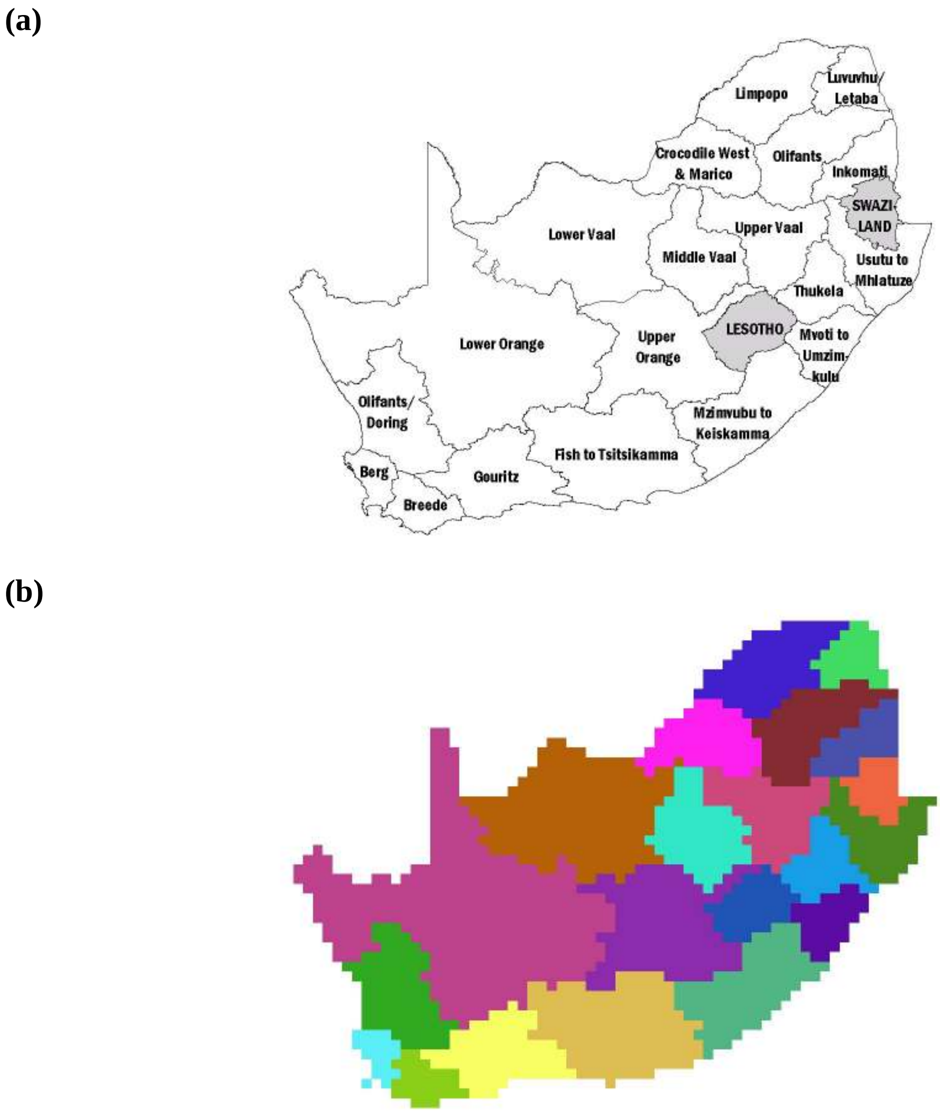

Figure 5.1. (a) Map of South Africa depicting international boundaries and Water Management Areas (WMAs). (b) Visual representation of WMAs in the CORMAS program.

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

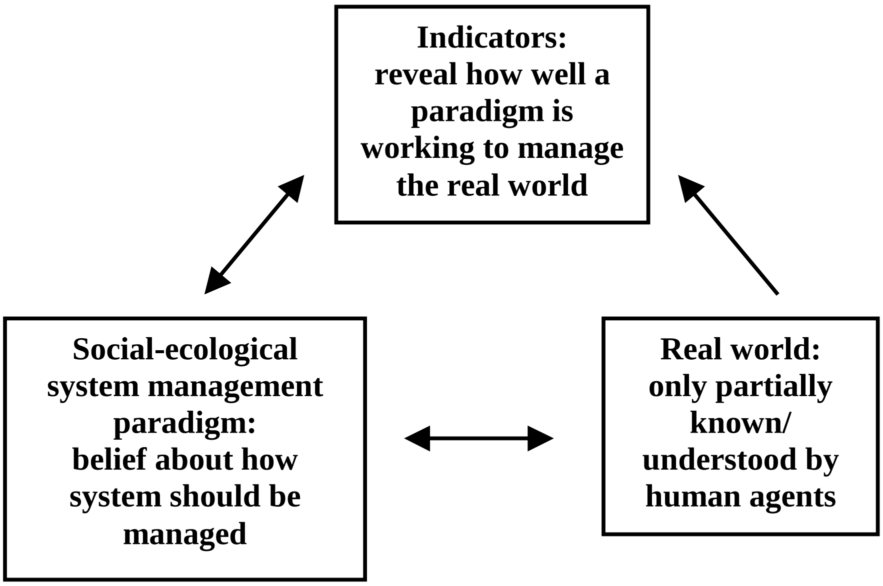

Figure 5.2. Schematic of major relationships governing an actual and perceived environment in a social-ecological system. Indicators are a link between management paradigms and the ‘real’ world. The selection of indicators may be refined with changes in the paradigm or observations of the real world; 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.

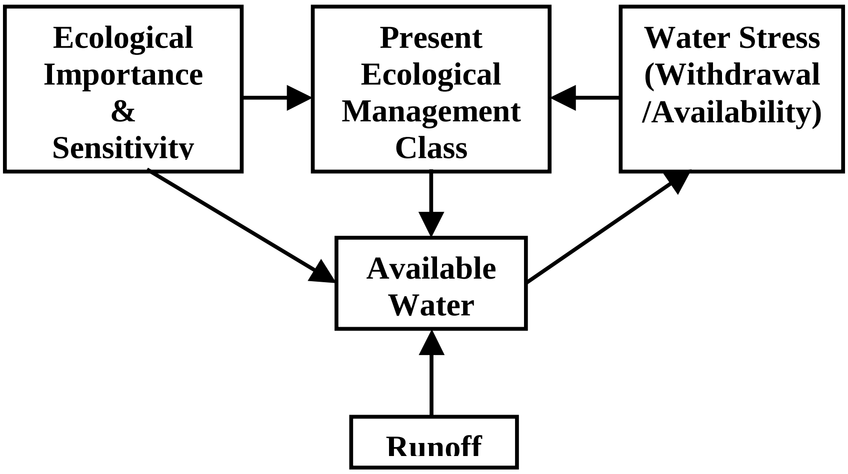

Figure 5.3. Ecological feedbacks in the WaterScape model. Ecological condition, indicated by the present ecological management class value, deteriorates when water stress, determined by the withdrawal-to-availability ratio, exceeds a threshold value of 0.4. The extent of deterioration depends on both 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

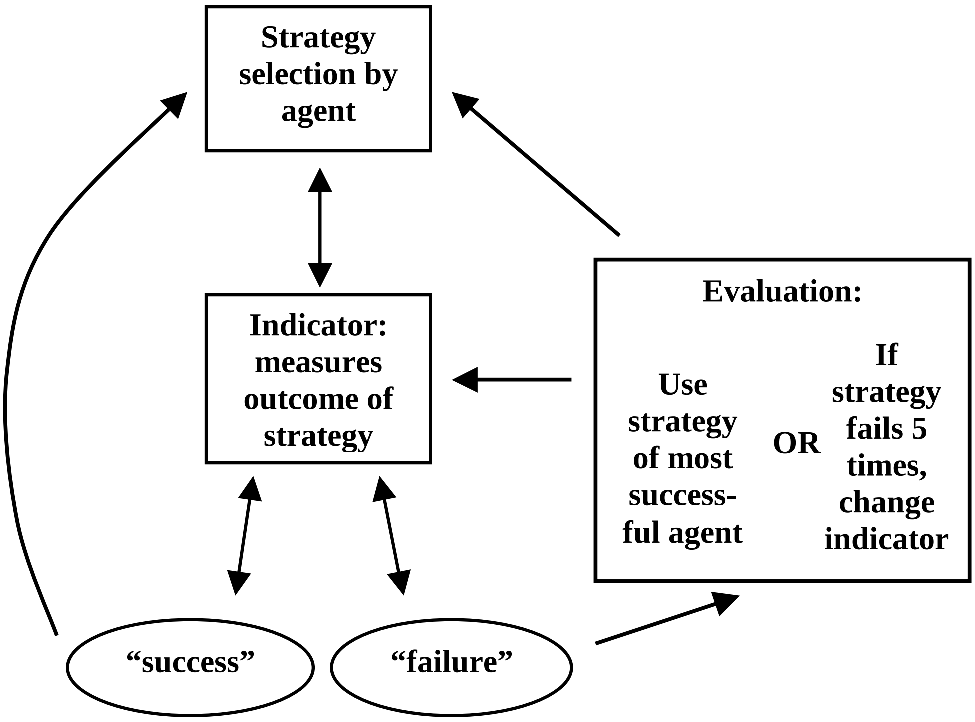

Figure 5.4. The mechanics of learning as represented in the WaterScape model.

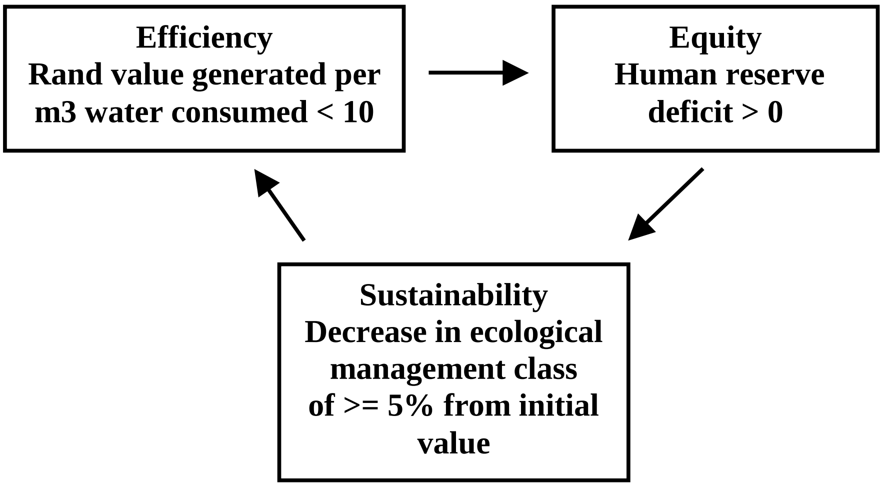

Figure 5.5. Sequence of indicator change. Agents who are unable to succeed using the efficiency indicator switch to more equitable water use; those who are unable to achieve equitable water use switch to sustainability; those who are unable to succeed using the sustainability indicator switch to efficiency.

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.

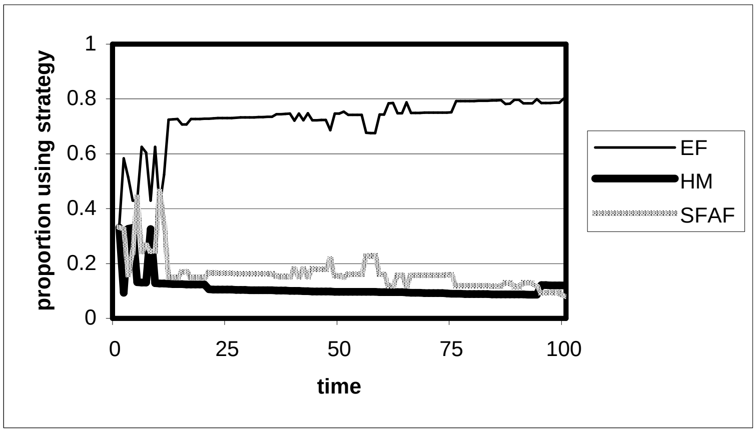

Figure 5.7. Strategy selection when all agents use the efficiency indicator (Rand value per cubic meter of water use). EF = Efficiency First, HM = Hydraulic Mission, SFAF = Some, for All, Forever.

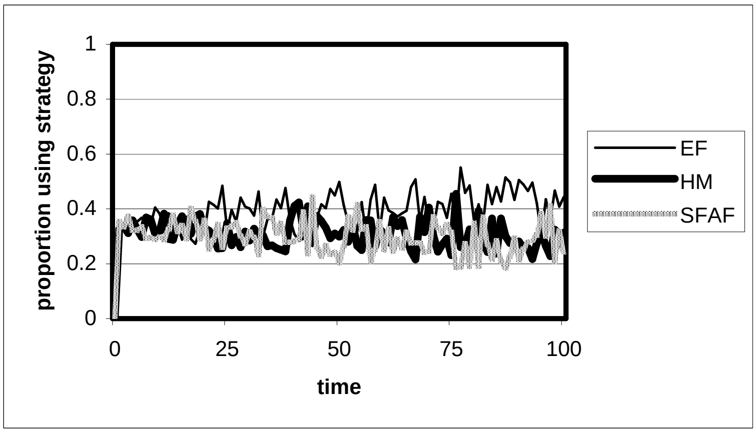

Figure 5.8. Strategy selection when all agents use the equity indicator (human reserve deficit).

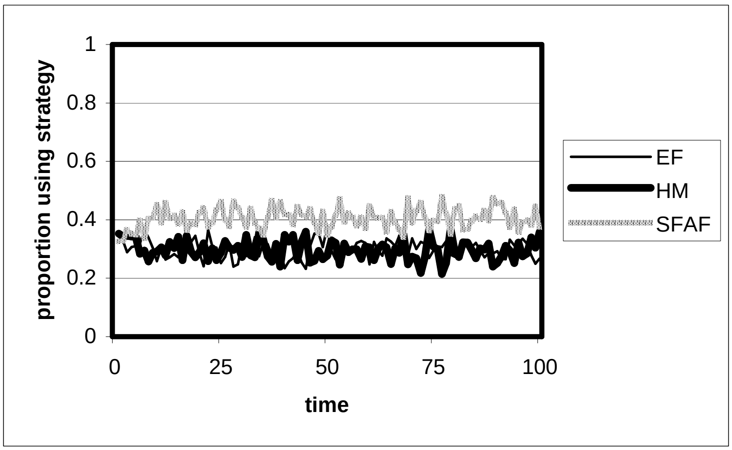

Figure 5.9. Strategy selection when all agents use the sustainability indicator (decline in present ecological management class from initial value).

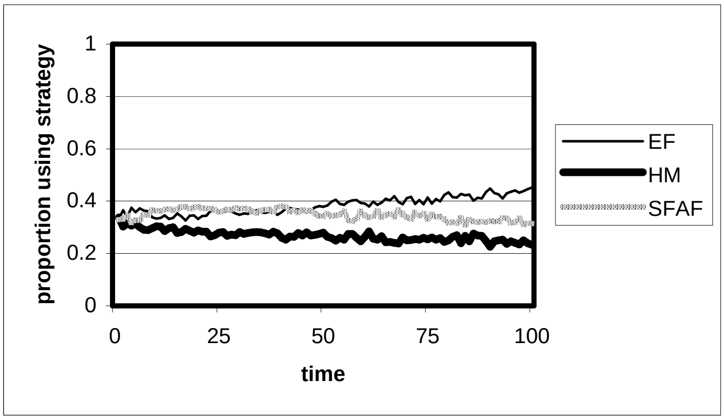

Figure 5.10. Strategy selection by agents when indicators are randomly assigned and fixed.

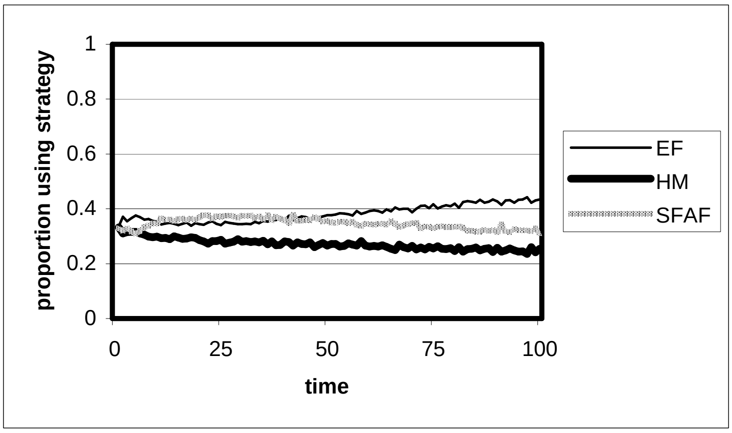

Figure 5.11. Strategy selection by agents when agents are allowed to change indicators.

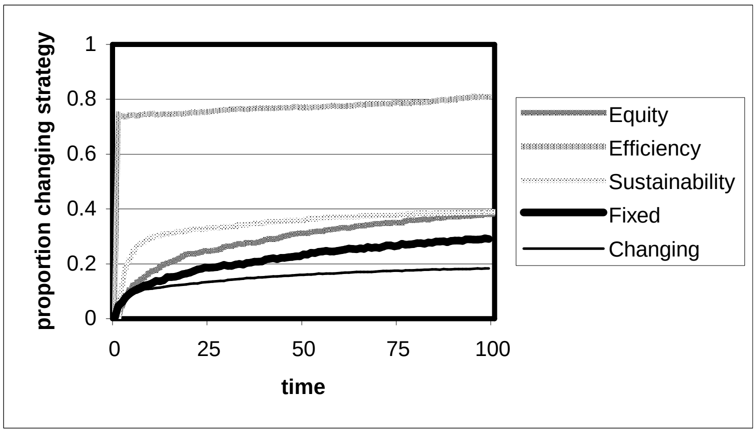

Figure 5.12. Strategy change when agents use the three single indicators, randomly-assigned fixed indicators, and changing indicators.

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.

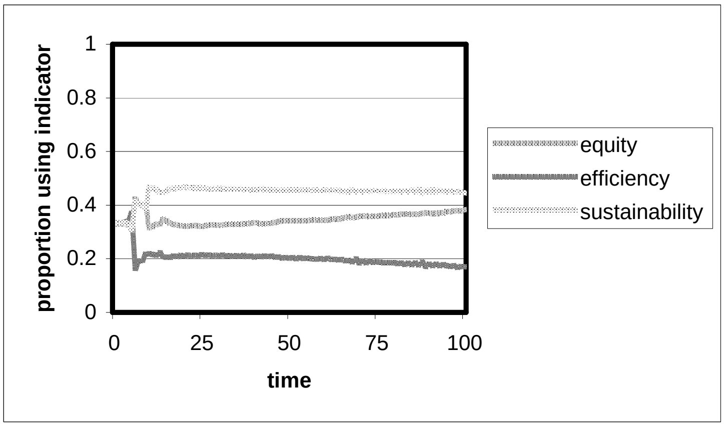

Figure 5.13. Indicator selection by agents with changing indicators.

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).

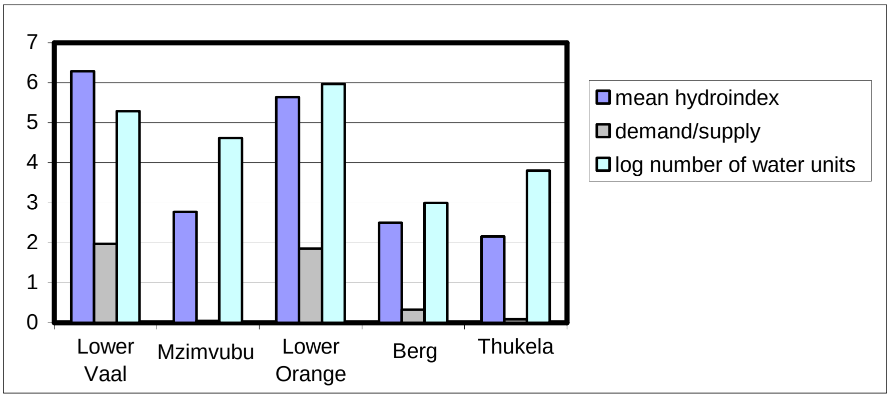

Figure 5.14. Hydrological variability (mean hydrological index value), water stress (ratio of demand to supply) and size (log number of water units) of five water management areas.

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).

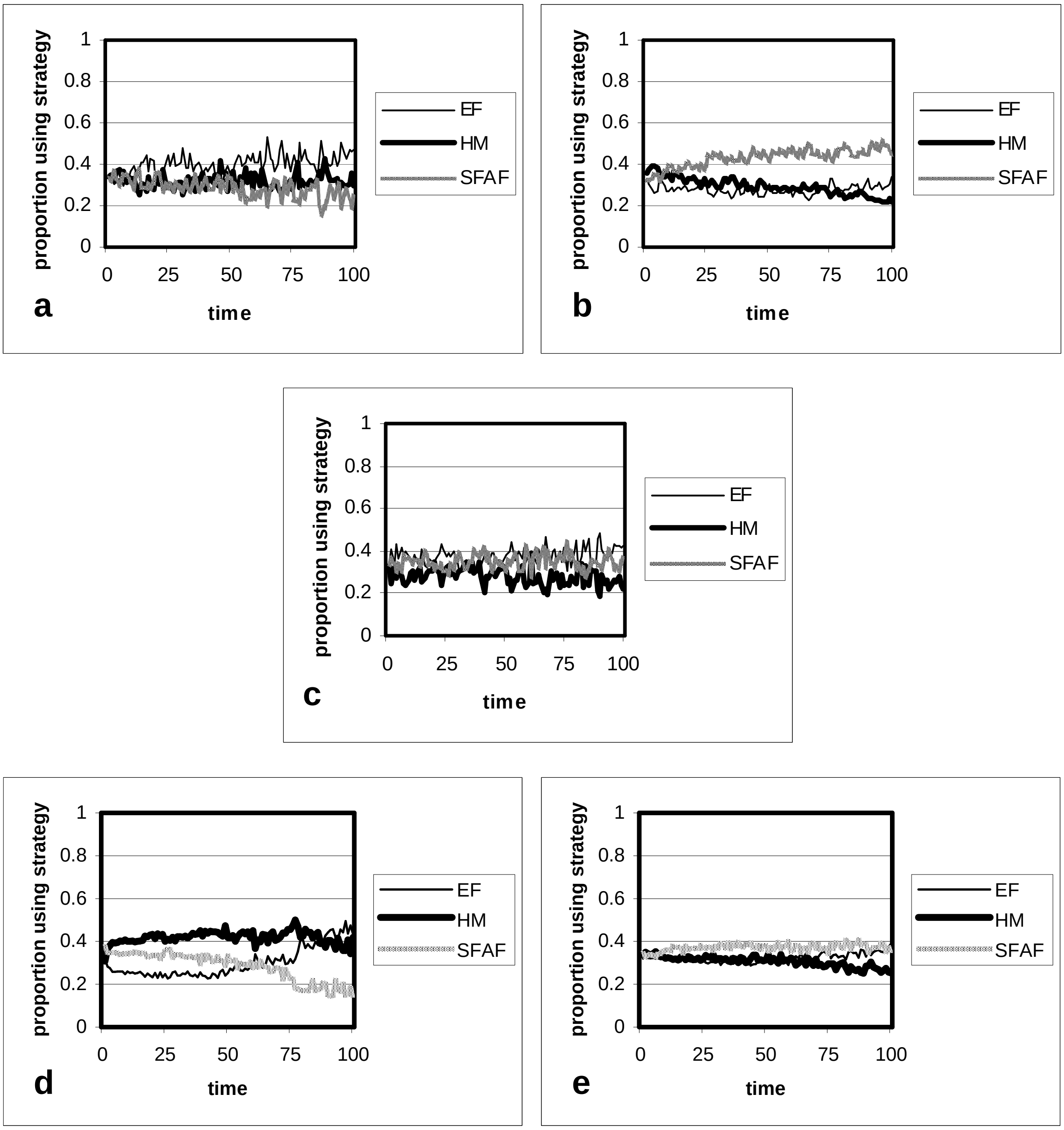

Figure 5.15. Strategy selection by agents in: a) most variable and water-stressed (Lower Vaal); b) least variable (Thukela); c) largest (Lower Orange); d) smallest (Berg); and e) least water-stressed (Mzimvubu) WMAs using randomly-assigned fixed indicators. EF = Efficiency First, HM Hydraulic Mission,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

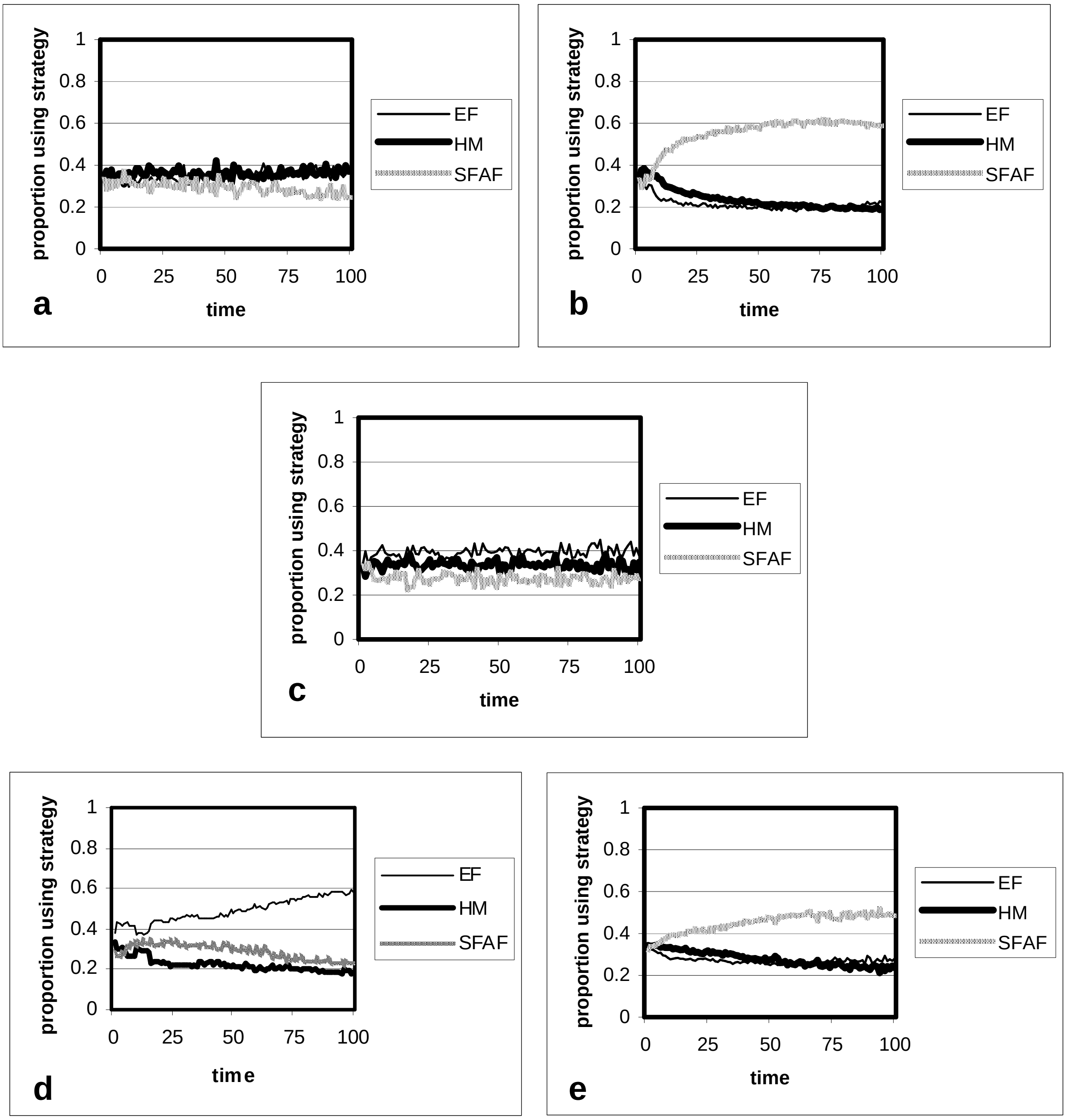

Figure 5.16. Strategy selection by agents in: a) most variable and water-stressed (Lower Vaal); b) least variable (Thukela); c) largest (Lower Orange); d) smallest (Berg); and e) least water-stressed (Mzimvubu) WMAs using changing indicators. EF = Efficiency First, HM Hydraulic Mission, SFAF = Some,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

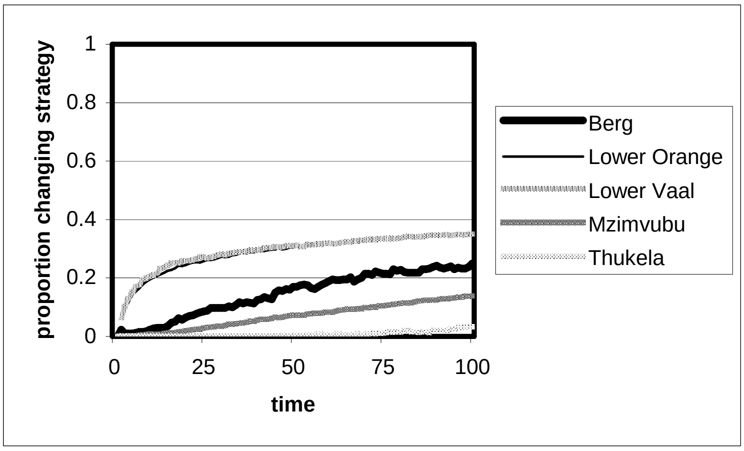

Figure 5.17. Strategy change by agents in five WMAs using randomly-assigned fixed indicators.

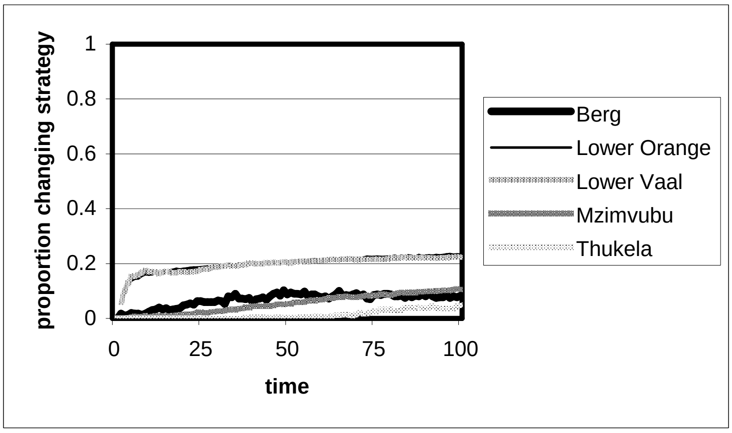

Figure 5.18. Strategy change by agents in five WMAs with changing indicators.

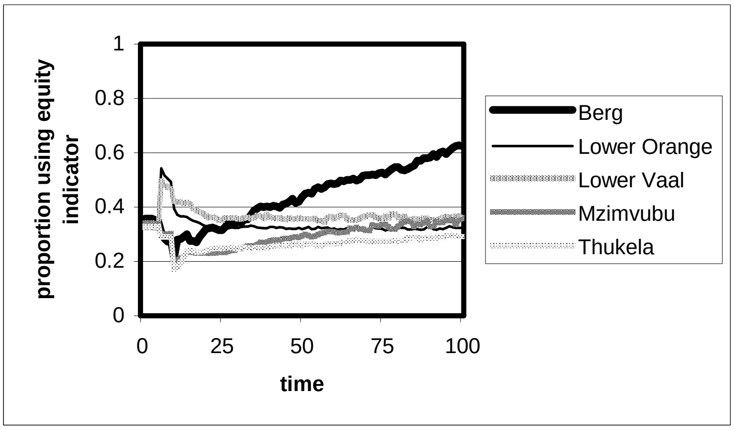

Figure 5.19. Selection of equity indicator by agents in five WMAs.

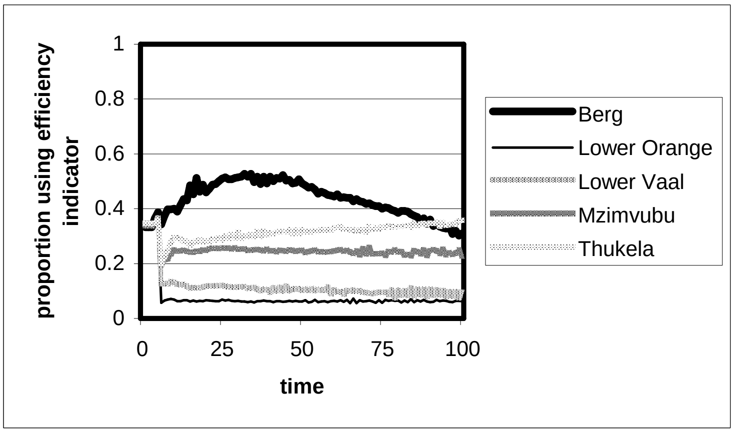

Figure 5.20. Selection of efficiency indicator by agents in five WMAs.

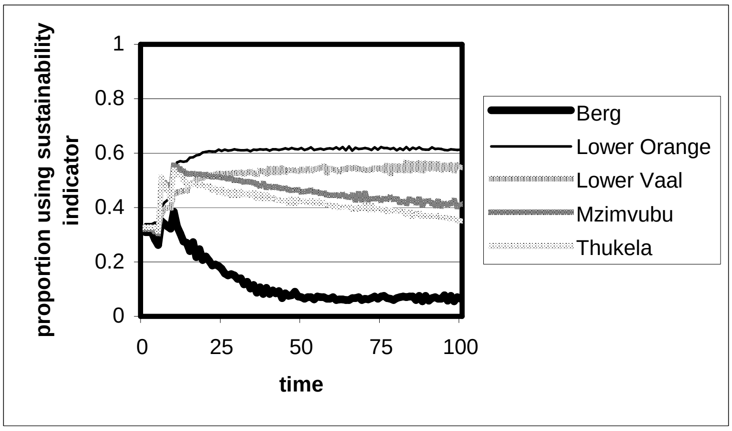

Figure 5.21. Selection of sustainability indicator by agents in five WMAs.

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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