Invasive alien trees and water resources in South Africa: case studies of the costs and benefits of management

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Abstract

Invasive alien plants are consumptive water-users, and may have reduced river flows in South Africa by about 6.7% according to a broad-scale study. An effective programme to bring the invasions under control would cost about US$ 92 million per year for the next 20 years. This paper reports on studies of four representative catchments (the Sonderend, Keurbooms, Upper Wilge and Sabie-Sand) to assess the impacts and costs of invasions at a scale that is more relevant to managers. Several alien plant species have invaded the catchments. Non-riverine invasions are mainly *Pinus* and *Hakea* species in Sonderend and Keurbooms, eucalypts in the Upper Wilge, and pines and scramblers (e.g. *Lantana camara*) in the Sabie-Sand catchment. Riverine invasions are dominated by *Acacia mearnsii* and, to a lesser extent, *A. dealbata*, except in the Sabie-Sand and the lower Sonderend River where *Eucalyptus* species are important. About 44% of the Sonderend, 54% of the Keurbooms, 2% of the Upper Wilge and 23% of the Sabie-Sand catchments has been invaded to some degree. The corresponding reductions in the natural river flows attributed to these invasions are about 7.2, 22.1, 6.0 and 9.4%. If the invasions are not controlled they could potentially spread, and occupy 51, 77, 70%, respectively, of the first three catchments. At an annual expansion rate of 10–15% this would take about 13, 26 and 63 years, respectively. The invadable areas in the Sabie-Sand catchment are already invaded so invasions will only increase in density. It would take about 26–30 years to reach 100% canopy cover. The projected flow reductions for the four catchments would increase to 41.5, 95.5, 25.1 and 22.3%, respectively. The estimated cost of the control programmes to prevent these losses would be about US$ 13.2, 9.9, 4.1 and 6.6 million for the Sonderend, Keurbooms, Upper Wilge and Sabie-Sand catchments, respectively. Should the catchments be allowed to become fully invaded before control operations were started, then the costs would rise to US$ 86.5, 20.5, 278.0 and 11.1 million, respectively. The impacts and costs are significant and are comparable with those calculated independently for other South African catchments. Water is acknowledged to be a key constraint to economic growth in South Africa and there is considerable pressure for efficient and sustainable use of the limited water resources. The projected impacts would justify control programmes aimed at clearing alien invaders for water conservation. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Natural forests in southern Africa are surprisingly limited in their extent. Areas that receive in excess of

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800 mm of rainfall annually, at altitudes below 2000 m, are covered by grasslands or shrublands, while similar areas in other parts of the world would support natural forests (Holdridge et al., 1971; Schulze and McGee, 1978). One of the main reasons for this disparity is repeated fires which prevent the establishment of forest species (Moll et al., 1980; Manders, 1990; Manders and Richardson, 1992). In areas which are sheltered from regular fires, forests can and do develop (Geldenhuys, 1994), and forests tend to have fuel properties that do not promote fire (van Wilgen et al., 1990), ensuring their survival in the fire-prone landscape. Nonetheless, natural forests in southern Africa cover less than 0.25% of the landscape (Low and Rebelo, 1996; Midgley et al., 1997).

The lack of a natural source of fast growing timber trees led to the establishment of plantations of alien (introduced) species, beginning in the late 19th century (King, 1943; Le Maitre, 1998a). Plantations of alien trees, primarily pines and eucalypts, now cover 1.52 million ha in South Africa (FOA, 1998). These plantations have brought many benefits. Plantation forestry contributes US$ 300 million, or 2%, to the GDP and employs over 100,000 people. Downstream industries, based on forestry, produce products worth a further US$ 1.6 billion, much of which is exported, earning valuable foreign exchange (FOA, 1998).

However, the establishment of these plantations has not been without cost. The negative impacts of afforestation include significant reductions in surface streamflow (Van Lill et al., 1980; Bosch and Hewlett, 1982; Bosch and von Gadow, 1990). Commercial plantations are estimated to have reduced surface runoff by about 1.4 billion m^3 per year or 3.2%, at a national scale (Le Maitre et al., 1997; Scott et al., 1998a). These reductions are important because South Africa has a mean annual rainfall of only 490 mm and less than 10% of this becomes surface runoff (Alexander, 1985). Commercial plantation forestry is the only land-use which is restricted because its impacts of afforestation on streamflow (Van der Zel, 1995). Plantations also have substantial impacts on biodiversity and the functioning of natural ecosystems (Armstrong and van Hensbergen, 1996; Allen et al., 1997).

The National Water Act recognises that a portion of the available water needs to be reserved for basic human needs and to sustain natural ecosystems; this places additional constraints on the water available for other uses (Anon., 1970; DWAF, 1986; Walmsley and Davies, 1991; DWAF, 1996). Water is the primary resource that will ultimately limit development in South Africa and efficient management and allocation of water resources is a national imperative (DWAF, 1996).

Unfortunately, many of the plantation species have become major invaders, spreading the negative impacts far beyond the afforested areas. Foremost amongst these are several species of pine (*Pinus*) and wattle (*Acacia*). The forestry industry recognises these problems and subscribes to a code of conduct which, among other things, requires that riparian zones and non-afforested areas within the forest estates are kept clear of invading alien plant species (FIEC, 1995). The forest industry has also recognised that the impacts of plantation trees on streamflow are far greater in the riparian zone than outside it (Scott and Lesch, 1995; Scott et al., 1999), and follow a policy of non-afforestation of such zones (FIEC, 1995). The industry also actively supports the government's alien plant control programmes by funding control operations, providing expertise and forming partnerships with Working for Water.

Commercial forestry based on alien trees is a well-established feature of the South African landscape and economy, but the invasions that are associated with it are going to have to be managed to minimise conflicts around scarce resources, especially water. As a first step, a clear understanding of the magnitude of the problem needs to be developed, especially in order to establish whether the costs of clearing invaded areas can be justified. Studies to quantify the relative benefits of clearing have been carried out in the Western Cape Province, where mountain catchment areas covered with fynbos shrublands have been invaded by pines and wattles (Le Maitre et al., 1996; van Wilgen et al., 1996, 1997). These areas are subjected to fires at about 15-year intervals; the fires trigger the spread of alien trees, initially from adjacent plantation areas, and subsequently from invaded areas in the catchment.

As the problem of invasive alien trees and their impacts was not restricted to the Western Cape Province (Henderson, 1995; Dye and Poulter, 1995), a study was commissioned to estimate the predicted impact on a national level. This study found that about 10.1 million ha, or 6.8% of South Africa has been invaded to some degree (Versfeld et al., 1998). These

invasions were estimated to be using almost 6.7% of the country's runoff, and would cost an estimated US$ 0.86 billion to clear over 20 years (Le Maitre et al., 2000). While these results were based on very crude estimates of the extent of invasion they were nonetheless convincing enough for the national government to launch an extensive and ambitious control programme aimed at minimising the effects on water resources (van Wilgen et al., 1998).

This paper summarises the findings of management plans that were developed for alien plant control in four representative catchments in South Africa. The aim of these plans was two-fold—firstly to test, at a finer scale, the broad-scale predictions of significant benefits from clearing programmes, and secondly to provide project managers with reasonable estimates of the extent of the task that they faced. In this paper, we compare the composition, extent and impacts of invasive alien trees in the four catchments and provide estimates of the costs and benefits of control operations.

2. Study sites

We selected four catchments, representative of a cross-section of the catchments in South Africa in terms of their climate, natural ecosystems, kinds of land-use and the composition of the invading plants (Table 1, Fig. 1).

2.1. Sonderend River

This catchment is situated in the rugged Cape Folded Mountains with peaks of over 1600 m in the Stettynskloof range in the west, Langeberg in the north and Riviersonderend in the south (Gelderblom et al., 1998). The mean annual rainfall varies from 1895 mm in the upper catchment to 350 mm in the lower lying areas (Midgley et al., 1994). The dominant vegetation in the lower regions of this catchment was renosterveld (Table 2), a low shrubland which occurs on shale-derived soils; most of the renosterveld is now cultivated land and less than 5% is currently formally conserved (Low and Rebelo, 1996; Gelderblom et al., 1998). The dominant vegetation in the mountain areas is fynbos, a species-rich shrubland with numerous rare and endemic plants.

The runoff from the high-yielding sub-catchments at the western end of the Sonderend supplies the Theewaterskloof dam (capacity 484 million m^3) which is an important source of water for the greater Cape Town metropolitan area, and for irrigation of deciduous fruit (van Wilgen et al., 1997; Gelderblom et al., 1998).

2.2. Keurbooms River

The southern boundary of the Keurbooms catchment is situated on the coast. The mountains to the north are rugged and barely accessible (Gelderblom and Rowlinson, 1999). The main Outeniqua mountain range, elevation >1200 m, runs east-west and the south-facing slopes are significantly moister than the north-facing slopes. The coastal section includes a broad elevated coastal plateau (150–250 m) with deeply incised river valleys. The mean annual rainfall ranges from 664–997 mm in the different sub-catchments and is distributed through the year (Table 1).

The dominant vegetation is mountain fynbos shrublands (Gelderblom and Rowlinson, 1999). There are also extensive areas of the temperate Afromontane forest which is situated mainly in valleys, on south-facing slopes of the coastal mountains and the coastal plateau (Geldenhuys, 1994).

Table 1
Salient features of the four South African catchment areas used in this study[a]

Catchment area	Area (km^2)	Climate and rainfall season	Mean annual rainfall in the catchment (mm)	Mean annual runoff (millions of m^3)
Sonderend	2242	Warm temperate, winter	634	459
Keurbooms	1380	Warm temperate, all-year	811	215
Upper Wilge	6160	Cool temperate, summer	723	451
Sabie-Sand	6322	Temperate to sub-tropical, summer	891	732

[a] See Fig. 1 for the location of the catchments. Catchment areas, rainfall, evaporation and surface runoff data from Midgley et al. (1994).
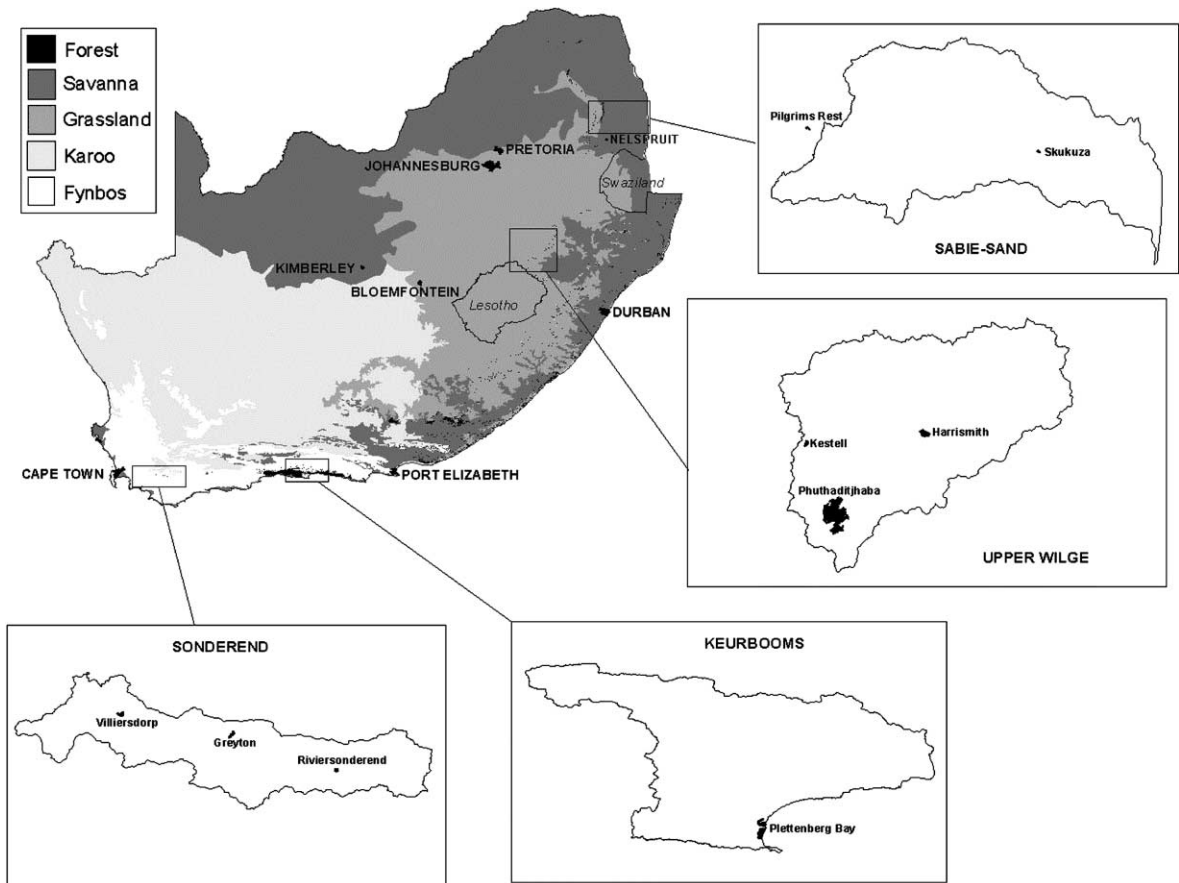
Fig. 1. The distribution of the major biomes in South Africa (Low and Rebelo, 1996) and the location of the four catchments in this study.

The cultivated areas are situated on the coastal plateau in the south-eastern part of the catchment and a substantial area is under plantations (Table 2, Gelderblom and Rowlinson, 1999). The town of Plettenberg Bay near the estuary of the Keurbooms River is a major tourist resort. The agricultural activities include irrigated vegetable and deciduous fruit production and intensive grazing for dairy farming (Gelderblom and Rowlinson, 1999). Agriculture is currently the major water-user and demand for water for agriculture and urban use is expected to increase 2–3 times by 2020 AD (Ninham-Shand, 1996).

2.3. Upper Wilge River

The Upper Wilge River catchment is situated on the inland plateau of South Africa. The upper, southern-eastern headwaters are situated along the crest of the Drakensberg Escarpment and in the Maluti Mountains of Lesotho where the peaks reach 3200 m (Bailey, 1997). The lowest regions in the north-west are 1600–1700 m with low hills and ridges, gently sloping valleys and meandering rivers. The mean annual rainfall is 723 mm (Table 1) and varies from 600–1500 mm. There are frequent frosts, and snowfalls in winter in the Maluti Mountains.

The vegetation is mainly a winter-dormant grassland dominated by temperate grasses with woodland or forest limited to river floodplains and sheltered valleys in the mountains (Table 2). There are extensive wetlands which cover about 22 km^2. The major land-use practices are extensive grazing, dryland cultivation—mainly for maize production—and irrigated agriculture. There are densely populated townships in

Table 2
The original vegetation (Low and Rebelo, 1996) and the current land cover (Thompson, 1996, Fairbanks et al., 2000) in the four South African catchment areas used in this study (Bailey, 1997, Gelderblom et al., 1998, Gelderblom and Rowlinson, 1999, Nel et al., 1999)

Catchment area	Original vegetation (% of area in parentheses)	Major forms of land cover (% of area in parentheses)
Sonderend	Renosterveld (63)	Natural vegetation (45)
	Mountain fynbos (36)	Cultivated lands (53)
	Afromontane forest (1)	Forest and plantations (0.3)
Keurbooms	Mountain fynbos (75)	Mountain fynbos (65)
	Afromontane forest (34)	Indigenous forest (18)
	Dune thicket (1)	Cultivated lands (9)
	Renosterveld (2)	Forest plantations (7)
Upper Wilge	Moist cold highveld grassland (46)	Natural vegetation (69)
	Wet cold highveld grassland (43)	Cultivated lands (25)
	Moist cool highveld grassland (9)	Degraded lands (3)
	Afromontane forest (1)	
Sabie-Sand	Mixed lowveld bushveld (52)	Natural vegetation (62)
	Sour lowveld bushveld (30)	Degraded lands (14)
	Sweet lowveld bushveld (6)	Forest plantation (14)
	Lebombo arid mountain bushveld (6)	Cultivated lands (5)
	North-eastern mountain grassland (4)	

Phuthaditjhaba (Fig. 1). Large areas in this vicinity have been over-grazed and degraded because of the over-population of these fragile lands. The catchment is a key water supply area for the major industrial and urban areas of Greater Johannesburg, Pretoria and Vereeniging.

2.4. Sabie-Sand

The Sabie-Sand River system has its source in the Drakensberg escarpment, about 2130 m, and flows eastwards to Mozambique (Nel et al., 1999). Mean annual rainfall drops steeply across the escarpment, from 1200–1500 mm in the headwaters to about 460–530 mm in east. The natural vegetation in the upper reaches is winter-dormant, temperate grassland (Table 2) with extensive areas of Afromontane forest in the valleys and the sheltered slopes of the escarpment (Nel et al., 1999). The vegetation of the lower areas comprises closed to open woodlands, savanna and grasslands with gallery forests along the main rivers.

Extensive plantations of pines (mainly *Pinus patula*) and eucalypts (mainly *Eucalyptus saligna*) have been established in the upper catchments of both the Sabie and Sand River systems (Table 2, Nel et al., 1999). In the middle reaches, commercial agriculture, mainly irrigated sub-tropical fruit, is the main land-use

in formal agricultural areas, while subsistence agriculture is the main land-use in the very densely populated, communally-owned rural areas. About a third of the area falls in the Kruger National Park, a conservation area of international importance.

The water resources in the rivers are heavily utilised (Nel et al., 1999). Plantations in the upper reaches have reduced the natural flow in the Sabie and Sand River systems by about 45 and 31%, respectively (Le Maitre et al., 1997). Irrigation used about 14% of the natural flow in 1987 while human use and water for livestock accounted for about 1% of the flow (Nel et al., 1999). There is concern about the ecological impacts of flow reductions on the rivers in the Kruger National Park (Weeks et al., 1996). The flow in the Sabie River almost ceased at the peak of the most recent drought. The demand for water is projected to increase by 115% by 2010 AD mainly due to increases in human use (800%) and irrigated agriculture (200%) (Nel et al., 1999).

3. Methods

3.1. Mapping of invaders

Different methods were used to map invaded areas in the different catchments. Field mapping was used

for the Sonderend and Sabie-Sand catchments and for parts of the other two. Mapping followed the guidelines developed by Le Maitre and Versfeld (1994) which provide for a range of density classes from rare (invaders known to be present but canopy cover less than 0.01%) to closed (100% canopy cover). The spatial extent of the invasions was recorded on acetate overlaid on maps from the standard 1:50,000 series for South Africa. Parts of the Upper Wilge River catchment were mapped using high resolution (1–5 m pixel size) aerial video photography (Bailey, 1997). The information from the video images was transferred to map overlays and verified in the field. Parts of the Keurbooms River catchment were mapped from a helicopter using a Global Positioning System (GPS) (Gelderblom and Rowlinson, 1999). All the spatial data were converted to GIS data layers in Unix *ArcInfo* format.

Invaded areas were divided into landscape invasions, and riparian and floodplain invasions. This was done to facilitate field mapping and because the invading species and invasion processes differ between the two categories (Le Maitre, 1998b). Landscape invasions are typically extensive and most easily drawn as polygons. Riparian invasions were assessed along segments of the stream or river and the width of the invaded strip was estimated. This width was subsequently used in the GIS to buffer the digitised watercourse and create a polygon. The density class or percentage cover of each species in the invaded area was estimated. The field data were captured and stored as data files in the GIS database. Some of the invasions mapped using videography were not identified to the species level and these were converted to species data using information on the typical proportions of the different species.

3.2. Additional spatial information

Information on rainfall and the estimated natural (pre-development) surface runoff was obtained from Midgley et al. (1994). This data set provided estimates of rainfall, surface runoff and evaporation for each sub-catchment comprising the study catchment. The runoff data were supplemented with other information collated during the preparation of the management plans. The catchment boundaries were obtained from coverages made available by Midgley et al. (1994) and

Ninham-Shand (1996). The distribution of the original vegetation types was obtained from GIS data layers prepared by Low and Rebelo (1996) at a scale of about 1:500,000. The extent of different categories of current land-use at 1:250,000 was obtained from the national land cover database using Thompson's (1996) classification. The national land cover data were used in all the analyses except for the Keurbooms catchment where the land cover data was supplemented with more detailed information (Ninham-Shand, 1996).

3.3. Calculation of water-use

Water-use was estimated using the biomass-based regression model developed by Le Maitre et al. (1996) and adapted and applied by Versfeld et al. (1998). This model estimates the reduction in streamflow (mm) in invaded areas relative to the natural vegetation based on the total above-ground biomass of the invading plants. The model was developed using data from long-term studies which compared the streamflow from natural fynbos shrubland catchments and catchments afforested with pines (Van Wyk, 1987; Scott and Van Wyk, 1992). The relationship is as follows:

$$\text{stream flow reduction (mm)}$$
$$= \text{biomass (g/m}^2) \times 0.238, \quad r^2 = 0.75, \quad n = 9$$

Each invading tree and shrub species was assigned to one of three biomass categories: tall shrub, medium tree and tall tree based on its size when mature and known or estimated water-use. The biomass relationships were as follows (Le Maitre et al., 1996).
Tall shrubs:

$$\text{biomass (g/m}^2) = 5240 \times \log_{10}(\text{age in years}) - 415$$

Medium trees:

$$\text{biomass (g/m}^2) = 9610 \times \log_{10}(\text{age in years}) - 636$$

Tall trees:

$$\text{Tall trees} \quad \text{biomass (g/m}^2)$$
$$= 20000 \times \log_{10}(\text{age in years}) - 7060$$

The above relationships require data on, or an estimate of, the age of the plants. Fynbos landscapes burn at intervals between about 10 and 20 years (Richardson et al., 1994). Using the average of 15 years and

assuming an equal area of each age, this gives a mean age of 7.5 years for landscape invaders in the fynbos areas (Sonderend and Keurbooms). Riparian invaders reach substantially greater ages than landscape invaders, as riparian areas do not burn regularly. In addition, plantation trees in riparian areas use more water than trees of the same age and species away from rivers (Scott et al., 1999). In the fynbos catchments the water-use of species which primarily, or only, invade riparian areas was doubled. In the grassland catchments—Upper Wilge and Sabie-Sand—areas the invasions are primarily riparian, with a mixed age structure. A mean age of 20 years was used for all invasions in riparian or non-fynbos areas.

As water-use estimates were based on a formula derived from plantations with dense stands of trees, we calculated the "equivalent dense" area for invasions in order to estimate streamflow reductions. This is the equivalent extent of the invasion if the canopy cover is adjusted from the actual value to 100% (Le Maitre et al., 2000). For example, if the mean canopy cover of an area of 100 ha is 25%, then the equivalent dense area is 25 ha. This adjustment of the areas assumes that the relationship between stand density and water-use is linear.

3.4. Cost of clearing

Information on the cost of clearing was obtained from managers of clearing programmes in each of the catchments. In most cases the cost data were obtained in the form of the costs of each operation (e.g. clearing, follow-up) for each of the species and subdivided into three density classes: light (0–25%), medium (25–50%) and dense (>50%) cover (Le Maitre et al., 2000). Species-specific data were preferred because the cost often differs markedly between species: for example, the one requires herbicides to prevent resprouting and the other does not sprout. In some cases, such as the Sabie-Sand catchment, some species occur consistently together as highly variable mixtures. In this case the cost data were specified for the mixture and used in this form. The cost data were expressed as the total cost for the mean percentage cover of each density class, and a linear regression was fitted using the percent canopy cover as the independent variable and cost per hectare as the dependent variable. In some cases a non-linear (exponential)

relationship gave a better fit and was used in place of the linear regression.

The data from the mapping of the invaders did not always use the same set of density classes. Therefore all the density classes were converted to the mean percent canopy cover for that class. The percentage cover from the mapped data for each species, or species mixture, was used to calculate the costs per hectare for each year's operations for that species using the regression described above.

The next step in the calculations had to take the following two facts into account (Le Maitre et al., 2000): (a) areas or sites (polygons) invaded by alien species typically have a mixture of species with each occurring at a different density; and (b) the costs per hectare for each species, as given by the managers, included overheads (e.g. transport, administration). If there was more than one species in the invaded area the overhead cost would be distributed between those species; simply adding the species costs would involve double accounting for the overheads. The solution which gave the most reasonable results was to weight each individual species cost using its equivalent dense area—a measure of its relative density. The costs were then summed and divided by the total equivalent dense area to give a weighted mean which included the both different cost for each species and its relative density. The weighted mean cost per hectare was multiplied by the total invaded area to get the total cost for that area and summed for each catchment or management unit.

3.5. Projection of future expansion and water-use

Invasions of areas by alien organisms typically show a sigmoid growth curve over time, involving an initial lag period, a period of rapid (exponential) expansion and the final period when expansion slows as the available habitat becomes fully invaded (Drake et al., 1988; Hengeveld, 1989; Le Maitre, 1998b). This curve can be approximated by the logistic growth curve in its discrete or continuous form (Le Maitre, 1998b). We used the discrete form of the logistic curve with an annual time step to estimate the spread of invaders under a scenario of no control.

Given a suitable homogenous habitat, invasions of large areas would probably proceed at essentially the same rate as smaller areas, with the rate being determined largely by factors such as dispersal curves

and population growth rates and long range colonisations (Skellam, 1951; Mack, 1985; Birks, 1989; Hengeveld, 1989; Clark, 1998). In the real world large areas tend to become invaded more slowly than smaller areas because: (a) larger areas typically contain more variation in habitat suitability or more habitats, not all of which are equally suitable for invasion; and (b) large areas have often been fragmented by human developments which create a mosiac of non-invadable and invadable land-uses. Dispersal rates are reduced by the habitat variability and the fragmentation (Dyer, 1995). The annual rate of increase of the invaded area during the exponential phase ranges from 10 to 30%, with rates being inversely proportional to the area suitable for invasion (Le Maitre, 1998b). Projections of future invasions were done using expansion rates of 10 and 15% per year.

All areas of land that were cultivated, improved grassland (pasture), plantation, urban, mines, quarries or water bodies were classified as non-invadable or transformed. The remaining land, essentially the remaining natural vegetation, was considered invadable. In the Keurbooms catchment, about 23% of area is indigenous forest, which is relatively resistant to invasions. The invaded area of forest was assumed to increase at only 1% per year for this analysis. All of the projected invasions assumed that the relative species composition and the mean density of the invaded areas would remain essentially unchanged as the invaded area increased. In the Sabie-Sand catchment, all the potentially invadable land was mapped as invaded to some extent, or was communal land which was unlikely to be invaded because the plants would be cut down to provide fuel and building materials (Nel et al., 1999). Thus there could be no projected increase in the invaded area and the future condensed area would equal the total invadable area. In this case, the estimates of future impacts were based on rates of increase of 10 and 15% per year in the density of the invasions.

The estimates of the current volume of water lost from the catchment were based on the equivalent dense (condensed) invaded area. The total volume of water lost was divided by the total condensed area to give a standard reference value in cubic metres per hectare. This value was multiplied by the projected condensed area to calculate the volume of water that could be lost in the future.

4. Results

4.1. Land-use

The Sonderend catchment has the greatest area under cultivation with 53% under annual crops and deciduous fruit orchards and the smallest area under plantations (0.3%) (Table 2). Less than 30% of the renosterveld is left, mostly in small isolated remnants. Most of the vegetation in the Keurbooms catchment is still relatively natural, only 16% has been transformed. About 10% of the fynbos and about 50% of the indigenous forest have been transformed. About 25% of the grasslands in the Upper Wilge catchment are now cultivated land; the small area of degraded land is situated mainly in the Phuthaditjhaba area. The Sabie-Sand catchment has the largest area under plantations, all situated in the headwater catchments, with cultivated and degraded lands in the middle reaches and the bushveld in the lower reaches inside the Kruger National Park. More than three quarters of the natural grasslands of the upper escarpment have been converted to plantations.

4.2. Major invading species

In the Sonderend catchment the pines are the most widespread invaders (total invaded area 92,200 ha), although only a small portion (670 ha) of the catchment is under pine plantations (Tables 3 and 4). The second most important invader is *Hakea sericea* which is almost exclusively found in the montane fynbos and has invaded about 60,900 ha. Most watercourses and rivers have been invaded to some extent. The upper river valleys have been invaded by *Acacia mearnsii*. *Eucalyptus camaldulensis*, together with *A. mearnsii* has invaded the floodplain of the Sonderend River, particularly the lower reaches, to form closed stands (canopy cover >75%) with trees up to 30 m tall. In some areas the invaded portion of the floodplain is greater than 200 m wide.

Invasions in the Keurbooms catchment are similar to those in the Sonderend. The most widespread invader is *H. sericea* which has invaded a total of 43,500 ha (33% of the catchment) or the equivalent dense area of 14,192 ha (Table 3) followed by the pines with an equivalent dense area of 7654 ha. Both hakeas and pines are largely confined to fynbos areas

Table 3

Important invasive tree and shrub species and extent of invasion in four South African catchment areas[a]

Species	Growth form	Catchment			
		Sonderend	Keurbooms	Upper Wilge	Sabie-Sand
Cluster pine (*Pinus pinaster*)	Tree	8772 (41.0)	5033 (23.1)	–	–
Monterey pine (*P. radiata*)	Tree	46 (0.3)	2621 (10.6)	–	–
Silky hakea (*Hakea sericea*)	Tree	1783 (27.4)	14192 (32.6)	–	–
Sugar Gum (*Eucalyptus cladocalyx*)	Tree	1507 (8.8)	–	–	–
Black wattle (*Acacia mearnsii*)	Tree	3662 (12.7)	2928 (36.3)	Included under *Acacia* species	948 (3.3)
Port Jackson willow (*A. saligna*)	Tree	513 (8.2)	3 (0.5)	–	–
Rooikrantz (*A. cyclops*)	Tree	88 (6.16)	162 (2.0)	–	–
Long-leaf acacia (*A. longifolia*)	Tree	627 (5.2)	–	–	–
Eucalypt species	Tree	–	52 (1.6)	2306 (0.8)	3668 (7.3)
Acacia species	Tree	–	710 (2.3)	2211 (0.6)	645 (2.2)
Pine species	Tree	–	705 (4.0)	424 (0.3)	2718 (6.4)
Poplar (*Populus canescens*)	Tree	146 (0.9)	–	292 (0.1)	256 (1.1)
Willow (*Salix babylonica*)	Tree	64 (1.4)	–	707 (0.4)	–
Bugweed (*Solanum mauritianum*)	Shrub	–	–	–	5993 (6.2)
Lantana (*Lantana camara*)	Scrambler	–	–	–	5867 (10.5)
Guava (*Psidium guajava*)	Tree	–	–	–	2659 (9.1)
Brambles (*Rubus cuneifolius*)	Scrambler	44 (0.9)	–	–	2119 (3.5)
Mauritius thorn (*Caesalpinia decapetala*)	Scrambler	–	–	–	1979 (8.0)
Prickly pear (*Opuntia stricta*)	Succulent	5 (0.8)	–	–	1746 (11.1)
Other	Various	795	335	411	3018

[a] Data are in hectares of equivalent dense infestation (see text); the total invaded area as a percentage of the catchment area is given in parentheses. *Acacia* species: mixture of *A. mearnsii*, *A. dealbata* in the Upper Wilge and *A. melanoxylon* in Sabie-Sand. Eucalypt species: mainly *E. grandis* in the Sabie-Sand. Pine species: mainly *P. patula*, *P. elliottii* except in the Keurbooms.

in the inland mountains. *A. mearnsii* is found along all the major rivers in the catchment where it has invaded the floodplain, in places more than 100 m across, and is spreading up the tributaries. *A. melanoxylon* (blackwood) is a significant invader of indigenous forests and riparian areas although its density is still low (2.5% cover).

The Upper Wilge catchment is the least invaded of the four included in this analysis (Table 4). The most important invaders are eucalypts and pines (Table 3)

Table 4

Current extent of transformed land, plantations and current and projected extent of alien plant invaded areas in four South African catchments[a]

Catchment	Area of transformed land excluding commercial plantations (ha) (% of catchment)	Area under plantations (ha) (% of catchment)	Total invaded area [equivalent area of dense invasion] (ha)		Range of time period (years) needed to reach 95% of potential invasion at expansion rates of 10 and 15% per year
			Current	Potential	
Sonderend	108615 (48.6)	746 (0.3)	97725 [17941]	114849 [22851]	11–16
Keurbooms	9608 (6.9)	6138 (4.4)	74092 [26683]	106475 [41079]	21–31
Upper Wilge	196538 (31.9)	1456 (0.2)	11771 [6347]	431118 [232462]	50–76
Sabie-Sand	207367 (32.8)	102833 (16.3)	143305 [31 619]	143305 [143305]	26–30

[a] Transformed land includes all areas where the natural vegetation has been transformed to cultivated land, urban land (including industrial), waterbodies, mines and quarries. In the Sabie-Sand transformed land includes the communal land (182,000 ha) which has generally been disturbed or degraded and includes many dense settlements. All the invadable land in the Sabie-Sand catchment was already invaded to some extent so the projections are for the time required to reach a mean density of 100% canopy cover. This is why the projected equivalent dense area is the same as the invadable area.

which have spread from woodlots, shelter belts and other amenity plantings. *Acacia* species, notably *A. mearnsii* and *A. dealbata*, are widespread along the rivers together with willow and poplar species.

Pines are the major invaders of the grasslands in the upper catchments of the Sabie-Sand Rivers (Table 3), but in the plantation areas and grasslands the major invaders are *Solanum mauritianum*, *Lantana camara* and *Rubus* species, often occurring in mixtures. The plantation margins and the unplanted riparian strips are particularly susceptible to invasion. In the lower regions of the plantations *Psidium guajava* becomes an important member of these mixtures. *Caesalpinia decapetala* is a major invader in the middle and lower reaches of the river systems. Invasions by *Eucalyptus* are largely confined to the plantation areas at present but they could also spread downstream. In the lower parts of the catchment, where the rainfall is less than about 800 mm, invasions are largely confined to the riverbanks and watercourses. The exception to the riparian rule is *Opuntia stricta*. This species occurs in the Kruger National Park where it has invaded 69,800 ha of the bushveld savanna and woodland and has a mean canopy cover of 2.5%.

4.3. Current and projected invasions

Close to half the area of the Sonderend catchment has been transformed and most of the remaining natural vegetation has been invaded (Table 4). About three quarters of the invaded area is in fynbos and the rest in renosterveld. The mean percentage cover in the invaded areas is 18% with riparian invasions being dense to closed compared with sparse invasion on the mountain slopes. The invaded area can potentially increase by at least 18% and this could happen in a period of 11–16 years depending on the annual rate of expansion of the invaded areas.

In contrast, close to 90% of the Keurbooms catchment is still under natural vegetation although about 65% of the fynbos has been invaded to some degree (Table 4). The indigenous forest is the least affected by invasions which cover about 25% and have a mean canopy cover of 18%. Most of the invaded area is concentrated in the medium (25–50% cover) to dense (>50% cover) riverine invasions. The mean canopy cover in the invaded areas is high at 37% and approximately 9500 ha has dense or closed invasions.

The total invaded area could increase by about 44% during the next 20–30 years with virtually all of the increase being in the fynbos catchments which have the highest water yields.

About 30% of the natural grasslands of the Upper Wilge catchment has been converted to cultivated lands, mostly for maize production (Table 4). The area under plantations is very limited and unlikely to increase because the cold climate does not favour commercial forestry. Less than 2% of the catchment has been invaded at present but very large areas are still natural grassland and potentially could be invaded over the next 50–76 years. The projected area and the time period for the invasions are highly dependent on the extent to which grassland management practices (such as fire exclusion and overgrazing) prevent or limit invasions of non-riparian areas. Riparian areas are naturally prone to invasions and could be invaded far faster than the landscapes. Riparian invasions currently cover 4–15% of the river length (mean 7%) but, given an increase in extent of 20% per year, which is likely, the entire river system would be invaded in about 35 years.

More than half of the Sabie-Sand catchment has either been transformed or put under plantations (Table 4). About 23% of the catchment has already been invaded but, as this represents the full extent of habitat suitable for invasion, only the density of the invasions is expected to increase. Without control operations it is likely that all the currently invaded areas will increase in density from 22 to 100% canopy cover in the next 20–30 years. This estimate may well be conservative given the known rapid growth rates and effective dispersal of aggressive invaders such as *L. camara* and *C. decapetala*.

4.4. Current and projected impacts on water resources and costs of clearing

Invading alien plants in the Sonderend catchment are estimated to have reduced river flows by 7% and have the potential, if uncontrolled, to reduce the flow by more than 40% (Table 5). Dense stands of invaders reduce flows by the equivalent of 1856 m^3/ha per year, essentially the same as the plantations at 1876 m^3 per year. Pines account for more than half the volume of water, *A. mearnsii* a further 20%, eucalypts 12% and *Hakea* species 6%. At the current levels of infestation

Table 5
Estimated reduction in water yields and costs of clearing at current and expected future invasions of alien plants, mainly woody shrubs and trees, in four South African catchment areas[a]

Catchment area	Water-use (millions of m^3 and % of total runoff)			Cost to clear (US$ millions)	
	Commercial plantations	Invasive trees (current)	Invasive trees (potential)	At current levels of infestation	At future levels of infestation
Sonderend	1.4 (0.3)	33.3 (7.2)	190.8 (41.5)	13.2	86.5
Keurbooms	11.5 (5.7)	47.4 (22.1)	204.2 (95.5)	9.9	20.5
Upper Wilge	0.5 (0.1)	26.9 (6.0)	1127.4 (251)	4.1	278.0
Sabie-Sand	138.2 (18.9)	69.3 (9.4)	162.9 (22.3)	6.6	11.1

[a] The flow reductions due to plantations are calculated from data in Le Maitre et al. (1997). In the Upper Wilge catchment the flow reductions at maximum potential invasion exceed 100%. If reductions are restricted to 100% of the flow, the corresponding invaded area would be 184,136 ha which would be reached after 35 years; the costs of clearing would then be US$ 102.6 million.

the costs of clearing the invaded area would be US$ 13 million or US$ 738/ha for the equivalent dense stands. Long-term maintenance after the initial programme is completed would cost about US$ 0.4 million per year. The cost of the control programme would increase more than 6.5-fold over the next 11–16 years if no action was taken. The current plan for the catchment is that the clearing programme will spend about US$ 8.4 million over the next 5 years on clearing and initial follow-up on most of the invaded area, The highest priority will be given to clearing the invaded riparian areas, starting with the most upstream invaders.

Invading alien plants have reduced surface runoff in the Keurbooms catchment by about 20%, four times as much as the plantations. Invading pines account for 46% of the total volume of water, *Hakea* species 32% and *Acacia* species, notably *A. mearnsii*, for 21%. The flow reductions per unit area are similar to those for the Sonderend at about 1874 m^3 per year for plantations and 1776 m^3 per year for invading plants. In the absence of clearing, the estimated flow reduction would increase about five-fold over the next 20–30 years, resulting in the loss of virtually all the surface water in the Keurbooms river system. The total cost of controlling the invaders is currently about US$ 9.9 million in total, or US$ 372 per equivalent dense ha, and these total costs can potentially double if no action is taken. The costs per unit area are much lower than those for the Sonderend mainly because *Hakea* was excluded from the clearing because effective biocontrol agents are already present. About 61% of the total budget would be spent on clearing pines and 36% on clearing *Acacia* species.

The impact of plantations on surface runoff in the Upper Wilge catchment is negligible but invaders are estimated to have reduced runoff by 27% or 4219 m^3 per year (Table 5). Eucalypts account for 39% of the water by volume, *Acacia* species 37%, *Salix* species and pines each 7% and *Populus* species 4%. If the invaders were allowed to spread unchecked into the grasslands they could use all the surface runoff in the catchment in about 35 years time. As pointed out above, the rivers could be invaded even more rapidly. The total cost of the control programme, currently US$ 4.2 million (US$ 645 per condensed ha), would increase more than 25-fold over those 35 years. Control of *Acacia* species comprises about 40% of the total cost, eucalypts 26%, *Salix* species 11%, pines 7% and poplars 6%.

In the Sabie-Sand catchment the current total flow reduction due to invasive aliens (estimated at 69 million m^3 per year) is about half that of the plantations but could exceed that of plantations in the next 25–30 years (Table 5). On a unit area basis the invaders are estimated reduce the flow by about 2192 m^3 per year compared with plantations at 1344 m^3 per year. Eucalypts account for 24% of the total flow reduction, followed by pines (18%), *Solanum* (14%), *Lantana* (13%) and *Acacia* species (10%). The control costs are currently about US$ 6.6 million (US$ 210 per condensed ha) and would increase 1.7 times if no control programmes were implemented. The costs increase relatively little despite the projected increase in density largely because the costs for dense stands were little higher than for medium density stands. Control operations for invasions comprising mixtures

of *Lantana, Solanum, Caesalpinia* and *Rubus* account for about 76% of the total costs for the catchment, with 9% for pines, 8% for eucalypts and the remainder for acacias. Clearly the benefits in terms of water yield are higher per unit area for clearing eucalypts and pines than for other species.

5. Discussion

5.1. Invasion patterns

The invaded state of the four catchments reported on here is typical of those in the higher rainfall areas of South Africa. These catchments have a relatively high agricultural potential and the natural vegetation on the arable areas has been transformed or modified by use for extensive grazing. The extensive invasions in the Sonderend and Keurbooms catchments are typical of those of mountain catchments in the Western Cape (Le Maitre et al., 2000). Fynbos is known to be peculiarly susceptible to invasions by woody shrubs and trees, notably the pines and *Hakea* species (Macdonald, 1984; Richardson and Cowling, 1992; Richardson et al., 1992). A wide range of invading species like those found in the Sabie-Sand catchment is typical of the high rainfall, warm temperate and sub-tropical areas of South Africa (Macdonald, 1983; Henderson and Wells, 1986; Henderson, 1989).

Riparian zones appear to be particularly prone to invasion, probably because they are often disturbed by floods, include extensive ecotones which are the preferred habitat of many invaders, and water is freely available for growth and seed dispersal (Henderson and Musil, 1984; Thebaud and Debussche, 1991; Pysek and Prach, 1993; Le Maitre, 1998b). Major invaders of the riparian zones in all these catchments are *A. mearnsii* or *A. dealbata*. The extensive invasions by *Eucalyptus* species in the lower Sonderend River are unusual as this genus is rarely invasive (Richardson, 1998). Similar invasions are found in the lower Berg River in the Western Cape (Versfeld et al., 1998) but the factors facilitating these invasions are unknown.

The low degree of invasion of catchments such as the Upper Wilge should not be a cause for complacency. The potential for spread is significant and the catchment is still in the early stage of invasion when

expansion rates can be expected to be low (Le Maitre, 1998b). Modelling of the expansion suggests the exponential phase of the expansion will be reached in about 15 years time (Le Maitre unpublished data), and probably sooner in the rivers. The annual investment needed even to maintain the status quo at that stage will be much greater than it would be now. The invasions in the Sonderend and Keurbooms catchments are in the exponential phase although effective biocontrol of *H. sericea* in the Keurbooms catchment could limit expansion rates in that catchment (Gelderblom and Rowlinson, 1999).

5.2. Flow reductions

The model used to estimate the impacts of invading plants on streamflow is a very simple one and there is concern about the reliability of its estimates (Le Maitre et al., 2000). The predicted reductions, mean 1900 m³/ha per year, were more than twice those estimated for plantation areas in South Africa of 930 m³/ha per year (Le Maitre et al., 1997; Scott et al., 1998a). These differences could be explained by the lower mean age of plantations and because the afforested areas generally exclude riparian zones (Le Maitre et al., 2000). Although the biomass model is based on data that gave a reasonable fit (Le Maitre et al., 1996), it is derived from winter rainfall catchments (Le Maitre et al., 2000). Nevertheless, its predictions for streamflow reductions are in line with those reported for summer rainfall catchments afforested with pines and eucalypts in South Africa (Bosch and von Gadow, 1990; Dyer, 1995; Scott et al., 1999) and elsewhere (Bosch and Hewlett, 1982). A number of short-term studies have also shown that clearing of invaders results in enhanced streamflow, supporting the basic principle that invading trees use more water than the indigenous vegetation (Dye and Poulter, 1995; Olbrich and Poulter, 1997; Prinsloo and Scott, 1999).

Two independent studies have been done in the KwaZulu-Natal Province (Umgeni Water, 1998a,b). The impacts on river flows were estimated using a detailed soil moisture budgeting model (Schulze et al., 1995). Current reductions were estimated at 11 and 19 million m³ per year, respectively, and would increase to 21 and 30 million m³ per year, respectively, in 20 years time if no control operations were implemented.

On a unit area basis the initial reductions are equivalent to 5602 and 4354 m³/ha per year, respectively, greater than those for any of the catchments in our analysis. These findings provide further support for our estimates.

5.3. Reliability of the estimates

The impacts described are substantial and it is important to give an indication of their reliability. This is not a simple issue as there are several sources of uncertainty (see also Le Maitre et al., 2000). The regression equations used to estimate biomass from age and flow reduction from biomass all have 95% confidence limits of ±20–30%. The assignment of species to biomass categories, based on expert opinion in the absence of water-use data, also introduces an unknown degree of error in the water-use estimates. The mapping of the invaded areas, information on the species composition and density, and the estimated age of the invaders are potentially further sources of error; their magnitude and whether any of them has been either under- or over-estimated is simply not known at present. These estimates are the best possible under the circumstances and, given that the impacts will increase because the invasions will become worse, should support the argument that pre-emptive action is wiser than waiting for more accurate data.

5.4. Costs

The costs of these control programmes appear to be prohibitive but this depends on how the costs are interpreted. If, for example, a control programme would require 15 years to complete and would save 50% of the total volume of water that would have been lost through invading plants during that time, the costs would be as follows: Sonderend 7¢ per m³, Keurbooms 3¢ per m³, Upper Wilge 2¢ per m³ and Sabie-Sand 1¢ per m³. As the additional water would be available in perpetuity, the long-term benefits would be substantially greater. In the Sonderend catchment, the current water allocation to various user groups is about 266 million m³ per year and the charges for water range from 0.01¢–4.44¢ per m³ (Gelderblom et al., 1998). The cost of the control programme could be financed with an additional levy of about 1¢ per m³ and the income from a levy of 0.15¢ per m³ would cover long-term maintenance. Alternatively the income from the water released by clearing, at the current tariffs, would more than cover the costs of maintenance. The opportunity costs of the water currently used by alien invaders, if charged at the agricultural sector tariff of 2¢ per m³, would amount to US$ 0.55 million per year. A similar analysis for the Keurbooms River catchment gives an additional charge of 1¢ per m³ for the control programme and 0.1¢ per m³ for long-term maintenance (Gelderblom and Rowlinson, 1999). In this case the opportunity costs of the water used by alien plants, at 2¢ per m³, are US$ 1.09 million per year.

Our analyses have focussed on the direct costs of control and the opportunity cost of the additional water transpired by invading plants at the tariffs charged for water resources. These are only a small proportion of the total economic benefits that can be obtained from water (e.g. income from crops, industry and the meeting of basic human needs and health requirements) (Gleick, 1998; Schreiner, 1999). A comparison of the benefits accruing from water used for irrigated crops and commercial tree production in the Crocodile River catchment, adjacent to the Sabie-Sand catchment, found that income from off-farm sales ranged from US$ 0.10–US$ 2.92 per m³ with a mean of US$ 0.77 per m³ (Olbrich and Hassan, 1999). Based on these values, the opportunity cost of the flow reductions due to alien plant invasions in the Sabie-Sand River system is about US$ 53 million per year.

The introduction of biocontrol agents to reduce seed production by the major invaders which are still used commercially (e.g. pines, *A. mearnsii*) will reduce conflicts of interest and also could reduce control costs significantly in the future (van Wilgen et al., 2000). Ongoing maintenance to eliminate new invasions will also reduce expenditure in the long-term.

5.5. Other benefits

Clearing infestations of invading alien plants will have many other benefits, besides enhancing water supplies. These include preventing the loss of biodiversity, reducing fire hazard, stabilizing catchment areas and preventing erosion, and deriving social benefits from job creation in labour-intensive clearing programmes.

Invasive organisms are considered to be one of the most important threats to biodiversity worldwide (Vitousek et al., 1997; Bright, 1998) and the situation in South Africa is no different. The Cape fynbos flora is renowned for its biodiversity with about 8754 plant species, 68.2% of which are endemic. A large number or rare and endangered plants species are known to occur in the fynbos in the Sonderend and Keurbooms catchments and the indigenous forest in the latter provides a habitat for endemic bird and mammal species (Gelderblom et al., 1999; Gelderblom and Rowlinson, 1999). The Maluti Mountains in the Upper Wilge catchment are part of the Eastern Mountain centre of plant biodiversity which includes at least 30 endemic plant species (Davis and Heywood, 1994; Cowling and Hilton-Taylor, 1994). The Drakensberg escarpment in the Sabie-Sand catchment is part of the Wolkberg centre of biodiversity (Cowling and Hilton-Taylor, 1994), with about 163 red data book plant species (Matthews et al., 1993; Nel et al., 1999) as well as red data bird species (Allen et al., 1997), reptiles, amphibians and mammals. The Sabie-Sand River system also supports a rich aquatic fauna, including endemic fishes (Russel and Rodgers, 1989; O'Keeffe et al., 1996; Weeks et al., 1996).

Invasions by alien trees and shrubs increase the fuel loads and thus the intensity and severity of the resulting fires (van Wilgen and Richardson, 1985). The increased intensity of fires in invaded areas makes them more difficult to control (Chandler et al., 1983). The increased severity of the fires also results in greater damage to soils through heating and combustion of the organic matter which, in turn, can result in water repellency and severe soil erosion (DeBano and Rice, 1973; Giovannini and Lucchesi, 1983; Scott and Van Wyk, 1990, 1992; Scott, 1993; Scott et al., 1998b). The risk of severe flooding is also increased by the increased surface runoff and higher peak flood water volumes (Scott et al., 1991). The effects of the changes in soil wettability and water infiltration can persist for many years (Scott and Van Wyk, 1992). The risks of damage to property and the loss of human lives or severe injuries are also greatly increased. The severe fires also kill seeds in the soil and sprouting plant species (Richardson and van Wilgen, 1986; Holmes et al., 2000).

One of the major motivations for the alien plant control programme is its success in achieving its social objectives through job creation (van Wilgen et al., 1998; Working for Water, 1999). This is why the main source of income for the programme is government and donor poverty-relief funds. The programme has been used to provide employment to thousands of previously unemployed South Africans. It has focussed on issues such as gender and racial equity, opportunities for the youth, the disabled and single parents, training and empowerment, and environmental awareness. This focus has meant that the benefits of employment are carried beyond mere job creation towards the reforming of society. Such an approach can have benefits that are difficult to quantify in monetary terms.

The results of these studies support the belief that clearing programmes are a wise and cost-effective method of protecting vital water resources in South Africa. It should be noted, however, that alien tree species have brought many benefits beside those from commercial plantations. Alien trees play important roles in providing fuel and other products to rural communities, in land restoration, and in the developing agro-forestry field. The key is to identify strategies that will allow for minimisation of the costs of controlling invading plants while maximising the benefits. Key elements in this approach will include the establishment of early warning systems and other precautionary measures to either exclude highly invasive species or to eliminate unwanted invasions at an early stage.

Acknowledgements

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