Open access • Journal Article • DOI:10.1890/1540-9295(2007)5[261:LESAWR]2.0.CO;2

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Published on: 01 Jun 2007 - Frontiers in Ecology and the Environment (Ecological Society of America)

Topics: Ecosystem services, Land degradation, Water resources, Land rehabilitation and Ecosystem

Linking ecosystem services and water resources: landscape-scale hydrology of the Little Karoo

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There is growing acknowledgement of the dependence of human society on ecosystem services and of the fact that service delivery is being compromised by human impacts on ecosystems. This paper describes the linkage between landscape-scale hydrology and ecosystem services, and how degradation of the landscape is believed to have altered the delivery of those services. The Little Karoo, an arid environment in South Africa that encompasses a remarkable diversity of plant species, has been degraded by inappropriate agricultural practices, mainly overgrazing, cultivation, and irrigation. Landscape linkages, such as hydrological flows and the recycling of organic matter and nutrients, have been disrupted, resulting in net losses at all scales, from the shrub patch to the river basin. Land rehabilitation, while in most cases too expensive at the farm scale, may be economically feasible at the river basin scale, provided that some of the economic benefits are used to rehabilitate and manage areas as socioecological systems.

Front Ecol Environ 2007; 5(5): 261–270

Ecologists have stressed for decades that humanity is highly dependent on the services ecosystems provide, both material and non-material (Ehrlich and Ehrlich 1992; Costanza *et al*. 1997; Daily 1997). This message has been strengthened by the recent Millennium Ecosystem Assessment (MA), which shows that human activities are eroding the ability of ecosystems to deliver these services and meet human needs across the globe (MEA 2005). The conclusions of the MA and the increasingly evident seriousness of this situation reinforced the validity of a range of actions already initiated to tackle the problem (eg Walker *et al*. 2002; Palmer *et al*. 2004). But the challenge of stemming and reversing the loss of ecosystem services cannot be addressed by ecologists on their own; it will require the active participation of all interest groups: society, government, and business (Kremen and Ostfeld 2005; MA 2005). This is not a "green" or "brown" issue – it will require new insights and ways of thinking drawn from a range of disciplines that have traditionally operated in isolation (Lubchenco 1998). The consequences need to be spelled out in language that is equally relevant to the wealthy and the poor. Here, we address one aspect of this challenge: investigating the links between biodiversity, ecosystem integrity, and the delivery of ecosystem services to society. Water is our focus because it is the basis of life and is the primary constraint on development in a small region of South Africa known as the Little Karoo. We follow Bengtsson's (1998) and Kremen's (2005) approach of identifying the key ecosystem service providers and assessing how these may be affected by human activities.

In a nutshell:

- Human well-being is directly dependent on the services provided by ecosystems, but society continues to degrade these ecosystems
- In the Little Karoo, an arid environment containing an exceptional diversity of plant life, land degradation by grazing, cultivation, and irrigation is believed to have altered the flow of water through the landscape
- Impacts in this landscape are manifested at a range of scales, from shrub patches (m^2) to major watershed systems (10^3–10^4 km^2), as changes in the flow patterns of ground and surface waters, nutrients, organic matter, and sediment, and increases in the salinity of the main rivers
- Current land-use practices are not sustainable without external inputs, setting the livelihoods of many people at risk
- Landowners will not be able to finance the full cost of rehabilitating their lands, so a systems approach is needed, which will involve the participation of all stakeholders and appropriate sharing of costs and benefits

Numerous studies have dealt with land-use change and its hydrological impacts, but only a few (eg Tomich *et al*. 2004; case studies in Aronson *et al*. [2007]) have assessed the changes from an ecosystem service perspective. These studies agreed that:

- the delivery of ecosystem services is altered by land-use or land-cover change;
- the loss of ecosystem services has substantial economic impacts, which affect a wide range of stakeholders; and

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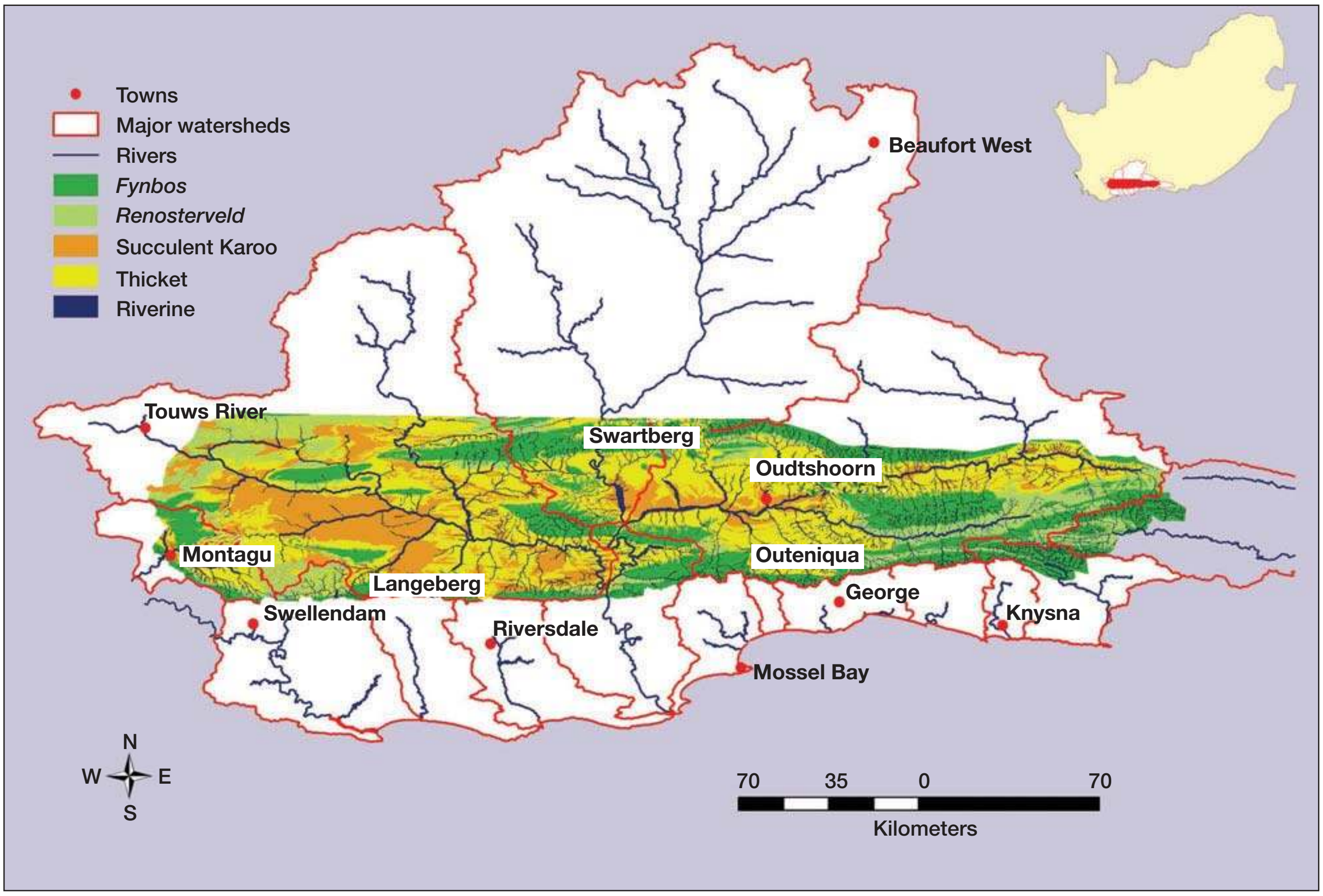

Figure 1. *Map of the vegetation of the Little Karoo, showing the major vegetation types and their locations within South Africa, the Gouritz River system, and adjacent watersheds.*

- reversing these impacts is likely to have net positive benefits when executed appropriately.

The ecosystem services of water flow regulation and water quality maintenance are tightly linked because both are controlled primarily by soil characteristics and their interaction with living organisms in and on the soil (Daily *et al.* 1997). Soils are not inert, but highly complex and dynamic ecosystems. Fertility, water absorption, and holding capacity are the outcomes of intricate linkages and feedbacks among components of the physical environment – rock type, mineral composition, past and present climate, topographic position – and components of the living environment – microbes, plants, and animals. Both classes of components are equally important (Bardgett *et al.* 2005). Soils are therefore a key factor in ecosystem productivity, as are water flow regulation and water quality.

■ The Little Karoo

The Little Karoo is an east–west oriented valley in South Africa, located between two roughly parallel mountain ranges running along the south coast of the Western Cape (Figure 1). The mountains have relatively high rainfall (> 900 mm per year), but the Little Karoo is in a rain shadow and receives only 150–350 mm annually. The rainfall season occurs in summer in the east and in winter in the west. Most of the water in the major river systems, and much of the groundwater, originates from the montane areas. Only the major rivers in the Little Karoo are perennial.

The montane vegetation is composed of tall, tough-leafed, evergreen shrubland (*fynbos*) that grades into grassy shrubland (*renosterveld*) and thicket on the more fertile lower slopes. On the valley floor, the soils are deep, fine-textured, rather saline colluvium and alluvium, with occasional islands of acidic white quartz. Where protected from trampling, soils are coated with a dense biological soil crust (biocrust) formed by cyanobacteria, lichens, and mosses (Esler *et al.* 2006). The dwarf (< 50 cm tall) Karoo shrubland is rich in endemic succulents, particularly Aizoaceae and Crassulaceae. Slightly raised, more-or-less circular features about 20–40 m in diameter known locally as "*heuweltjies*" (diminutive hills) develop over buried termite nests (Midgley and Musil 1992). These evenly spaced structures give the otherwise uniformly grey–green shrubland a dappled appearance (Figure 2). Riverbanks and floodplains support reedbeds or trees and shrubs with an herbaceous understory (Figure 3). This vegetation type differs in dynamics and productivity from adjacent dryland environments and provides key resources for wild and domestic animals (Acocks 1979).

Principal land uses in the Little Karoo are flood-irrigation farming for fodder crops, fruit, and vines on alluvial deposits of the floodplains, and extensive grazing by small stock and ostrich on the footslopes. The area has been settled by Europeans since the early 1800s and there is evidence that human activities, particularly overgrazing of drylands and cultivation of alluvial areas, have resulted in hydrological and vegetation changes over large areas of the Little Karoo. These appear to have exacerbated drought effects and caused a loss of productivity (Dean and Macdonald 1994; Cupido 2005; Figure 3) and biodiversity (Thompson *et al.* 2005; Vlok *et al.* 2005; Table 1). Farm and river names (eg Olifantsrivier [elephants river] and Moerasrivier [marsh river] in the arid Oudtshoorn area) suggest that the perennial rivers once supported fertile wetlands, attractive to buffalo, elephant, and hippopotamus (Acocks 1979; Dean and Milton 2003).

■ Resource retention and transfer

Like other semiarid to arid ecosystems, productivity of the Little Karoo's dryland vegetation is limited by the quantity and timing of rainfall. Rainwater infiltrating the soil within vegetation patches triggers a series of processes (Figure 4), depending on, among other factors, the size and timing of the rainfall event or pulse (Noy-Meir 1973; Schwinning and Sala 2004). Water that infiltrates into the soil and is not taken up and transpired by the vegetation percolates down the profile, recharging soil moisture and potentially reaching the water table, thereby replenishing groundwater (Ludwig *et al.* 2005; Seyfried *et al.* 2005; Figure 5). The amount of water captured by plants depends on the depth and density of their root systems, on how rapidly water is absorbed by the roots, and how quickly water percolates through the rooting zone.

On fine-textured, shale-derived soils, such as those of the Little Karoo, infiltration is generally better near shrub clumps where sand has been deposited by wind (Mills and Fey 2004) and on organically enriched *heuweltjies* than on bare soil (Midgley and Musil 1992). Overland flow will therefore occur more rapidly in open areas (Snyman and van Rensburg 1986) and water will be redistributed and trapped in vegetation patches as it moves down the slope

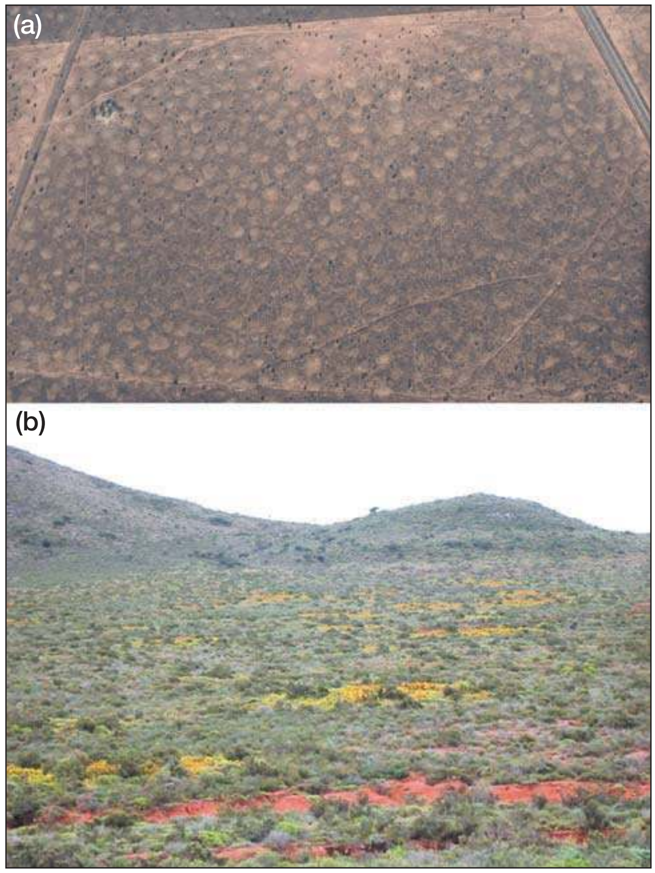

Figure 2. *(a)* Heuweltjies *(~ 20 m diameter) in the Oudtshoorn district have been more intensively grazed by ostrich than the surrounding vegetation and appear here as light areas of bare soil from which ostrich tracks radiate. Vegetation has also been removed by ostrich activity within a radius of 50 m from containers where supplementary feed is provided for the birds. (b)* Heuweltjies *near Vanwyksdorp appear as yellow patches in the grey–green vegetation, due to dominance by unpalatable yellow-flowered annual plants.*

(Figure 5). Runoff water transports fine dust, soil, and organic matter into the vegetation patches, making them more productive (Ludwig *et al.* 2005). When there is enough rainfall in a single shower, or a sequence of showers, to exceed infiltration rates in the vegetation patches, overland flow redistributes water and waterborne material

Table 1. Summary of the state of degradation of the Little Karoo study area for each of the major vegetation categories and riparian areas (from Thompson *et al.* 2005)

Transformation	*Category*	Fynbos Fynbos (%)	Fynbos Renosterveld (%)	*Thicket (%)*	*Succulent Karoo (%)*	*Watercourses* *Source (%)*	*Watercourses* *Drain (%)*	*Total (% in category)*
Severe	Urban	0.01	0.24	0.11	0.72	0.16	0.21	0.21
Severe	Water	0.05	0.26	0.38	0.29	1.07	2.67	0.41
Severe	Cultivation	4.05	20.34	6.18	8.87	18.74	33.90	9.84
Severe	Grazing	8.21	3.79	19.57	28.17	7.21	14.47	15.43
Moderate	Grazing	2.96	7.68	62.09	60.12	11.65	37.50	36.51
Pristine	Grazing	84.71	67.69	11.66	1.83	61.18	11.26	37.58
All severe		12.32	24.62	26.25	38.05	27.17	51.24	25.90
Totals (% of total area)		**25.86**	**12.60**	**35.19**	**17.39**	**3.44**	**5.52**	**100.00**

Values in each column are the percentage area in each degradation category for that vegetation or watercourse type. Source watercourses are characterized by freshwater species and drains by salt- and saline-water tolerant species.

Figure 3. *(a) Evidence of a more productive past: eroded remnants of formerly productive bottomlands near Ladismith, probably cultivated for annual crops or overgrazed in the past. (b) Spanish reed* (Arundo donax) *forms dense stands along a perennial river in a narrow Little Karoo valley. Vegetation on the hillslopes is succulent thicket mixed with* renosterveld *shrubland. The valley bottom has been transformed for establishment of pasture and vineyards, and is moderately invaded by black wattle* (Acacia mearnsii)*. (c) View of a river, showing the marked contrast between the taller and greener riverine woodland and the adjacent dryland vegetation. (d) Matjiesrivier valley in the Little Karoo, showing* fynbos*-clad mountains (yellow–green), lower slopes with intact* renosterveld *(blue–green), transformed bottomlands plowed for cereal crops, and the poplar-invaded riverbed. The natural vegetation of the riverbed would have included tall grasses,* Acacia karroo *trees, and bird-dispersed shrubs* (Euclea, Olea, Rhus).

downslope to the next patch or *heuweltjie*. The overland flows accumulate downslope, ending up in the stream or river, recharging alluvial deposits, and eventually generating runoff in the stream reach at the base of the hillslope (Belnap et al. 2005; Figure 5). Thus, the balance between infiltration and overland flow determines the amount of water and waterborne materials that are retained or exported from a patch and, ultimately, a hillslope, to river systems and the ocean.

The responses of large spatial units may not simply be the sum of the smaller units nested within them. A stream or river system is not homogenous, but varies in the way water and waterborne material move and are interchanged through lateral and vertical inflows and outflows (Ward 1998). As more flow accumulates, streams transform from ephemeral to seasonal to perennial, although even large river systems may remain seasonal in arid areas (Belnap *et al.* 2005). The effects of large and spatially extensive rainfall events may be felt far downstream of the area that is directly affected. For example, in July 2006, heavy rainfall in the mountains caused flooding in Little Karoo valleys that had received little rain.

In some situations, a substantial portion of the rainwater may follow subsurface pathways and reach the stream after delays caused by the nature of those pathways. If there is substantial flow through pathways that permit rapid flow, or if the underlying rock has many fractures or openings, the responses can be rapid (hours to days), but in other situations the delays (lags) in discharge responses may range from weeks to years (McGlynn *et al.* 2003; Skøien *et al.* 2003). The rapid fluctuations that characterize processes and responses at smaller scales are smoothed out and lagged at larger spatial and temporal scales.

Water accumulating in the rivers and alluvial aquifers of valley bottoms and floodplains sustains the relatively tall and dense riparian vegetation (Figure 3). This vegetation stabilizes riverbanks, provides refuges and habitat for animals, and regulates river flows. Groundwater discharge zones result in ecohydrologically distinct patches or linear features in the landscape. Springs typically have point discharges, which result in small wetlands and headwaters, with flows that may vary seasonally or are relatively constant (Cleaver *et al.* 2003). Deep-rooted riparian trees and reeds depend on water in the alluvial aquifers, releasing groundwater to the atmosphere via transpiration (Ward and Breen 1983). However, the proportions of groundwater, soil water, and river water used in this way are not known and may vary temporally. Alluvial aquifers are also important for humans because they hold relatively large volumes of water as compared to rock aquifers, where water is confined to fractures and faults. Groundwater in the alluvium was accessible before modern technology allowed boreholes to be drilled into the underlying fractured rock, providing early settlers with dependable water supplies in the absence of springs.

Infiltration is therefore a key process at the hillslope and landscape scale, like the flow-driven processes at stream and river-reach scales. The links between landscape characteristics, particularly the spatial patterns in geomorphology and land cover, and rivers are a vital and integral part of the functioning of streamflow (Ward 1998; Hancock *et al.* 2005). Lateral linkages – dryland to riparian and vice-versa – are as important to the structure and functioning of aquatic ecosystems as the up and down river linkages emphasized in the past (Belnap *et al.* 2005; Ludwig *et al.* 2005).

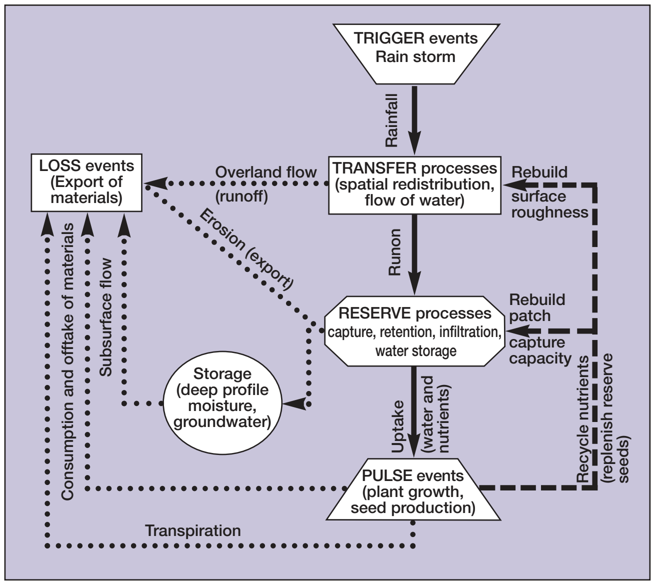

Figure 4. *The trigger–transfer–reserve–pulse model, which illustrates how temporal events (eg water input from rainfall) initiate a number of other events (adapted from Ludwig* et al. *[2005]). Solid arrows indicate direct action of flows of water, dashed arrows indicate feedbacks, and dotted arrows indicate losses, including transpiration, lateral subsurface flow, and groundwater recharge.*

■ Original and degraded states

Land degradation generally changes the balance between overland flow and infiltration, resulting in increased erosion of fragile soils and altered flow patterns in rivers (Snyman and van Rensburg 1986; Friedel *et al.* 1990; Keay-Bright and Boardman 2006; Figure 6; Table 2). Similar changes are believed to have occurred in the Little Karoo, particularly during the late 1800s, when stocking rates were extremely high (Dean and Macdonald 1994; Hoffmann *et al.* 1999). The rate of consumption of palatable plant material by domestic livestock exceeded annual production, resulting in a net loss of biomass of these species and, subsequently, in their failure to set the amount of seed needed to maintain population sizes (Milton and Wiegand 2001). The high stocking levels were sustained by access to groundwater using pumps, driven at first by wind (Archer 2002) and later by cheap electricity, and by fodder grown under irrigation that allowed farmers to reduce their reliance on the declining and variable yields of natural vegetation.

Reduction in vegetation cover exposes more of the soil surface, increases surface flows, and reduces infiltration of water (Snyman and van Rensburg 1986; Mills and Fey 2004; Roth 2004). Biocrusts are destroyed as a result of intensive trampling by livestock (including ostrich; Esler *et al.* 2006), and, on fine-textured soils, are replaced by mineral crusts. Both biological and mineral crusting can reduce infiltration of water into soil (Roth 2004; Mills *et al.* in press). However, it is likely that conversion of biocrust to mineral crust reduces surface irregularities that retain water at the crust–shrub scale (Figure 7), thereby altering the connectivity and fluxes among the spa-

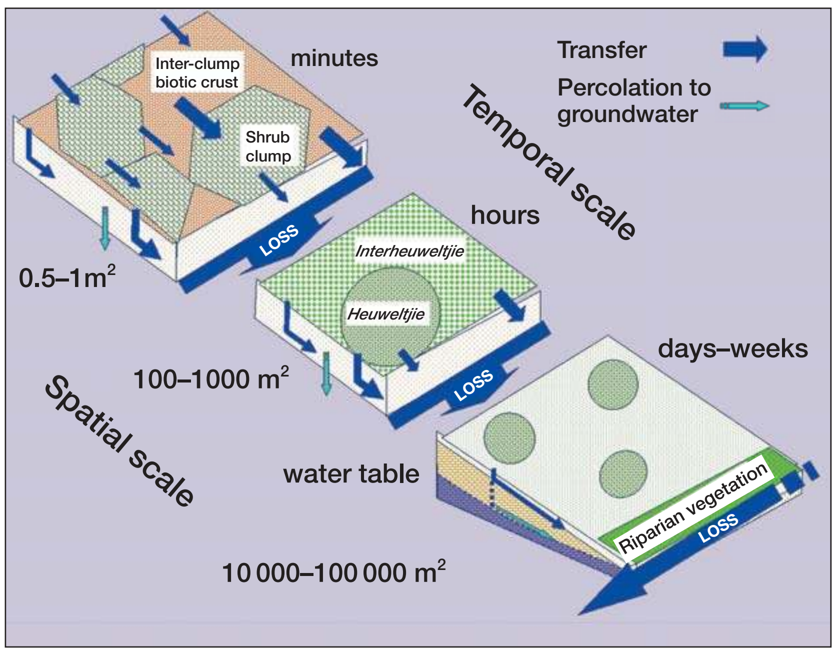

Figure 5. *The interrelationships within and between units at different scales. The blue arrows represent fluxes of water and dissolved and waterborne materials; the light blue arrows represent water percolation beyond rooting depth to recharge groundwater.*

Table 2. Summary of the initial and degraded states of spatial units at various scales

Spatial unit	*Function/feature*	*Initial state*	*Degraded state*
Shrub – inter-shrub crust			
Crust	**H_2O retention**	**High**	**Very low**
	Infiltration	Moderate	Minimal (cracks provide preferential flow but may close rapidly)
	Groundwater recharge	Moderate	None
	Overland flow	**Moderate**	**High**
	Nitrogen	Fixation	No fixation
	Soil surface	**Stabilized**	**Destabilized**
Shrub clump	H_2O retention	High	Low
	Infiltration	**High (animal burrows soil, structure open)**	**Low (few animals, soil structure closed)**
	Soil-water use	High	Low
	Groundwater recharge	Low	None
	Overland flow	**Low**	**High**
	Organic matter	Accumulation	Loss
	N fixation	Some	Little or none
	Soil surface	Stabilized	Destabilized
***Shrub – crust mosaic (matrix)* – heuweltjies**			
Shrub crust	Shrub clumps	Closely spaced	Thinned out
	Biotic crust	Well developed	Lost
	H_2O retention	**High**	**Very low**
	Infiltration	Moderate	Low
	Groundwater recharge	**Moderate**	**Very low**
	Overland flow	**Moderate**	**High, channelling, rills, dongas**
	Nitrogen	Some fixation	Reduced fixation
	Soil surface	Stabilized	Destabilized
Heuweltjie	H_2O retention	High	Low
	Infiltration	**Very high (termite nests, animal burrows, soil structure open)**	**Low (few animals, mineral crust)**
	Soil-water use	High	Low
	Groundwater recharge	**High**	**Low**
	Overland flow	**Low**	**High**
	Organic matter	Accumulation	Net loss
	Soil surface	Stabilized	Destabilized
Hillslope – floodplain and river			
Hillslope	Vegetation mosaic and *heuweltjies*	Shrub clumps closely spaced, biotic crusts, *heuweltjies* well vegetated	Degraded shrub clumps sparse *heuweltjies* degraded
	H_2O retention	High	Low
	Infiltration moderate	Moderate	Low
	Groundwater recharge	**Moderate**	**Very low to none**
	Overland flow and sediment loss	**Low to moderate**	**High**
	Nutrient and organic matter loss	**Low**	**High**
Floodplain and river	H_2O capture	High	H_2O capture low?
	Vegetation-water use	**High**	**Higher replacement by invasive species**
	Organic matter and nutrients	Gains balance losses	Accumulation?
	Alluvial aquifer recharge and retention	**High for both**	**High and low? (respectively)**
	Alluvial sediment	**Stable**	**Accumulation**
	Alluvial system	**Stabilized against most floods**	**Destabilized, channel incised? Floods more severe and more frequent, loss of braiding (aquatic habitat)**
	Groundwater discharge	Sustained	Less sustained
	Fauna	Diverse, supported by high grass cover	Depauperate, little or no grass cover

Bold = key changes in processes and ecosystem states tial units (Trimble and Mendel 1995). Reduction of perennial vegetation cover also reduces the biotic activity that is essential for maintaining soil integrity (Milton and Dean 1992; Doran and Zeiss 2000). Infiltration rates might have been further reduced by topsoil losses that exposed deeper and less permeable clays (Mills and Fey 2004), or by a reduction in plant litter and hence organic matter binding the soil particles into aggregates. The reduction in soil moisture recharge is likely to have reduced plant productivity (Figure 6), increasing the impacts of overgrazing on the already stressed vegetation. All these processes tend to be self-reinforcing.

Overgrazed areas in the Little Karoo show a decrease in both the cover and diversity of perennial plants (Cupido 2005). Dwarf succulents, only a few millimeters in height, are associated with stable soil (Schmiedel 2002) and are particularly susceptible to trampling. As soil stability and vegetation cover decrease, annuals tend to replace perennials. Annuals die during dry times, so that drought-breaking rains fall on bare soil, further eroding and aridifying the slopes. This cycle partially explains why overgrazed succulent thicket fails to re-establish on slopes dominated by short-lived, alien, invasive plants (such as *Atriplex lindleyi*) that replace it (Thompson *et al.* 2005).

There has also probably been a localized loss of biodiversity and ecosystem function because biocrusts that contribute nitrogen to the system and retain nutrients (Belnap *et al.* 2005) have been reduced by trampling (Table 2). In areas which have been more intensively grazed, biocrusts have been lost completely, leaving areas of exposed mineral soil that are easily sealed by dispersed clay or eroded by wind and water (Mills *et al.* in press). The loose, friable soils of *heuweltjies* tend to erode and become localized depressions when devegetated (Vlok *et al.* 2005).

Effects of vegetation loss and soil surface changes on hydrological responses are not necessarily direct or linear (Trimble and Mendel 1995; Wilcox *et al.* 2003). Infiltration and moisture retention may be affected by a variety of factors, including variability in rainfall. The erosion and infilling process may result in a smoother surface with fewer fine-scale irregularities to retain rainwater and encourage infiltration. Changes may occur very rapidly while the degradation is still in the early stages, may be linear, or may become evident only once degradation is very advanced, as is typical of threshold responses. Factors such as soil porosity and texture and characteristics of vegetation may influence the nature of the response. These changes may also alter groundwater recharge (Figure 6; Table 2) and discharges of groundwater at springs and into other surface water systems. The net result is likely to be an alteration, degradation, or loss of groundwater-dependent ecosystems, whether wetlands, spring ecosystems, or alluvial aquifer and floodplain vegetation.

At the watershed and river basin scale, the sediments, salts, organic matter, and nutrients eroded from slopes accumulate in river systems (Figure 6; Table 2). An accumulation of sediments along the watercourses may alter

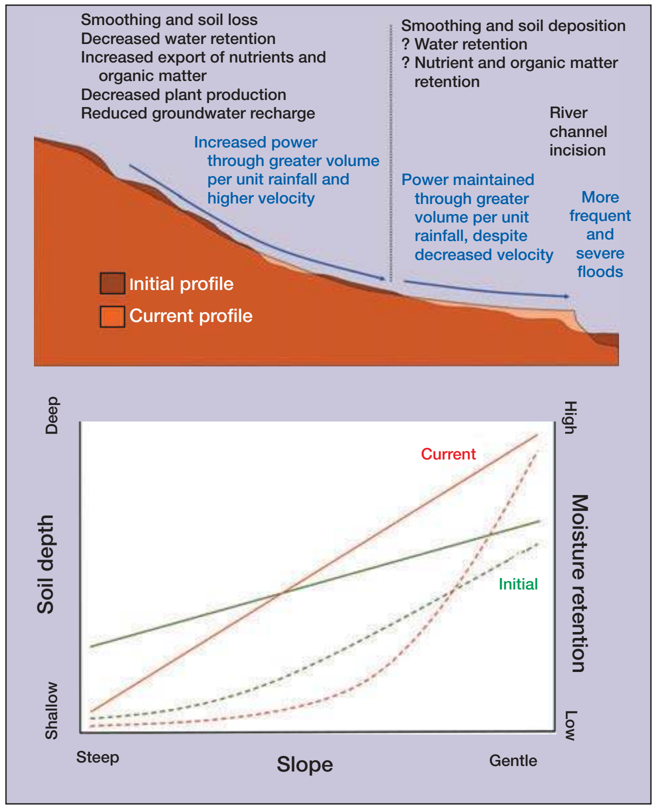

Figure 6. *(a) Key changes in the surface of the landscape and their impacts on water fluxes down the hillslope and in the stream or river at the base of the slope. (b) Hypothetical changes in soil depth (solid lines) caused by degradation from the initial or pre-colonial state to the current state, and corresponding effects on moisture capture and retention (dashed lines).*

water-holding capacity (Costelloe *et al.* 2005), but the net effects on river flows are not known. It is likely that the net downslope accumulation of sediment has increased the amount of water that can be stored in the footslopes, relative to the middle and upper slopes (Figure 6).

Extensive cultivation of alluvial soils for dryland and irrigated agriculture has resulted in the removal of riparian vegetation and its replacement by crop systems, thereby changing alluvial aquifer dynamics and river flows. Flood irrigation is still the dominant practice (DWAF 2003), and generally results in return flows that are enriched with nitrogen and have relatively high salinity. Although groundwater occurring in shales of the Little Karoo has naturally moderate levels of salinity considered marginal for human consumption (DWAF 2003), the names of farms established in the early 19th century suggest that salt-intolerant hippopotamus once inhabited river reaches that are now saline (Dean and Milton 2003).

The withdrawal of large volumes of water has important impacts on flow regimes in rivers and thus on the associated aquatic ecosystems. In addition to undergoing physical and chemical changes, the large rivers are increasingly subjected to more extreme and episodic flows due to a combination of increased surface runoff from hillslopes and decreased interflow and groundwater discharge to rivers

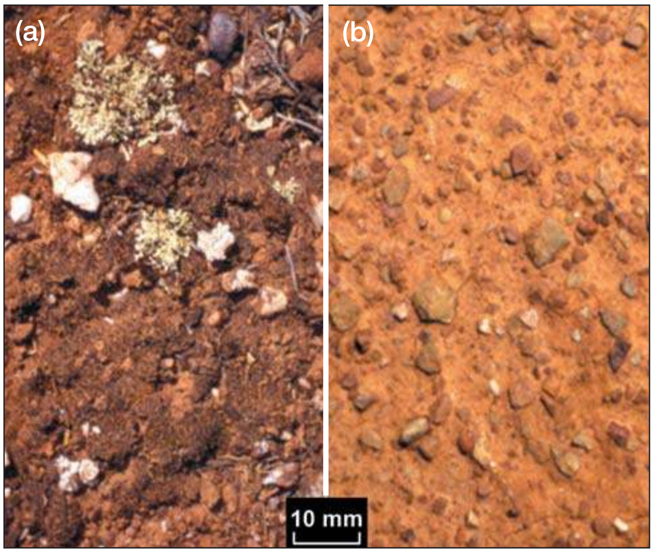

Figure 7. *(a) Typical biological crust and (b) mineral crust from a road verge and ostrich camp, respectively. Note the changes in surface roughness and the sealed mineral surface with a loss of loose pebbles on the mineral crust. These photographs were taken within 5 m of each other.*

(Friedel *et al.* 1990). The more variable flow regimes, particularly flash floods, may have altered the river systems by focusing flows in single, incised channels cutting through formerly braided systems and may have changed groundwater regimes in the alluvial deposits. It is also likely that deepening of rivers to "reclaim" marshy alluvium in valley bottoms changed both flow regimes and water quality.

Changes in water, nutrient, and organic matter fluxes may explain the successful colonization of these systems by sprouting, multi-stemmed alien plant species, adapted to trap and exploit accumulating silt. Among these, *Populus* spp and *Nerium oleander* are generally confined to freshwater reaches, while *Tamarix ramosissima* and *Arundo donax* are more salt tolerant (Figure 3). The changes in species composition may have resulted in a substantial increase in transpiration rates from riparian areas. In these stands, as well as in the indigenous riparian vegetation, the once-prominent grasses have been grazed nearly to the point of disappearance (Acocks 1979).

About 26% of the Little Karoo has been severely degraded, with a further 38% moderately degraded (Table 1; Thompson *et al.* 2005). River floodplains have been severely affected, with 51% of all lower river reaches (Vlok *et al.* 2005) being severely degraded and only 11% in good condition. Less than 2% of the area of succulent Karoo plant communities is still in good condition, compared with 12% of the thicket, 68% of the *renosterveld*, and 85% of the *fynbos* (which is well preserved mainly because it provides poor grazing for livestock). In 2005, about 60% of Little Karoo farms were overstocked, and rangeland condition was poorest in ostrich camps and near livestock watering and feeding points (Cupido 2005). Recent analyses suggest that use of the Little Karoo for grazing or ostrich farming is barely profitable because of the high operating costs of small farms (Cupido 2005). Irrigation farming is currently the only economically viable option, but this is limited to 4% of the land (DWAF 2003). However, when the benefits of irrigation are viewed against its impacts on downstream water quantity and quality, the costs may be found to outweigh the benefits. The economic viability of many farms is maintained because they double as tourist facilities and because they also rely on both crops and ostriches, the ostriches being sustained by forage imported from other parts of the country (Cupido 2005).

The effects of land-use practices on ecosystem services in the Little Karoo have been profound, covering a range of scales, from a few square meters to entire river systems. The impacts vary over these scales, largely because of the way water moves through landscapes. For example, sediments, organic matter, and nutrients have been lost from hillslopes and accumulated along the rivers, resulting in reduced soil moisture on the slopes. This, in turn, has impacted plant productivity and further aggravated the impacts of overstocking. At the same time, it is likely that increased surface runoff has changed flow regimes in rivers and probably increased the frequency of flash floods, some of which have done extensive damage.

Future options

The early European settlers may not have been aware that they had overstocked the landscape of the Little Karoo and were consuming natural capital accumulated over decades, as they had no prior experience of stochastic arid environments or any understanding of the fragility of these ecosystems. Moreover, the impacts of high livestock densities and continuous grazing may have been exacerbated by the relatively dry conditions in the 19th century (Keay-Bright and Boardman 2006). It would appear that the indigenous herbivores were nomadic, as were the indigenous herders, and they retreated to better watered, if less nutritious, rangeland during dry periods (Elphick 1985).

The question is, can these trends in vegetation and hydrology be reversed? Studies in the Great Karoo to the north provide some evidence of a gradual increase in vegetation cover between 1945 and 2002 (Keay-Bright and Boardman 2006), but erosion, once initiated by heavy rains on bare ground, results in a steepening of slopes that promotes accelerated runoff. Thus, erosion events become self-perpetuating.

Ideally, resources (money, people, and technology) should be made available to rehabilitate degraded lands in the Little Karoo, providing sustainable livelihoods in these fragile environments. Rehabilitation is a process that can take decades or centuries, and in the case of the Little Karoo, it will need to address problems pertaining to hydrological, edaphic, and vegetation characteristics. Appropriate interventions might include a combination of livestock reduction, stabilization of the upper parts of gullies, creation of mini-catchments and other small-scale structures to improve infiltration, reseeding, and removal of alien trees in water courses (Esler *et al.* 2006). Unfortunately, the costs of such a program are likely to be prohibitive when weighed against the ability of the farmers themselves to repay the investments. We believe that an assessment of rehabilitation needs based on short-term economic benefits alone takes too narrow a view. A multi-scale, systems approach is needed to determine whether the balance between potential costs and benefits changes with spatial and temporal scale (Aronson *et al.* 2007). This approach also needs to expand the concept of benefits to include supporting and provisioning goods and services and ecosystem resilience to drought as well as reduced flood risk, job creation, and conservation of a global biodiversity hotspot (Thompson *et al.* 2005).

■ Conclusions

We have presented evidence to demonstrate that the effects of human activities on the Little Karoo over the past 120 years have been severe, and have led to changes in plant populations and vegetation composition, and a decline in forage production. We suggest that reduction of perennial vegetation cover has changed patterns of retention and transfer of water, nutrients, and organic material at the scale of the shrub–biotic crust (m^2). Increased transfers at this scale have propagated down hillslopes into the river systems (km^2). The losses have exceeded the ability of the ecosystems to replenish these resources, resulting in an ongoing net loss from the hillslopes. Human activities have also degraded the ecosystems of the floodplains

The Little Karoo provides an opportunity for assessing the costs and benefits of reversing the impacts of land degradation in an arid socioecological system, and at a range of spatial scales, by finding techniques and approaches that are affordable, practical, sustainable, and socially acceptable. The key will be to ensure that an appropriate share of the profit gained from these services is invested in managing the ecosystems and landscapes that generate that profit. Ecosystem service improvements and other benefits of restoration need to be discussed and demonstrated, as success can only be achieved with the full participation of all the stakeholders.

■ Acknowledgements

DCLM, CJ, CAC, and IS acknowledge the support of Natural Resources and Environment CSIR for this work. SJM acknowledges support from the National Research Foundation of South Africa under grant #2053674 and from DST/NRF Centre of Excellence for Invasion Biology.

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