Technical note

The impact of invading alien plants on surface water resources in South Africa: A preliminary assessment

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Abstract

The impacts of the widespread invasions by alien plants in South Africa are increasingly recognised. Most of the past concern has been about the impacts on conservation areas, other areas of natural vegetation, and on agricultural productivity. The potential impact of invading alien woody plants on water resources was known to be serious but there has been no information available to evaluate the significance of these water losses across the whole country. This paper reports on the results of a preliminary survey aimed at obtaining an overview of the extent, impacts and implications of alien plant invasions at a national and regional level for South Africa and Lesotho. Data on the extent and location of the invaded areas were obtained from a variety of sources including detailed field mapping, mainly at a 1:250 000 scale with some at 1:50 000 and 1:10 000, and generalised information on species and densities. The density class of each species in each polygon was mapped and used to derive the condensed areas (the equivalent area with a canopy cover of 100%). Each of the invading species was classified as a tall shrub, medium tree or tall tree - based on growth form and likely water use - and its biomass was estimated from a function based on vegetation age. The incremental water use (i.e. the additional water use compared with the natural vegetation) was calculated using the following equation: Water use (mm) = 0.0238 x biomass (g/m^2) which was derived from catchment studies.

Alien plants, mainly trees and woody shrubs, have invaded an estimated 10.1 million ha of South Africa and Lesotho, an area larger than the province of KwaZulu-Natal. The equivalent condensed area is 1.7 million ha which is greater than the area of Gauteng Province. The Western Cape is the most heavily invaded at about a third of the total area, followed by Mpumalanga, KwaZulu-Natal and Northern Province. The catchments of the Berg and Breede Rivers are the most heavily invaded followed by the George-Tsitsikamma region, Port Elizabeth coastal region and the Drakensberg escarpment in Mpumalanga. The total **incremental** water use of invading alien plants is estimated at 3 300 million m^3; of water per year, equivalent to about 75% of the virgin MAR of the Vaal River system. About a third of the estimated total water use, by volume, is accounted for by alien invaders in the Western Cape, followed by KwaZulu-Natal (17%), the Eastern Cape (17%) and Mpumalanga (14%). The greatest reduction, as a percentage of MAR, was found in the arid Northern Cape (17%), followed by the Western Cape (15%) and Gauteng (10%). For primary catchments, the greatest percentage reductions were in the Namaqualand coast (catchment F, 91%), followed by the Eastern Cape Coast (P, 42%) and the south-western Cape (G, 31%). The extent and density of the invasions and thus the impact on water resources could increase significantly in the next 5 to 10 years, resulting in the loss of much, or possibly even all, of the available water in certain catchment areas.

Alien plant control is expensive but it has been shown that control programmes are cost-effective compared with alternative water supply schemes. This preliminary assessment needs to be interpreted with caution because the results are based on a data set that contains some important uncertainties. The water-use estimates also involve some critical assumptions. Nevertheless, the scale of the invasions, the magnitudes of the impacts, and the rapid expansion we are observing are such that a national control programme is essential if the country's water resources are to be protected.

Introduction

There is increasing concern worldwide about the impacts of invading alien (exotic) plants (Drake et al., 1989; OTA, 1993; IUCN, 1997; Vitousek at al., 1996; 1997). Historically, the concerns were mainly about the impacts on human society, for example through lost agricultural production, but there is growing recognition of the impacts on biodiversity and natural systems (Clout, 1995; IUCN, 1997). Many alien plant species are categorised as serious and dangerous invaders in the USA (OTA, 1993) and losses of agricultural production alone are estimated at US$7 bn./yr (Babbitt, 1998). New Zealand has 240 alien species recognised as invasive weeds and more than 580 000 ha of nature reserve land is threatened by invasion in the next 10 to 15 years (Owen, 1998). Various South African scientists have recognised the potential impacts of alien invaders on indigenous vegetation (Stirton, 1978; MacDonald et al., 1986) and the ecological services that could be lost (Van Wilgen et al., 1996, Higgins et al., 1997). The potential impacts on water resources were also recognised half a century ago by Wicht (1945) and the reductions in streamflow were expected to be similar to those under pine plantations (about 350 mm per year) by Kruger (1977) and Van Wilgen et al. (1992). Modelling of the potential impacts of invading species on streamflow from fynbos catchments showed that the impacts could have severe implications for Cape Town's water supplies (Le Maitre et al., 1996). The findings of these studies were a key factor in the initiation of the *Working for Water Programme* in October 1996. This is a national programme for controlling woody invading plants which is managed by the Department of Water Affairs and Forestry (DWAF, 1997).

In January 1996 the Water Research Commission appointed the CSIR to carry out a research project on behalf of the *Working for Water Programme*. The objectives of the project were to determine the extent of invasions by alien plants, their impact on surface water resources, the costs of controlling the invaders and to

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devise a national strategy for a control programme (Versfeld et al., 1998). This paper reviews information in that report, focusing on the impact of alien invaders on water supplies.

In this paper we distinguish between riparian invasions - which are confined to stream and river valleys, banks and beds, and wetland edges - and landscape invasions which are of dryland areas. Another set of terms for this same distinction would be between bottomland (riparian) and upland (landscape) invaders. This distinction is related largely to the availability of water, the different suites of invaders which invade these habitats, and the amount of water they can potentially use.

Methods

Approach to modelling water use

The approach that Versfeld et al. (1998) used to estimate the water use of invasive aliens differs from those used in other studies (e.g. Midgley et al., 1994; Scott et al., 1998), so the rationale behind it is described in some detail below.

Selection of an appropriate model

The model used to calculate water use had to find a balance between simplicity and reliability as well as being appropriate for the regional scale of this study. Reliable data on tree water use were available at an appropriate (landscape) scale from catchment experiments which compared the streamflow under natural vegetation and that under commercial plantations (Dye, 1996; Scott et al., 1998). The issue was: how could these reductions for commercial plantations be extrapolated to the wide variety of invading plant species and over a wide range of rainfall? Reviews of catchment experiments worldwide have shown that streamflow changes are directly related to changes in the extent of forest or plantation cover, whether the catchment was afforested or deforested (Bosch and Hewlett, 1982; Sahin and Hall, 1996). Numerous studies have shown that forest water use can be related to leaf area (e.g. Jarvis and McNaughton, 1986) and leaf area is related to biomass, growth and productivity (Waring, 1983). The idea that water use could be related to biomass was used by Bosch et al. (1986) to develop a model which related increases in water yield after fires in fynbos to the post-fire decrease in biomass. This idea was taken further by Le Maitre et al. (1996) and Van Wilgen et al. (1997) who related streamflow reduction to fynbos and plantation biomass. The biomass model was based on data from catchment experiments in the winter rainfall regions of South Africa. Data on the reductions in streamflow are available from similar catchment experiments in the summer rainfall regions (e.g. Van Lill et al., 1980; Scott et al., 1998) but reliable data on the biomass of the plantations were not available for these studies. The model predicts the **incremental** water use, i.e. the additional water used by the plantation trees compared with the indigenous vegetation it has replaced, and not the **total** water use.

Limited water availability

The model does not allow for the impact of drought years and for the possibility that reductions in dry season (low) flows may be proportionately greater than for total annual flows (Scott and Smith, 1997). The estimated streamflow reduction also does not allow for the effects of limited water availability. In most of South Africa, invasions by alien woody plants are largely, or almost entirely, confined to the riparian strips (river banks and valley bottoms) (Versfeld et al., 1998). The main exception to this generalisation is in the Cape mountains and along the eastern escarpment, for example the Drakensberg. Many of the streams and rivers in these areas are perennial, so the riparian plants will have free access to water. The rainfall is also generally sufficient to ensure that landscape invaders will not experience much moisture stress. There are two special cases which do not conform to this generalisation, both situated in areas where surface runoff is often highly seasonal or ephemeral: invasions by *Prosopis* species in the arid interior and by *Acacia cyclops* and *A. saligna* on the coastal lowlands of the West Coast and parts of the Agulhas plain. In these areas the plants probably are using shallow groundwater and thus will not have a direct impact on the surface runoff. The procedure used to adjust water-use estimates from the biomass model for limited water availability is described below.

TABLE 1
DENSITY CLASSES FOR FOUR VEGETATION TYPES AND THE SCALING FACTOR FOR THE INVADED AREA AS A FRACTION OF A CLOSED CANOPY

Density class	Canopy cover (%)	Scaling factor
Rare	<<0.1	0.0001
Occasional	< 5	0.0250
Scattered	5 - 25	0.1500
Moderate	25 - 75	0.5000
Dense	> 75	0.8750

TABLE 2
ABOVE-GROUND BIOMASS (B) AND GROWTH CURVES (LE MAITRE ET AL., 1996) FOR THREE CATEGORIES OF VEGETATION BASED ON POST-FIRE AGE (a = AGE IN YEARS)

Equation number	Vegetation structure	Biomass (g/m^2)
1	Tall alien shrubs	$b=5\ 240\ \log_{10}(a) - 415$
2	Medium alien trees	$b=9\ 610\ \log_{10}(a) - 636$
3	Tall alien trees	$b=20\ 000\ \log_{10}(a) - 7060$

Details of the water-use model and its application

The model converts estimates of biomass into estimates of streamflow reduction in millimetre rainfall equivalents using the following equation - in which streamflow reduction is a function of biomass (Le Maitre et al., 1996; Van Wilgen et al., 1997):

$$\textit{Streamflow reduction (mm)} = 0.0238 \times \textit{biomass} \ (g/m^2) \quad (r5 = 0.75, n = 9) \qquad (1)$$

As this equation was based on data from mature plantations with a closed canopy, the canopy cover in areas with less than 100% had to be adjusted to equate to a canopy cover of 100%. This was done by reducing the size of the invaded area to its equivalent had the canopy cover been 100%. This we termed the ‘condensed’ area. For example, an area of 100 ha with 50% cover is equivalent mathematically to a condensed area of 50 ha with 100% cover (see Table 1).

TABLE 3
ALIEN SPECIES AND ASSOCIATED BIOMASS EQUATIONS USED IN CALCULATING THE IMPACT OF INVADERS ON WATER RESOURCES. BIOMASS EQUATIONS ARE BASED ON SPECIES GROWTH FORM (SEE TABLE 2). DECIDUOUS SPECIES ARE INDICATED WITH #

Invading alien species	Biomass equation no.	Invading alien species	Biomass equation no.
Acacia baileyana	2	*Leptospermum laevigatum*	1
Acacia cyclops	2	*Melia azedarach* #	2
Acacia decurrens	2	*Morus alba* #	2
Acacia elata	3	*Nerium oleander*	2
Acacia longifolia	2	*Opuntia* spp.	1
Acacia melanoxylon	3	*Pinus* spp.	3
Acacia pycnantha	2	*Pittosporum undulatum*	1
Acacia saligna	2	*Populus* spp. #	3
Acacia mixed spp.	3	*Prosopis* spp.	2
Alnus viridis	3	*Psidium guajava*	1
Arundo donax	2	*Pyracantha* spp.	1
Caesalpinia decapetala	1	*Quercus robur* #	2
Chromolaena odorata	1	*Robinia pseudoacacia* #	2
Cupressus glabra	2	*Rubus* spp.	1
Eucalyptus spp.	3	*Salix* spp. #	2
Ficus spp.	3	*Sesbania punicea*	2
Gleditsia triacanthos #	2	*Solanum mauritianum*	1
Hakea spp.	1	*Tamarix* spp.	2
Jacaranda mimosifolia #	2	Uncertain	3
Lantana camara	1		

Estimating the biomass

The biomass of plants is related to their age and typically increases in a sigmoidal fashion, but Le Maitre et al. (1996) simplified this to an asymptotic curve. They also developed growth curves which related biomass to plant age for each of the three biomass classes: tall shrub, medium tree and tall tree (Table 2). All the important invader species identified in this study were assigned to one of the three different biomass classes based on their growth form and likely water use relative to pines and eucalypts (Table 3). The species not considered to be significant water users or which are minor invaders were excluded from the water-use estimates

Estimating the age of invaders

The mean post-fire vegetation age differs between landscape and riparian areas because of the frequency with which the areas are disturbed, primarily by fire. In the winter rainfall region, fires occur during the dry summers, either as a result of veld management or as wild fires, every 8 to 20 years (Van Wilgen et al., 1992). If the typical period between successive fires in any one place is once in every 15 years, and fires are evenly distributed, the mean vegetation age of a large, fynbos catchment will be about 7.5 years. This age was used for all biomass model estimates in the Western Cape Province. Riparian vegetation burns more rarely so that the plants frequently attain greater ages (30 to 40 or more years) as well as growing larger and more rapidly. To compensate for this the water use of the tall acacia species which principally invade riparian zones (e.g. *Acacia mearnsii*, *Acacia dealbata*) was doubled.

No information on, or estimates of, the mean age of invading alien vegetation could be found for the summer rainfall regions. Veld fires in grassland and savanna areas, although normally occurring with a periodicity of 1 to 4 years, often do not burn through invaded areas such as riparian zones, allowing large trees to grow there. Trees invading the grassland and savannah typical of landscapes in this region are also able to survive fires by sprouting or through the protection of thick bark. Information obtained during mapping, and general observations have indicated that most invasions occur in riparian habitats and that the trees are typically mature. Therefore a mean age of 20 years has been used for invading vegetation in the summer rainfall region.

Adjusting the estimates for limited water availability

The biomass model is based on data from catchment experiments in areas where moisture supplies are seldom limiting or, if they are, the limitations apply only for a small portion of the year and are unlikely to have a significant impact on tree water use. The most straightforward method of allowing for limited water availability was to adjust the model's estimates using a simple index of availability proposed by Görgens (1998). The index was calculated as the proportion of the months with zero flow in the synthesised monthly flow records for each quaternary catchment. The synthesised flow records were obtained from data sets provided by the WR90 study (Midgley et al., 1994). The estimated incremental water use by each species for each quaternary catchment was then reduced by the proportion of the time in which there was zero flow. These adjusted figures are used throughout this analysis unless otherwise specified.

Spatial and surface runoff data

The names and boundaries of the quaternary catchments in South Africa, including the coastline, were obtained from the data sets used for the project 'Surface Water Resources of South Africa 1990' also known as the WR90 study (Midgley et al., 1994). Provincial and national boundaries were obtained from a central spatial database maintained by the CSIR. Data on the virgin mean annual runoff for quaternary catchments were obtained from the CD-ROM which contains summary data from the WR90 study.

Lesotho was included in this study because it contains the headwaters of the Orange River, but Swaziland has been excluded. The Umzimkulu district of the Eastern Cape Province has been included within KwaZulu-Natal for practical reasons.

Mapping of alien invaders

The short duration of the project precluded detailed mapping and required an approach which combined the knowledge of experts and included existing data wherever possible (Versfeld et al., 1998). The aim was to collect, collate and analyse the spatial data using a GIS (*Arc/Info*). The GIS would also allow the spatial data to be edited and updated as more detailed data for different areas became available. The heterogenous nature of the data introduced a variety of difficulties in reconciling different scales, accuracies, resolutions and attribute data recording specifications in both existing data sets and newly mapped data. A detailed description of the mapping methodology and the different data sets is given in Versfeld et al. (1998). Mapped data were digitised on a *Calcomp* 9500 digitizer using standard tolerances and projections and edited or imported using *Arc/Info* GIS software on a Sun work station.

Expert knowledge

The primary method used in mapping alien invaders was to capture the knowledge of landowners and land managers familiar with the areas under their jurisdiction. This technique assumed that these people were well acquainted with the situation and would be able to map invaded areas with a reasonable degree of accuracy. As far as possible the mapping was done in workshop format, which allowed for peer review and a degree of consensus.

The workshops were convened by province, region or district depending on the participants. The workshop groups included members of local conservation agencies, officials from the Departments of Agriculture and of Water Affairs and Forestry, landowners, research organisations, and any other identified knowledgeable individuals. A list of the more than 140 persons who participated in these workshops, or who were otherwise approached or consulted, is given in Versfeld et al. (1998).

The mapping was done using the standard 1:250 000 scale topographic map series as printed by the Directorate of Mapping and Surveys. These maps were covered with a transparent acetate overlay and fine permanent pens in bright colours were used to record the spatial data. The non-spatial (attribute) data were recorded using the specifications and guidelines given by Le Maitre and Versfeld (1994). This approach was specifically designed to facilitate the mapping of extensive areas to a uniform standard. In essence, the invaded areas were mapped as areas (polygons) or as line segments (rivers, roads or railway lines). Where line segments were mapped the width of the invaded strip was also indicated and used to buffer the line to obtain a polygon. Small areas (typically < 5 ha) which were mapped as points also were buffered to obtain the specified area. Each polygon or line segment was given a unique label by the person doing the mapping. The density class of each species in that unit was recorded on a data form together with the label. Mixed stands, as far as possible, were described in terms of the density of the different component species. The density classes given in Table 1 were used except for some areas where the density class **rare** was omitted.

Converting generalised data

There were also large regions of South Africa where surprisingly little "expert knowledge" could be extracted. These areas included much of KwaZulu-Natal, the Northern Province and large areas of Mpumalanga. Although some areas were mapped to a reasonable level of detail, for others the best data that could be obtained was in the form of generalisations: "all the rivers on the highveld have....." or "all rivers in the subtropical coastal belt of KwaZulu-Natal have...". The biogeographic boundaries indicated by the experts were used to define polygons with a homogenous invader species composition. Data on the river systems were taken from a 1:500 000 river data layer (coverage), clipped using these polygons, and then buffered to a width of 30 m either side, unless otherwise specified. The resulting riparian strips (polygons) then were coded with the species composition and densities indicated by the experts.

Existing data sets

A number of existing data sets were included in the database. The most important of these were as follows:

- Western Cape Nature Conservation: 1:50 000 mapping of the State Land and Proclaimed Mountain Catchment areas, from the Cederberg to the Outeniqua Mountains; mapped mainly by Dr C Marais according to the specifications given by Le Maitre and Versfeld (1994); data captured on a GIS by Ninham Shand.
- Eastern Cape Nature Conservation: maps based on aerial photography for the Kouga/Baviaanskloof and Tsitsikamma regions which used generalised mixtures (e.g. *Acacia* spp.); data captured on a GIS by Melissa Moffet; species mixtures converted by the CSIR.
- KwaZulu-Natal (Department of Agriculture): 1:50 000 map data compiled by Department of Agriculture extension officers for the former Natal (areas of KwaZulu were not mapped) for less than half the 1:50 000 maps of the province. This data set, which was captured by the CSIR, included both detailed mapping and generalised polygons and a variety of density classifications.
- Umgeni Water: high-resolution, aerial-videography based maps prepared and captured on a GIS by Murray, Biesenbach and Badenhorst for quaternary catchments above Midmar Dam and selected catchments in the Llovu, Mvoti and upper Tugela River systems. Only a 30 m wide zone either side of the rivers was mapped except in the upper Tugela where non-riparian invasions of *Acacia mearnsii* were included; the data were recorded as generalised species mixtures and information on species frequencies in the different density classes (Umgeni Water, 1997) was used to determine the percentage cover by species.
- Rand Water: mapping of the Vaal River subcatchments above the Vaal Barrage on 1:250 000 map overlays; data on invaded areas compiled from aerial photographs and fieldwork by staff from the CSIR (see Versfeld et al., 1997 for details).

The final database also included the map data captured by the CSIR at a scale of 1:50 000 for management plans - for the *Working for Water Programme* - of the Riviersonderend and Sabie-Sand catchments.

Results

Distribution and extent

National overview

About 10 million ha (8.28%) of South Africa and Lesotho have been invaded to some degree by a wide range of alien species (Table 4). If the invaded area is 'condensed' to adjust the cover to 100%, then the equivalent of about 1.7 million ha (1.39%) has been fully invaded. This is more than the extent of commercial forestry at 1.4 million ha in 1994/95, and larger than the area of Gauteng Province. The degree of invasion varies very markedly between provinces but the comparative figures must be treated with caution. For example, KwaZulu-Natal appears lightly invaded compared with Mpumalanga or Northern Province. This is a result of the relatively poor mapping of this province (see **Converting generalised data** above). This caveat also applies to the Eastern Cape Province where areas of the interior and the former Ciskei and Transkei have not been thoroughly mapped. The proportion of these provinces that actually has been invaded is probably much closer to those recorded for the provinces with similar climates, especially rainfall, such as Mpumalanga and the Western Cape.

The differences in the extent of invasion between the primary catchments are large (Table 5). The most heavily invaded are the catchments of the mountains and coastal plains of the Western

TABLE 4

AREAS INVADED BY ALIEN PLANTS IN THE DIFFERENT PROVINCES BOTH AS HECTARES AND AS A PERCENTAGE OF THE AREA OF THE PROVINCE. THE CONDENSED AREA IS THE TOTAL AREA ADJUSTED TO BRING THE COVER TO THE EQUIVALENT OF 100%.

Province	Area (ha)	Total area invaded		Condensed invaded area	
		(ha)	(%)	(ha)	(%)
Eastern Cape	16 739 817	671 958	4.01	151 258	0.90
Free State	12 993 575	166 129	1.28	24 190	0.19
Gauteng	1 651 903	22 254	1.35	13 031	0.79
KwaZulu-Natal	9 459 590	922 012	9.75	250 862	2.65
Lesotho	3 056 978	2 457	0.08	502	0.02
Mpumalanga	7 957 056	1 277 814	16.06	185 149	2.33
Northern Cape	36 198 060	1 178 373	3.26	166 097	0.46
Northern Province	12 214 307	1 702 816	13.94	263 017	2.15
North West	11 601 008	405 160	3.49	56 232	0.48
Western Cape	12 931 413	3 727 392	28.82	626 100	4.84
RSA+Lesotho	**124 803 707**	**10 076 365**	**8.07**	**1 736 438**	**1.39**

TABLE 5

AREAS INVADED BY ALIEN PLANTS IN THE DIFFERENT PRIMARY CATCHMENTS BOTH AS HECTARES AND AS A PERCENTAGE OF THE AREA OF THE CATCHMENTS. THE CONDENSED AREA IS THE TOTAL AREA ADJUSTED TO BRING THE COVER TO THE EQUIVALENT OF 100%.

Primary catch-ment	River system	Area (ha)	Total invaded area		Condensed invaded area	
			(ha)	(%)	(ha)	(%)
A	Limpopo	10 873 288	726 084	6.68	122 457	1.13
B	Olifants	7 350 308	1 532 606	20.85	217 855	2.96
C	Vaal	19 629 440	362 351	1.85	64 632	0.33
D	Orange	40 876 535	1 045 393	2.56	141 012	0.34
E	Olifants (W Cape)	4 906 252	528 972	10.78	37 623	0.77
F	Namaqualand coast	2 850 621	237 244	8.32	46 618	1.64
G	W Cape & Agulhas coast	2 524 373	1 597 036	63.26	384 636	15.24
H	Breede & SW Cape coast	1 551 872	741 408	47.78	84 398	5.44
J	Gouritz	4 513 434	711 436	15.76	59 399	1.32
K	S Cape coast	716 816	132 030	18.42	52 993	7.39
L	Gamtoos	3 473 106	277 428	7.99	34 289	0.99
M	Port Elizabeth region	261 156	70 376	26.95	11 358	4.35
N	Sundays	2 122 532	25 191	1.19	3 964	0.19
P	E Cape coast	530 806	74 174	13.97	22 894	4.31
Q	Gt Fish	3 022 811	27 199	0.90	6 980	0.23
R	Border coast	791 830	24 781	3.13	12 483	1.58
S	Great Kei	2 048 307	57 196	2.79	30 694	1.50
T	Transkei region	4 662 380	302 131	6.48	68 493	1.47
U	S KwaZulu-Natal	1 829 337	151 747	8.30	46 442	2.54
V	Tugela	2 903 885	258 260	8.89	62 151	2.14
W	N KwaZulu-Natal & Mpumalanga highveld	4 507 461	341 362	7.57	100 574	2.23
X	Mpumalanga escarpment	2 857 157	851 962	29.82	124 494	4.36
	RSA+Lesotho	**124 803 708**	**10 076 365**	**8.07**	**1 736 438**	**1.39**

Cape (Catchments G and H) followed by the Mpumalanga escarpment (Catchment X), the Port Elizabeth region (Catchment M) and the Olifants River (Catchment B) in Mpumalanga and Northern Province. Some catchments appear relatively free of invasions, for example the Orange River. More than 20% of the area of some tertiary catchments in the Western Cape and the Northern Province has been invaded.

The worst invaders

The species which have invaded the largest **total** area are *Melia azedarach* and the pines (mainly *Pinus pinaster* and *Pinus patula*), followed by *Acacia mearnsii*, *Prosopis* species and *Lantana camara*, each of which has invaded more than 2 million ha (Table 6). The principal species in terms of **condensed** area are *Acacia cyclops*, which is found in the Western and Eastern Cape, and *Prosopis* species which are found mainly in the Northern Cape. *Acacia mearnsii* is ranked third on the basis of condensed area. The different *Acacia* species could not always be separated, resulting in an additional category called *Acacia* mixed species. This category generally comprises *A. mearnsii* mixed with other species such as *A. dealbata* and *A. decurrens.* Overall, *Acacia* species are the most important with three species in the top ten and a further three species (notably *A. dealbata*) in the top 25 species. Together, they have invaded about 4.7 million ha, about half the area of KwaZulu-Natal, and the equivalent condensed area is greater than 700 000 ha, more than 80% of which is in the Western and Eastern Cape provinces. Species in the top ten based on **total** area (and which do not appear in Table 6) include *Eucalyptus* species, *Opuntia* species and *Jacaranda mimosifolia* with a further five species each having invaded more than one million ha. The importance of riparian invasions is shown by five species in the top 10 being primarily riparian invaders despite the relatively limited extent of riparian habitat in South Africa. The data on areas invaded by individual species must be interpreted correctly; the areas cannot simply be added because there are often overlaps where species occur in mixtures.

TABLE 6

Top 10 Invading Species or Groups of Species in South Africa Ranked by Condensed Invaded Area. Habitat - Indicates the Main Habitats Invaded by the Species: l = Landscape, r = Riparian, R(a) = Alluvial Plains. The Condensed Area Is the Total Area Adjusted to Bring the Cover to the Equivalent of 100%. Density Is the Estimated Mean Cover over the Total Invaded Area.

Species	Habitat	Condensed invaded area (ha)	Total invaded area (ha)	Density (%)
Acacia cyclops	l	339 153	1 855 792	18.28
Prosopis spp.	R(a)	173 149	1 809 229	9.57
Acacia mearnsii	r,l	131 341	2 477 278	5.30
Acacia saligna	l,r	108 004	1 852 155	5.83
Solanum mauritianum	r,l	89 374	1 760 978	5.08
Pinus spp.	l	76 994	2 953 529	2.61
Opuntia spp.	l	75 356	1 816 714	4.15
Melia azedarach	r,l	72 625	3 039 002	2.39
Lantana camara	r	69 211	2 235 395	3.10
Hakea spp.	l	64 089	723 449	8.86

Water use

National overview

The **incremental** water use of alien invaders in South Africa and Lesotho is an estimated 3 300 m^3/yr per year or 6.67% of the mean annual runoff (MAR) (Table 7). This is equivalent to 190 mm/yr (1 900 m^3 per ha) for a closed canopy (i.e. based on the **condensed** area) and 33 mm/yr when calculated using the **total** invaded area of 10.1 million ha. The greatest percentage impact was found in the Northern Cape where water use by invaders, primarily *Prosopis*, is equivalent to about 17% of the MAR, or the equivalent of 910 m^3/ha/yr using the **condensed** area. A similar situation is found in the North West province but here a greater proportion of the invasions are by riparian species such as *Melia azedarach* and wattles. Northern Province also has large areas with a low rainfall but most of the invaded areas are located within its high-rainfall catchments (Drakensberg escarpment, Soutpansberg and similar areas) and thus have a disproportionate impact on the surface runoff in the province as a whole. The Western Cape loses the greatest volume of runoff mainly because large areas of the mountain catchments are invaded by pines, and most river systems are invaded by wattles.

An analysis of the impact on the runoff in the different primary catchments also highlights some of the worst affected areas

TABLE 7

Impact of the Water Use of Invading Alien Plants on the Mean Annual Runoff (MAR) in Each of the Provinces and in Lesotho

Province	Mean annual runoff (millions of m^3)	Condensed invaded area (ha)	Incremental water use (millions of m^3)	Water use (% of MAR)	Water use in rainfall equivalents (mm)
Eastern Cape	9 998.76	151 258	558.19	5.58	369
Free State	3 546.10	24 190	86.19	2.43	356
Gauteng	551.97	13 031	53.93	9.77	414
KwaZulu-Natal	12 517.61	250 862	575.74	4.60	230
Lesotho	4 647.19	502	1.88	0.04	374
Mpumalanga	6 303.01	185 149	446.29	7.08	241
Northern Cape	910.94	166 097	150.86	16.56	91
Northern Province	3 383.63	263 017	297.70	8.80	113
North West	1 081.57	56 232	95.40	8.82	170
Western Cape	6 555.18	626 100	1 036.82	15.82	166
South Africa	**49 495.96**	**1 736 438**	**3 303.00**	**6.67**	**190**

TABLE 8

Impact of Water Use by Invading Alien Plants on the Mean Annual Runoff (MAR) in Primary Catchment Areas of South Africa and Lesotho. See the Text for a Discussion of Why Certain Catchments Have Such High Reductions.

Primary catchment	River system	Mean annual runoff (millions of m^3)	Condensed invaded area (ha)	Incremental water use (millions of m^3)	Water use (% of MAR)	Reduction in rainfall equivalents (mm)
A	Limpopo	2 381.82	122 457	190.38	7.99	155
B	Olifants	2 904.10	217 855	290.44	10.00	133
C	Vaal	4 567.37	64 632	190.53	4.17	295
D	Orange	7 147.76	141 012	141.40	1.98	100
E	Olifants, Sout & Doring	1 008.35	37 623	35.52	3.52	94
F	Namaqualand coast	25.01	46 618	22.76	91.00	49
G	W Cape & Agulhas coast	2 056.75	384 636	646.50	31.43	168
H	Breede & Riversdale coast	2 088.35	84 398	181.63	8.70	215
J	Gouritz	670.63	59 399	74.79	11.15	126
K	S Cape coast	1 297.30	52 993	134.46	10.36	254
L	Gamtoos	494.71	34 289	96.53	19.51	282
M	PE Coast, Swartkops & Coega	150.04	11 358	40.18	26.78	354
N	Sundays	279.89	3 964	8.34	2.98	210
P	Bushmans & Alexandria coast	172.92	22 894	73.08	42.26	319
Q	Gt Fish	520.72	6 980	21.12	4.06	303
R	Border Coast	578.91	12 483	55.58	9.60	445
S	Great Kei	1 042.35	30 694	138.22	13.26	450
T	Former Transkei	7 383.76	68 493	217.38	2.94	317
U	S KwaZulu-Natal	3 121.20	46 442	126.37	4.05	272
V	Tugela	3 990.88	62 151	104.67	2.62	168
W	N KwaZulu-Natal	4 741.74	100 574	229.86	4.85	229
X	Komati to Nwanedzi	2 871.4	124 494	283.26	9.86	228
	RSA	**49 495.96**	**1 736 438**	**3 303.00**	**6.67**	**190**

(Table 8). The highest impact, on a percentage basis, is found in the arid Namaqualand coastal region (catchment F) which has very low surface runoff. The main invading species are the wattles, especially *Acacia cyclops*, which are probably exploiting groundwater and fog, and thereby utilising more water than is directly available as surface runoff. A similar situation is found in the relatively dry coastal catchments from Port Elizabeth to Port Alfred (catchments M-P) where dense invasions of wattles are found in the extensive coastal dune-fields. The substantial impact of invading plants on the amount of runoff in the Olifants (catchment B, Mpumalanga) and Limpopo River (catchment A) systems also stands out clearly. The high runoff catchments of the southwestern Cape (catchment G) have also been severely affected at 31% of MAR, mainly because of extensive landscape invasions by pines and riparian and landscape invasions by *Acacia* species, especially on the coastal lowlands.

Greatest water users

A small subset of invading species accounts for most of the water used by invaders. The most important species, by this standard, is *Acacia mearnsii* followed by *A. cyclops* (Table 9). The impact of the latter species on surface runoff is limited because of its coastal distribution pattern except where communities depend on groundwater supplies, as in the case of the town of Atlantis in the Western Cape. As a group the acacias, with seven species in the top 25 - notably *A. mearnsii, A. cyclops* and *A. dealbata* - are the prime water users, accounting for 55% of the total water use. They are followed by pines, eucalypts, *Prosopis* species and *Melia azedarach*. The top ten account for 81% of all water used by invading aliens.

Discussion

The problem would appear to be very serious. An area of about 10.1 million ha, greater than the province of KwaZulu-Natal, has been invaded to some degree. If this area is condensed, by adjusting the canopy cover to 100%, the area is about 1.7 million ha, greater than that of Gauteng Province and the total area of commercial plantations. The incremental water use of the alien plants is estimated to be 3 300 million m^3/yr. Put in perspective, this volume is equivalent to about 72% of the virgin mean annual runoff of the Vaal River, and about the same as the virgin MAR of Northern Province (Table 7). Even at a conservative rate of new invasion of 5% per year the size of the invaded area could double in 15 years (Versfeld et al., 1998). If the density, species composition and plant age distribution of the total invaded area (and thus the incremental water use per ha) does not change significantly, then the impact on water resources would also double. These figures have some serious implications and need to be assessed carefully before actions are taken. The data have been gathered from a variety of sources and the water-use modelling involves some important assumptions. These issues are discussed below.

TABLE 9
ESTIMATED MEAN ANNUAL WATER USE OF INVADING SPECIES FOR THE WHOLE COUNTRY, RANKED ACCORDING TO THEIR RELATIVE WATER USE

Species	Water use (millions of m^3)	Cumulative percentage of the total water use
Acacia mearnsii	576.58	17.46
Acacia cyclops	487.63	32.22
Acacia dealbata	248.32	39.74
Acacia mixed spp.	242.63	47.08
Pinus spp.	231.53	54.09
Eucalyptus spp.	213.98	60.57
Prosopis spp.	191.94	66.38
Acacia saligna	171.13	71.56
Melia azedarach	164.91	76.56
Solanum mauritianum	139.97	80.79
Lantana camara	97.14	83.73
Chromolaena odorata	68.26	85.80
Hakea spp.	66.30	87.81
Populus spp.	53.83	89.44
Jacaranda mimosifolia	48.40	90.90
Sesbania punicea	42.57	92.19
Rubus spp.	41.33	93.44
Acacia longifolia	38.73	94.62
Psidium guajava	37.31	95.75
Caesalpinia decapetala	33.82	96.77
Salix spp.	33.21	97.78
Acacia melanoxylon	32.20	98.75
Acacia decurrens	9.83	99.05
Quercus spp.	7.24	99.27
Other spp.	17.27	100.00

Extent and water use

There are no data sets which can be used to assess the accuracy of the mapped data collected for this study. The only other national data set on invasions by exotic species is the South African Plant Invaders Atlas (SAPIA) database maintained by L Henderson of the Plant Protection Research Institute; see Henderson (1998) for a description of the types of data. Unfortunately, although the SAPIA records do have a spatial location, the descriptions in the records makes it very difficult to convert this to an invaded area. The data can be used to get a crude index of the abundance per standard 1: 50 000 map sheet or quarter degree square (15'x15'). Maps of the abundance of the most important invading weed species were created from the SAPIA data by Versfeld et al. (1998). Visual comparisons and overlaying of these maps with those from this study showed that there were no glaring gaps and that the relative abundances corresponded in both data sets.

The impact on water resources can be put into perspective by comparing it with recent estimates of the water use of plantations (data from Le Maitre et al., 1997; Scott et al., 1998):

Water use by commercial forestry:	1 399 million m^3/ yr
Water use by invading aliens:	3 303 million m^3/yr
Area covered by commercial forestry:	14 389 km^2
Area covered by invading aliens:	17 364 km^2 (condensed area)

In millimetre rainfall equivalents this equates to about 93 mm/yr (930 m^3/ha) per year for plantations compared with 190 mm/yr (1 900 m^3/ha) per year for invaded areas. The incremental water use of alien invaders (per unit area) is clearly substantially greater than that of commercial plantations. The main reasons for this difference are the lower mean age of plantation trees (about 10 years) compared with invaders (about 20 years) and the concentration of invasions in riparian strips where the trees have free access to water. We return to this point later.

The incremental water use of invading alien trees in riparian zones, mainly wattle and eucalypt, has also been estimated using the ACRU model (Smithers and Schulze, 1995). The parameters for the model were derived for plantations and from data for the Umgeni catchments above the Midmar Dam (Umgeni Water, 1997). The estimated incremental water use, on a condensed area basis (unit reference area) was about 560 mm/yr. This is substantially higher than the 368 mm estimated for the same catchments by Versfeld et al. (1998) using the same data on the invaded areas. Some recent, short-term studies of the increases in streamflow following clearing of alien invaders have recorded increases of 10 to 12 m^3/ha cleared per day during base-flow periods (Dye and Poulter, 1995; Prinsloo, 1998). Data are not available for a full year yet but these findings indicate that clearing does increase streamflow. Research projects currently in progress will provide more information on the water use of invading plants and will help to refine the estimates provided by this study.

Factors related to the degree of invasion

Moisture availability is a key factor limiting plant growth and vigour and a strong positive relationship between rainfall and the degree of invasion could reasonably be expected. But the correlations between invasions and rainfall *per se* over the whole country (e.g. using catchment MAP) are weak. This could be due to various factors. Many of the invaded areas are in riparian zones where the degree of invasion is largely independent of the rainfall in the surrounding areas. For example, perennial or seasonal rivers running through arid areas can be heavily invaded by species unable to invade the surrounding landscape. Several invaders have invaded large areas in the semi-arid and arid catchments, for example the Cactaceae (Henderson, 1995). *Prosopis* species have invaded arid landscapes but are generally confined to low-lying alluvial plains, locally termed 'leegtes', where their root systems, which can be very deep, can reach groundwater (Harding and Bate, 1991). Landscape invasions by other species (pines, acacias, eucalypts) appear to be confined to areas with an annual rainfall of more than 500 mm, except for *Acacia cyclops* on the Western Cape coastal plains where the rainfall of 150 to 250 mm per year is supplemented by regular fogs (Versfeld et al., 1998).

It seems likely that invasions are initiated more readily in high rainfall areas, partly because the degree of human disturbance and land cover transformation is greatest in these areas. Many riparian invasions came about through the introduction of invading species into the upper catchments; these species have subsequently spread rapidly downstream. Degradation of riparian habitats due to inappropriate land-use practices has also facilitated invasion as these zones are naturally prone to invasions (Henderson and Wells, 1986; Rowntree 1991; Pysek and Prach, 1993). Rainfall, together with temperature, appears to be related to the diversity of species that can invade. Areas with moist subtropical climates appear to have the greatest variety of invader species (Dean et al., 1986; Richardson et al., 1997). A more limited suite of species is found in fynbos and grasslands and especially on the highveld and in the dry interior. Once again riparian situations prove the exception,

TABLE 10 COMPARISON OF LENGTH OF RIVER (m) MAPPED AT A SCALE OF 1:50 000 AND AT 1:500 000				
Region	Map scale		Ratio	Map sheets
	1:50 000	1:500 000		
Drakensberg Escarpment	410 520	92 610	4.43	2828DB Witsieshoek & 2829CA Bergville
Southern Cape	777 604	262 942	2.96	3323DD, 3324CA-CD; Kouga & Kromriver, Baviaanskloof, Suuranys, Tsitsikamma

probably because ready access to water enables a number of species, which could not survive in the drier surrounding areas, to invade.

In many cases landscape invasions are also related to land-use practices, with invasion rates being directly related to the degree of degradation of the natural vegetation (Hobbs, 1988; Noble, 1989; Richardson and Cowling, 1992). In other areas there were large-scale introductions of invader species, for example the extensive driftsand 'reclamation' operations which began in the late 1800s (Keet, 1936; Walsh, 1968). Fynbos communities, dune ecosystems and sub-alpine or alpine grasslands are exceptional in that landscape invaders, particularly pines, appear to be able to invade healthy vegetation under natural disturbance regimes (Richardson and Brown, 1986; Richardson and Cowling, 1992; Richardson et al., 1994). Forest vegetation also appears to be susceptible to some invasive species (e.g. *Rubus*, *Acacia melanoxylon*, *Caesalpinia decapetala*) even under natural disturbance regimes (Geldenhuys et al., 1986).

Uncertainties in the data and estimated impacts

The extent of the invaded area

As described under **Methods**, this database has been compiled from a variety of sources which varied in their spatial scale, accuracy, and reliability. This means that it is impossible to give a single quantitative statistic to describe the likely errors in the data and at a national or provincial level. The Western Cape is the most thoroughly mapped province while the most incompletely mapped are KwaZulu-Natal and Mpumalanga. Overall, we believe that the data are adequate for the purpose of providing an overview - at national, provincial and primary catchment scales - of the extent of the invasions, and thus meet the objectives of the project.

Riparian invasions

Most of the quantitative data on riparian invasions have been derived from generalised descriptions, notably in KwaZulu-Natal and parts of Mpumalanga. The descriptions were converted into invaded areas using the best national data set that could be obtained for rivers. However, the river data were digitised from 1:500 000 maps which do not include many of the rivers and streams shown on 1:50 000 maps. Observations and the detailed map data that were available show that in most areas all perennial, and many non-perennial rivers shown on 1:50 000 maps have been invaded. This means that the digitised rivers generally comprise only a small fraction of the total riparian zone which could be invaded. The degree to which the river length was underestimated was determined by comparing the 1:500 000 data set with data for a small sample 1:50 000 maps (Table 10). A visual comparison of river lengths at a scale of the 1:250 000 and 1:500 000 showed similar differences in the Vaal River system (Versfeld et al., 1997). There the ratio of river length for perennial rivers ranged from about 1.8:1 on the highveld near the Vaal Dam to 2.5 to 3.8:1 in parts of the Upper Wilge River and Liebenbergsvlei catchments on the Drakensberg escarpment. Our analysis considered only invaders along the rivers mapped at the 1:500 000 scale and may, therefore, have significantly underestimated the true extent of the problem. These shortcomings will have to be addressed in future studies.

Biomass estimates

There are three main sources of uncertainty in the biomass model and in how it was applied:

- Accuracy of the biomass estimates used to derive the model
- Categorisation of a variety of species into three biomass classes (tall shrubs, medium trees and tall trees)
- Estimated mean age of the alien invaders.

The biomass data used to develop the water use relationship were taken from the few available studies in pine afforested and fynbos catchments (Le Maitre et al., 1996). The data for tall invading shrubs and medium trees were not obtained from catchment studies but fall within the range of biomass used to develop the model so no extrapolation of the original relationship is needed. These studies provide the best available estimates of the biomass for those situations. The biomass classes were a compromise between the available data on biomass and the different growth forms of the alien trees, and also took into consideration the likely water use based on knowledge of their ecology and growth rates and whether or not they were deciduous (Versfeld et al., 1998). The age estimates used in this analysis were a reasonable estimate based on the judgement and experience of experts.

Water use estimates

There are a number of uncertainties in the estimation of the water use of alien invaders. The most important are:

- the limited database on the water use of different species;
- extrapolation of the biomass model into different environments;
- high water use of alien invaders relative to plantations; and
- the adjustment of the water use to compensate for limited water availability.

Data on water use

The data on water use by trees in catchments comprise very good information for two species of pines and one species of eucalypt (Scott et al., 1998), and limited data for a number of other species (Dye, 1996). The most important uncertainty is the water use of *Acacia mearnsii* and the other Australian wattle species with a similar growth form (*A. dealbata*, *A. decurrens*, see Table 9). Scott et al. (1998) considered water use by *A. mearnsii* to be similar to that of pines because its ability to grow well in dry areas suggests that it regulates its transpiration when water becomes limiting - as do pines (Dye, 1996). In this study we have assumed that wattle water use is similar to that of pines. Another important uncertainty is that the biomass model predicts incremental water use, i.e. the increase in the amount of water used relative to the original vegetation. In many areas invaded by species such as *Rubus* and *Lantana*, the natural communities could be using as much water, so clearing would not result in a net increase in streamflow. These species were classified as 'tall shrubs' (Table 3) which results in their water use being insignificant relative to tree species (Table 9), and which compensates for this uncertainty.

The impact of aliens was estimated using naturalised flow volumes (Midgley et al., 1994) which may have already been adjusted to implicitly include the impact of invaders; therefore there may be some double accounting. In some cases, too, it is probable that individual catchments are particularly severely affected by invaders but the water observed in the rivers is supplied by other catchments upstream. Water from upstream catchments is not included in the surface runoff estimates for downstream catchments in Midgley et al.'s (1994) analysis.

Model extrapolation

Extrapolation of a model based on catchment data from the winter rainfall regions to the summer rainfall areas is problematical because of marked differences in the seasonal distribution of driving factors, such as evaporative demand, and in growing conditions. The catchment data do, however, show that the measured reductions in streamflow under plantations in both the summer and winter rainfall regions fall within a similar range (170 to 450 mm, Versfeld, 1993). The similar impacts can also be seen in data which show that evaporation from plantations generally also stabilises at about 1 200 mm per year in both the summer and winter rainfall regions (Bosch and Von Gadow, 1990; Dye, 1996). Streamflow reduction curves developed by Scott and Smith (1997) suggest that reductions in the winter rainfall catchments are less than those in the summer rainfall catchments (on a percentage basis), suggesting that estimates using the winter rainfall biomass model may be conservative.

Comparison with other estimates of water use

We have compared the water-use estimates from the biomass model with those from an analysis of the impact of commercial plantations taken from Le Maitre et al. (1997) and Scott et al. (1998). These studies were based on the use of runoff reduction models developed from the same kinds of catchment data, and relate the plantation age to the percentage reduction in streamflow compared with the natural vegetation. Rainfall-runoff relationships were used to estimate the mean annual runoff (in millimetres) under natural vegetation and these were then reduced by the mean, annual, percentage reduction over the rotation period (time from planting to clear felling) of the plantations. These models therefore take the actual runoff into account and reduce it by a percentage. This differs from the biomass model which calculates the reduction directly in millimetres. The reduction curve models also take site conditions into account. The Scott et al. (1998) approach probably would provide more accurate estimates of the water use but it would not be easy to use these models in this analysis because they are far more data-intensive (e.g. data on the growth potential would be needed) and the biomass data are insufficient to parameterise the curves properly.

The results of the comparison showed that the impacts of alien invaders were estimated to be substantially greater than those of plantations. There are a number of factors which could account for this, the most important being that:

- Most of the alien invaders mapped for this study occur along riverbanks. Trees in these moist areas are known to use two or more times as much water as non-riparian trees in the same catchment (Scott and Lesch, 1995).
- The biomass models used a mean age of 20 years for invading plants, except in the Western Cape. This is substantially greater than the typical mean age of plantations which is half the mean rotation lengths and thus of the order of 10 years (Scott et al., 1998).

Adjusted water use

The adjusted water use may well underestimate the true amounts used where the plants occur along perennial rivers which are sustained by flow from upstream catchments. The adjustments also will not hold in situations where plant roots could still access water stored in the soil profile, river banks and shallow aquifers. The approach also does not allow for the fact that currently invaded areas upstream (and future increases in the invaded areas) may reduce water availability downstream. Nevertheless, we believe that it does provide more reasonable estimates of the actual incremental water use by invading exotic plants than the unadjusted biomass model, particularly in the semi-arid and arid regions of the country. On the other hand the invading trees could be making use of shallow groundwater reserves which were not considered in this study. The impacts can be substantial in arid situations with high evaporative demand (Busch et al., 1992). Studies of invading riparian *Tamarix* in the Mohave desert have shown that water use can be as high as 1.6 to 2.0 times the reference evaporation estimated using the Penman-Monteith model (Sala et al., 1996; Devitt et al., 1997).

Conclusions

This study has indicated that alien invading plants have a significant impact on the water resources of South Africa. The findings presented here are based on a preliminary assessment and must be treated with caution because they involve a number of critical assumptions and generalisations as described in this paper. The water-use model is empirical and based on data from catchment experiments which are restricted to a limited number of species in relatively wet catchments. Data on water use by the different invading species, notably *Acacia mearnsii*, are lacking and research to address these gaps should have a high priority. It is also likely that in some places the extent of invaded areas has been underestimated, especially in KwaZulu-Natal. Whatever reservations there might be about either data or calculations, the estimated impact of invading aliens on the water resources of South Africa, at about 6.7% of the total surface runoff, is substantial. Even at a conservative rate of new invasion of 5% per year the size of the invaded area could double in 15 years (Versfeld et al., 1998), potentially doubling the water use. Analyses of specific catchments and data collated for management plans show that clearing aliens is cost-effective (Higgins et al., 1997; Van Wilgen et al., 1997). There is clear evidence that given time and sufficient area to invade, alien species will increase in extent and density to use an even greater proportion of the available water in catchment areas. The issue that faces decision-makers is not whether or not to undertake control operations but how to plan and execute them to ensure that the resources allocated to control operations are used as effectively as possible to minimise the loss of valuable water.

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