CHAPTER 11

SOCIAL-ECOLOGICAL RESILIENCE IN A DRY ENVIRONMENT: PEOPLE AND WATER RESOURCES IN THE LITTLE KAROO

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ABSTRACT

The Little Karoo is a semi-arid environment with highly variable rainfall and has a history of recurrent floods and droughts. The historical development of the social-ecological system (SES) has been characterised by increasing exploitation of, and dependence on, water resources and decreasing resilience, both ecological and social. The modified SES is now fragile and vulnerable to climatic and economic volatility. These insights into the SES need to be evaluated and the social components, particularly the approaches to natural resource management, so that the resilience of the ecological components can be rebuilt to support sustainable use of the water resources in the Little Karoo. This transformation can only be achieved by changing the way environmental goods and services are perceived, managed and used throughout society.

KEYWORDS

Social-ecological system, resilience, sustainability, water scarcity, water use efficiency, groundwater resources, causal linkages, land transformation, environmental history, future options

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INTRODUCTION

South Africa is a semi-arid country with an average rainfall of just 450 mm, compared with a global average of about 860 mm (NWRS, 2004). Only 9.0% of the rainfall ends up in the rivers or groundwater (NWRS, 2004); the rest evaporates or is transpired by plants. The rainfall also varies significantly from year to year and over longer cycles, which results in very low long-term yields[1] from water supply schemes - with the maximum potential yield being about 3.7% of the rainfall (NWRS, 2004). Put in a different way, if the available water resources were distributed across the current population of South Africa it would be equivalent to about 966 people per Mm^3 of water per year. This would almost be classified as a situation of chronic water scarcity (Falkenmark, 1989), well below the quantity required for an acceptable standard of living. The Little Karoo, which is situated in southern South Africa and is the focus of this chapter, exemplifies these characteristics because it includes some of the driest areas of the country and is very obviously facing serious water shortages (DWAF, 2004).

The aims of this study are: (a) to investigate the complex inter-relationships between people and their environment, with a focus on water resources, using the Little Karoo as a case study; and, (b) to use these insights to identify development options that could increase the resilience of the social-ecological system (SES) of the Little Karoo and, thereby, facilitate progress towards sustainability. We use a resilience analysis approach to understand the SES and to develop ideas for re-building system resilience. This requires understanding of both the ecological and social components of the SES and their inter-dependencies, and the vulnerability of the social-economic system elements to the impacts of natural events and anthropogenic factors.

Following this introduction to the chapter, we next discuss some basic concepts relating to the resilience of SESs and their ecological and social components. We then describe the Little Karoo environment, focusing on water resource limitations and how these relate to key events in the social-economic history of the area. In the final

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[1] The sustainable yield as used in this chapter refers to the amount of water that can be provided by dams of a given capacity and risk of failure (e.g. 1 in 50 years). The yield is typically only a proportion of the mean annual runoff because: (a) the large volume flows, especially the floods, are included in the calculation of the mean and tend to shift it upwards; (b) high flows fill and overflow the dams and so are not stored; (c) evaporation losses from dams are high and directly reduce yield; and, (d) because water release has to be controlled to ensure a continued supply during extended periods of below average inflows. Although agriculture can use variable yields by increasing or decreasing cultivated areas or intensifying cropping, urban and industrial water use is less flexible and the high cost of sourcing emergency supplies results in a preference for minimizing the risk of a failure in supply over higher yields.

sections of the chapter we propose some interventions that can aid in building the resilience of the SES, focusing on water management. It should be noted that our proposals complement an analysis presented in another chapter in this volume, which elaborates on other aspects of the Little Karoo social-ecological system and approaches to building system resilience. In this regard, O'Farrell *et al.* (Chapter 12, this volume) focus on land degradation and its impacts on the SES, using the town of Vanwyksdorp in the Little Karoo as a case study.

SOCIAL-ECOLOGICAL SYSTEMS AND RESILIENCE

The term social-ecological system (SES) was coined to give explicit recognition to the fact that they are characterized by intricate patterns of causal links and interdependencies within and between the different social (including economic and governance aspects) and ecological components (Berkes and Folke, 1998 in Anderies *et al.*, 2004; Carpenter *et al.*, 2001; Liu *et al.*, 2007; Du Plessis, Chapter 3, this volume). Social-ecological systems are characterised by non-linear relationships, thresholds, emergence, renewal, self-organisation and reorganisation, historical dependencies and multiple possible states and outcomes – i.e. they are complex systems (Carpenter *et al.*, 2001; Scheffer *et al.*, 2001; Cilliers, Chapter 2, this volume; Peter, Chapter 14, this volume). The complexity of SESs is increased by their sensitivity to forces and events that cross (transgress?) scales and system boundaries and can initiate cascades of change in the SES as system components respond (Kinzig *et al.*, 2006). Some of these farces or events act in a gradual fashion and can shift the SES towards the boundaries of its current state; others act suddenly and are experienced as triggers or shocks that shift an SES across critical thresholds (Carpenter *et al.*, 2001). Human history contains many accounts of societies collapsing because they have failed to anticipate or adapt to changes in the delivery of ecosystem services (environmental goods and services) - changes that were brought about by the impacts of their actions on the resilience of the ecosystems providing those services (Holling and Meffe, 1996; Diamond, 2005).

There are a number of different nuances in the way resilience has been defined in the literature on ecosystems and social-ecological systems (Holling 1973, 1996; Westman 1978; Peterson *et al*., 1998; Holling and Gunderson, 2002; Cumming *et al*., 2005). A number of these nuances arose as the concept was extended from the purely ecological domain to apply to SESs (Folke, 2006; see **Box 1**). The first characteristic of the definition in **Box 1** is what has generally been termed "ecological" resilience (e.g. Holling 1973, 1996; Peterson *et al*., 1998). A number of authors have distinguished this from the "engineering" concept of resilience: the rate at which a system returns to a single steady or cyclic state following a perturbation (Peterson *et al*., 1998). The ecological and engineering definitions describe two distinct properties, or even two different aspects, of resilience. This distinction is useful, but Holling (1973, 1996) recognized that the two interpretations also characterise two different views (or paradigms) that people have adopted for managing an ecological system or an SES.

Box 1. "Resilience" as applied to ecosystems, or to integrated systems of people and the natural environment, has three defining characteristics:

- The amount of change the system can undergo and still retain the same controls on function and structure
- The degree to which the system is capable of self-organization
- The ability to build and increase the capacity for learning and adaptation (Carpenter *et al*., 2001; Resilience Alliance, 2007).

The "engineering" approach has its roots in the management philosophy of command and control and is founded on the belief that complex systems can be reduced to manageable entities that follow mechanistic rules. The aim typically is to maximize the sustained yield of goods and services. Analyses of a number of examples show that engineering of SESs inadvertently alters the ecosystem components in subtle but important ways, causing them to lose their resilience and ability to maintain their integrity and function when exposed to changes in the driving forces and when they cross thresholds (Holling 1996; Holling and Meffe 1996; Walker *et al*., 2006 and other papers in that special issue of *Ecology and Society*; Kareiva *et al*., 2007). During the engineering process, the dynamics of the ecological system and the human system become disconnected. As the states of the social and economic systems, inevitably, diverge from the ecological system (which itself is changing), so the SES's resilience also decreases (van der Leeuw and Aschan-Leygonie, 2000). Humans typically respond to this divergence by engineering in additional controls, making the systems more complicated and increasing the resource inputs required to sustain them (Holling, 1996; Holling and Meffe, 1996; Allen *et al*., 2001).

Incompatibilities between ecological resilience and human engineered resilience are evident in many situations world wide (Anderies *et al*., 2004, 2006; Olsson *et al*., 2004; Lebel *et al*., 2006; du Plessis, Chapter 3, this volume). Examples are explored in this chapter, which focuses on the impacts on SES resilience attributable to water constraints within the Little Karoo. O’Farrell *et al*. (Chapter 12, this volume) draw similar lessons from their study.

THE SOCIAL-ECOLOGICAL SYSTEM OF THE LITTLE KAROO

As described above, an SES can be divided into its major components: the ecological and the social, which are linked in many ways. We have tried to capture the key elements of the main components or domains of the SES dealt with in this analysis in **Figure 1**: the ecological component and the economic and governance domains of the social component of the SES. They are shown as discrete entities, but they are interlinked in many ways and are also linked to others not shown here. Also, each one of these domains is not a single system – they contain many nested sub-systems making them a system of systems. A simple example from the hydrological domain is a primary catchment within which the sub-catchments are nested. The sub-catchments comprise areas that are linked into a hierarchy by the linear tributaries of the river systems whose flows are modified by water abstractions for urban and agricultural uses. The following discussion deals with selected aspects of the ecological and social components of the Little Karoo SES.

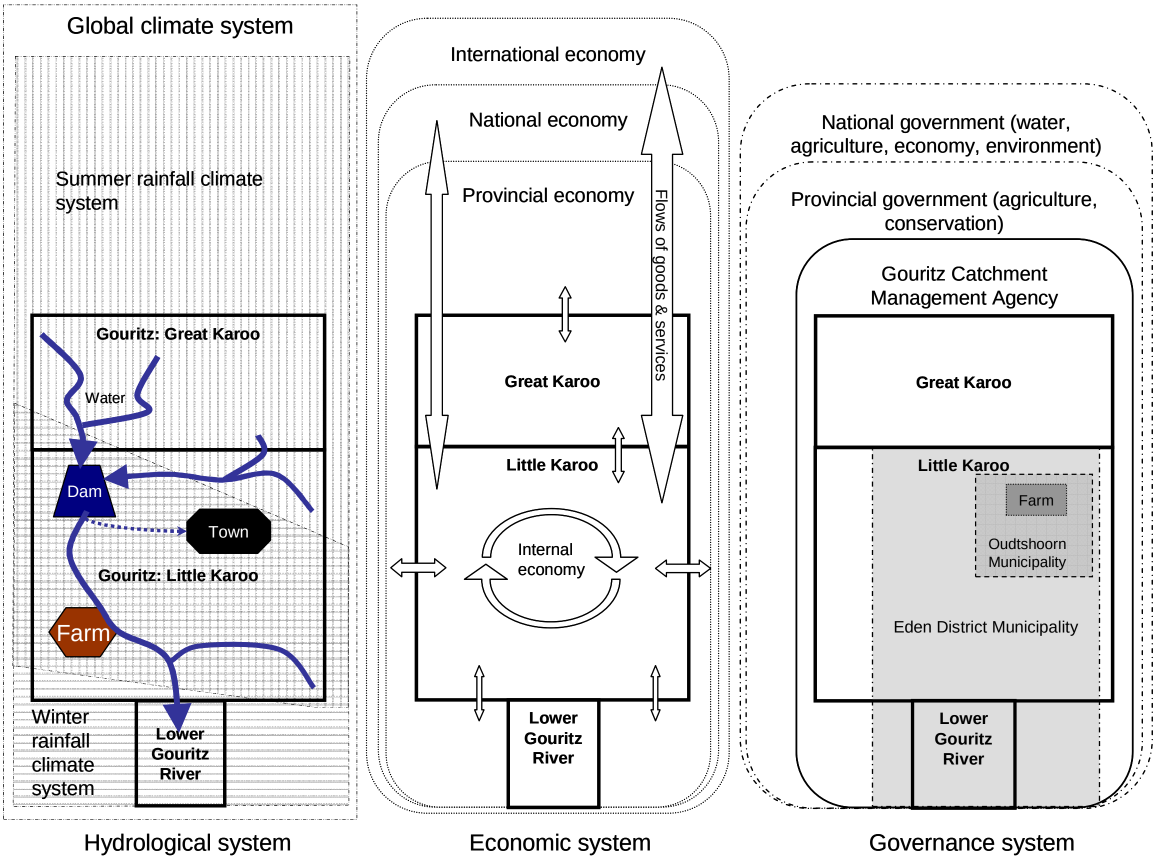

Figure 1. Three components of the Little Karoo SES and their various linkages with other systems outside the geographic boundaries of the system. Each component includes internal dynamics – e.g. the use of water by the town alters the flows of water to the farmer situated downstream. Governance structures are particularly complicated with nested national, provincial and municipal government with jurisdictions that are not aligned with catchment boundaries. They also have differing jurisdiction over different natural resources. The national Department of Water Affairs has influence over municipalities through the Water Services Act and over farmers through the Water Act. The Provincial Government has no direct role in water resource management, but does have some jurisdiction over land management activities such as agriculture and conservation.

The geographical boundary of the Little Karoo SES is relatively easy to define on the basis of the outer boundary of the watersheds (catchments) that form part of the Gouritz River system (**Figure 2**). Note, that this boundary differs somewhat from the one used by O’Farrell *et al.* (Chapter 12, this volume), which is based on the combination of administrative district and biogeographical boundaries used by Vlok *et al.* (2005). The Gouritz River catchment is about 4.5 million ha, and the Little Karoo comprises about 1.9 million ha (42%) of the total. Part of the Great Karoo, including the headwater catchment of the Touws River, is included in the study area. The rational for this is that the tributaries of the Gouritz River, which originate in the Great Karoo, flow through the core of the study area and are a source of water supply to irrigation farmers situated in the Little Karoo. The Montagu-Koo and Barrydale areas, which are hydrologically part of the Breede River system, are excluded from our analysis due to a lack of suitable water-related data.

The boundaries of the social domains of the SES are not as easily defined because there are numerous transboundary links that can be defined, for example, by the flows of economic goods and finance between the Little Karoo, the rest of South Africa and internationally (**Figure 1**). Note, that du Plessis (Chapter 3, this volume) presents a conceptual framework for defining SESs.

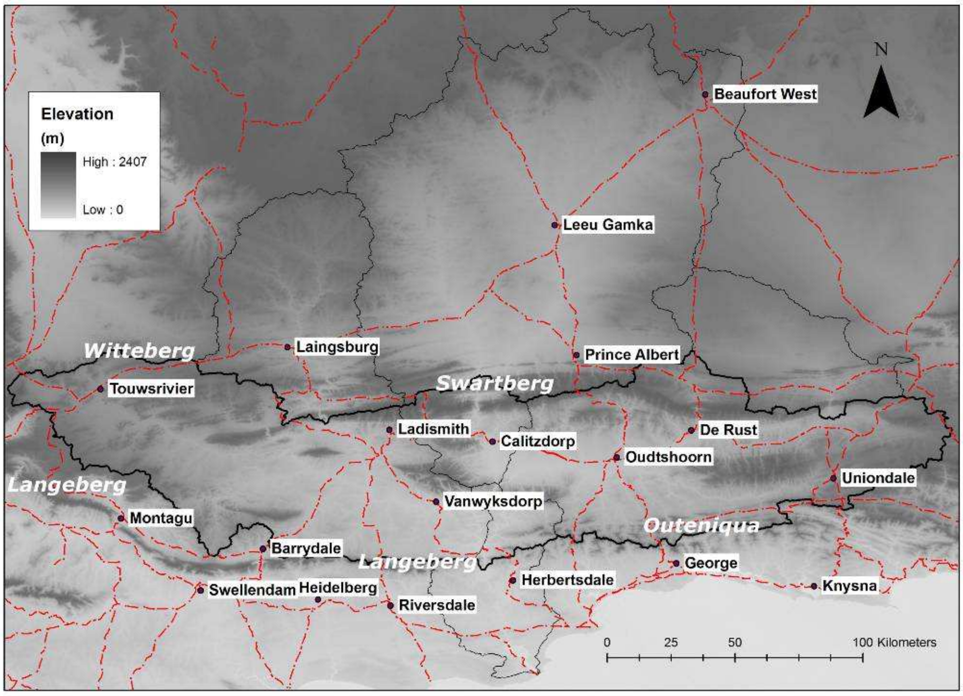

Figure 2. Study area (thick black line) with the main towns, road (dashed lines) and mountain ranges indicated. The Gouritz River sub-catchments are indicated by the thin black line. Names of the major tributaries of the Gouritz River are given in Figure 3.

The ecological component

Physical setting

The Little Karoo is a broad inter-montane valley that extends some 370 km from east to west and about 40-70 km from north to south (**Figure 2**). The northern boundary is defined by the crest of the Witteberg and Swartberg mountains, and the southern boundary by the Langeberg and Outeniqua mountains. The elevation of the crests of the mountains is generally greater than 1000 m, with the Swartberg range exceeding 2000 m. The elevation of the central valley varies from 250 to 700 m. The Huis River mountains run from north to south and divide the Little Karoo into its western and eastern sections. The mountain ranges are formed from the highly fractured sandstones of the Table Mountain Group (TMG), which generate shallow, rocky, nutrient-poor soils. The lowlands are formed from the shale-dominated Bokkeveld Group and the conglomerates of the Uitenhage Group, which were deposited over the TMG. There is an outcrop of the basement rocks of the Kango Group associated with the Cango Fault on the southern side of the Swartberg Mountains. This includes limestones, characterized by a number of cave systems. The shales, conglomerates and limestones all give rise to fine-textured, relatively fertile soils.

Rainfall

The Little Karoo is situated in the transition zone from winter rainfall in the west to summer rainfall in the east (**Figure 1**). The Great Karoo, situated north of the Swartberg Mountains, is predominantly a summer rainfall area. Winter rainfall is associated with cold fronts that sweep from west to east, crossing the southern mountains of the Little Karoo and also bringing rain to the northern mountains (Desmet and Cowling, 1999). Summer rainfall is dominated by convective systems associated with air masses drawn from the Indian Ocean (Tyson, 1986). The mountain areas of the Little Karoo receive more than 900 mm/yr of rainfall; however, its broad valley lies in the rain shadow of the southern mountains and receives only 250-350 mm/yr (Lynch, 2004; **Figure 3**). The western region is drier than the east, with some areas receiving as little as 20 mm/yr of rainfall. Mean annual potential evaporation ranges from about 1000 mm/yr on the upper slopes of the southern mountains to more than 2500 mm/yr in the low-lying areas, with a mean of about 2200 mm (Schulze *et al.*, 1997). This is 10 or more times the annual rainfall. Evaporation rates especially from open water are, therefore, very high making dams an inefficient way of storing water.

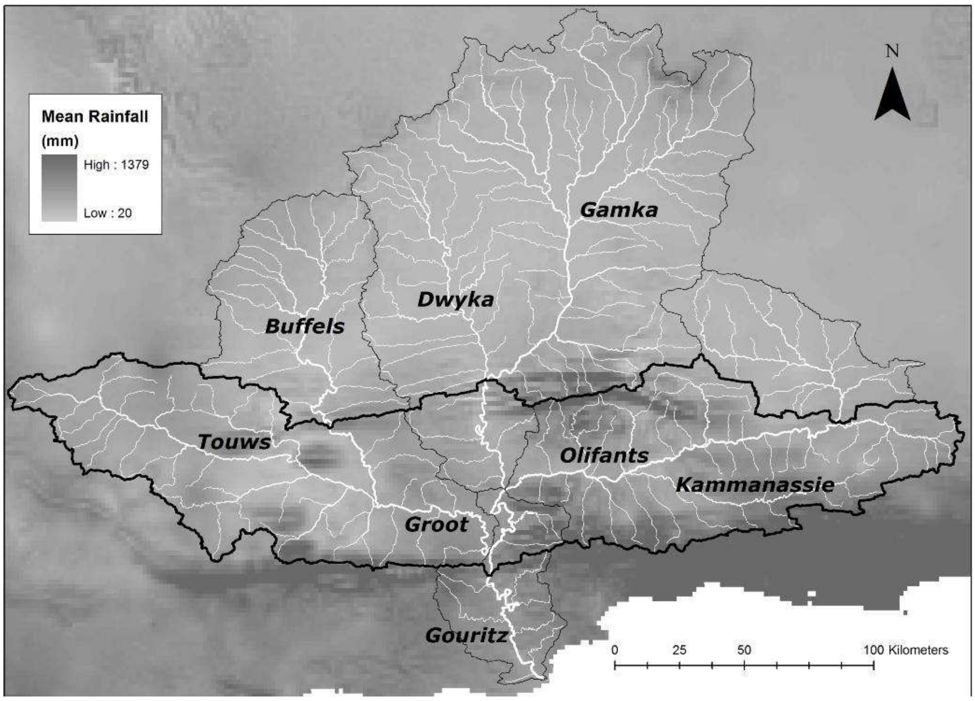

Figure 3. Mean annual rainfall for the major sub-catchments of the Gouritz River system and the adjacent areas based on data from Lynch (2004). The Little Karoo study area and included sub-catchments are outlined in thick and thin black lines respectively. The main tributaries have been labelled and the width of the river reach corresponds to the Strahler order (1 = headwater).

The rainfall in southern Africa is strongly influenced by multi-year dry and wet cycles of 16-20 years and 10-12 years associated, respectively, with the summer and winter rainfall systems (Tyson *et al*., 1975). Both of these cycles affect rainfall in the Little Karoo. The rainfall regime is also characterised by extremely intense rainfall events associated with cut-off low pressure systems that can result in major floods (Desmet and Cowling, 1999; **Table 1**). Examples of floods include: the widespread flooding from Laingsburg to Montagu to Calitzdorp in January 1981; at Montagu in March 2003; and, at Zoar near Ladismith in January 2004. The area also is subject to periodic, and often prolonged, droughts that have affected agricultural activities and resulted in severe periodic water shortages in towns such as Oudtshoorn (**Table 1**).

Table 1. Summary of the history of the Little Karoo, with the emphasis on events and developments relating to water resources and their utilisation for social and economic development. Where the source of the information is not specifically indicated, this is Burman's (1981) book on the Little Karoo.

Date	Notes
1725-1800	• First farms granted on the inland side of the Langeberg in the Koo-Montagu area, followed by the Warmwaterberg-Ladismith, Calitzdorp and Kango areas by 1762.
1801-50	• 1825-1829 were dry years; 1830-33 and 1844-1848 wet years (Tyson, 1986). • In 1806 the British allowed free trading of goods to boost economic growth (Whiting

	Spilhaus, 1966). • Tobacco under irrigation expands, especially in the Grobbelaars River valley near Oudtshoorn.
1851-70	• 1852-60 were wet years (Tyson, 1986), but in 1859 Oudtshoorn experienced drinking water shortages due to drought. In 1865 prolonged drought in Oudtshoorn brought poverty for many - 34 people jailed for stealing food. In 1867 a flood in Montagu killed 12 people. In 1869 Oudtshoorn experienced severe floods, the Schoemanspoort road was washed away and there was extensive flood damage along the Grobbelaars River (Ross, 2002). • By 1856 riparian rights to water were established in law and the principle of state ownership of public water was abandoned (Tewari, 2002).
1870-80	• 1872-78 wet years (Tyson, 1986). • Lucerne introduced for ostrich fodder, encouraging farmers to switch from other, more risky crops and to expand irrigated lands. • The Right of Passage of Water Act of 1876 and the Cape Irrigation Act of 1877 provided for co-operation between farmers to develop irrigation schemes, but with little success (Hall, 1939; Beinart, 2003).
1881-1900	• 1881-1885 dry years (Tyson, 1986). • In 1885 Oudtshoorn had severe floods recording 31 hours continuous rain; Victoria Bridge over the Olifants River was washed away. March 1894 brought a severe storm, which destroyed crops. Heavy rains and thunderstorms damaged infrastructure in Oudtshoorn. • In 1896 both Calitzdorp and Oudtshoorn experienced drought, the latter again in 1899; domestic water supplied by bucket in Oudtshoorn.
1900-10	• Droughts in 1909-10 (Levenkind, 1941). • After 1903 the 2nd ostrich boom encourages farmers to drop other crops and livestock. • In 1904 the Oudtshoorn–Port Elizabeth railway line is opened, facilitating the export of products. • Department of Irrigation established in 1903 to promote the development of large irrigation schemes, again with little success (Beinart, 2003). The Cape Irrigation Act of 1906 formalised the existing practice and extended the kinds of sharing of water between land owners (Hall, 1939; Tewari, 2002; Beinart, 2003).
1910-20	• Drought in the Calitzdorp region in 1914-1915; nearly 50% of the SW Cape experiences <62% of its normal rainfall (Levenkind, 1941). 1918 was a dry year and 1919 was a major drought year, with 87% of South Africa receiving about 69% of the normal rainfall; 78% of the SW Cape experienced 79% of the normal rainfall. 1920 was also a dry year. • Completion of the Oudtshoorn-George-Mosselbay railway line opened up trade in perishable produce (Ross, 2002). • The collapse of the ostrich industry in 1914 forced many farmers off the land; survivors switched to other crops and livestock. • The Calitzdorp (Nels River) Dam was completed in 1918, followed in 1920 by the Bellair dam, which remained empty till 1922 and was first filled in 1981. The Prinsrivier dam was completed in 1920.
1921-30	• 1923-1928 dry years (Levenkind, 1941) especially in the Calitzdorp area. • In 1924 the Kammanassie Dam was completed. • In 1926 the Ladismith-Touws River railway line was opened, stimulating growth and diversification in the farming industry in the western region. • The Kango Tobacco Co-Op was formed in 1926 to simulate irrigated tobacco, vine and fruit growing.
1931-60	• 1932-33, 1935-1949, 1956, 1958 and 1960 were dry years (Levenkind, 1941; Zucchini and Adamson, 1984). • The 1932 Soil Erosion Act initiated state support and intervention in erosion control

	measures and works (Beinart, 2003). • The Marketing Act of 1937 establishes control of agricultural markets (Vink and Kirsten, 2000). Ladismith Co-Op formed in 1939 to market fruit, wine and dairy products; followed in 1940 by the Langeberg and Barrydale Co-Ops. The former establishes a canned fruit factory which opened new markets. • Floriskraal dam completed in 1956, exclusively for irrigation.
1961-90	• 1961-69, 1972-74, 1978-80 were dry years (Zucchini and Adamson, 1984). In 1963 the Barrydale-Ladismith area received 300 mm of rain in three days and floods damaged roads and farmlands. In 1974 the Baden area near Montagu has flash floods. On 25-26 January 1981 a cut-off low pressure system brought heavy rain (Kovacs, 1982). Montagu's Hot Springs Hotel and campsite were destroyed, 13 people drowned; Barrydale flooded but no damage; Ladismith lost its railway line and there was severe damage to orchards and lucerne lands; Huis River pass bridge washed away. • Gamkapoort Dam completed in 1967. A number of groundwater water supply schemes are developed for urban and rural supply; • Protective measures and agricultural subsidies were phased out during the late 1980s, drastically reducing dryland grain cropping, particularly of wheat (Vink and Kirsten, 2000; Kirsten and Vink, 2003). • Production of vegetable seed under irrigation expanded rapidly.
1991-date	• Late 1980s to early 1990s dry years, likewise late 1990s to early 2000s. 21-26 November 1996 floods over Little Karoo, including Oudtshoorn, Uniondale, Calitzdorp and Ladismith. In February 2000 there were floods in Calitzdorp (WCDA, 2003). Robertson, Montagu (500 people evacuated) and Barrydale flooded in April 2003, wall of the Bellair Dam broken (IOL, 2003); January 2004 Zoar and August 2006 produce heavy rains at Oudtshoorn, flooding in Calitzdorp, Meiringspoort and Garcias Pass closed. • National Water Act of 1998 radically transformed water legislation. • Little Karoo Rural Water Supply Scheme inaugurated in 1993; supplies 1.1 Mm^3/yr of groundwater to rural communities (±31600 people) and for irrigation (DWAF, 2004) • The monopoly of the Little Karoo Agricultural Co-Op ended in 1993 and the 1996 Marketing of Agricultural Products Act ended the era of market control (Kirsten and Vink, 2003).

Water Resources

Surface runoff

Orographic gradients in the mean annual runoff are steeper than those of the rainfall. Only a few of the highest peaks generate more than 500 mm of runoff and for most of the Little Karoo this is less than 5 mm (**Figure 4**). The effect of the rain-shadow on the northern slopes of the coastal mountains and the importance of the central Swartberg mountain range for runoff manifest clearly. The mean annual runoff for the Gouritz River system is about 674 Mm^3/yr (**Table 2**), with the Great Karoo contributing just 31% of this total - although it accounts for most of the Gouritz River catchment (**Figure 3**). The runoff from the Great Karoo is important because it feeds the Floriskraal and Gamkapoort dams, which sustain irrigation areas near Ladismith and Calitzdorp respectively.

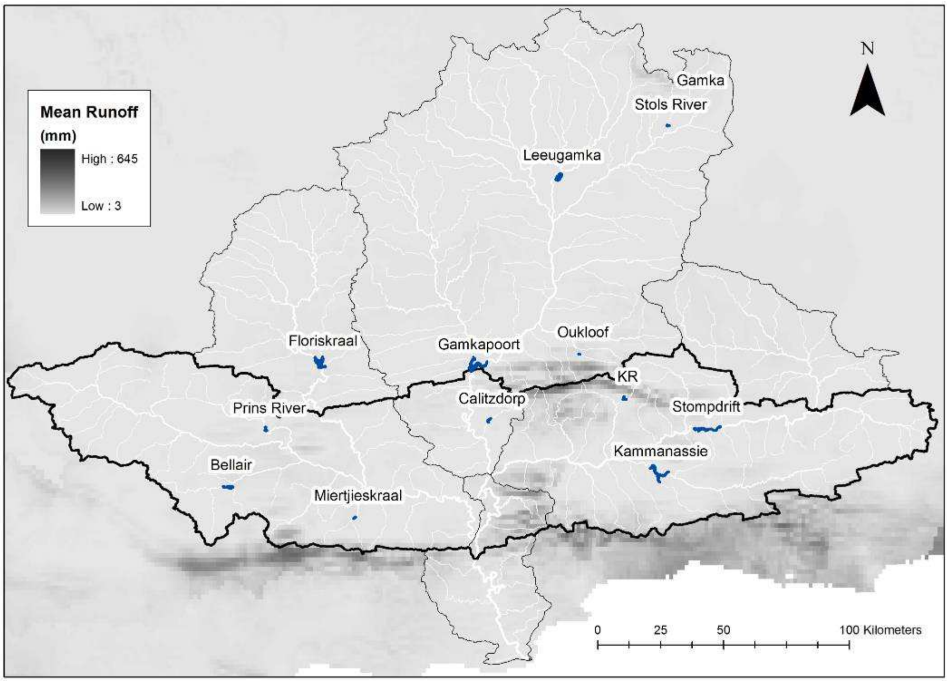

Figure 4. Mean annual runoff for the major sub-catchments of the Gouritz River system and the adjacent areas based on the rainfall data from Lynch (2004) and rainfall-runoff relationships developed by Midgley *et al.* (1994). The Little Karoo study area and included sub-catchments are outlined in thick and thin black lines respectively. The width of the river reach corresponds to the Strahler order (1 = headwater). The names and locations of the main dams are also shown (KR = Koos Raubenheimer dam).

The mean annual runoff is statistically misleading because it is strongly biased by the high volumes in years when floods are recorded (**Figure 5**). The frequency of extended periods with flows that are less than the mean is indicated in the multi-year trends in the cumulative deviations (e.g. 1940-1950 at Calitzdorp). The spatial variation in wet and dry cycles is also evident: from 1920-1940 Bellair and Prinsrivier in the western Little Karoo show a long downward trend; at Calitzdorp (central) the trend is upwards; and, at Kammanassie in the east it is upward and then downward. The monthly inflows into dams are, therefore, highly erratic, with the coefficient of variation being 1.5-3.5 times the mean.

When considered in terms of the mean annual runoff (including the contribution derived from Great Karoo portion of the Gouritz River catchment), the Little Karoo seems to be in a favourable situation in terms of water availability for human use. Given the population of about 132 000 (GAP, 2007), there are about 245 people per Mm^3/year - a situation that does not indicate stress (Falkenmark, 1989). However, if the sustainable yield of the water supply systems is used as the benchmark, there are 822 people per Mm^3/yr – which falls within the definition of a water-stressed situation. No data are available on the sustainable yields of the Little Karoo systems on their own, but it is likely that this would equate to more than 1000 people per Mm^3/yr – a situation of absolute water scarcity.

Water quality is an important issue in the Gouritz River system, with salinization of the surface waters and water pollution being important issues (DWAF, 2003, 2004). Salinization, attributable to high evaporation rates and naturally saline groundwater derived from certain rock types (e.g. shales and conglomerates), is a major concern within the Little Karoo. The salinity of the Touws, Buffels and Groot rivers is due to both the natural salinity of much of the region’s groundwater and return flows of water from irrigated areas in their catchments. The water quality is generally acceptable in the upper catchments, except for the Buffels River above the Floriskraal Dam; however, it deteriorates downstream in terms of the uses to which it can be put (DWAF, 1996).

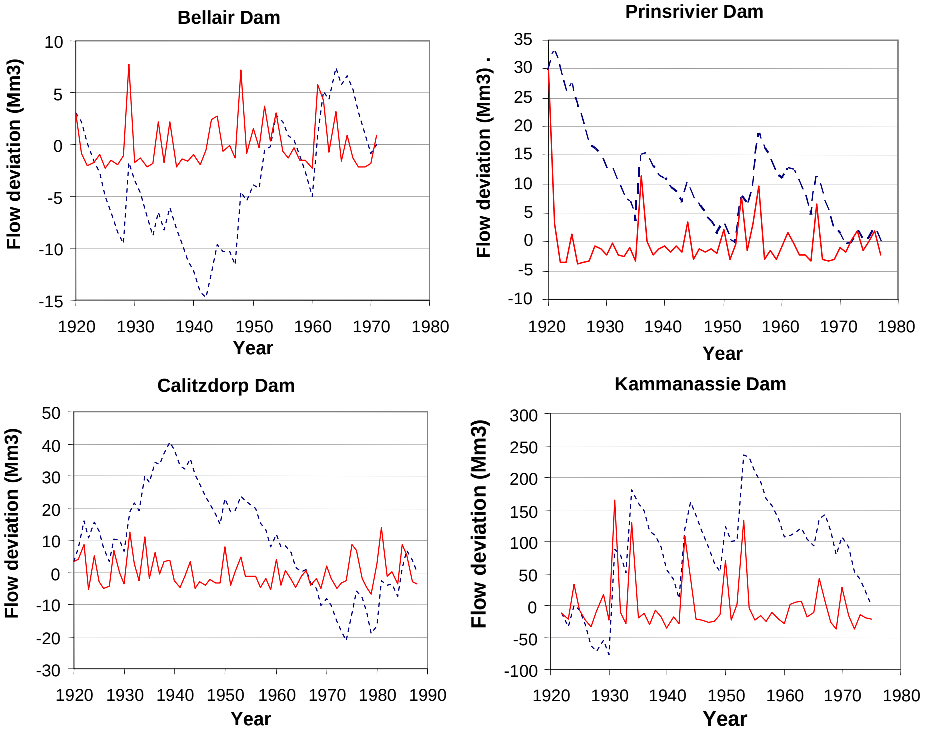

Figure 5. Variability and trends in the annual inflows for dams in the study area, showing the annual deviation from the mean (solid line) and the cumulative deviations (dashed line). Data taken from the naturalised flow records for the catchments of the Water Resources 1990 study (Midgley *et al*., 1994). Dam locations are shown in Figure 4.

Groundwater

There are no reliable data on the availability of groundwater in the Little Karoo. Groundwater recharge (**Figure 6**), an estimate of the amount of water potentially available, was derived from data on chloride concentrations in groundwater, rainfall and lithology (DWAF, 2005). The high recharge on the fractured TMG sandstones of the mountain ranges stands out clearly, as does the higher recharge in the eastern region of the Little Karoo. The Great Karoo has low recharge values because of the low permeability of the shales and the fine textured soils derived from them. Snow is thought to contribute significantly to recharge in the montane areas (Parsons, 2002); however, its contribution has not been quantified. The total recharge for the Gouritz River catchment is about 305 Mm^3/yr, or 45% of the mean annual runoff (**Table 2**). The TMG continues under the Little Karoo from the southern to the northern mountains. Some of the groundwater flows through these formations, reaching as deep as 3 km and taking hundreds to thousands of years to emerge, explaining the hot springs such as those at Calitzdorp (Harris and Diamond 2002; Meyer, 2002). Similar springs are found at Montagu, Warmwaterberg, Calitzdorp and Toorwater near Uniondale. Spring discharges can be quite substantial and range from 0.7-11.0 megalitres per day (Burman, 1981; Meyer, 2002). Most of the groundwater discharges through springs and wetlands directly into water courses.

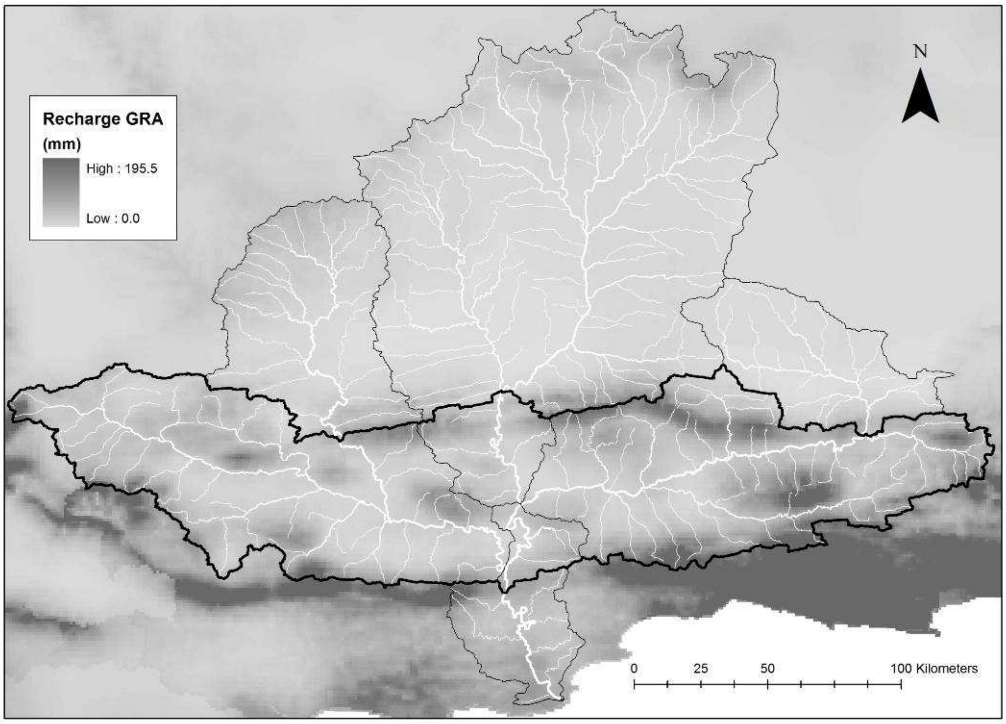

Figure 6. Groundwater recharge estimate based on mean annual rainfall, chloride concentration data and lithology (DWAF, 2005).

Groundwater quality is directly related to the lithology of the aquifer. The Bokkeveld Group shale, Enon Group conglomerate and surficial (alluvial) deposits and, to a lesser extent, the Witteberg Group sandstone have high Total Dissolved Solids (TDS, 601-1800 mg/l or more), electrical conductivities (EC) and chloride levels (Le Maitre *et al*., 2007). The TMG sandstone, which occurs primarily in areas with high rainfall and recharge and comprises the sources of the perennial rivers, provides ideal quality groundwater except for the low pH. Overall, the high TDS and EC values for groundwater, except where this is associated with the TMG, make it marginal for domestic use according to the domestic water quality standards (DWAF, 1996). Recharge is relatively high in the TMG, and this resource has been exploited for municipal supplies from well fields - for example, the Little Karoo Rural Water Supply Scheme, which supplies water to more than 30 000 people and also supports irrigation schemes (Cleaver *et al*., 2003; DWAF, 2003).

Table 2. Percentages of the area, mean annual runoff (MAR) (Midgley *et al*., 1994) and groundwater recharge (derived from DWAF, 2005) contributed by the areas of the Gouritz River catchment situated in the Great Karoo and Little Karoo as well as its Coastal portion. The Great Karoo includes the northern slopes of the Swartberg-Witteberg ranges and the Coastal portion includes some of the southern slopes of the Outeniqua range and coastal plateau, which does not supply water to the Little Karoo.

River systems	Great Karoo	Little Karoo	Coast	Total	Percent of overall total
	Area (% of km^2)			**Area (km^2)**	
Touws, Buffels, Groot	30.3	69.7		13312	29.49
Dwyka, Gamka,	92.3	7.7		18484	40.95
Olifants, Kammanassie	27.8	72.2		11017	24.41
Gouritz		29.1	70.9	2321	5.14
All	53.5	42.8	3.6	45134	
	MAR (% of Mm^3)			**MAR (Mm^3/yr)**	
Buffels, Touws, Groot	28.5	71.5		105.07	15.58
Gamka, Dwyka	83.5	16.5		205.88	30.53
Traka, Olifants, Kammanassie	3.5	96.5		228.86	33.94
Gouritz		36.5	63.5	134.49	19.95
All	31.1	56.2	12.7	674.30	
	Recharge (% of Mm^3)			**Recharge (Mm^3/yr)**	
Buffels, Touws, Groot	12.5	87.5		90.30	29.62
Gamka, Dwyka	75.4	24.6		48.23	15.82
Traka, Olifants, Kammanassie	2.1	97.9		118.11	38.74
Gouritz		34.5	65.5	48.24	15.82
All	16.5	73.2	10.4	304.89	

Availability

Water availability is determined primarily by: (a) how much of the rainfall becomes available as water in rivers or in the ground; (b) how variable rainfall and resultant flows are; and, (c) losses from storage systems. In the catchments of the Gouritz River, only about 5-6% of the rainfall is converted to runoff. This is much less than the average of 9% for South Africa, 30% for the continent as a whole, but comparable with arid regions globally (McMahon, 1979). The high variability of the rainfall results in low sustainable yields (**Table 3**), even though the dams are situated on relatively strongly flowing rivers. The influence of the high variability can be seen in the low percentage yields for both the major tributaries and for the three river systems indicted in **Figure 7**, combined.

Table 3. Rainfall, runoff and reservoir yields in selected catchments in the Karoo. MAP = mean annual rainfall; MAR = mean annual runoff; Mm3 = millions of cubic metres. The yield as a percentage of the MAR is calculated for a hypothetical reservoir (situated at the same site as the current dam) with a storage capacity equal to the mean annual runoff and for a 1 in 50 year failure to sustain that yield (Braune and Wessels, 1980).

River	**Location**	**Area (km^2)**	**MAP (mm)**	**MAR (Mm^3)**	**Reservoir Yield (% MAR)**
Prins	Prinsrivier Dam	757	421	3.5	36.4
Brak	Bellair Dam	558	288	2.3	35.3
Nels	Calitzdorp Dam	170	383	6.7	67.4
Kammanassie	Kammanassie Dam	1505	837	38.7	46.0

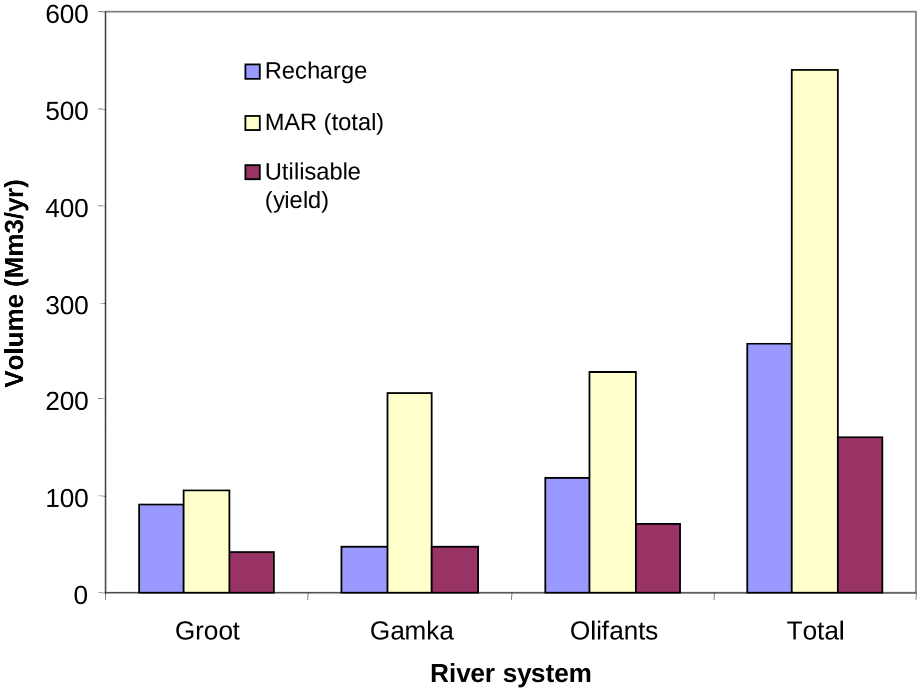

Figure 7. Volumes of groundwater recharge, essentially all of which contributes to the mean annual runoff (MAR), and the utilisable yield from the current water schemes in each of the main sub-catchments of the Little Karoo study area (DWAF, 2003, 2004). The coastal sub-catchment has been omitted because it has little impact on water availability in the study area.

Demand

Irrigation demand currently accounts for 84-92% of the water used in the Groot, Gamka and Olifants river systems (DWAF, 2004; **Figure 8**). There is, therefore, considerable pressure to retain all flood water in local dams, which results in heavily modified flow regimes and significant impacts on aquatic and riparian ecosystems (King and Brown, 2006). Note: the available desk-top estimates of the sustainable yields do not include the river flows required to maintain ecologically important and generally groundwater-dependent vegetation of the riparian and floodplain ecosystems (Milton, 1990; Milton *et al*., 1997; Boulton and Hancock, 2006). These ecosystems, whilst playing an important role in stabilising river banks and floodplains (Tabacchi *et al*., 2000), are targeted for agricultural cultivation.

The current total demand exceeds the estimated sustainable yield of the river systems of the Little Karoo by a substantial margin (**Figure 9**). Considering future demand, the projected water balance in 2025 was estimated using two different scenarios - one with limited increase in use, and one with a high level of increase (DWAF, 2003; **Figure 9**). Even the baseline scenario results in a 23% increase in water use relative to the situation in 2000, and the high level scenario projects an increase of nearly 150%.

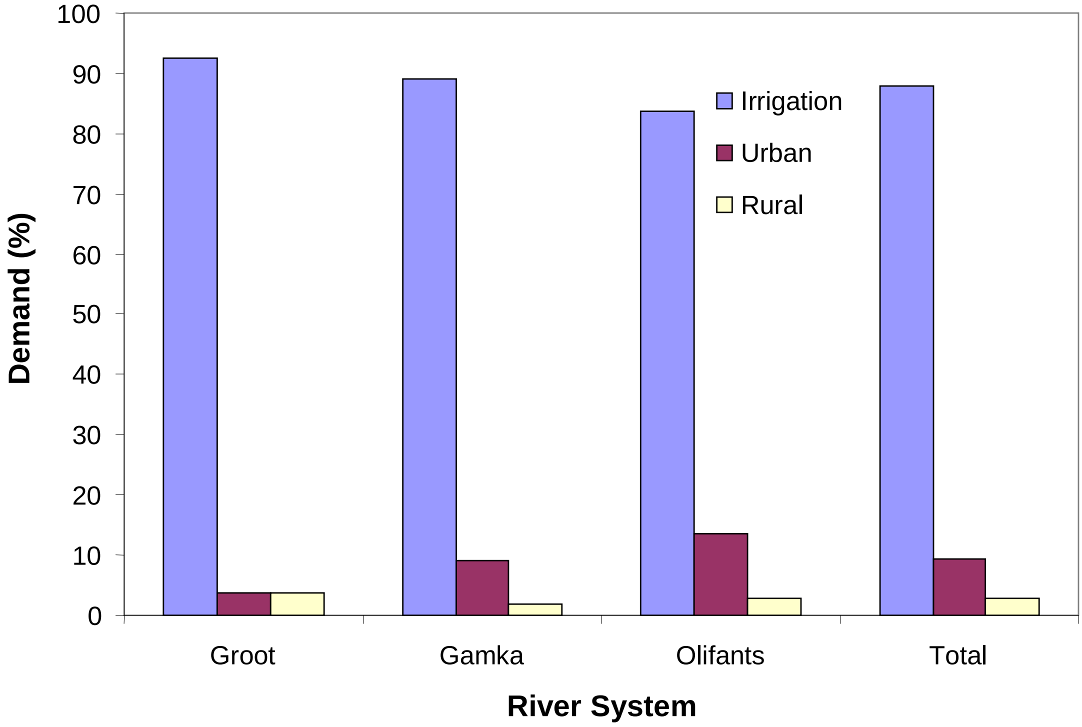

Figure 8. Water demand by sector (percent of the available yield) for each of the main sub-catchments and the total for all three based on data from water resource assessments (DWAF 2003, 2004).

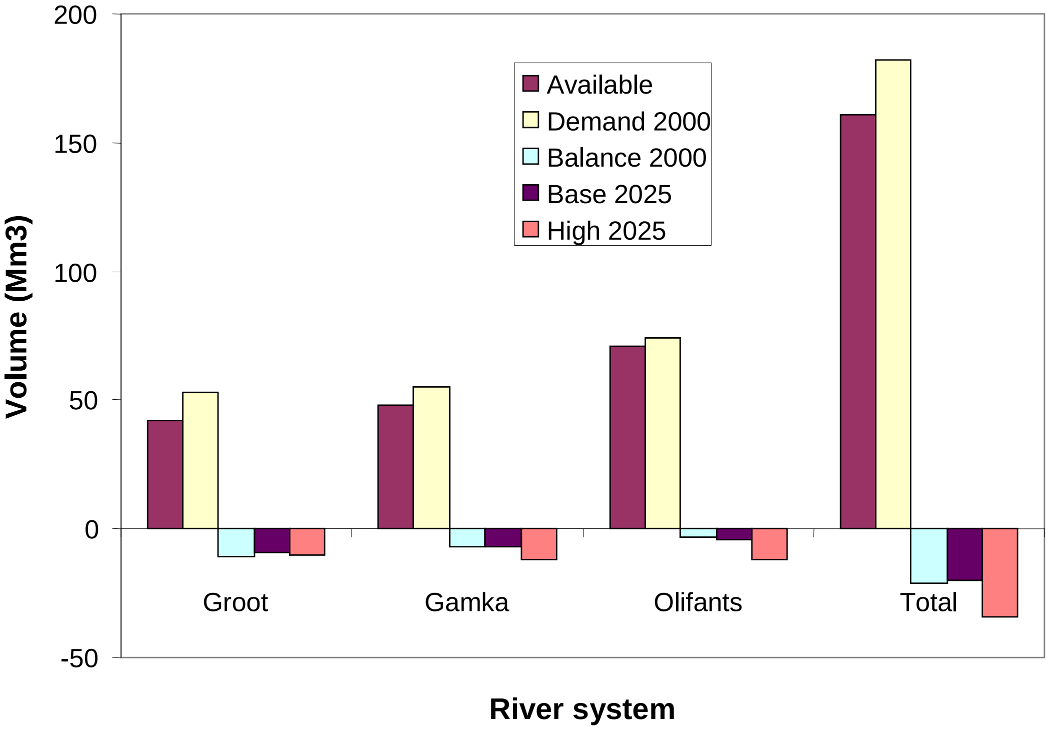

Figure 9. Available water versus demand estimated for 2000, and projections for minimum (base) and high demand for 2025 for each of the main tributaries of the

Gouritz River system within the Little Karoo (modified from DWAF, 2005b; see Figure 3 for the tributaries).

Water from the existing dams generally has been over-allocated. For example, the combined allocation from the Stompdrift and Kammanassie dams (in the Olifants River system) is 87.7 Mm^3/yr, which is 266% of their combined 1:50 year yield of 33 Mm^3/yr (DWAF, 2003). These historical allocations can be expected to result in conflicts because of the political pressure to establish new schemes for formerly disadvantaged farmers and to develop general livelihood opportunities for rural communities. The projected water demand is very unlikely to be met for users who require reliable supplies (e.g. households and industry) because the catchments have highly unpredictable flows that cannot be converted into guaranteed minimum flows through additional impoundments and water release management. The level of exploitation of the water resources is clearly increasing the vulnerability of the SES to natural variability in rainfall such as droughts. Although the ecological component has borne the brunt of this, there is little doubt that the resilience of the social components is also being reduced.

Vegetation

The vegetation of the Little Karoo has been described in detail by Vlok *et al.* (2005) and at a less detailed spatial resolution by Mucina and Rutherford (2007). The montane areas and TMG sandstones support Fynbos, a species-rich vegetation, that is largely intact because of its insignificant agricultural value other than for wild flower and herbal product harvesting (Thompson *et al.*, 2005; Vlok *et al.*, 2005). Relatively high water yields are associated with Fynbos. Renosterveld, also a species-rich, shrub-dominated vegetation, occurs on the shales. Unlike Fynbos, its soils are more suitable for the cultivation of dryland crops and 25% of the vegetation has been cleared for agriculture (Thompson *et al.*, 2005). Thicket vegetation, which is dominated by clumps of evergreen shrubs that typically have spines or thorns, forms the riparian vegetation on flood plains. It is utilised for livestock grazing, and some 20% and 60% of its area has been severely and moderately degraded, respectively. A further 6% of the Thicket has been transformed for irrigated agriculture. Succulent Karoo is an open, low, shrubland with a rich variety of succulent-leaved plant species, bulbs and annuals growing between and under the shrubs. Grazing has severely degraded about 26% of this shrubland, with a further 60% having been moderately degraded, and about 9% having been transformed by cultivation. Pervasive degradation of vegetation throughout the Little Karoo has undoubtedly had an impact on both the productivity and the resilience of the ecosystems to which the vegetation contributes, altering a range of processes and having impacts on the ecosystem services they deliver, including good quality water production (Le Maitre *et al*., 2007; O'Farrell, *et al*., Chapter 12, this volume).

Socio-economic system

The fertility of the soils and favourable temperature regimes for plant growth make the Little Karoo a productive environment for agriculture, provided that sufficient water is available. However, as has been described, water is extremely limited and highly variable in terms of flow, and this has had a strong influence on social and economic development (**Table 1**; O'Farrell *et al*., Chapter 12, this volume). The following sections focus on the development of the governance and economic domains both outside and within the Little Karoo (**Figure 1**), with an emphasis on water as a key limiting factor. The governance domain is an example of a nested structure, with the national government typically establishing policies and law, which provide the boundaries within the provincial and local governments can create their own policies and laws and fulfil their administrative functions accordingly.

The Gouritz Catchment Management Agency (CMA) is an example of a cross-sectoral structure created to manage the water resources of the Gouritz river system, as well as the adjacent coastal catchments. Representatives of all the different water user groups direct and support the CMA in implementing water-use strategy (DWAF 2004). Conflicts over access to land water have been a feature of South African social and legal history, and the development of the water law is discussed in some detail below. Ashton *et al*. and Funke *et al*. (chapters 9 and 10, this volume) provide insights into water conflicts at both international and local scales.

The influence of water law

During the period under Dutch rule there were no formal water laws, and principles of Roman-Dutch Law were applied (Hall, 1939; Tewari, 2002; Beinart, 2003; Funke *et al*., Chapter 10, this volume). The basis of this law was that all water was regarded as public water, provided it came from a permanently flowing (perennial) source and flowed in a water course or river. If the river water flowed only seasonally, or the source was groundwater, it was considered a limited resource and was defined as private and for the exclusive use of the land owner - i.e. ownership as defined by Schlager and Ostrom (1992). Public water was shared between water users, a form of authorised use (Schlager and Ostrom, 1992), with upstream users having to consider the needs of downstream users. In practice, the inability to control upstream abstractions often led to legal disputes over access to water, which were initially resolved by local magistrates and later by the Cape Supreme Court and the Water Court (established in 1906).

In time, the doctrine of riparian rights was transferred from Britain. This replaced the principle of public water and linked the title to the land with access to water (Hall, 1939; Tewari, 2002; Hodgson, 2004). The linking of land ownership to the right of access to water increased the value of land with water rights, especially in the case of land that included the sources of rivers and streams (Hodgson, 2004). People without title to land could only gain access to water through the courts. Where litigation was not possible, for example due to limited financial resources, much of the population was left without any legal access to water (Tewari, 2002; Hodgson, 2004; Funke *et al.*, Chapter 10, this volume). Those with water rights could use this privilege as an asset to obtain loans for development, for example, of farm dams and lands for irrigation, thereby accentuating economic disparities. This undesirable situation was formalised by the Irrigation and Conservation of Waters Act (No 8 of 1912). This act resulted in the development of private irrigation schemes involving groups of farmers, leading to the construction of dams and extensive reticulation systems in the Little Karoo (**Table 1**). This promoted expansion of the fruit and wine industries in the area, as well as the production of lucerne and vegetable seeds. In most cases, the cost of the infrastructure was paid for by the government, or through subsidised loans, reducing the cost of water and encouraging inefficient irrigation practices, *inter alia* leading to adverse impacts on riparian environments.

The 1956 Water Act continued with the ownership, rights-based system, but did mitigate this by allowing the government to control abstraction by individual farmers in Government Water Control Areas. It was not until 1998 that long overdue reforms were introduced. The current National Water Act (No 36 of 1998) gives effect to the basic human right to water and addresses the previous inequalities and deficiencies through providing for equitable access and the efficient, sustainable and beneficial use of water (Schreiner *et al.*, 2002; Tewari, 2002; Hodgson, 2004). All water has reverted to being public property, with water ownership rights having been removed and replaced with a licensing system - a form of authorised use as defined by Schlager and Ostrom (1992). The Act requires water to be allocated to meet basic human needs, the ecological requirements of riparian and groundwater-dependent ecosystems, and international obligations for shared rivers prior to allocations for any other uses (see Ashton *et al.* and Funke *et al.*, chapters 9 and 10, this volume). The government is using the licensing system to allocate water to rural communities that have acquired land through a political reform programme, bringing together authorised water use and land rights with the aim of leveraging economic development (Hodgson, 2004). The implementation of the new dispensation is a complex and involved process and requires special measures to ensure that the diverse views of the wide range of social groups and organisations are taken into account (Sherwill *et al*., 2007).

As noted earlier, the current levels of water utilisation in the Little Karoo are not sustainable, and finding a solution that meets new and competing demands for water will be a significant challenge, especially if the interests of social groups that were denied or deprived of access prior to 1998 are to be accommodated equitably (Ashton and Haasbroek, 2002; Schreiner *et al*. 2002). Many of the legacies of the old approach remain, including the under allocation of water to maintain the ecology of the river systems and over-use of water by irrigators because development costs have been subsidised by taxpayers. The resilience of the riverine environments has been significantly reduced and little, if any, of the original vegetation and wildlife remains in the lower reaches of all the major river systems in the Little Karoo (Dean and Milton, 2003; Thompson *et al*., 2005).

Land tenure and agricultural policy

During the first phase of colonial settlement in South Africa, access to land was regulated by the Dutch East India Company (DEIC) using a system of temporary grazing rights (Beinart, 2003; Funke *et al*., Chapter 10, this volume). In 1708 this was replaced by an annually renewable "loan" farm system. The British Colonial government introduced a perpetual quitrent system[2], with full agricultural rights introduced in 1813, and freehold title introduced in 1878 (Theal, 1909 in Beinart, 2003; Talbot, 1961 in Hoffman *et al*., 1999). One of the key incentives for these developments was to do away with seasonal trekking by pastoralists and their livestock, and to encourage settlement that facilitated government control and collection of taxes. The Land Acts of 1913 and 1936 entrenched land ownership in the Little Karoo in "white" hands and, together with many other acts, weakened the rights and access to economic resources of "non-white" communities, turning them into migratory farm labourers (Vink and Kirsten, 2000).

The pressure on farmers to settle permanently resulted in increased grazing pressure on the land, especially around the few permanent watering points within the Little Karoo, and undoubtedly contributed to land degradation observed, for example, by

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[2] A legal arrangement where rent is paid for the land and the lessee is free (quit) from any obligation to render any other services to the owner (in this case the government).

colonial botanists as early as the 1860s (Brown, 1875; Dean and Macdonald, 1994; Beinart, 2003; O’Farrell *et al*., Chapter 12, this volume). This pressure was exacerbated as the discovery of diamonds (in 1867) and gold (in 1886) opened up new markets in the interior for farmers in the Little Karoo. The Land Acts of 1913 and 1936 did not recognise any “homelands” for “non-whites” within the Little Karoo, but they entrenched land ownership in “white” hands and, together with many other acts, weakened the rights and access to economic resources of “non-white” communities (Vink and Kirsten 2000).

The agricultural policy during the colonial period was largely piece-meal, initially aimed at securing produce for the Dutch East India Company and, under the British, at making the colony both self-sufficient and a net exporter of produce to other parts of the empire (Beinart, 2003). The first organised attempts to control agricultural markets emerged in the 1930s, following on the hardships induced by fluctuations in the value of key products (e.g. ostrich feathers). The formation of the Kango Tobacco Co-Operative in 1926, which preceded the Marketing Act of 1937, allowed farmers to regulate markets and control prices (Vink and Kirsten, 2000). This Act facilitated the formation of other co-operatives in the Little Karoo to market dried and canned fruit, wine, dairy products and later wool. The establishment of the Klein (Little) Karoo Agricultural Co-operative (KKAC) in 1945 created a monopoly over the ostrich industry (KKG, 2006).

Subsidised loans from the Land Bank, established in 1910, together with the collective power of the co-operatives, were used for land development and the expansion of irrigated lands, putting increased pressure on the limited water resources and riverine ecosystems. This increased the engineered resilience of some of the social and economic components of the SES, but reduced the resilience of others - in particular, communities excluded from the benefits of economic development by racially discriminatory laws.

In the late 1980s the government started phasing out import tariffs and other protective measures and subsidies for the agricultural sector. This resulted in drastic reductions in the production of wheat and other dryland crops (Vink and Kirsten, 2000; Kirsten and Vink, 2003). The change of government in 1994, together with a new constitution and policies that promoted land redistribution and economic redress, brought about even greater changes in the agricultural economy - the effects of which are still being worked out (O’Farrell *et al*., Chapter 12, this volume). Significantly, these changes have also created additional pressure on water resources, since access to water is a key factor for economic development in communities formerly denied these resources.

The provision of formal housing for shack dwellers will also have a significant impact on water demand and on water supply systems for the towns of the Little Karoo (Ninham Shand, 2005). This will potentially bring farmers and urban communities into direct conflict over water resources in an environment where demand already exceeds the sustainable yields. These developments, combined with a shift in political power away from the farmers and white urban residents to the urban township dwellers, farm-workers and rural communities, have created a politically fluid situation.

Economic and technological development

The history of the economic development of the Little Karoo shows a clear trend of increasing economic connectedness with the rest of South Africa and the world - from the early, self-sufficient and highly isolated pioneers, to a modern, highly connected and interdependent economy (**Figure 1**). Many of these developments can be directly linked to technological innovations, which improved communication and increased the reliability of water supply systems.

Settlers arriving at the Cape soon seized the opportunity to colonise the interior of the sub-continent, and in less than 75 years established the first settled farms in the Little Karoo (Beinart, 2003; **Table 1**). The early farmers in the region obtained water for basic flood irrigation of agricultural lands from springs and river diversions (Beinart, 2003). Tobacco, which was grown under flood irrigation, was one of the early commercial crops grown because it could be transported to markets outside the Little Karoo without incurring damage and losing value.

By the early 1800s farmers began building farm dams to supplement their water supplies in summer, enabling them to increase the area and duration of irrigation (Beinart, 2003). Demand for lucerne from the ostrich industry, after the 1870s, stimulated the expansion of irrigation farming; however, production was limited by water availability coupled with the limited capacity of farm dams. Growth in the agricultural economy was also limited by underdeveloped transport systems, which improved over time with the construction of passes through the rugged mountains ranges that bound the Little Karoo (**Table 1**). In the 1900s, the construction of railways and an improved road system (**Table 1**) opened up markets for much wider trade in a range of more easily damaged and perishable agricultural products. The subsequent diversification of crops, and the ability to market higher value produce, increased the economic resilience of farmers.

Economic development following the discovery of the Witwatersrand gold reefs in 1886 increased the demand for cement for large infrastructure and housing construction. The development of the cement industry reduced the cost of cement nationally, and made possible the construction of large, concrete-walled dams - for example, the Calitzdorp, Prinsrivier and Kammanassie dams (**Table 1**), which could supply multiple-farm irrigation schemes. All of these developments shifted farming away from rangeland-based livestock production towards the production of vegetable seed, deciduous fruit and lucerne (which sustains the ostrich and dairy industries). Such production depends directly on a sustained supply of water (**Figure 10**). For example, vegetable seed production requires irrigation every few days at certain stages; fruit trees are very vulnerable to water shortages during the summer, and can lose their fruit or die-back partially or completely where irrigation fails.

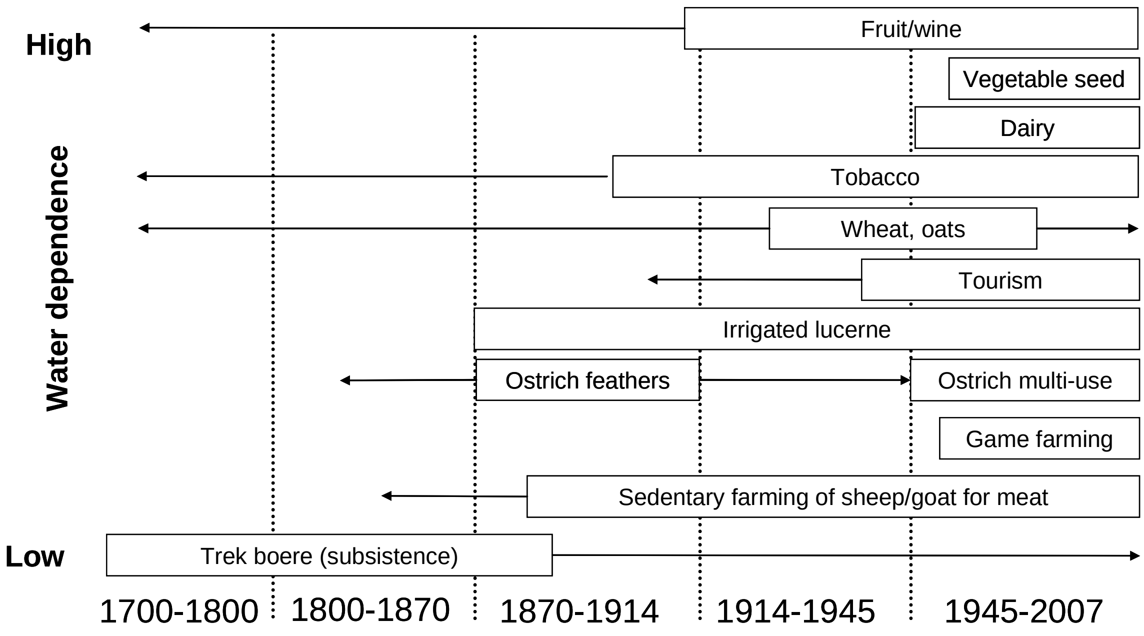

Figure 10. Timeline of the different agricultural products and changes in their importance, indicating that the vulnerability of the agricultural economy to water shortages has changed.

As indicated in **Figure 11**, ostriches contribute about 42% of the gross farm income in the Little Karoo, followed by vegetable seeds and vegetables (24%) and fruit and wine (23%). About half the gross farm income generated within the Little Karoo is associated with industries that are highly dependent on reliable water supplies. No data were available on the how much of the lucerne required by the ostrich and dairy industries is produced locally, but the total is expected to be considerable. This means that these industries are extremely sensitive to fluctuations in the amount of lucerne grown in the Little Karoo which, in turn, is directly related to the availability of water for irrigation. The economy is, therefore, very vulnerable to decreases in water availability.

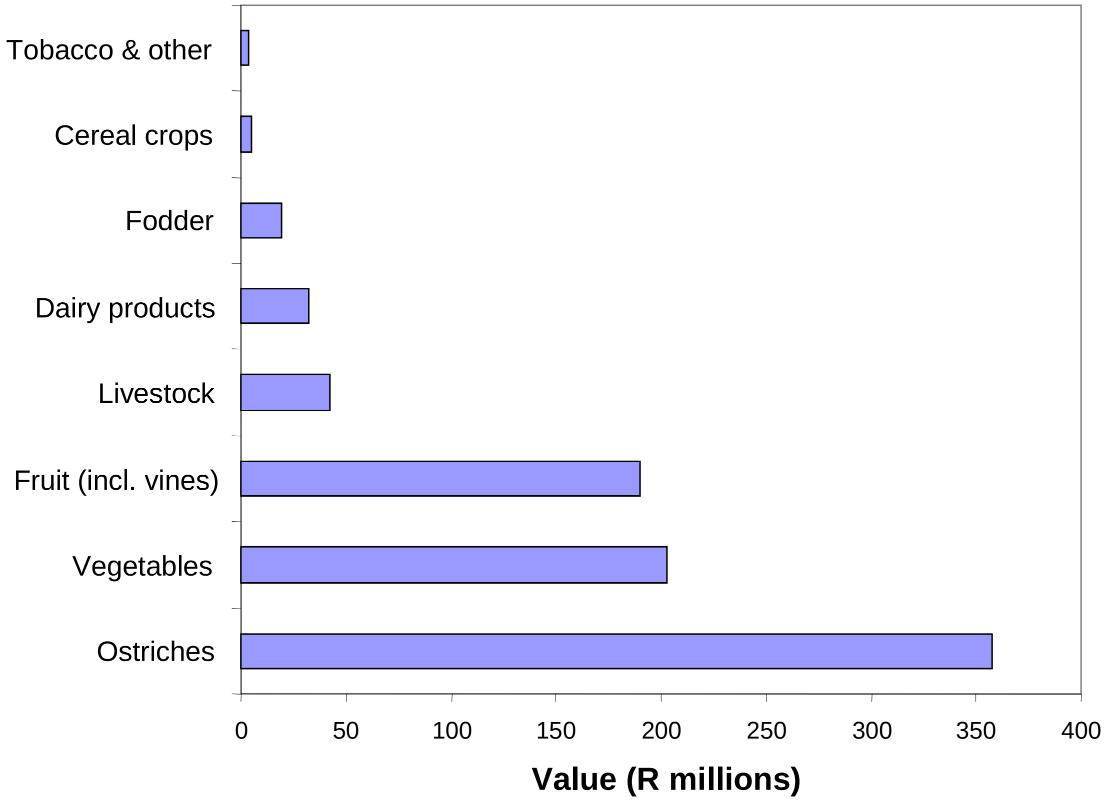

Figure 11. Value (gross farm income) derived from the main groups of agricultural produce in the agricultural districts comprising the Little Karoo: Montagu, Ladismith, Calitzdorp, Oudtshoorn and Uniondale. Data from Stats SA (2002).

Reliable economic data relating to tourism are not available for the Little Karoo; however, total tourism spend in Oudtshoorn alone in 2004 was estimated to be about R394 million (Oudtshoorn, 2005). Although the tourism industry is dependent on a reliable water supply, it is much less vulnerable than agriculture because the volume of water required is relatively low, and is largely supplied by water supply systems designed for a low risk of failure of supply. Property and house values in a number of small towns in the Little Karoo have risen sharply in the last decade as wealthy people buy houses for weekend breaks or retirement. This brings money into the local economy; however, it also imposes above average per capita demand on municipal water supplies because most new owners will add swimming pools and develop gardens using water-demanding plants and water features.

Environmental transformation and degradation attributable to land use

Beinart (2003) and many other authors (e.g. Dean and Macdonald, 1994; Hoffman *et al.*, 1999) have summarised the causes of the progressive degradation of the vegetation of the whole Karoo, to the point where it can no longer sustain either the mega-fauna that occurred there historically or historical stocking rates for domestic livestock (Acocks, 1979; Dean and Milton, 2003). The roles and relative importance of long-term rainfall cycles and shifts in the seasonality of rainfall are still being debated, but farming undoubtedly has had a significant impact on the productivity of the Little Karoo.

Overgrazing leads to a reduction in vegetation cover and severe trampling by livestock, which has the following effects on the hydrology: it exposes the soil surface to raindrop impacts, which can result in the formation of mineral crusts, thereby reducing infiltration (Mills and Fey, 2004); it reduces soil stabilisation by vegetation, which facilitates soil erosion; and, together with tramping by livestock, results in the loss of the biological crusts that provide nitrogen and, probably, facilitate infiltration (Dean, 1992; Greene and Hairsine, 2004; Roth, 2004; Le Maitre *et al*., 2007). The net result is increased surface runoff, loss of productive topsoil, sediment accumulation in river floodplains, and the reduced infiltration of water into the soil which, in turn, reduces vegetation productivity (Friedel *et al*., 1990; Mills and Fey, 2004; Ludwig *et al*., 2005). The increased surface runoff makes river flows more variable and reduces the amount of water yielded by storage dams, amplifying the effects of the inherently variable inflows on sustainable yields (**Figure 5**).

Riparian vegetation is typically more productive than the adjacent dryland environments and, as a result, has been heavily grazed. Together with the clearing of these areas for cultivation (particularly in the 20th century), this has resulted in severe degradation of these environments (Thompson *et al*., 2005; Allsop *et al*., 2007). The hydrological impacts of land degradation in the Little Karoo have not been properly quantified. It is, however, likely that the amount of runoff per unit rainfall has increased because of reduced infiltration and soil storage capacity. An analysis by Braune and Wessels (1980) suggested that erosion control measures may have increased infiltration and, thus, explain decreases in the amount of runoff per unit rainfall observed over a period of a decade or more in the 1930s and 1950s in some Karoo catchments.

Invasive plant species have a substantial impact on the hydrology of the catchments in the Little Karoo (DWAF, 2004). These plants have decreased the mean annual runoff of the Touws, Gamka and Olifants river systems by transpiring, respectively, about 6, 14 and 20 Mm^3/yr more than the natural vegetation they have replaced. This reduces the 1 in 50 year yield of these systems by about 36 Mm^3/yr (DWAF, 2004). These estimates are based largely on invasions in the headwater catchments, mainly by *Acacia mearnsii* and *Populus canescens*, which invade riparian areas, and *Hakea* species, which invade Fynbos and Renosterveld within drier environments (Versfeld *et al*., 1998). Many of the river systems also have extensive invasions of *Arundo donax,* a species believed to have a high water-use. By reducing river flows, alien plant invasions increase the salinity of the downstream reaches of affected rivers.

RATES OF CHANGE IN DRIVING FORCES: VARIABILITY AND SHOCKS

Social-ecological systems have demonstrated an ability to shift between different locally-stable states. Responses to changes in slow- and fast-changing variables influence these state changes (Carpenter *et al*., 2001). Examples of fast-changing variables include shocks such as floods, disease outbreaks or changes in government policies. Slow-changing variables include droughts (often characterised by thresholds in plant responses), the process of soil formation or climate change. Slow-changing variables generally constrain the influence of fast-changing variables; however, the latter can sometimes force a change in the former (Gunderson and Holling, 2002). Environmental triggers and shocks may have significant impacts on natural systems, agricultural production systems, or both. The relative susceptibility of different components of a social-ecological system provides a good indication of the resilience of such systems to these events and to the feedbacks they may induce. Natural systems are typically highly resilient, but changes brought about by human interventions can make them more susceptible to these events.

As noted earlier, several of the major agricultural systems within the Little Karoo, which depend on reliable supplies of irrigation water (fruit, wine, vegetable seeds, dairy industry), are highly vulnerable to extended drought. Such events are common, and, given the limitations in water storage capacity in dams - aggravated by very high evaporation rates - vulnerability will increase as water demand by various social/economic sectors increases. At the opposite extreme, floods have triggered shocks within the Little Karoo SES, destroying large areas of irrigated land, the crops on these lands and infrastructure (Kovacs, 1982). Fruit and vegetable seed lands are particularly vulnerable to floods because they lack ground vegetation cover to stabilise soil against water erosion.

An example of a major anthropogenic shock to the socio-economic components of the Little Karoo SES is the shift in political power following the introduction of democracy in South Africa in 1994 and the drive for equitable access to development opportunities that has accompanied this. Other examples include the rapid opening-up of agricultural markets and the termination of agricultural subsidies, described earlier. Another shock that recently hit the Little Karoo was an outbreak of the H5N2 bird flu, which led to a 16 month ban on exports of ostrich products to the EU and restricted sales elsewhere (Oudtshoorn, 2005; KKG, 2006). This led to the slaughter of about 10 000 birds, the loss of about 20% of the jobs in the industry and an estimated loss to farmers and the industry as a whole of R200-300 million. This shock had knock-on effects for local lucerne farmers, because of the reduced demand for ostrich fodder. The suite of examples given here has had major implications for the resilience of the Little Karoo SES, which are not yet fully understood.

Climate change is an example of a slow-changing variable that can have far reaching effects, influenced by long lags between the driving factors and the responses. For example, reductions CO_2 emissions will only have an effect on air temperatures in 2-3 decades time. Some general trends anticipated by Midgley *et al.* (2005), which could apply to the Little Karoo include:

- A decrease in the total amount of winter rainfall.
- An increase in summer rainfall and in its intensity.
- Net changes in monthly rainfall may be as much as 10 mm or more.
- A rise in temperatures, particularly minimum temperatures.

The decrease in winter rainfall will affect the western regions of the Little Karoo, the southern mountains and the Swartberg mountain range. The increase in summer rainfall will mainly affect the eastern parts, but may also affect the central areas. The weakening of cold fronts, which is anticipated by Midgley *et al.* (2005), could trigger significant change in SES resilience if this decreases rainfall over the inland mountain ranges, which are the source of most of the surface water resources in the Little Karoo. Both maximum and minimum temperatures are expected to increase in the interior, perhaps by as much as 2-3˚C, which will increase the evaporative demand and, thereby, partially (or potentially completely) offset precipitation gains attributable to increases in summer rainfall. The variability of river flows might increase, with a tendency to more erratic flows and more frequent floods, reducing the sustainable yields.

RE-BUILDING SOCIAL-ECOLOGICAL SYSTEM RESILIENCE

This chapter has highlighted some of the linkages and interdependencies within the SES of the Little Karoo. The focus has mainly been on water resources and their linkages with the economic and social domains (**Figure 1**). The boundaries of these domains are open and have various interactions with ones that are outside the study area. For example, a company, its employees and employee households may form complex interlinked systems that potentially influence the flow of goods and services within and across the geographic boundaries of the Little Karoo SES. The Little Karoo is linked to both ecological and social components outside its geographic boundaries by, for example, weather systems, water flows, trade and communication. For example, the economic system comprises an internal economy, but is dominated by the flows of goods and services into and out of the Little Karoo (**Figure 1**). Changes in both the national and international economy have a significant impact on the economy of the Little Karoo, for example, by affecting demand for and profitability of local products.

The governance component is complicated and illustrates the nested position of the smallest administrative units, which are municipalities, within district municipalities, which are nested within provinces, within national boundaries, etc. Administrative units within the Little Karoo do not match hydrological boundaries. For example, the Gouritz Catchment Management Agency (CMA) is responsible for managing the water resources within the Gouritz River catchment and some additional coastal catchments. Management responsibilities thus span a number of distinct and independent river systems. Parts of municipalities and district municipalities fall inside the CMA, but other parts fall outside of it, under the jurisdiction of neighbouring CMAs. The complexity of governance can be explained by the fact that the different levels of government play different roles in influencing the management, for example, of the water, agricultural and environmental sectors (see Reyers *et al.*, Chapter 5, this volume). This militates against an integrated approach to water governance and the achievement of equity, efficiency and sustainability in water allocation and use. This is clearly a complex situation and the CMA will have to overcome many obstacles to achieve its goals of equitable, just and efficient distribution of water resources.

Social-ecological system resilience is compromised when ecosystem engineering is taken too far in order to promote economic aims and to respond to the demands of a growing population (Holling, 1973, 1996; Anderies *et al.*, 2004, 2006; Kareiva *et al.*, 2007). Within the Little Karoo, a history of engineering solutions has reduced SES resilience by transforming or degrading ecosystem components, which has had the unintended consequence of increasing the vulnerability of the socio-economic system components. It is clear that unsustainable water-related economic dependencies have been established that must ultimately fail. Explaining this, is the current situation where water demand exceeds estimates of the sustainable yield of water from the catchments that supply the rivers of the Little Karoo. Most of this water is used to support irrigated agriculture, which employs inefficient flood irrigation methods (DWAF, 2004).

Some suggestion on the way forward

The water resource strategy of DWAF (2004) has made some progress towards a common purpose in water resource management, but only narrowly addresses water resources – not the systemic social and economic linkages across the SES, which is where multiple failures are currently manifesting. In response, we offer a number of suggestions, which we believe can contribute to constructive debate aimed at defining a sustainable future for the Little Karoo SES. In this latter regard, one of the strongest messages emerging from the literature on SESs is that all the participants have to be involved, up-front, in such debate (Redman and Kinzig, 2003; Cumming *et al*., 2006) and that where this does not materialise, there is a high risk of failure in whatever process and solutions are devised for promoting SES sustainability.

The full economic benefits realised by the different irrigated agricultural sectors need to be compared and the comparison used as the basis for trade-offs between competing water uses, including uses by other economic and social sectors and ecological system components and processes (**Figure 12**). An obvious intervention to build SES resilience would be to improve the efficiency of irrigation, thereby releasing considerable volumes of water for other purposes, potentially without significant trade-off costs to agriculture. Water-use efficiency is directly influenced by the kind of technology used to apply the water, for example flood or drip irrigation. The choice of irrigation technology, in turn, can depend on the means that are used to capture the water (e.g. diversion of flood water, storage in dams or via artificial recharge), the kinds of crops that can be grown and the markets for them, and the knowledge gathered by the farmer and his ability to obtain and use financial or other forms of capital (**Figure 12**). The consumer and the farmer can both influence politicians to alter government policy to provide incentives for the acquisition of more water-efficient technology and crops. The consumer can also play a role influencing market prices by their product choices, including opting to buy goods certified as "fair trade", which ensures that the farmer gets a deserved share of the final price.

Choosing the latter option probably will cost the consumer more, but the eventual outcome is, potentially, a more sustainable farming system, reduced pressure on natural resources and a more sustainable Little Karoo SES.

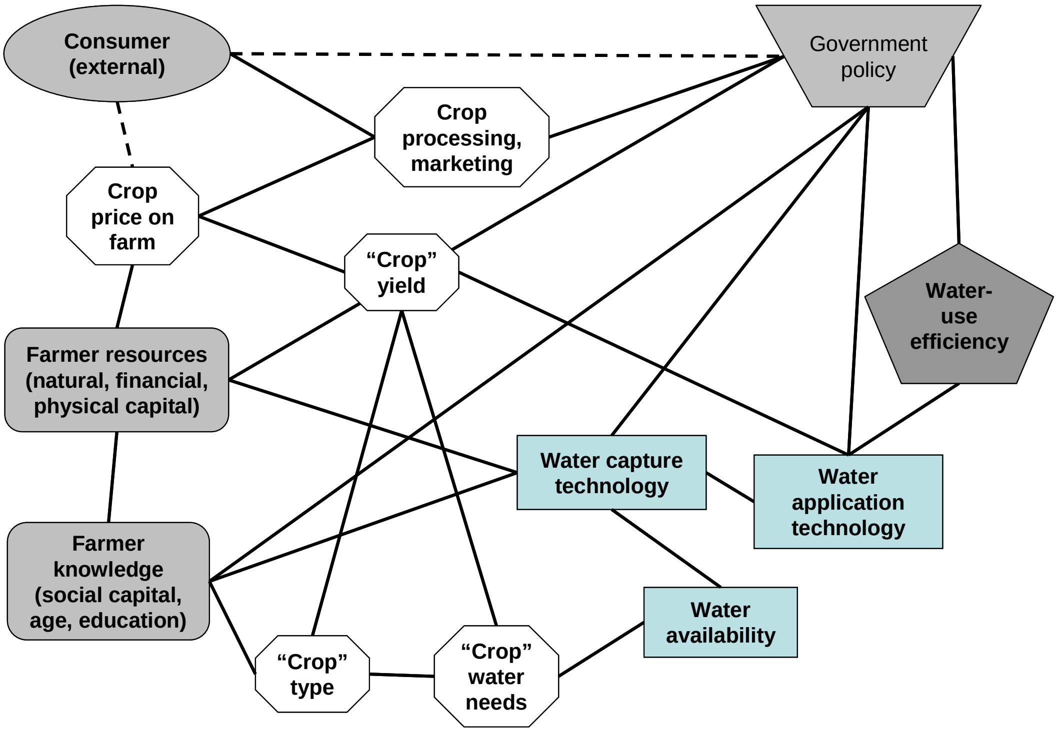

Figure 12. Diagram showing some of the inter-connections between human, agricultural and economic factors that potentially influence decisions and actions relating to increasing water-use efficiency in irrigation farming.

Economic analysis can reveal the relative values (in Rands) of gross farm income generated per m^3 of water used (**Figure 13**; see Appendix 1 for a description of the derivation of these values). Considering the value earned per unit of water used, the highest returns are achieved for ostrich farming. Lower returns are achieved for other livestock farming, with lowest returns achieved for fodder (lucerne) production. Lucerne also yields relatively small gross farm income compared with other produce (**Figure 11**). Considering that lucerne accounts for roughly 70% of the total water used by irrigated crops within the Little Karoo, this suggests that importing lucerne grown elsewhere in South Africa may be a good option to explore – potentially, releasing considerable quantities of water in the Little Karoo for other uses. This option would need to be weighed up against the impact of reduced lucerne production on the livelihoods of individual farmers and on industries that could be affected by an increase in the cost of imported fodder. Here, cognizance must be taken of the fact that lucerne is the one crop that can be cultivated, and survive, in areas that have a high risk that there may not be enough water to sustain the crop throughout the growing season. Whilst lucerne farmers could switch to alternative crops, which theoretically could earn a greater value per m^3 of irrigation water, the variability in water supply could obviously prevent this.

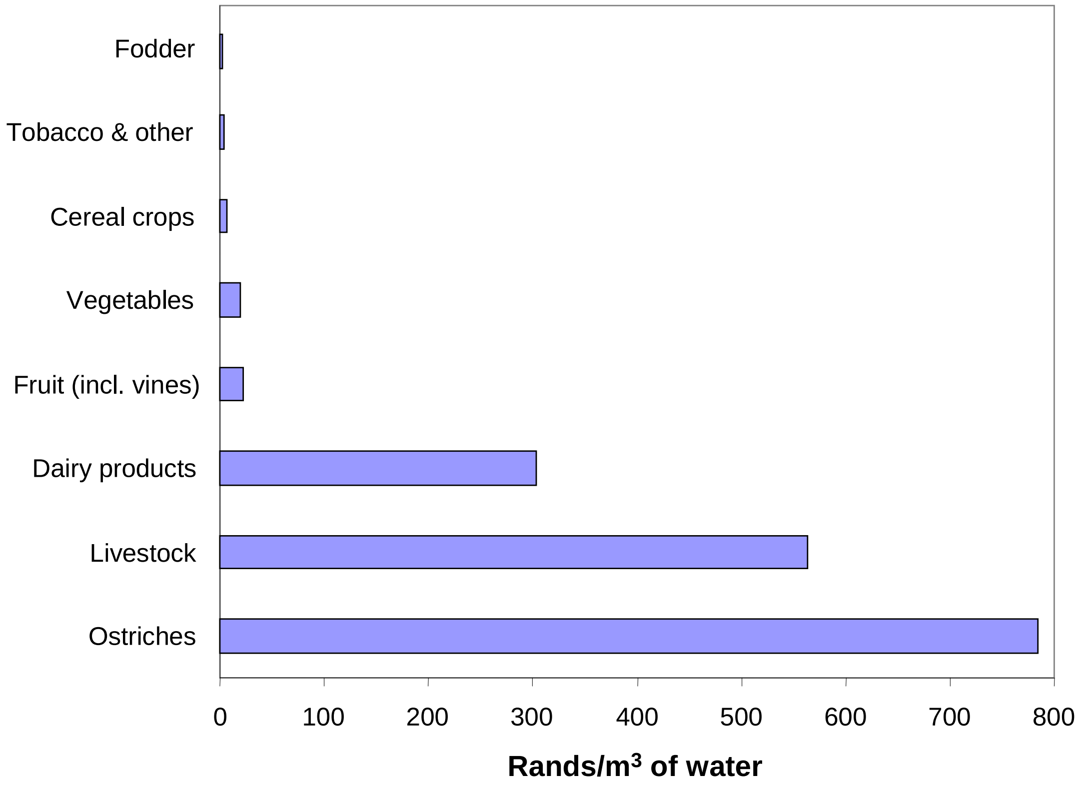

Figure 13. Estimate of the gross farm income per m^3 of water used by the agriculture industry based on crop-water use estimates from the SAPWAT model and basic livestock water needs. For more information see the text.

Another option for increasing the efficiency of water-use by agriculture within the Little Karoo would be to switch from flood irrigation of fruit and vines to drip irrigation systems. This would have establishment costs that would need to be factored into the related economic calculus. Even without such a technology switch, more widespread use can be made of monitoring systems for efficiently controlling the application of flood irrigation to reduce soil saturation and decease saline return flows to rivers.

In dryland situations, there are studies that suggest large gains can be made by reducing runoff, increasing infiltration and using the increased soil moisture availability to realise higher crop yields (Rockström *et al*., 1999, 2004). Similar gains can be expected in the Little Karoo in areas where there is sufficient rainfall for dryland crops.

In the town of Oudtshoorn, which is facing a critical water supply situation, there is a strong drive to increase the volume of the town's storage dams and to purchase farms in order to gain access to their water allocations (Ninham Shand, 2005). Increasing the town's water consumption would, however, affect all the users and ecosystems downstream of Oudtshoorn - in the Grobbelaars, Olifants and Gouritz river systems. It also would increase the salinity problems currently experienced in the lower reaches of these rivers by reducing freshwater inflows into the upper catchments. However, if this option was pursued - at the cost of some of farm livelihoods and wider economic cost attributable to reduced agricultural production - some of the additional water procured by the municipality could be used to offset and mitigate flow reductions.

A potentially more sustainable option would be for Oudtshoorn and the downstream beneficiaries to provide incentives to upstream farmers to invest in increasing the efficiency of their irrigation (already discussed) – which could more than offset the impacts of increases in the water consumption in Oudtshoorn. The town could also invest in decreasing its own water demand by providing (dis)incentives to residents and industries to make more efficient use of water, such as stepped water tariffs and subsidies for installing dual flush toilets, especially in new urban developments. There could be investment in programmes to remove invading alien plants and to restore degraded land (Milton *et al*., 2003). Ultimately, the people of the Little Karoo, individually and collectively, will have to find ways of living within the constraints of the available water resources.

Although the above suggestions don't reveal the high level of SES complexity, which militates against simple cause-effect-management intervention, they do illustrate significant cross-scale effects and system linkages and interdependencies within and outside the geographic boundaries of the Little Karoo. Single causes can have multiple effects, operate over multiple-scales and have both near and distant effects (Cilliers, Chapter 2, this volume). Most people in the Little Karoo are completely unaware of the many and pervasive ways in which they are linked to, and are ultimately dependent on, ecosystems and their services - whether those ecosystems are more or less natural/transformed. Like other societies world wide, they continue to make decisions and pursue activities that damage ecosystems despite clear evidence of negative trends in the state of ecosystem services that ultimately sustain them (MEA, 2005). Raising awareness and changing attitudes are complex undertakings, but there are studies and observations that suggest that it can be achieved provided the approach is sensitive to local context and circumstances (Schlager and Ostrom, 1992; Anderies *et al*., 2006; Lebel *et al*., 2006; Roux *et al*., Chapter 18, this volume).

There are many reasons for the apparent lack of awareness and action regarding the necessary transitions to SES sustainability within the Little Karoo. These include ignorance and desperation, arising from poverty traps. Also, disbelief of the evidence indicating an unsustainable development trend within the SES - insofar as water is a determining factor - would seem to prevail. However, our brief sketch of SES resilience makes it sufficiently clear that major changes, or even revolutions, in the prevailing economic and social development trajectories are necessary. We acknowledge that finding solutions will not be a simple process, particularly given South Africa’s history of social discrimination and the way that access to water was used to create social divides (Schreiner *et al*., 2002; Turton and Meissner, 2002; Hodgson, 2004). Clearly, ‘solutions’ will need to be experimental and iterative in nature, since SES complexity precludes full predictability of outcomes. However, the greater the acknowledgment of SES connectedness, particularly regarding the ultimate dependency on social well-being on the sustained delivery of an essential ecosystem services such as water, the greater the prospect of success.

CONCLUSIONS

The Little Karoo is characterized by low and variable rainfall that results in very low, and even more variable, surface runoff. Groundwater resources are limited, with most groundwater discharging into the river systems and springs to contribute to the surface water resource. The sustainable yields are low, with demand currently exceeding the yield. This situation is likely to be aggravated by climate change.

It is clear that there are no simple, piecemeal solutions to the current unsustainable economic and social development trends. The sustainable management of social-ecological systems requires decision-makers to begin to understand the complexities and interdependencies that characterize such systems and the full ramifications of policy and management decisions. Joined-up thinking is essential when dealing with complex SESs like the Little Karoo (Ashton and Haasbroek, 2002; Poff *et al*., 2003; Liu *et al*., 2007; Turton *et al*., 2007; Reyers *et al*., Chapter 5, this volume).

Analyses of the resilience of social ecological systems, and of failures of these systems, are increasingly showing that human-engineered resilience ultimately fails because: (a) it locks social and economic systems into particular states and trajectories that result in reduced resilience (Anderies *et al*., 2004); and, (b) it typically reduces the resilience of the ecosystems that support the social and economic system components - to the point where they easily shift into states where they no longer deliver the levels of ecosystem services society requires (Holling, 1996; Gunderson, 2000; Olsson *et al*., 2004). The capacity to adapt or move away from the current trend of declining resilience depends very much on the resources the human population comprising the SES have access to, how they choose to draw on them, their ability to identify and agree on a desired SES state, and on an adaptable management approach and willingness to co-operate to achieve that state (Anderies *et al*., 2004; Olsson, 2004; Roux *et al*., 2006).

Within the Little Karoo SES, the basic concern is how to adapt, transform or re-design the social and economic structures to cope with the quantity and, even more importantly, the variability in the delivery of natural resources, particularly water. The solutions appear to be easiest to achieve within social groupings where there are: (a) close social and economic ties between all the participants (resource users and use regulators); and, (b) strong social sanctions on abuses because the rules on resource use are seen and understood by all to be fair and in their own best interests (Schlager and Orstom, 1992; Anderies *et al*., 2004; Bromley, 2007; Cocklin *et al*., 2007). This is much harder to achieve when larger groups are involved, but it can still materialise provided the right kinds of incentives and disincentives are in place and the people are able to adapt timeously when potential problems are identified (Schlager and Orstom, 1992; Anderies *et al*., 2004).

Devising interventions that promote SES resilience will involve major re-design of the approach to decision-making if we are to avoid the kinds of decisions that have created the sustainability challenges currently faced by the people of the Little Karoo. Problems like these can only be addressed by a fundamental shift in the way the social components of SESs are organized. The focus need to move from engineering resilience to ecological resilience, with its properties of persistence, re-organization, renewal, and supple responses to changes in external driving forces whether natural or anthropogenic. The physical reality is that land productivity underpins the economy of the Little Karoo and the productivity of the land, whether natural or cultivated, is primarily water limited. The history of this SES is one of people attempting to reduce the vulnerability of the SES to natural variability in rainfall using engineering solutions – and it has not worked. It is time to start the search for solutions that will increase the resilience of the social components to the limits of, *inter-alia*, the water resources and the natural variability in the climatic regimes, and to restore or maintain the resilience of the ecological components that support the SES.

We have proposed a number of management interventions that can enhance SES resilience. Whilst we believe these interventions have merit, we suggest that they are not sufficient because they do not address all the dimensions required for SES sustainability. Increasing water-use efficiency in irrigation is a "good" and necessary thing to do and will ameliorate shortages and increase the earnings per litre; however, it does not change the social and economic structures and dynamics that have created the current problem. A more radical option for developing resilience, in particular to cope with variability in water availability, would be to design and build an SES that accumulates reserves of social, financial and physical capital during times when, for example, agricultural productivity is high. The farmers would be able to draw on the reserves in hard times. Those in areas with plenty would provide reserves which could be used to help others in areas with needs at that time. At the same time there has to be some measure of control over the behaviour of the individuals and interest groups in the system (Anderies *et al*., 2004; Lebel *et al*., 2006) - for example, laws to ensure that the interests of communities and individuals are balanced and that safeguards are in place to prevent individuals or interest groups from exploiting the system. Ultimately, the system would have to be based on trust and reciprocity for it to work. Social and economic engineering could be used to achieve these aims, but research suggests that educating people and promoting self-regulatory approaches, together with incentives, are much more likely to succeed than command and control approaches (Cocklin *et al*., 2007). This option may appear to be a re-creation of institutions such as the engineering resilience-based agricultural Co-Operatives, but the key difference is that the proposed approach is designed to promote ecological resilience rather than engineering resilience. This suggestion may also appear to be strongly socialist but it is not; it is about enlightened self-interest where the loss of immediate or short-term individual benefit is more than offset by the long terms gains from reciprocity, reductions in conflicts and increased social cohesion. The successful SESs described by Schlager and Ostrom (1992), and in the resilience literature, have many of these elements and suggest that highly idealistic proposals like our one for the Little Karoo may actually be achievable and, therefore, worth striving for.

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Appendix 1. Derivation of the Rand value per unit of water used

This calculation involves a number of provisos and assumptions; nevertheless, the estimates provide an acceptable basis for making the comparisons presented in this chapter.
:

- The Rand value cannot be attributed to the volume of water alone because there are other input costs, such as cultivation and fertiliser that differ widely between the different products and have significant impacts on the net farm income or profitability. Therefore, they must be treated as relative and not absolute values.
- The Rand/m^3 values for livestock and ostriches do not include the fodder used by the ostriches; this would reduce the Rand per m^3, but estimating the actual values would require data that are not readily available at present.
- The values are for gross farm income, which ignores the potentially substantial value added by secondary processing, which will vary between crops.
- The crop water-use was estimated using the SAPWAT model (Crosby, 1996), the farm income and areas cropped from Stats SA (2002), and livestock water use from data collated by W. De Lange (CSIR, pers. comm. 2007); the values should be regarded as a first approximation. Areas under crops, and their water consumption, include both dryland and irrigated areas for the cereals and the lucerne. The livestock water consumption excludes the water used to produce the forage that they obtain from natural vegetation.

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