IMPACT ON INVASIVE ALIEN VEGETATION ON DAM YIELDS

David Le Maitre · Andre Görgens

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Water Research Commission

IMPACT ON INVASIVE ALIEN VEGETATION ON DAM YIELDS

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

Study objectives

The Working for Water programme is investing hundreds of millions of Rand on invasive alien plant clearing programmes each year. Invasive alien plants are estimated to be using the equivalent of 6.7% of the mean annual surface runoff of South Africa. Studies of the impact of invading plants on water resources have not yet addressed the issue of how much of the increase due to clearing can actually be utilised to achieve measurable societal benefits, thus justifying the present levels of expenditure. Doubts have been raised over whether or not invader clearing programmes can be expected to have a significant or, indeed, any effect on the assurance of supply from typical large dams. This study was conceived and funded by the Water Research Commission to provide provisional information on this and other questions about the link between clearing programmes and potential increases in utilisable water in rivers.

The basic objective was to produce first approximations of the impacts of invasions by alien plant species on the assurance of supply from typical dams in typical catchments in the form of a limited-budget, short-term study. The study was to focus on impacts at spatial resolutions at both multi-tributary river system scale and single tributary scale across a range of catchments with different current and projected future invasion patterns and bio-climatic regimes.

Study Areas

A number of different catchments were selected to represent different bioclimatic regions and differences in the compositions and pattern of invasions. The catchments were also selected because alien invading plant management plans for these catchments had been prepared for the Working for Water Programme or for the relevant Water Board. These plans provided the detailed information on alien plant invasions that was used to prepare the streamflow series in this study. The catchments span a range from primarily winter rainfall to summer rainfall regions and from the coastal mountains to the highveld and eastern escarpment. The river systems analysed were the Upper Mngeni above Midmar Dam, the whole Sonderend system, the Upper Wilge catchment and the Sabie-Sand system upstream of the Kruger National Park.

Methodology

The methodology employed in this study comprised five stages:

- ◊ quantifying current levels of infestation
- ◊ projecting future (10 years) levels of infestation
- ◊ formulating a suitable proportional streamflow reduction model for each selected catchment system
- ◊ estimating the respective streamflow sequences for natural, current-level invaded and future-level invaded scenarios via rainfall-runoff catchment modelling, using the Pitman Model linked to the streamflow reduction models described above

◊ determining the yields, at a range of assurance levels, deliverable from a range of hypothetical impoundment sizes for each invasion scenario via reservoir water balance modelling

◊ determining the incremental reductions in yields, from natural, for the range of cases analysed.

In the interests of clarity and economy of effort, it was necessary to ignore all existing human-derived impacts in the selected catchments. In this way, the estimated streamflow reductions due to alien plants could be clearly illustrated, uncluttered by the effects of other physical developments on the streamflow regimes of catchments. All alien plant-related impacts on streamflows were therefore juxtaposed with the naturalised streamflows generated by means of Pitman Model parameters determined during the WRC's "WR90" surface water resources assessment published in 1994 (Midgley et al. 1994).

Findings

(i.) This study has shown that it is feasible to estimate the potential streamflow reduction impacts on utilisable water in South African river systems (expressed as yield from impoundments) for which reasonably reliable data bases on invasion patterns exist.

(ii.) A workable approach has been found to combine empirical long-term streamflow reduction prediction models with monthly time series rainfall-runoff catchment modelling.

(iii.) Both the potential *absolute* reductions (in Mm^3/a) in yield, and the *MAR-standardised* values of those reductions, in the Sabie-Sand and the Sonderend river systems far exceed those in the Upper-Mngeni and Upper-Wilge systems. For example, in the Sabie-Sand system, potential yield reductions can be expected to already exceed 60 Mm^3/a, and to start approaching $100Mm^3/a$ in 10 years' time, if not checked. Such differences may have implications for the prioritisation of alien plant eradication projects.

(iv.) The *proportional* yield reductions in the Sabie-Sand and the Sonderend river systems are considerably more significant than in the other two river systems. For the Sabie-Sand system the proportional yield reductions for dam sizes equal to or greater than 50% natural MAR averages at about 8% (present) and 11% (future). For the Sonderend the proportional yield reductions for dam sizes equal to or greater than 50% natural MAR averages at about 4% (present) and 6% (future).

(v.) On average over the four systems, for a given level of assurance of yield, the proportional reductions are relatively constant for storage sizes equal to or exceeding 50% of the natural MAR.

(vi.) In general, for any give dam size over 50% of the natural MAR, there is relatively little difference in the proportional reductions at different assurances of yield.

(vii.) Potential yield reductions at the scale of specific quaternaries can be very different from the aggregated impact on the full river system. For instance, for current-day conditions, quaternary H60K (Sonderend) shows potential proportional yield reductions of about 30%, while the full system of which it forms part shows potential reductions of about 4%.

Recommendations

(i.) The assumption of a sigmoidal relationship between streamflow reductions and biomass *per se* has been questioned recently on the grounds of a number of empirical observations of a strong correspondence between *current annual increment* in biomass and consumptive water use (P. Roberts, pers. com., 2001). It is recommended that data of this nature be assembled and used to review the biomass-based model proposed here.

(ii.) Towards the conclusion of this study the cause of the commonly smaller magnitude of the proportional potential yield reductions for the smallest dam size case of 20% MAR (natural), compared with other dam sizes, was investigated in greater detail. As the yields from small (relative to MAR) dam sizes are known to be particularly sensitive to the low flow regime of a river, there might be concern that the results of this study might be too optimistic in terms of low flows. To investigate this further, a pilot assessment was made on the Sonderend River. The riparian model used here was replaced with the simple assumption that riparian consumptive use would equal that of nett open water evaporation. This change caused the proportional reductions for the 20%MAR dam size to increase from about 2.5% to about 3.5% for the system as a whole, with little change in the reductions for larger dam sizes. It is recommended that this adjustment to the way riparian invasives are treated in the modelling process be further evaluated and, if necessary improved.

(iii.) It is recommended that this investigation be extended to include analyses of multi-land-use, multi-reservoir river systems so that the integrated effects of alien plant invasions on such complex systems may be quantified under current-day development conditions.

1. INTRODUCTION

1.1 Background

The Working for Water programme is investing hundreds of millions of Rand on invasive alien plant clearing programmes each year. Invasive alien plants are estimated to be using the equivalent of 6.7% of the mean annual surface runoff of South Africa (Versfeld et al. 1998, Le Maitre et al., 2000). A number of studies have reported increases in, or resumption of streamflow following clearing (Dye and Poulter 1995, Prinsloo et al. 1999), substantiating the argument that clearing programmes increase the streamflow. This has been a major motivation for spending large amounts of money on control operations. Some studies have already been done to show that flow reductions caused by invading plants can affect the unit costs and effectiveness water supply schemes (van Wilgen et al. 1997, 1999).

Studies of the impact of invading plants on water resources have not yet addressed the issue of how much of this increase can actually be utilized to achieve measurable societal benefits, thus justifying the present levels of expenditure. One example is the many large storage dams, which supply the major urban and industrial complexes and large irrigation schemes. Large dams with a capacity greater than the mean annual inflow typically fill in years of above average rainfall, retain relatively good storage for many years and are only drawn down to low levels during extended drought periods. However, the impacts of invading plants on the large volumes of surface runoff, including floods, generated during periods with good rainfall can be expected to be proportionally small. Against this background, doubts have been raised over whether or not invader clearing programmes will have a significant effect, or indeed any effect at all, on the assurance of supply from typical large dams. The study reported on here was designed to provide provisional information on this and other questions about the link between clearing programmes and potential increases in utilisable water in rivers.

1.2 Study objectives

In recognition of an urgent need for first approximations of the impacts of invasions by alien plant species on the assurance of supply from typical dams in typical catchments, the Water Research Commission initiated this limited-budget, short-term study. The study was to focus on impacts at spatial resolutions at both multi-tributary river system scale and single tributary scale. These first approximations would then be available to help guide and prioritise clearing programmes and would also inform the planning of water resource augmentation schemes. For this study a comparative analysis was to be undertaken for a range of catchments with different current and projected future invasion patterns and bio-climatic regimes. It was expected that the approach and the procedures developed for this study should be applicable to any catchment and could be expanded to assess additional issues such as meeting run-of-river needs and in-stream flow requirements.

2. STUDY AREAS

A number of different catchments were selected to represent different bioclimatic regions and differences in the compositions and pattern of invasions (Table 1). The catchments were also selected because alien invading plant management plans for these catchments had been prepared for the

Working for Water Programme or for the relevant Water Board. These plans provided the detailed information on alien plant invasions that was used to prepare the streamflow sequences used in this study.

The catchments span a range from primarily winter rainfall to summer rainfall regions and from the coastal mountains to the highveld and eastern escarpment.

Two types of invasions were recognised throughout this study: riparian invasions which occur along watercourses and non-riparian or landscape invasions which occur in dryland areas. The two categories were chosen because (Versfeld *et al.* 1998, Le Maitre et al. 2000): (a) the freely available water in riparian areas will allow invading shrubs and trees to use more water than in the landscape situation especially in the dry season; and (b) the species composition in riparian and landscape habitats often differs, particularly in the lower rainfall areas. Riparian areas (habitats) are known worldwide to be particularly susceptible to invasions. They are invaded by a wide range of species and invasions can be very rapid.

Table 1: Basic data on the different catchment areas selected for this study. The catchment areas and climatic data were obtained from the data bases for quaternary catchments prepared for the WR90 study (Midgley et al. 1994). The summary of the land cover data was obtained from reports on the catchments (see the text). MAP = mean annual precipitation; MAR = mean annual runoff .

Catchment	Catchments	Area (km^2)	Climate (mm)	Vegetation and land-cover
Sonderend	Tertiary H60	3371,1	MAP: 361-1895 MAR: 41-1207	Fynbos and renosterveld (68%): dryland cultivation and irrigated land
Upper Wilge	Tertiary C81	6160,4	MAP: 612-892 MAR: 34-150	Grassland used as natural pasture (61%): dryland cultivation
Upper Mgeni (Midmar)	Quaternaries U20A-U20C	925,1	MAP: 932-1010 MAR: 184-290	Grassland used as natural pasture, plantations, irrigated areas and dryland cultivation
Sabie-Sand	Secondary X3	6321,8	MAP: 460-1334 MAR: 4-543	Bushveld, grassland and forest (46%): commercial plantations, irrigated agriculture and dryland cultivation (subsistence)

Sonderend

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 westernmost sub-catchment to 350-450 mm in the lower lying central and eastern sub-catchments (Table 1, Midgley et al., 1994). The dominant vegetation in the lower regions of this catchment was renosterveld, 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. The runoff from the high-yielding sub-catchments at the western end of the Sonderend supplies the Theewaterskloof dam (capacity 484 million m3) 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).

Upper Wilge

The Upper Wilge River catchment is situated on the inland plateau, or highveld, 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 3 200 m (Bailey et al., 1997). The lowest regions in the north-west are 1 600 - 1 700 m with low hills and ridges, gently sloping valleys and meandering rivers. The mean annual rainfall varies from 612 mm in the northern sub-catchments to about 1 500 mm in the Maluti Mountains in the south. There are frequent frosts in winter and snowfalls in winter in the Maluti Mountains. The vegetation is mainly a winter-dormant grassland dominated by temperate grasses with a very limited area of woodland or forest along rivers and in sheltered valleys in the mountain areas (Low and Rebelo, 1996). 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 Phutadichaba in the upper catchment. Large areas in this vicinity have been over-grazed and degraded because of the over-population of these marginal agricultural areas.

The catchment is a key water supply area for the major industrial and urban areas of Greater Johannesburg, Pretoria and Vereeniging. It includes the Sterkfontein dam which is supplied from the Tugela-Vaal transfer scheme (Bailey et al., 1997).

Upper Mngeni

This catchment comprises the three quaternary catchments that supply Midmar Dam, situated to the north of Pietermaritzburg. The Upper Mngeni and Lion's River catchments are situated between 1000 and 2000 m in altitude and there are extensive wetlands in the headwaters of the Mngeni River (Kienzle et al. 1997). The rainfall occurs primarily in the summer and varies from more than 1100 to less than 800 mm and mist occurs frequently in the summer. The vegetation is predominantly grassland - mainly Short Mistbelt, Moist Upland and North Eastern Mountain Sourveld - with some woodland and woody scrub along the water courses (Low and Rebelo 1996). The main land-uses are commercial pine plantations, dryland cultivation and irrigated agriculture (Kienzle et al. 1997).

The Midmar Dam is one of the five main dams which supplies water to the Umgeni Water Board and thus to Pietermaritzburg and the adjacent areas (Kienzle et al., 1997, MBB 1997).

Sabie-Sand

The Sabie-Sand River system has its source in the rugged and scenic Drakensberg escarpment, about 2130 masl, and flows eastwards to join the Incomati River in 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 the Kruger National Park. The natural vegetation in the upper reaches is winter-dormant, temperate grassland with extensive areas of Afromontane forest in the valleys and the sheltered slopes of the escarpment (Low and Rebelo, 1996; 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 and eucalypts have been established in the upper catchments of both the Sabie and Sand River systems (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.

The water resources in these 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).

3. METHODOLOGY

The methodology employed in this study comprised five stages:

- ◊ quantifying current levels of infestation
- ◊ projecting future (10 years) levels of infestation
- ◊ formulating a suitable proportional streamflow reduction model for each selected catchment system
- ◊ estimating the respective streamflow sequences for natural, current-level invaded and future-level invaded scenarios via catchment modelling, linked to the streamflow reduction models
- ◊ determining the yields at a range of assurance levels deliverable from a range of hypothetical impoundment sizes for each invasion scenario via reservoir water balance modelling
- ◊ determining the incremental reductions in yields, from natural, for the range of cases analysed.

In the interests of clarity and economy of effort, it was necessary to ignore all existing human-derived impacts in the selected catchments. In this way, the estimated streamflow reductions due to alien plants could be clearly illustrated, uncluttered by the effects of other physical developments on the streamflow regimes of catchments. All alien plant-related impacts on streamflows were therefore juxtaposed against naturalised streamflows. The generation of these natural streamflows and of the impacts is explained in Section 3.4 below.

3.1 Mapping of alien plant invasions

The data on the extent, density and composition of alien plant invasions was extracted from the databases prepared for each of the management plans. The mapping methods differed between the catchments and this is described below.

Sonderend

The catchment was mapped by fieldworkers onto standard 1:50 000 base maps following the procedures and standards set up by Le Maitre and Versfeld (1994) and the data standards developed for the Working for Water Programme (Muller et al. 1999). The species composition was recorded as the percentage canopy cover class for each species. Each mapped area was identified as riparian or non-riparian except in the catchment above the Theewaterskloof Dam where the riparian polygons were not distinguished. The area of the riparian invasions in this portion of the catchment was estimated from the invasions of the species in these polygons, which are known to be primarily riparian invaders.

Upper Wilge

The catchment was mapped with a combination of field work, using 1:50 000 base maps, and high resolution video imagery which was interpreted onto base maps and verified with field work (Bailey et al., 1997). The field data were mapped according to the Working for Water standards (Muller et al. 1999). The video data were mapped as species or species combinations with the specified density classes. The mean proportion of the total cover value was given was for each species in the species combinations so that the data could be converted to the specified standard. Riparian and landscape polygons were not distinguished so the area of riparian invasions was estimated from the estimated width of the invaded strip along the rivers and data on the total length of river invaded in each quaternary catchment.

Upper Mngeni

Only a strip 60 m wide (30 m either side) of the rivers in these catchments was mapped onto base maps from high resolution video images (MBB 1997). No non-riparian areas were mapped. The length and density (sparse, medium, dense) of the invaded sections was recorded and the frequency of the different species was summarised. These data were converted to the percentage cover based on this data and information received from Kevin Meier (LRI pers. comm. 2000) who did the original modelling of the alien vegetation water-use using the ACRU model (MBB 1997).

Sabie-Sand

The catchment was mapped via fieldwork onto 1:10 000 and 1:50 000 base maps according to the Working for Water standards (Muller et al. 1999, Nel et al. 1999). The invasions within the plantation compartments were not recorded as these species are typically understorey species and may not have a significant impact on the total water-use. Almost all the invaded areas were in riparian habitats so landscape invasions were analysed and modelled as part of the riparian invasions.
s were analysed and modelled as part of the riparian invasions.

3.2 Modelling of invasions for management plans

This section describes the approach and methods used to estimate the increase in the extent and density of alien plants in each of the catchment areas included in this analysis. The overall approach followed that developed by Versfeld et al. (1998, Appendix 7) with the details differing between the different catchment areas depending on the state of the invasions and the nature of the mapping.

3.2.1 Modelling approach

In this study we have used an approach which was developed for catchment management plans prepared for the Working for Water Programme (Versfeld *et al.* 1998, Appendix 7). Invasion processes can be divided into two phases: (a) expansion via dispersal (spread) which results in an increase in the total area invaded, and (b) densification, i.e. an ongoing increase in the density of the invading species. Expansion can be characterised by a sigmoid curve with a slow initial expansion, a rapid increase in the middle and a slowing down as the available area decreases. This is conveniently represented by the discrete form of the logistic growth function:

$$N_t = N_{t-1} + r(1 - N_{t-1}/K)N_{t-1}$$

where N_t is the area at time step t, r is the rate of increase and K is the potentially invadible area (ha)

Expansion rates (r) generally range from 0.10 to 0.30 per year but for this study a conservative value of 0.10 was used for expansion and for increases in density (see below). A similar approach was used to estimate the expansion rates in riparian areas with the unit being a kilometre rather than the hectare used for landscape invasions (Versfeld *et al.* 1997).

Density increases also begin slowly and then rise non-linearly but there is no indication that the rate slows as stands become denser. This phase is characterised by the discrete form of a simple exponential growth function:

$$P_t = P_{t-1} + rP_{t-1}$$

where P = percentage cover; t = the current time step; t-1 = the previous time step; and r = the rate of increase in cover.

All newly invaded areas are given an initial cover of 1.0%. The species composition, i.e. the relative importance of each species, was assumed to remain constant for the projections of both the extent and the composition of the future invasions. The modelling of expansions assumes that the rate of increase in area matches the rate of increase in density in the existing invaded areas so that the mean density remains constant.

3.2.2 Land-cover and use

Land-cover and use is important for predicting landscape invasion patterns and certain land-uses and land-covers (vegetation types) are less susceptible to invasion than others. For this study we grouped the land-cover classes defined for the National Land Cover (Thompson 1996; Fairbanks et al., 2000) according to their susceptibility to invasion (Table 2). Natural vegetation and pasture is regarded as being susceptible to invasion but urban areas, cultivated lands, plantations and the like are excluded from invasions. Riparian invasions are assumed to increase without regard to the adjacent land cover types as there seem to be few, if any, limits on invasions of these habitats. The total area of the invasible land cover classes, both invaded and uninvaded, was used as the potentially invasible area for modelling the projected invasions. The model is therefore a 'lumped' one and does not take into account the effects of the spatial distribution or contiguity of the invaded and potentially invasible areas. This is one of the key reasons for adopting conservative values of 0.10 for the rate of expansion and density increase. The potential rates estimated from the invadable area or river length, using the relationship developed by Versfeld et al. (1998), were generally substantially higher (0.15-0.25).

3.2.3 Projecting the future state of invasions

Alien plant invasions are not static but will change with time. Three scenarios have been investigated: (a) pre-invasion conditions, (b) the current state and (c) a future invaded state in 10 years time assuming that no control operations take place. The state of invasions of the catchments differed, so the modelling approach was adapted to take this into account, as described below.

In the Sonderend catchment the invasions are already extensive, with a mean of 80% of the landscape and 82% of the river length in some quaternary catchments being invaded to some degree of density. This places the invasions at the top end of the logistic growth curve and the resulting expansion is slow. In this situation it is unreasonable to assume that the mean density will remain constant. A second scenario was therefore developed which allows for a 50% increase in the mean density of the invasions over the 10-year period. The density increase is conservative compared with the doubling in density, which would occur if the density increase was 10% per year but allows also for the limited expansions. In the Upper Wilge catchment the expansions were modelled without any additional increase in density, as the degree of invasion in these catchments is relatively low. In the Upper Mngeni only the increase in the extent (length) of the riparian invasions was modelled and the data were converted to areas using the width of 30 m either side of the river as used in the original mapping and modelling study (MBB 1997). In the Sabie-Sand catchments the invasions were almost entirely riparian and all the invadable areas were already invaded to some extent (Nel et al., 1999). Therefore only the increase in density was modelled.

Table 2: A summary of the invasibility of the different land-cover classes used for the National Land Cover Survey (Thompson 1996). Wetlands are assumed to be invasible as most wetlands are seasonally dry, or have extensive seasonally dry areas which are subject to invasions in contrast to the permanently wet areas mapped as waterbodies. The areas involved are generally also small and unlikely to significantly influence the results.

Invasibility for upland invasions	Land Cover Class
Not invisible	All classes of Urban / built-up land
	Mines and Quarries
	All classes of Cultivated land
	Forest plantations
	Water bodies
	Barren Rock
Invasible	All classes of natural vegetation
	Dongas & sheet erosion scars
	Wetlands
	All classes of Degraded land
	Improved and Unimproved Grassland

3.2.4 Output data

All the data were expressed as the condensed or the equivalent dense area, i.e. if the mean canopy cover of an alien species on an area of 100 ha is 25% then the equivalent dense area is 25 ha. This allows the stand to be treated as a dense stand for flow-reduction modelling purposes as well as simplifying the calculation of invaded areas. This assumes that the relationship between flow reductions and canopy cover over the range from low cover to canopy closure is linear. This relationship is probably non-linear, but the development of a generalised relationship between canopy cover and structure and its ultimate effect on flow reductions falls outside the scope of this limited study.

The condensed area data for the individual species were summarised using the "biomass" classification developed by Versfeld et al. (1998, Table 3). This groups species into either: tall trees, medium trees or tall shrubs based on: (a) their size and structure as mature plants, (b) whether they are deciduous or evergreen and (c) what is known of the relative impacts on streamflow and water-use of the main commercial plantation species (pines, eucalypts, see Scott et al. 1998).

Table 3:Alien species and associated biomass equations used in calculating the impact of invaders on water resources (after Versfeld et al. 1998). Deciduous species are indicated with a #. For more information see the text.

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 mearnsii	3	*Paraserianthes lophantha*	1
Acacia melanoxylon	3	*Pinus* spp	3
Acacia pycnantha	2	*Pittosporum undulatum*	1
Acacia saligna	2	*Populus* spp #	3
Acacia spp	3	*Prosopis* spp	2
Alnus viridis	3	*Psidium guajava*	1
Arundo donax	2	*Pyracantha* sp	1
Caesalpinia decapetala	1	*Quercus robur #*	2
Chromolaena odorata	1	*Robinia pseudoacacia #*	2
Cupressus glabra	2	*Rubus* Sp	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		

3.3 Impacts on streamflows

3.3.1 Streamflow and other hydrological information

Given the limited budget and time frame of this study, it was necessary to restrict both the degree of manipulation of original or "raw" hydrological information for, and the scale of discretisation of, the selected catchments. Therefore, the whole study was based on a spatial resolution of so-called quaternary catchments and on readily prepared information from the WR90 national water resources survey published by the Water Research Commission (Midgley et al. 1994). This approach enabled the use of a well-prepared and internally consistent set of information for each of the study catchments. For each quaternary catchment 70-year sequences of monthly rainfall were extracted from the data sets on the WR90 CD-ROM, as were mean monthly evaporation values and catchment model parameters. (The parameters for the Pitman model had been determined on a regionalised basis by the WR90 team through an elaborate process of catchment model calibration and verification, with full recognition of the historical human-derived impacts at the quaternary catchment scale.) Quaternary catchment streamflow sequences, for both natural and invaded scenarios and each 70 years in length, were then generated by means of the catchment model, as described in section 3.4 below.

3.3.2 Streamflow reduction calculations

The impacts on streamflow were calculated using revised versions of the age-biomass models for the different growth form categories (Table 3) and a proportional flow reduction model for the relationship between biomass and flow reductions. These age-biomass models were linked to a monthly catchment model, as described in Section 3.4 below.

3.3.3 Revised age and biomass models

The relationship between biomass and age for tall trees was developed using data on the biomass of 29 and 40 year old stands of *Pinus radiata* at Jonkershoek (Van Laar and Van Lill, 1978, Van Laar 1983) and data from a *Pinus radiata* height growth model parameterised using stand measurements from the Bosboukloof catchment (Le Maitre and Versfeld 1997). The height data were used to scale the biomass data for different stand ages. The scaled data on biomass at different ages were then used to develop the following sigmoid biomass growth curve for the pine stand (Figure 1):

Pine biomass (t/ha) = $300/(1 + e^{3.67947} \times \text{Age in years}^{-1.4109})$, $r^2 = 0.96$, $n = 9$, $P < 0.01$

The relationships between biomass and age for medium trees and tall shrubs (Table 3) developed by Le Maitre et al. (1996) were also recalculated. Data on biomass and age for medium trees were obtained from Milton and Siegfried (1981) and tested with different regression models. The high biomass of young stands was matched most closely by a log regression model which gave the following relationship, which is essentially the same as the one used by Le Maitre et al. (1996):

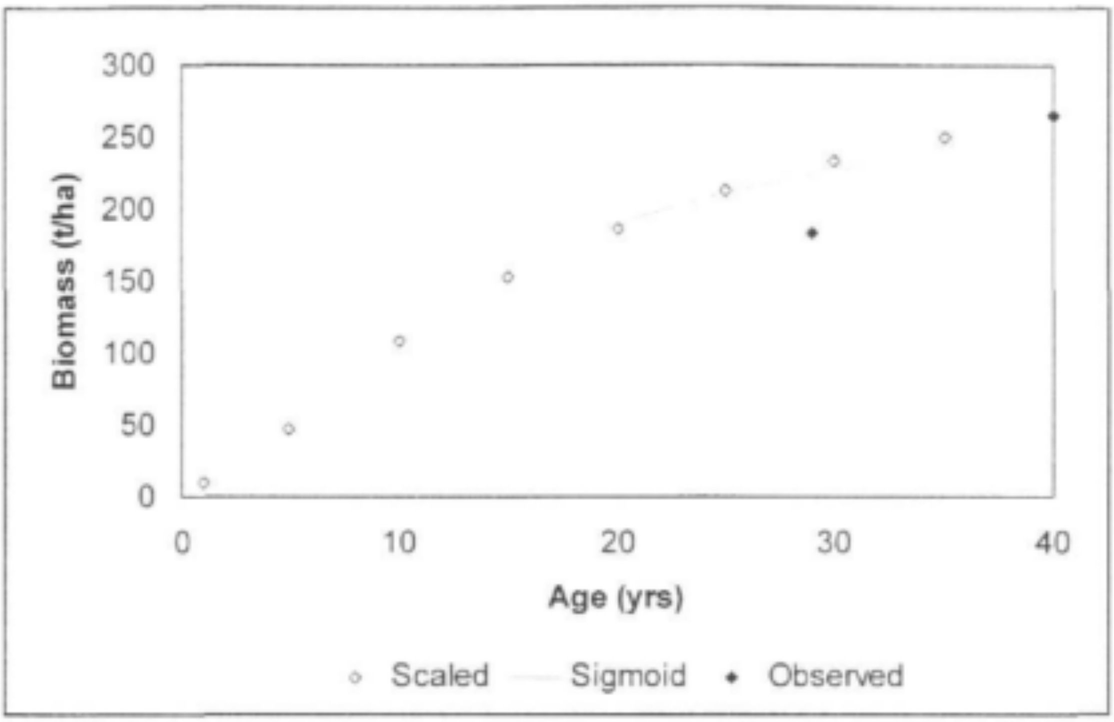


Figure 1 Relationship between age and biomass for *Pinus radiata* based on the scaled biomass using stand height and the biomass estimated from field studies. For more information see the text.

Medium tree biomass (t/ha) = 96.0732*$\log_{10}$(Age in years) - 4.8081, $r^2 = 0.98$, $n = 4$, $P = 0.01$

The biomass model for tall shrubs was developed by fitting a model to data on the age and biomass of fynbos from Kruger (1977) and Van Wilgen (1982). The only data available for the biomass of a tall shrub invaded stand is for a single, 9-year old *Hakea* stand (Van Wlgen et al. (1985). The sigmoid model for fynbos biomass was adjusted by altering the asymptote of the fitted model so that the predicted biomass at an age of 9-years matched that of the *Hakea* stand. This adjustment does not affect the other parameters. The final relationship is as follows:

Tall shrub biomass (t/ha) = $76/(1+e^{3.18628} \times \text{Age in years}^{-1.25973})$, $r^2 = 0.68$, $n = 12$, $P < 0.01$

The adjusted model now tends to a maximum biomass of about 76 tons per ha compared with the maximum of 40 tons per ha estimated for uninvaded fynbos.

3.3.4 Biomass and flow reduction

One of the complications inherent to this approach is that the flow reductions should represent the incremental flow reductions compared with a baseline state. In the case of the fynbos catchments the baseline state for the reduction is the post-fire condition where the evaporation is primarily from the soil and from resprouting plants with a low biomass (Bosch et al. 1986). The baseline in the afforested catchments was fynbos with a mixture of tall, proteoid shrublands and shorter vegetation (Rycroft 1945). The age of the fynbos was not recorded at the time but was about 19 years in the upper part of Biesievlei and about 6 years old in the lower part of the catchment (Van Wyk 1977). Assuming a mean age of 14 years, the estimated biomass of the fynbos would be about 21.4 tons/ha, equivalent to a reduction of about 0.6% of the annual runoff and 3.2% of the low flow. These values are low compared with the impacts of the plantations and well within the likely errors in the estimates; therefore the additional complications of estimating the incremental biomass relative to fynbos were omitted from this analysis. Data on the biomass of the pre-afforestation vegetation in the summer rainfall catchments were not available for calculating incremental impacts. It is unlikely that omitting the incremental biomass would have a significant effect on the results of this analysis.

An analysis of the impacts of plantations on streamflow by Scott and Smith (1997) identified two forms of flow reduction curves: (a) a long lag before a significant reduction in flow as recorded in Jonkershoek and Cathedral Peak catchments; and (b) a short lag as recorded for the Mokobulaan and Westfalia catchments. This distinction has been maintained in the development of these models with Biesievlei (*Pinus radiata*, Jonkershoek) and Westfalia D (*Eucalyptus grandis*) being selected as the two catchments for model development.

3.3.4.1 Long lag curves

The biomass model for a *Pinus radiata* stand (see above) was used to estimate the stand biomass at different ages in the Biesievlei catchment from data on the height growth of the stand (Le Maitre and Versfeld 1997). The pine biomass estimates were then regressed against the estimated percentage reductions in annual and low flows recorded for the Biesievlei catchment (Scott et al. 2000). A sigmoid relationship was evident in the raw data (Figures 2 and 3) so this form of model was used in the regression analysis. The initial regression models gave relatively high reductions (>10%) in the first and second years. An inspection of the data showed that the first two years after the planting of Biesievlei were relatively dry years. This resulted in the expected runoff values being reduced and, thus, in an overestimate of the reductions compared to later years. The values for the first two years were reduced by inspection to match the expected shape of the overall relationship. The regression analysis was repeated and the new model's predictions were much lower for the first few years.

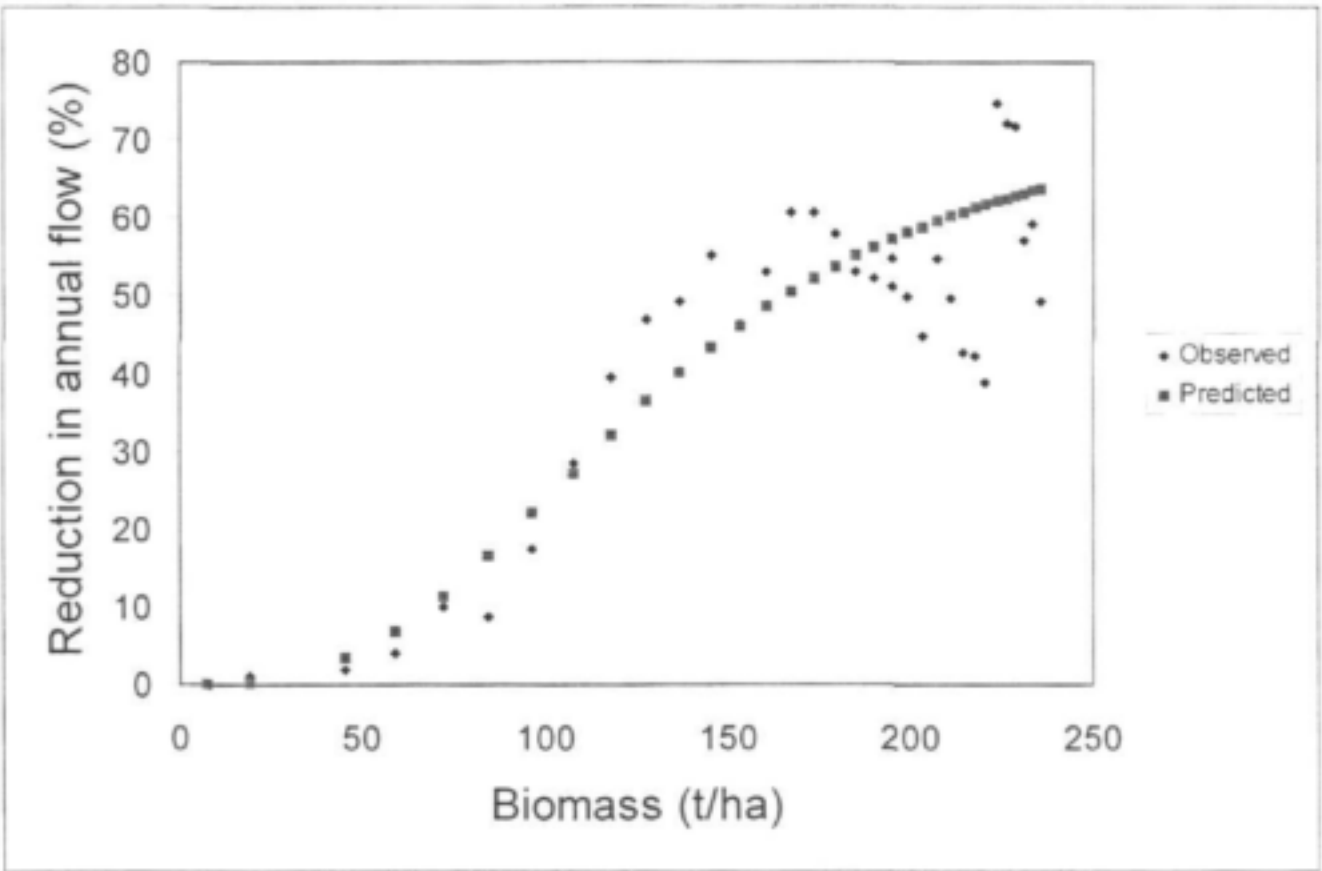


Figure 2 The relationship between the estimated biomass of a Pinus radiata stand (t/ha) and the observed annual flow reductions (%) for the Biesievlei catchment and the predictions from a sigmoid regression model. For more information see the text.

The new model of the long-lag relationship between biomass and annual flow reductions is as follows (Figure 2):

Annual flow reduction (%) = $75/(1 + e^{14.2216} \times \text{biomass (t/ha)}^{-2.9194})$, $r^2 = 0.83$, $n = 34$, $P < 0.01$

A similar procedure was used to develop a regression model of the relationship between the percentage low flow reduction and biomass (Figure 3):

Low flow reduction (%) = $100/(1+e^{10.0252} \times \text{biomass}^{-2.0927})$, $r^2 = 0.68$, n = 34, P <0.01

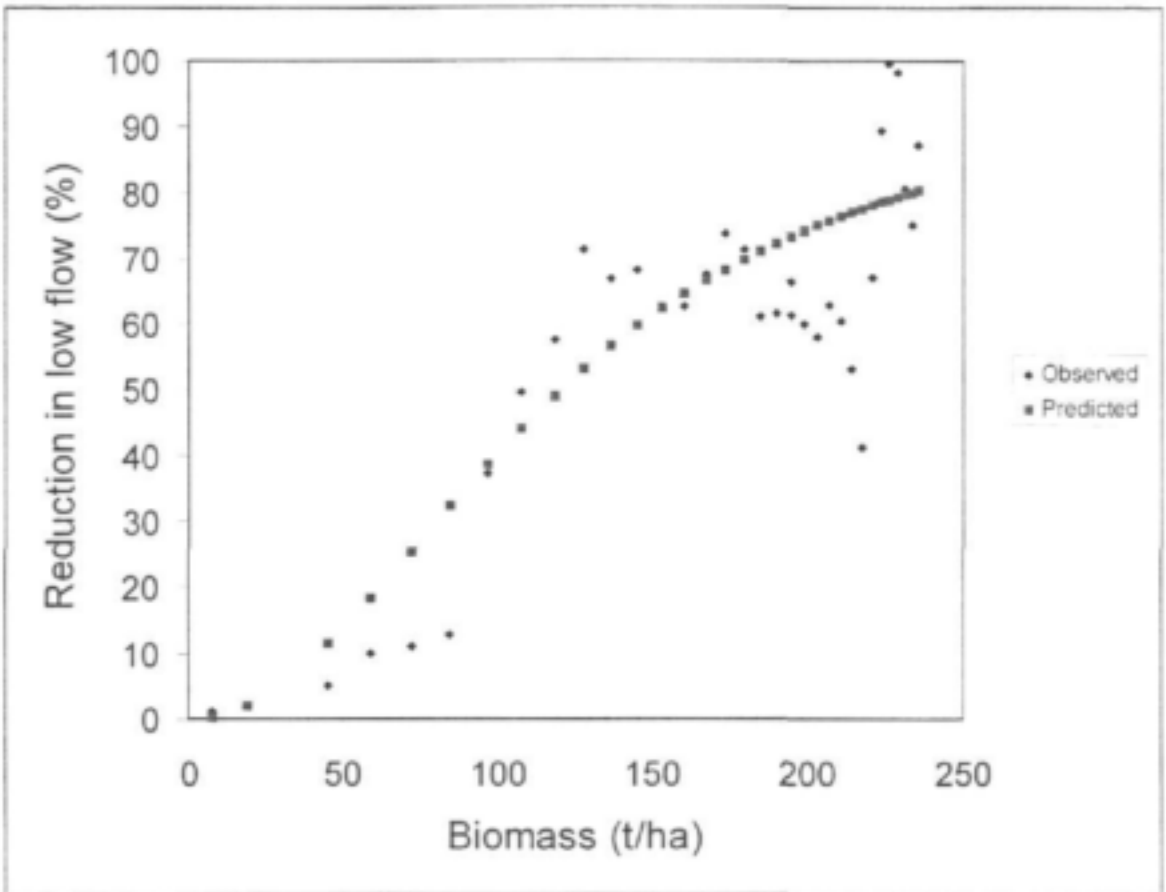


Figure 3 The relationship between the estimated biomass of a Pinus radiata stand (t/ha) and the observed low flow reductions (%) for the Biesievlei catchment and the predictions from a sigmoid regression model. For more information see the text.

3.3.4.2 Short lag curves

A biomass model was developed for *Eucalyptus grandis* (Le Maitre unpubl.) and regressed against the observed annual flow reductions in Wesfalia catchment D (Scott et al. in prep) and estimates of the low flow reductions (D. Scott unpublished). The initial regression models for annual and low flow reductions predicted high impacts (>15% and >25% respectively) in the first year after planting. As described earlier for Biesievlei, the impacts of the plantations at Westfalia were influenced by marked cycles in rainfall, which lasted for several years. In this case they resulted in high estimates of the flow reductions in the first year after planting: 13.6 and 9.1% for annual and low flow respectively. New models were fitted using the adjusted values for the first year after planting and gave the following relationships (Figures 4 and 5):

Annual flow reduction (%) = $100/(1+e^{2.2958} \times e^{\text{Biomass[t/ha]}*-0.02388})$, $r^2 = 0.86$, n = 13, P < 0.01

Low flow reduction (%) = $100/(1+e^{1.9677} \times e^{Biomass[t/ha]*-0.02474})$, $r^2 = 0.68$, $n = 10$, $P < 0.01$

3.3.4.3 Setting-up the flow-reduction models

These models can be scaled by adjusting the asymptote (numerator). They can be converted directly to proportional flow reduction models by changing the aymptote to the maximum proportional flow reduction that is expected. Because the data used to develop these models included percentage reductions much higher than the expected asymptotic values (see Figures 2-5), both the short and long lag curves of these models do not reach 100% reductions when using the tall tree biomass function for ages up to 40 years. To reach the percentage reductions suggested in Table 4, these functions need to be scaled using the following values for the asymptote (numerator):

Long lag annual flow reductions: 115
Long lag low flow reductions: 122
Short-lag annual flow reductions: 103
Short lag low flow reductions: 102

To get predicted reductions as proportions (i.e. % ÷ 100) of the flow, the asymptote's value should be divided by 100.

Table 4: Values for parameters of the flow reduction equations for the different catchments, upland and riparian invasions and annual and low flows. The low flow values represent the expected cumulative reduction over the three low flow months that occur in the average year. The values for the suggested maximum percentage and absolute reductions were selected to match the quality of the growing conditions in the different catchments. The mean age of the invaders in the different situations was based on the estimates of Versfeld et al. (1998).

Catchment	Situation	Flow period	Suggested Asymptote (%)	(mm)	Mean age (years)
Sonderend	upland	annual	83		7.5
		low flow	85		7.5
	riparian	annual	100	500	20
		low flow	100	30	20
Upper Wilge	upland	annual	100		20
		low flow	100		20
	riparian	annual	100	300	20
		low flow	100	6	20
Upper Mngeni	upland	annual	90		20
		low flow	95		20
	riparian	annual	100	400	20
		low flow	100	20	20
Sabie-Sand	upland	annual	90		20
		low flow	95		20
	riparian	annual	100	500	20
		low flow	100	35	20

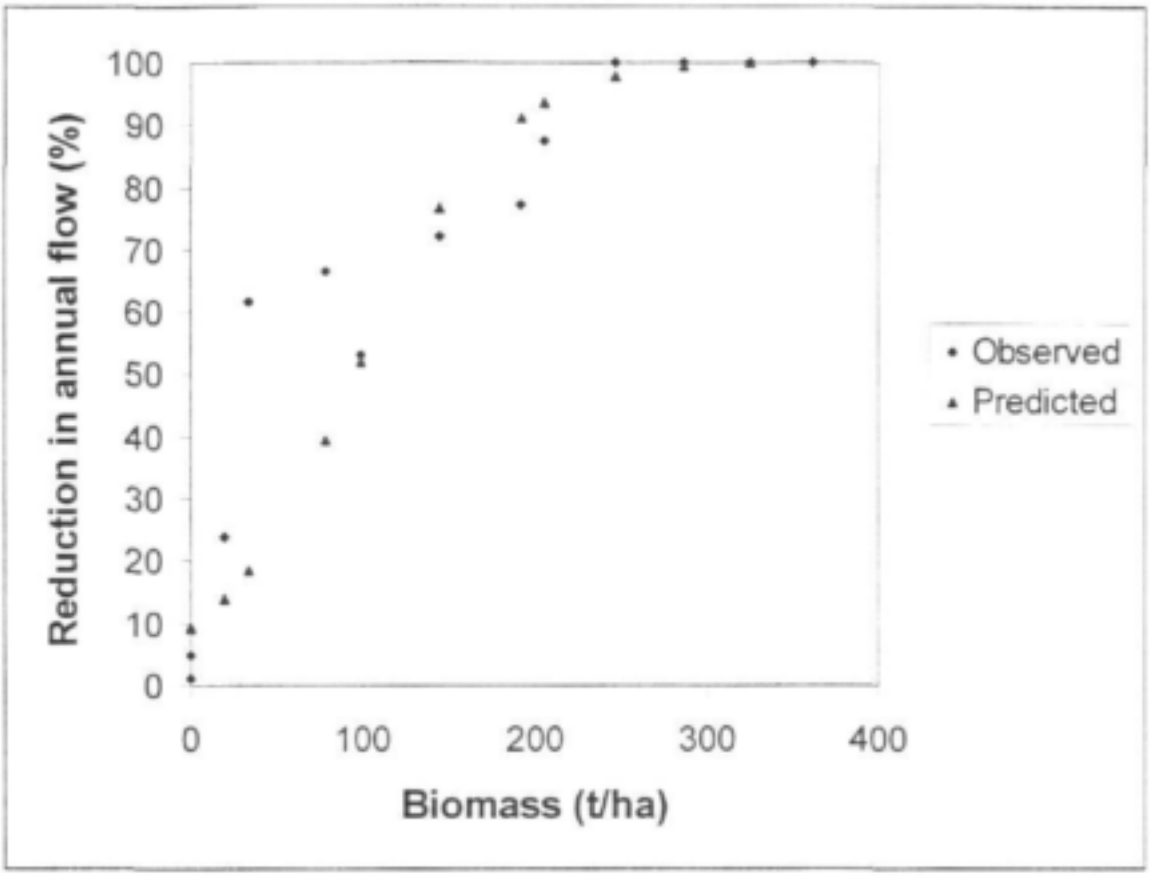


Figure 4 The relationship between the estimated biomass of a *Eucalyptus grandis* stand (t/ha) and the observed annual flow reductions (%) for Westfalia catchment D and the predictions from a sigmoid regression model. For more information see the text.

3.3.5 Calculating flow reductions

The new annual and low flow reduction models (see above) were used in conjunction with the models for the biomass and age to calculate the flow reductions for each of the biomass classes (*tall trees, medium trees* and *tall shrubs*) in stands of different ages. The values for each age in years were averaged to give the mean annual and low flow reductions (as a fraction) for stand of different mean ages. For example, if the mean age is 20 years and there is an equal area in each age class then the mean flow reduction is the mean of the age-specific annual or low flow reductions for stands of 1-40 years of age.

The models were applied to upland invasions as described above using the generated naturalised runoff for each quaternary catchment as the available flow and the suggested maximum percentage reduction (Table 4). Riparian situations are more complex, because the invader's root systems can tap either into lateral drainage towards the watercourse, or water drawn from the surface water flowing in the watercourse itself or both. Thus, the potential flow reduction in an invaded area in the riparian zone can exceed the available mean annual runoff (MAR) for the catchment if the prevailing climatic conditions do not limit evaporation to less than the MAR. The suggested maximum flow reduction (asymptote in mm in Table 4) for the catchment was used to calculate the potential reduction as a proportion of the naturalised runoff of each quaternary catchment. This was multiplied by the scaling value suggested above to give the final asymptote (numerator) for the flow reduction equations when applied to riparian invasions.

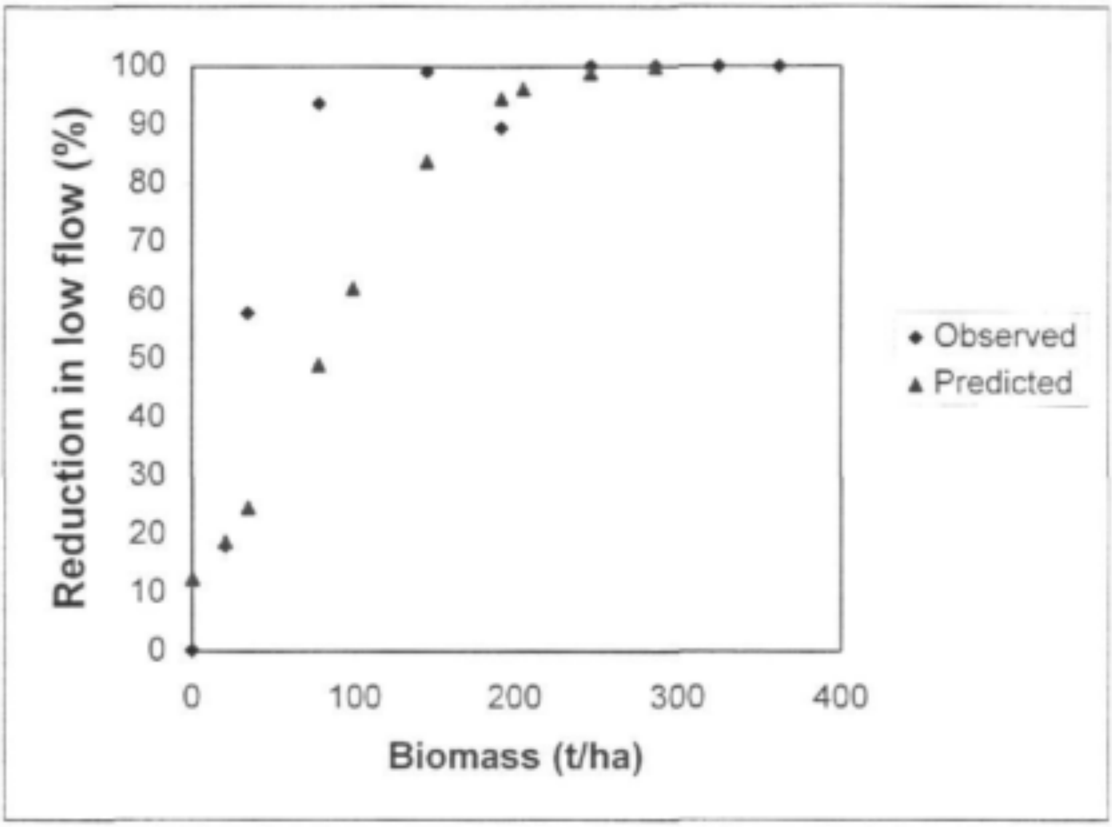


Figure 5 The relationship between the estimated biomass of a *Eucalyptus grandis* stand (t/ha) and the observed low flow reductions (%) for Westfalia catchment D and the predictions from a sigmoid regression model. For more information see the text.

3.4 Modelling of the impacts on reservoir yields

3.4.1 Catchment modelling strategy

The backbone software for this study was the SHELL modelling package, developed in-house by Ninham Shand (Berg, Beuster and Görgens, 1991). The SHELL package allows configuration of multi-catchments and multi-reservoir flow systems. It is similar to the WRSM90 modelling system (Midgley, Pitman and Middleton, 1994), but can handle a greater number of model components and human impacts than the latter, allows land-use impacts to progressively vary over time and is supported by transparent interfaces. SHELL incorporates the monthly Pitman model (Pitman, 1973), a standard rainfall/runoff model, and various other routines and can simulate, on a monthly basis:

- ◊ natural rainfall-runoff processes
- ◊ reservoir and farm dam balances
- ◊ irrigation and other abstractions

- ◊ land-use return flows
- ◊ streamflow reductions due to afforestation
- ◊ streamflow reductions due to invasive alien plants (i.e. using the equations in Section 3.3)
- ◊ alluvial river-bed transmission losses.

In the configuration of each selected catchment system the following "rules" were applied:

- ◊ each quaternary catchment was discretised into a number of modelling "cells", where each cell represented either the upland or the riparian area covered by any one of the three classes of alien plants described in Table 3, as well as one or more modelling cells representing the rest of the catchment
- ◊ the upland and riparian cells were sequenced in a manner that broadly reflected the physical reality of the catchment characteristics, so that, where applicable, riparian cells could impose streamflow reductions on flow entering from a neighbouring upstream invaded or natural cell
- ◊ in a particular quaternary all modelling cells shared the same MAP, 70-year proportional rainfall sequence, mean monthly evaporation values and model parameters (as per WR90)
- ◊ the individual quaternaries were sequenced in a manner that broadly reflected the physical reality of the catchment system characteristics, so that, where applicable, the riparian cells of downstream main-stem quaternaries could impose streamflow reductions on flow entering from a neighbouring upstream quaternary catchment.
- ◊ the degree of invasion represented by each invasion scenario was kept constant for the full 70-year simulation sequence
- ◊ no human-related impacts beyond alien plant invasions were imposed.

Diagram 1 presents a schematic for a hypothetical quaternary that illustrates the application of these "rules". Of course, each quaternary had a unique configuration that depended on its specific invasion characteristics.

3.4.2 Reservoir yield determination strategy

Reservoir yields were determined by execution of a 70-year monthly water balance, with full accounting for evaporation losses or rainfall gains, according to a "typical" log-linear surface area/storage relationship (see coefficients in Table 5). For this project *reservoir yield was defined as the maximum annual volume of water, at constant monthly distribution, that can be withdrawn from a reservoir of given size, with the reservoir "failing" a prescribed number of years out of the 70 years available.* Inability to supply the full monthly demand during at least one month in any particular year, owing to zero storage, signified one "failure". The assurance of supply of any particular yield value was intuitively defined by the prescribed number of non-failure years expressed as a percentage of 70. The recurrence interval (RI) of failure of supply was expressed by the inverse of the prescribed number of failure years expressed as a percentage of 70. Under these definitions, a 90% assurance yield, or a yield with a RI of failure of 1:10 years, represented a case of 63 non-failure years, or 7 years out of 70 in which zero storages were encountered. In favour of transparency and economy of effort, no separate allowance was made for releases for downstream environmental flow requirements. As a first approximation, such requirements could be said to form part of the particular withdrawal in any particular case analysed.

Diagram 1: Typical Shell Configuration

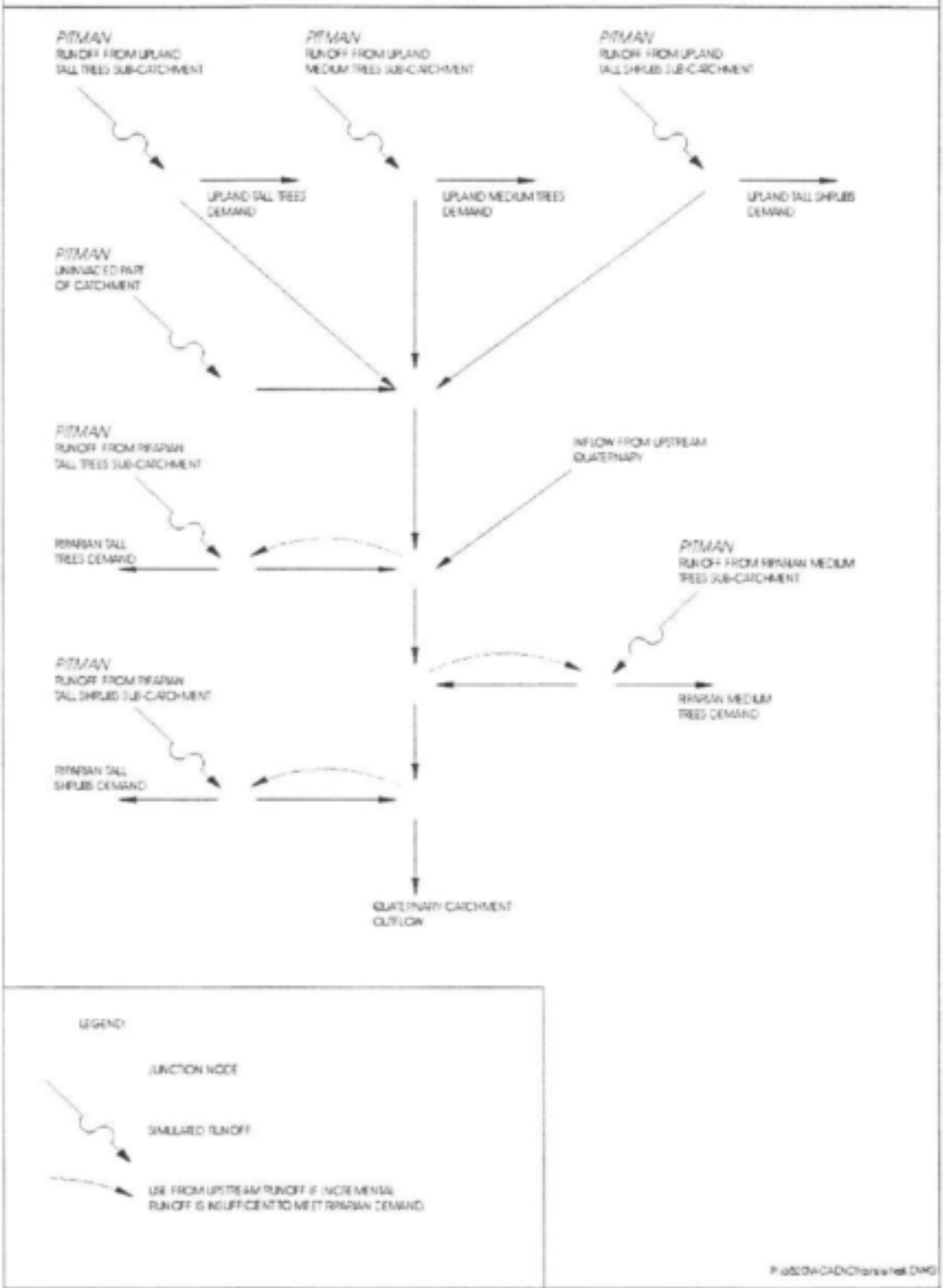


Table 5: Reservoir coefficients used for the relationship, *Area = A(Storage)^B*, for the "typical" hypothetical dams in each of the study catchments. For more information see the text.

Catchment	A	B
Sonderend	0.952	0.523
Upper Wilge	2.127	0.696
Upper Mngeni	0.429	1.009
Sabie-Sand	0.350	0.659

To accommodate the objective of exploring the influence of spatial scale on the findings, hypothetical dam sites were positioned as follows:

- ◊ *sub-system-scale*: at the most downstream point of each one of the selected river systems, i.e. all the quaternaries in that system contribute to inflow into the hypothetical reservoir
- ◊ *quaternary scale*: at the outflow point of each of a maximum of two individual tributary quaternaries in each selected system, chosen so that they represent different rainfall conditions

The reservoir balance simulations were conducted using the program, AUTORES, which performs an automatic search for a yield that causes a prescribed number of failures. The program progressively adjusts a user-supplied initial yield until the prescribed number of zero storages are achieved, according to a convergence testing procedure. Because different water user sectors have varying assurance of supply requirements, it was deemed important that the analysis should span a wide range of assurances/RIs of failure. Although seven different assurances were initially analysed, as shown in Figure 6, for the sake of clarity it was decided to report only on two: RIs of failure of 1: 70 years and 1:2 years, thereby spanning "droughts" from very extreme to very frequent in nature. An example of this form of reporting is given in Figure 7. The results for these two cases always enveloped the other five cases.

The case of RI=1:70 years can be loosely interpreted as the so-called "Historical Firm Yield" (HFY) according to current South African water resources analysis terminology. The HFY is a common measure used for inter-comparison of alternative proposed water resources schemes. In stochastic analyses across a range of South African river systems, the HFY has commonly been found to have RIs of failure between 1:50 and 1:150 years, which is the range within which a large part of urban domestic and industrial water supplies have to be assured. The 1:2 year RI yield is highly relevant to rural community water supplies and environmental requirements.

For each of the above prescribed RIs, a yield-storage relationship was developed over the following range of live storages: 20, 50, 100, 150, 200, 250% of natural MAR. Yield reduction impacts registered for the 20% MAR case can be said to approximate run-of-river conditions, which are particularly relevant to rural water supply schemes and for environmental requirements. The large (≥100%MAR) storages are included to throw light on the sensitivity of yield reductions in the situations where a major part of the yield is dependent on multiple years of above-average rainfall and runoff.

Surface area-capacity coefficients for the dams in each catchment (Table 5) were obtained from water resources consultants who have conducted studies for DWAF in each of those catchments and which represent typical, rather than specific, dams. Coefficients for the Sonderend and Upper Mngeni catchments were obtained from Ninham Shand and for the Wilge and the Sabie –Sand from BKS.

In all cases the storage-yield relationships were "standardised" (or made dimensionless) by expressing their values as a percentage of the naturalised MAR at the site of the hypothetical dam. This enabled comparisons across bioclimatic regions and spatial scales.

3.5 Potential impacts on reservoir yields and/or assurance of supply

To determine the potential impacts of invasions in the selected catchment systems on reservoir yields, the invaded scenario yields for specific RIs, as percentage of natural MARs, were subtracted from those for the natural condition, for each reservoir size and invasion case simulated. The results were displayed as incremental yield reductions versus reservoir size and are discussed in Section 4 below.

4. RESULTS

4.1 Dam storage-yield-assurance relationships

The results indicate a non-linear and complex relationship between dam size (as maximum live storage), yield and assurance level in all the catchments. These relationships are well-known to civil engineers and other water resources management practitioners, but for the benefit of readers from other disciplines and experience, these relationships are elaborated by using the Upper Wilge as an example. In Figure 6 it can be seen, for instance, that at a 99% assurance (failure of supply RI ≈1:70 years), a dam size on the Upper Wilge equal to 20% of naturalised MAR yields about 18% of MAR, while a dam size of 250% MAR yields about 43% of MAR. For all the assurance levels the increase in yield with increasing dam size is initially rapid but then decelerates towards an asymptote. For example, at 99% assurance (RI ≈1:70 years), an increase in dam size from 200 to 250% of MAR (increment of 225 million m^3) in the Upper Wilge yields only 1.1% (increment of 5 million m^3) more yield. In fact, any increase in dam size above 100% MAR (naturalised) appears relatively unfavourable, because of rapidly decreasing incremental yield returns. The yields, for a given dam size, also decrease rapidly as the level of assurance increases. In the Upper Wilge, the yield for a dam with a capacity of 100% of the MAR decreases from 87% to 37% as the assurance level increases from 50% (failure of supply RI = 1:2 years) to 99% (failure of supply RI = 1:100 years).

The latter observation has a significant implication for catchment situations where human-related impacts reduce streamflow, namely that the yield from a given impoundment can be maintained in the face of such impacts only if a lower assurance level, or higher RI of failure of supply, would be accepted by the affected water users.

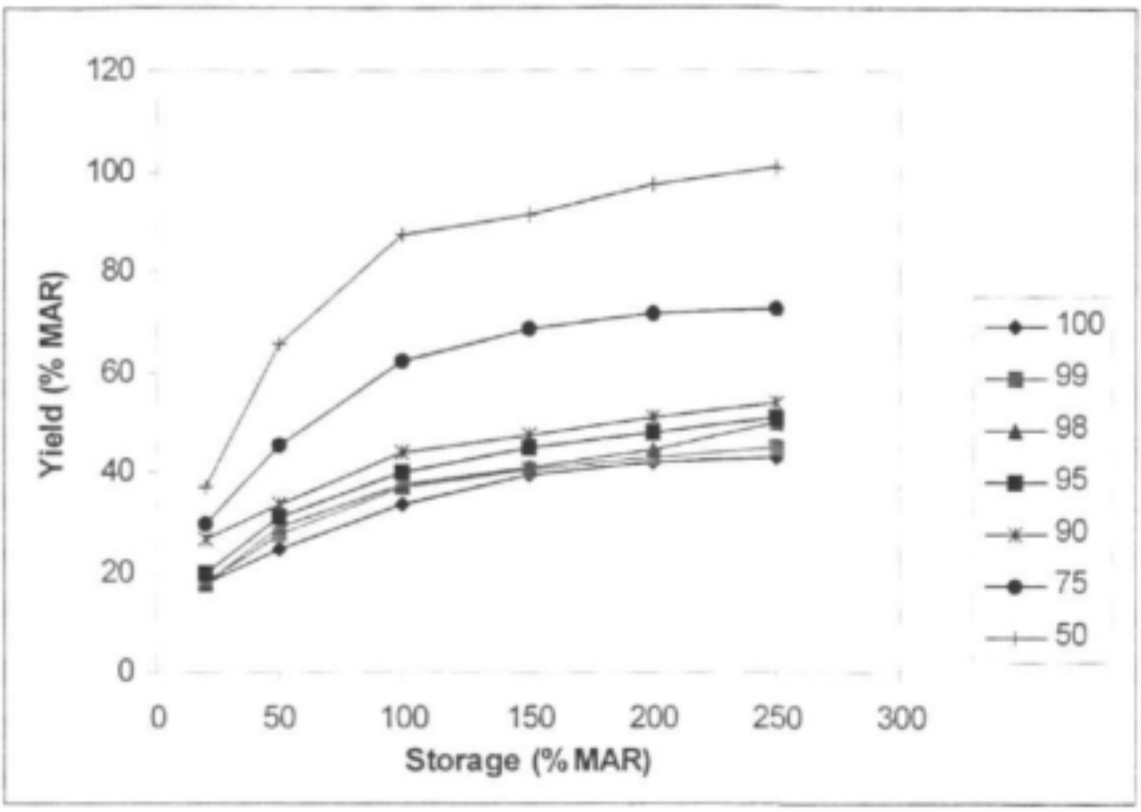


Figure 6: Relationship between storage capacity and the average yield for the Upper Wilge catchment for different levels of assurance of supply from 50% (35 failures years out of 70) to 100% (just avoiding one failure year in 70). This simulation was done using the naturalised monthlv flows. For more information see the text.

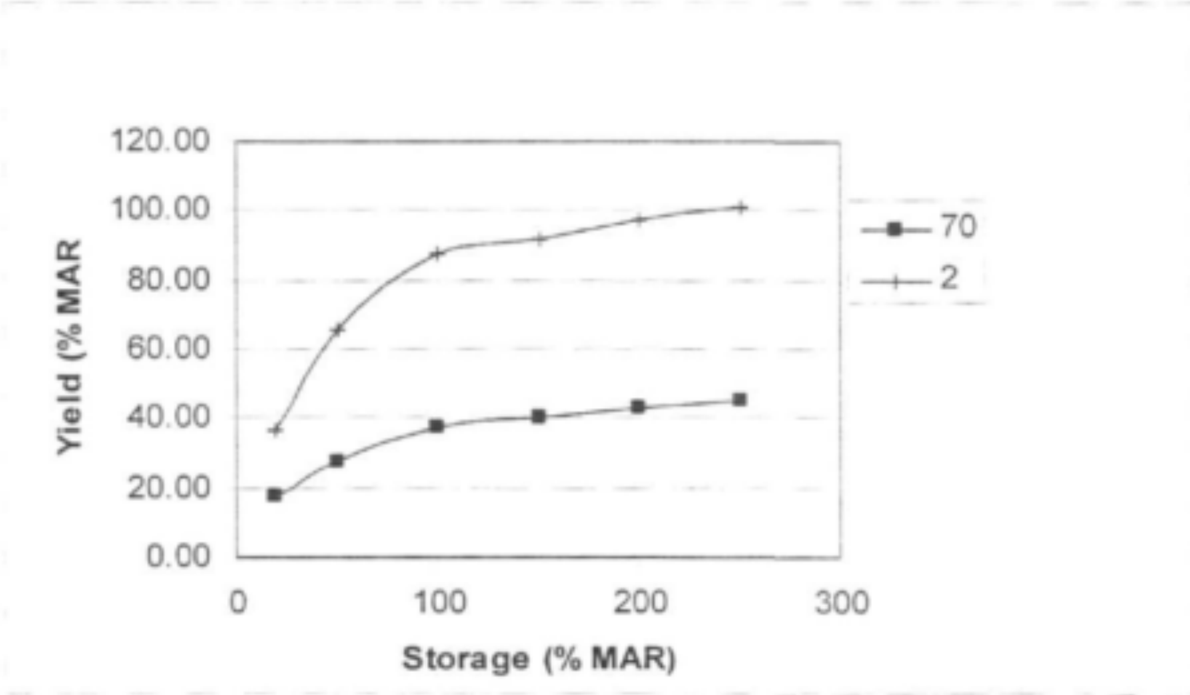


Figure 7: Relationship between storage capacity and the average yield for the Upper Wilge catchment for levels of assurance of supply for 50% (35 failures years out of 70) and 100% (just avoiding one failure year in 70). This simulation was done using the naturalised monthly flows. For more information see the text.

4.2 Degree of Invasion

The status of invasions differs among the four river systems (Table 6). The Sonderend has the greatest percentage invaded – 27% of the total area with a mean canopy cover of about 20%, which converts to 5.3% in terms of equivalent dense cover (i.e. expressed as the equivalent area of dense stands). Most of the invasions in this catchment are non-riparian and are dominated by tall trees such as pines in upland situations and black wattle and eucalypts along the rivers. The upper catchments are the worst affected with H60B having the most extensive invasions. The Upper Wilge system, by comparison, is the least invaded but the invasions are typically dense and dominated by tall trees, mainly wattle and eucalypts. Quaternary catchment C81A is the worst invaded – about 4% of the total area or about 2.0% using the equivalent dense area. The figures for the Upper Mngeni are misleading because only the riparian zones were mapped and these, of course, make up a small proportion of the catchment. A more meaningful figure is that about 41% of the riparian zones has been invaded, mainly by wattles, and the mean canopy cover is about 30%. The worst affected is catchment U20B where about 6% of the total area (2.1% equivalent dense) or 45% of the riparian zones has been invaded. About 23% (143 300 ha) of the Sabie-Sand catchment has been invaded (excluding invaders in plantation areas) with a mean canopy cover of 22%. Most invasions are in the riparian zones and these are dominated by tall shrubs (e.g. *Solanum mauritianum*, *Caesalpinia decapetala*). The worst affected quaternaries are X31G (49% of the total area), X32A (50%) and X32D (56%) with dense invasions along most rivers. Overall the Sand River appears to be more invaded than the Sabie River. There are few woody invaders in the sub-catchments of the lower system, especially below the Sabie-Sand confluence. There are extensive landscape invasions of *Opuntia* species in the Kruger National Park (tertiary X33) but they can be expected to have little impact on the streamflow.

Table 6: Summary of current and future extent of invasions in each of the catchments divided into upland and riparian situations, and different biomass classes. The equivalent dense area is the area when the average canopy cover is converted to 100%.

Catchment	Total invaded area (%) / mean canopy cover (%)	Situation	Biomass class	Equivalent dense area			
				Current		Future (10years)	
				(ha)	(%)	(ha)	(%)
Sonderend	27.0 / 19.7	Upland	Tall shrubs	1892	0.56	2981	0.88
			Medium trees	908	0.27	1440	0.43
			Tall trees	10873	3.23	17177	5.10
		Riparian	Tall shrubs	46	0.01	69	0.02
			Medium trees	842	0.25	1229	0.36
			Tall trees	3375	1.00	4870	1.44
Wilge	1.9 / 53.9	Upland	Tall shrubs	0	0.00	1	0.00
			Medium trees	317	0.05	772	0.13
			Tall trees	2071	0.34	4938	0.80

		Riparian	Tall shrubs	1	0.00	3	0.00
			Medium trees	259	0.04	559	0.09
			Tall trees	1164	0.19	2504	0.41
Upper Mngeni	5.6 / 30.7	Riparian	Tall shrubs	48	0.05	74	0.08
			Medium trees	37	0.04	56	0.06
			Tall trees	1889	2.04	2907	3.14
Sabie-Sand	22.7 / 22.1	Riparian	Tall shrubs	14295	2.26	23903	3.78
			Medium trees	7432	1.18	11482	1.82
			Tall trees	7979	1.26	12493	1.98

4.3 Reductions in MAR and monthly low flows

Table 7 demonstrates the potential decreases in MAR for *Naturalised*, as opposed to *Current* and projected *Future* infestation conditions, for the selected catchments at the full aggregated system scale. Significant loss of total runoff is evident in both the Sonderend and Sabie-Sand river systems and is projected to worsen markedly over the next ten years. The loss in total runoff is not yet severe for the Upper Wilge and the Upper Mngeni.

Table 7: Mean annual runoff (MAR) and the reductions in runoff as a result of current and predicted future (over 10 years) alien plant invasions in the study catchments.

Catchment	Naturalised MAR (million m^3)	Reduction in naturalised MAR as a percentage	
		Current	Future (10 years)
Sonderend	457	4.8	6.6
Upper Wilge	450	1.2	1.6
Upper Mngeni	207	1.5	2.1
Sabie-Sand	721	9.7	12.7

Impacts on low flows are particularly important to the run-of-river utilisation of the water resource; this is always the case for environmental water requirements and often the case for rural community water supply. Table 8 provides some indication of the extent of the impacts on the low flows, where the latter are defined as all monthly values below the 75th percentile of the monthly flow series in each case. Notable is the fact that in the three river systems located in the summer rainfall region, the relative impact on low flows appears to be more pronounced than on the rest of the monthly flow regime. In the Sonderend, which is subject to winter rainfall, this is not the case for current day conditions, but in 10 years' time, the relative low flow impacts are projected to start overtaking those imposed on the higher flows.

4.4 Reductions in reservoir yield at river system scale

Figures 8 to 12 and Table 9 present the potential reduction in yields versus dam size (as maximum live storage) for all the selected river systems for current and projected future invasions, as well as for the selected two RIs of failure of supply, in various formats and modes. Each presentation of the results is systematically discussed in the sub-sections below. The first two sections deal with the reductions in volume and the next two with the proportional reductions in yields relative to the yields under virgin conditions.

Table 8: Monthly runoff statistics for the different catchments for naturalised flow and the reductions in both low and high monthly flows due to current and projected invasions by alien plants.

Catchment	Statistic	Naturalised mean monthly runoff (million m^3)		Reduction in indicated component of monthly runoff as percentage of naturalised MAR			
		High[2]	Low[1]	Current		Future (10years)	
				High[2]	Low[1]	High[2]	Low[1]
Sonderend	Mean	50.27	1.84	5.3	3.8	6.6	6.0
	Median	34.16	1.46	4.9	3.8	6.9	6.2
Upper Wilge	Mean	49.27	2.19	1.2	1.8	1.6	1.9
	Median	13.16	2.21	0.9	1.8	1.4	1.9
Upper Mgeni	Mean	22.13	2.68	1.4	1.9	2.0	2.8
	Median	13.92	2.73	1.7	2.6	2.2	3.1
Sabie-Sand	Mean	74.82	15.77	9.0	10.7	13.0	15.5
	Median	42.47	15.64	9.5	10.9	12.9	15.9

[1] : Monthly streamflow values below the 75 %-tile; [2] : Monthly streamflow values above the 75th percentile

Table 9: Potential absolute reductions in yield (in Mm^3/a) for Recurrence Intervals (Ris) of failure for each of the selected river systems and for current and projected future invasions.

State of Invasion	River	Reduction in Yield for RI = 1:70 Years (in Mm^3)						River	Reduction in Yield for RI = 1:2 Years (in Mm^3)					
		Live Storage as % Nat. MAR							Live Storage as % Nat. MAR					
Present		*20*	*50*	*100*	*150*	*200*	*250*		*20*	*50*	*100*	*150*	*200*	*250*
	Mngeni	0.9	1.1	1.7	2.1	2.0	2.0	Mngeni	0.7	2.6	2.2	2.9	2.9	2.9
	Sonend	4.9	10.1	12.8	15.5	15.6	15.5	Sonend	2.7	12.6	17.6	26.0	25.6	27.8
	Wilge	0.7	1.2	1.3	1.3	1.7	1.7	Wilge	0.7	3.2	4.6	3.2	5.2	4.9
	Sabie	27.3	35.2	45.2	45.4	45.4	47.8	Sabie	32.7	43.7	51.9	49.4	78.5	68.4
Future														
	Mngeni	1.2	1.1	2.4	2.9	2.8	2.8	Mngeni	1.2	3.7	3.1	4.1	4.1	4.1
	Sonend	6.6	13.7	17.1	20.2	20.3	20.3	Sonend	3.8	18.5	22.9	34.4	33.6	32.5
	Wilge	0.8	1.5	1.2	1.5	2.3	2.3	Wilge	0.8	4.2	6.1	4.2	4.9	6.1
	Sabie	38.0	52.7	63.9	64.9	64.1	64.1	Sabie	42.7	65.4	72.7	73.6	114.0	96.7

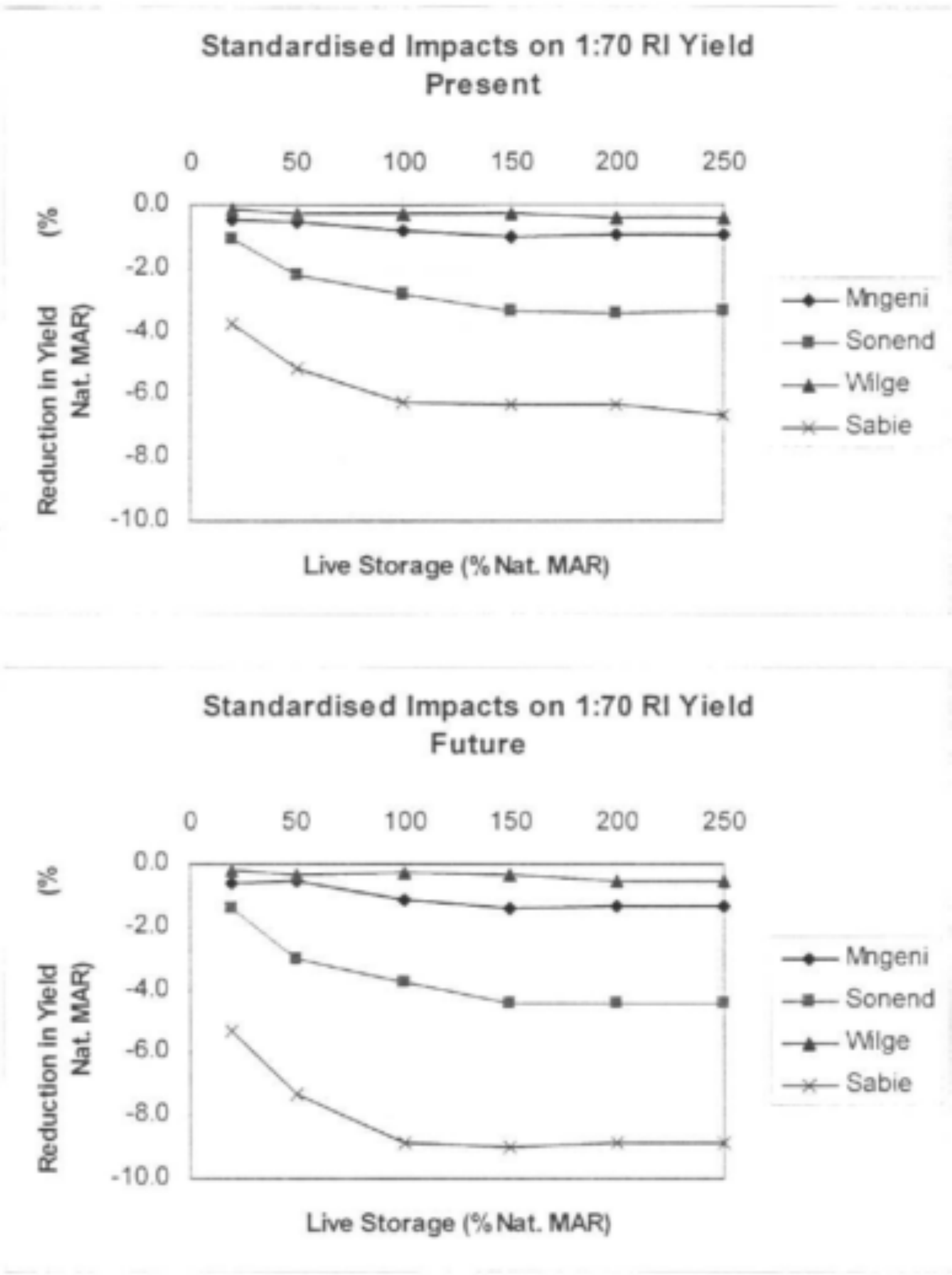
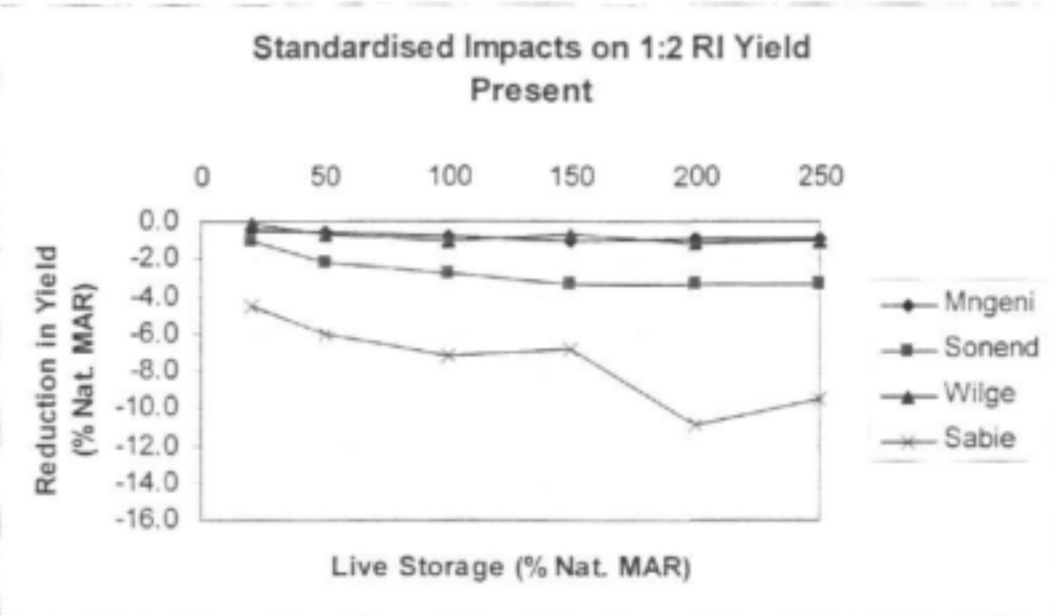


Figure 8: Potential *standardised* reduction in 1:70 year RI of failure yields as a function of maximum live storage for each the four river systems investigated and for both current and projected future (10 years) invasions.



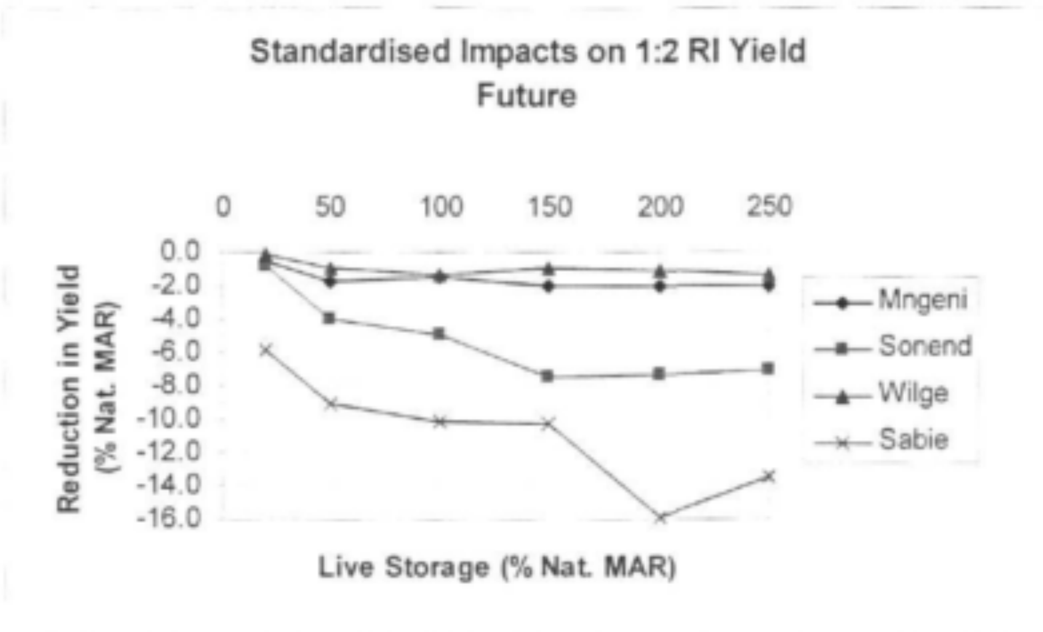


Figure 9: Potential *standardised* reductions in 1:2 year RI of failure yields as a function of maximum live storage for each the four river systems investigated and for both current and projected future (10 years) invasions

4.4.1 Yield reductions in absolute volumetric terms

Table 9[1] presents the *absolute* potential reduction in yields (in Mm^3/a) versus dam size (as maximum live storage) for all the selected river systems for current and projected future invasions, as well as for the target RIs of failure of supply. Most notable are the potential impacts in the Sabie-Sand system, where potential yield reductions can be expected to already exceed 60 Mm^3/a, and to start approaching 100Mm^3/a in 10 years' time, if not checked. The potential reductions (in Mm^3/a) in the Sabie-Sand and the Sonderend systems far exceed those in the Upper-Mngeni and Upper-Wilge systems. Such differences may have implications for the prioritisation of alien plant eradication projects.

4.4.2 Yield reductions in standardised volumetric terms

The results described above appear to be in line with the lower degree of invasion in the latter two systems reported in Table 6. However, results in such absolute terms are difficult to compare between catchments, given their differing areas and hydrological response characteristics. Therefore, to aid such a comparison, the yield reductions for each hypothetical dam were "*standardised*" by the naturalised MAR at each hypothetical dam site and presented graphically, as depicted in Figures 8 and 9[1]. The following points are of interest:

◊ The potential standardised reductions in yield for the Sabie-Sand and Sonderend River systems far exceed the equivalent values for the Mngeni and the Wilge – the latter two sets of impacts being relatively insignificant.

◊ The range of potential standardised reductions in yield for the Sonderend varies from about 3% to 8% of naturalised MAR for dam sizes exceeding 50% naturalised MAR across all cases considered. This can be compared with MAR reductions between 5% and 7%.

◊ The range of potential standardised reductions in yield for the Sabie-Sand varies from about 6% to 16% of naturalised MAR for dam sizes exceeding 50% naturalised MAR across all cases considered. This can be compared with MAR reductions between 10% and 13%.

◊ During the next 10 years marked increases in standardised yield reductions are estimated for the

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1 It should be noted that in some instances, for dam sizes of 100% naturalised MAR or greater, the potential yield reductions do not always increase uniformly, but may fluctuate. This is an artifact of two separate processes:

◊ the numerical convergence procedure used in the AUTORES program to determine yields according to prescribed numbers of failures

◊ the fact that for larger dam sizes the critical drawdown periods increase in duration and may change in timing of onset, which in turn have minor effects on the calculation of net evaporation, which ultimately affects the yield.

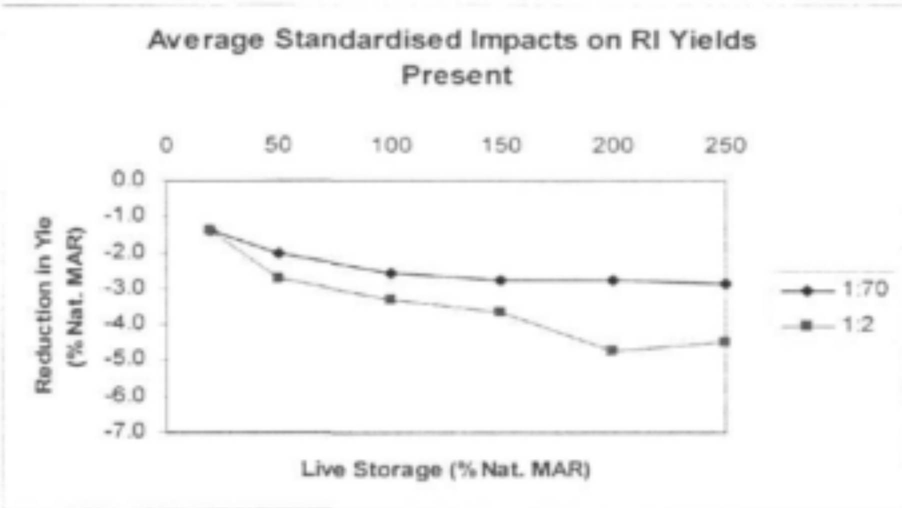
Fortunately, these artificial fluctuations are never large enough to obliterate the underlying patterns in the yield reductions.

Sabie-Sand and Sonderend Rivers.

4.4.3 Yield reductions in average standardised volumetric terms

Figure 10 depicts the potential standardised reductions in yields (as % naturalised MAR), *averaged* for all the selected river systems for current and projected future invasions, for the selected two RIs of failure of supply. The following points are of interest:

◊ For the high assurance case (RI of failure = 1:70 years) the average standardised yield reductions do not increase much with maximum live storage beyond a size somewhere between 100% and 150% naturalised MAR.



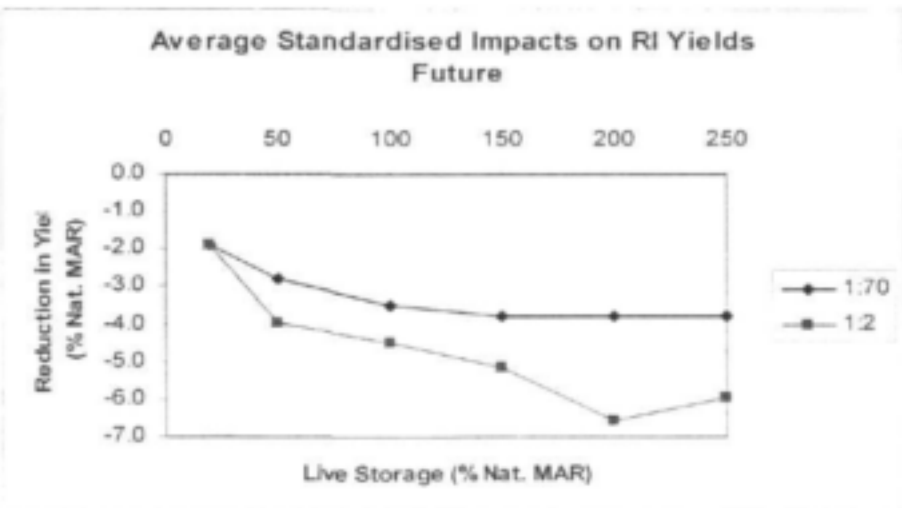


Figure 10: Potential *standardised* reduction in RI-based yields as a function of maximum live storage, *averaged* over the four river systems investigated and for both current and projected future (10 years) invasions.

- ◊ For the low assurance case (RI of failure = 1:2 years) the average standardised yield reductions continue to increase across the range of dam sizes examined, albeit at steadily reducing rate of increase.
- ◊ For all dam sizes beyond 50% naturalised MAR the magnitudes of the average standardised reductions are notably greater for the low assurance yields than for the high assurance values.
- ◊ The projected invasions during the next 10 years are estimated to increase the average low assurance yield reductions (standardised) generally by about 50% and the high assurance yield reductions (standardised) by about 35%, relative to naturalised conditions.

4.4.4 Yield reductions in proportional terms

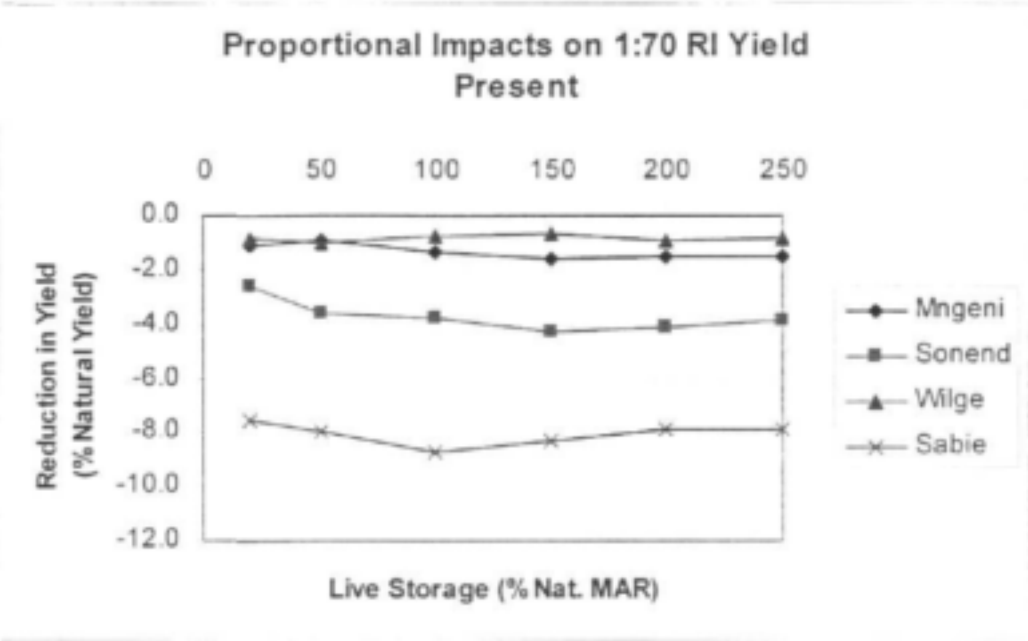
A useful format for comparison of upstream impacts on a characteristic of water resources is to express each impact as a *proportion* (or percentage) of the original value of the characteristic, as was done for MAR in Table 7. Figure 11 presents the comparison of potential yield reductions on such a proportional basis for the case of 1:70 years RI of failure of supply. The 1:2 years RI case is not shown, as it conveys a similar message as Figure 11. The following points are of interest:

- ◊ For dam sizes of 50% naturalised MAR and greater the proportional yield reductions are relatively constant.
- ◊ As can be expected, the proportional yield reductions in the Sabie-Sand and the Sonderend cases are considerably more significant than in the other two systems.
- ◊ For the Sabie-Sand the proportional yield reductions for dam sizes equal to or greater than 50% natural MAR averages at about 8% (present) and 11% (future). This can be compared with MAR reductions of 10% and 13%, and mean low flow reductions of 11% and 16%, respectively.
- ◊ For the Sonderend the proportional yield reductions for dam sizes equal to or greater than 50% natural MAR averages at about 4% (present) and 6% (future). This can be compared with MAR reductions of 4% and 6%, and mean low flow reductions of 5% and 7%, respectively.
- ◊ Increases in the proportional yield reductions between the present and the future scenarios are considerably less pronounced than for the standardised volumetric analysis presented in Section 4.4.2.

4.4.5 Yield reductions in average proportional terms

When the potential proportional yield reductions are presented as *averages* over the four systems investigated, then Figure 12 results. The following points are of interest:

- ◊ The averages for each RI case vary within a sensibly narrow range and for practical purposes can be viewed as constant for dam sizes greater than 20% naturalised MAR.
- ◊ The means of the average proportional yield reductions for the two RIs for dam sizes above 20% naturalised MAR are practically identical. For the present scenario the mean reduction is 3.6% and for the future scenario it is 5.0%. This can be compared with mean MAR reductions according to Table 7 of 4.3% and 5.8%, respectively.



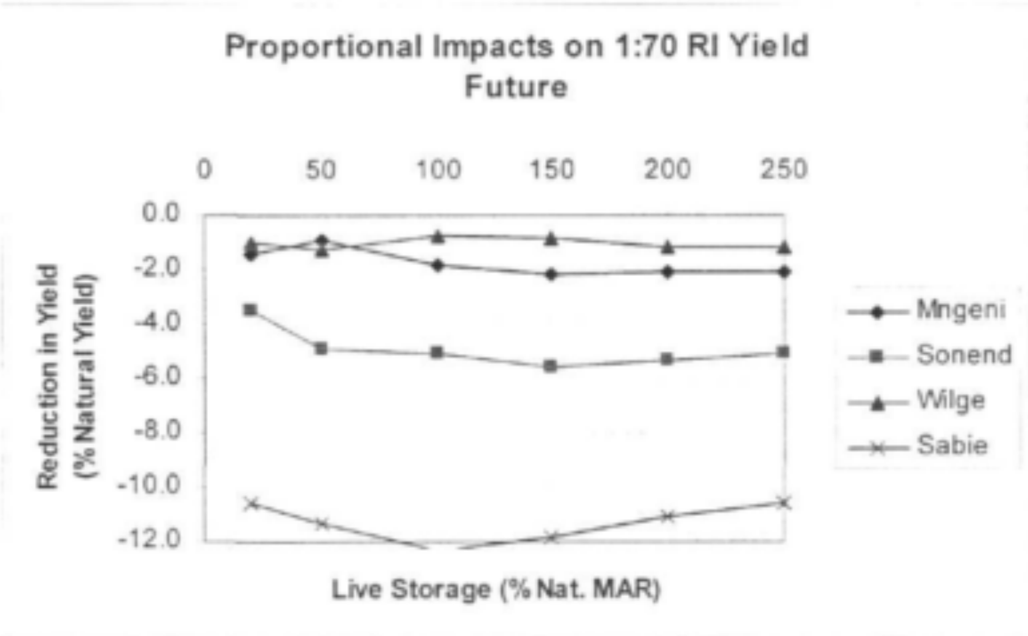
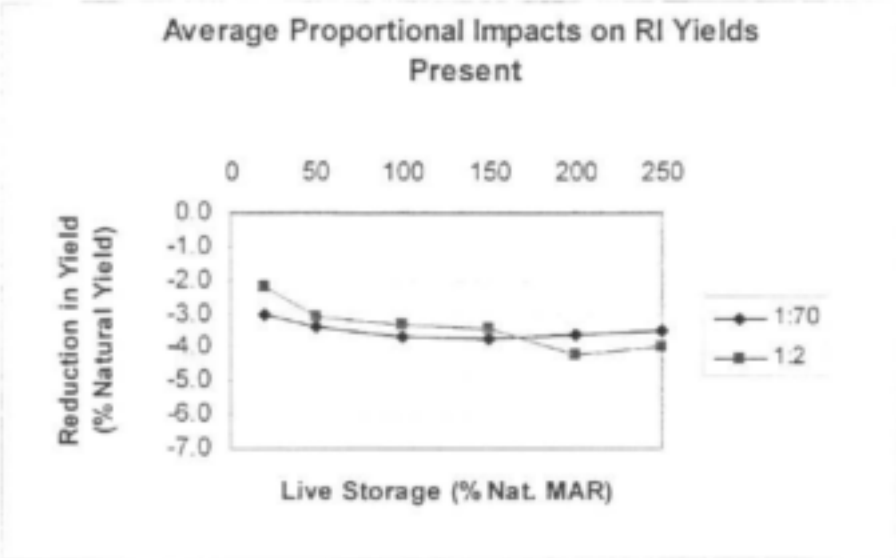


Figure 11: Potential *proportional* reduction in 1:70 year RI of failure yields as a function of maximum live storage for each the four river systems investigated and for both current and projected future (10 years) invasions.



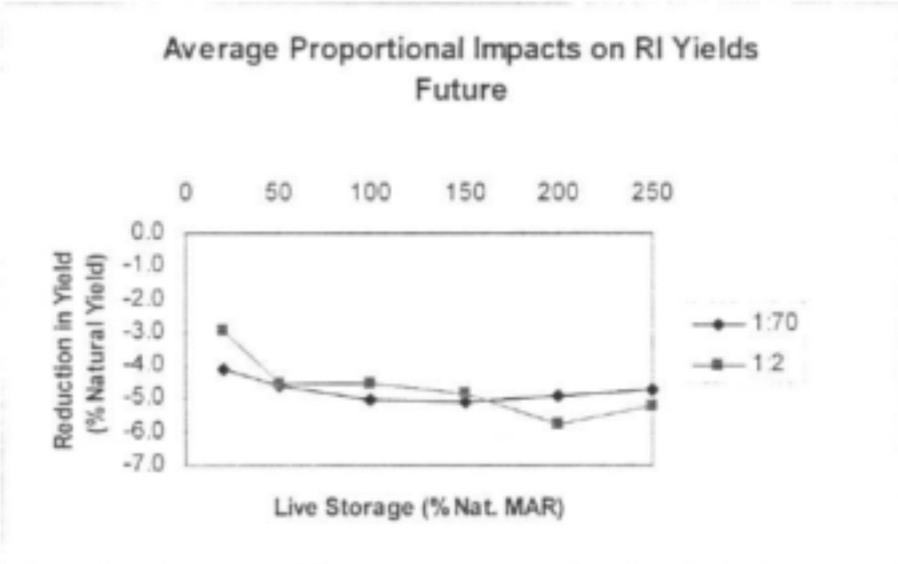


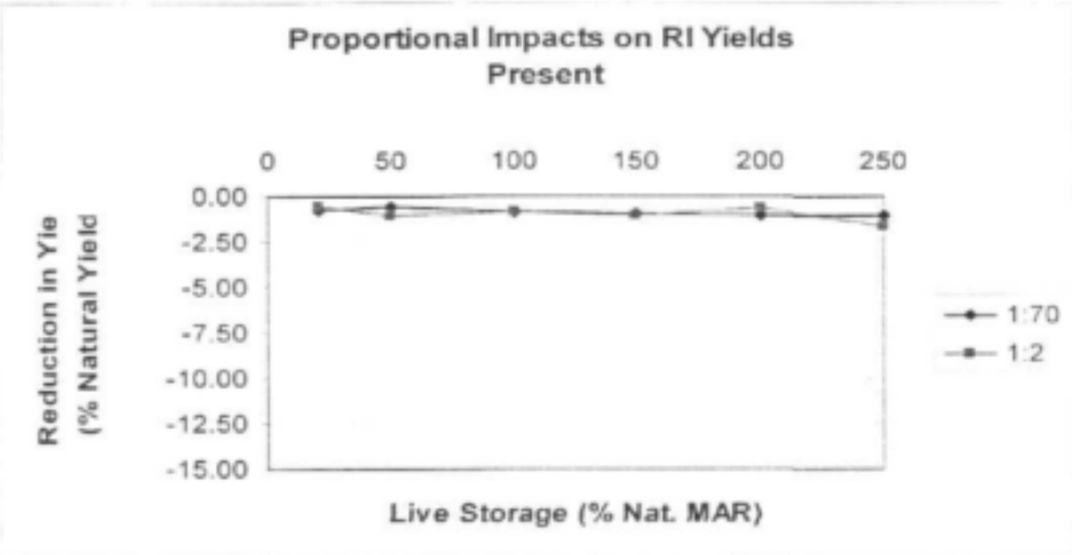
Figure 12: Potential *proportional* reduction in RI-based yields as a function of maximum live storage, *averaged* over the four river systems investigated and for both current and projected future (10 years) invasions.

4.5 Reductions in yield at quaternary catchment scale

Figures 13 to 19 and Table 10 present the proportional potential reduction in yields versus dam size (as maximum live storage) for selected quaternary catchments and for current and projected future invasions, as well as for the selected two RIs of failure of supply. Each presentation of the results is systematically discussed in the sub-sections below.

Mngeni U20B

Figure 13 presents the Mngeni proportional reductions. As can be expected from the relatively low level of general infestation, the proportional yield reductions are low and of a similar value to that for the whole Mngeni system. These potential reductions are also relatively constant over the range of dam sizes.



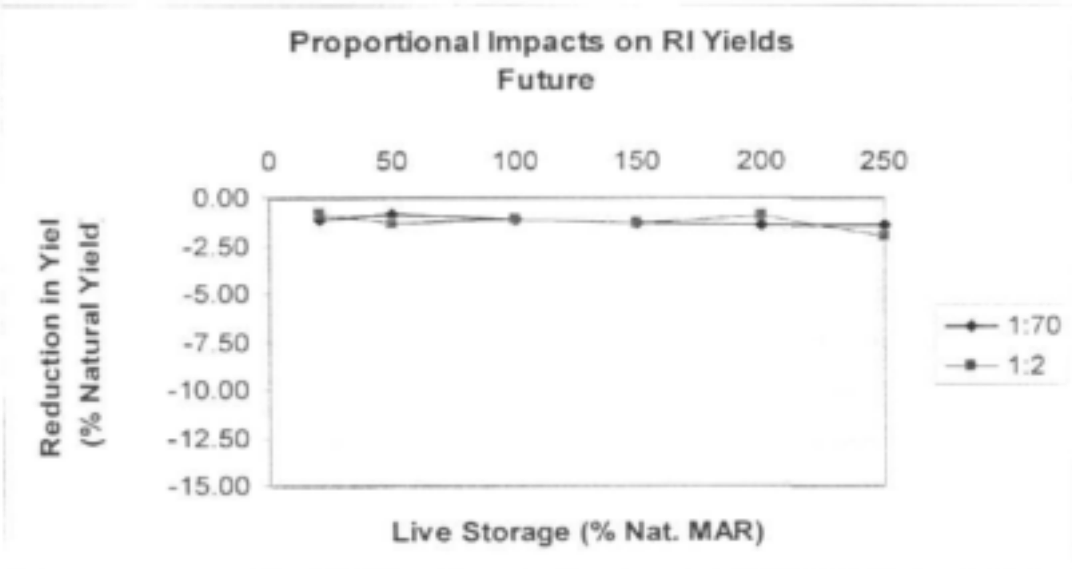
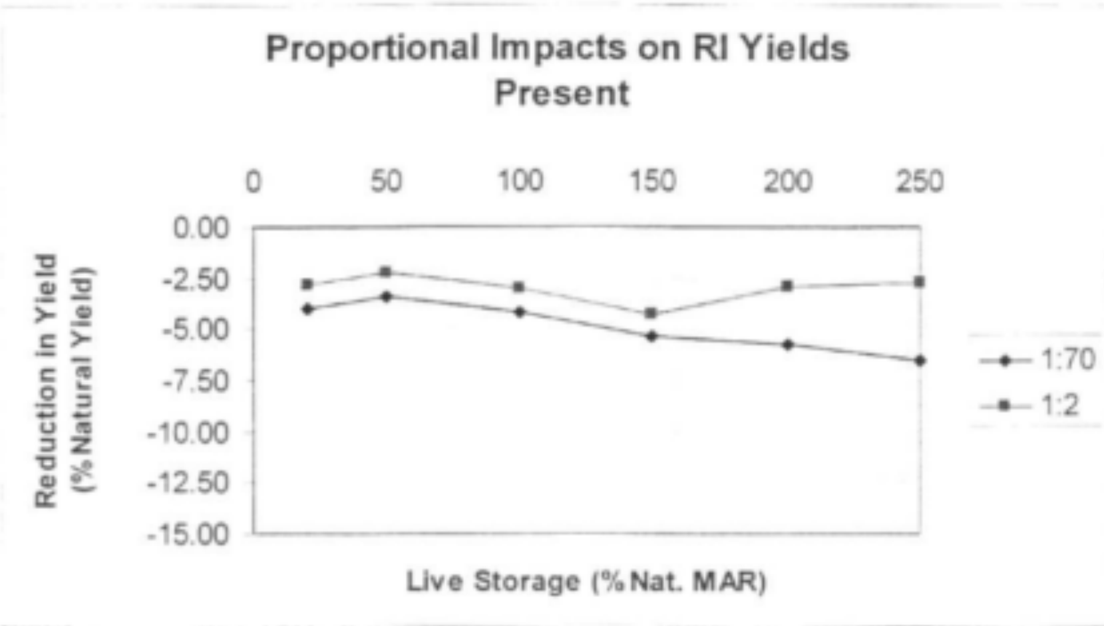


Figure 13: *Proportional* reduction in RI-based yields as a function of maximum live storage, for quaternary Mngeni U20B and for both current and projected future (10 years) invasions.

Table 10: Potential absolute reductions in yields (in Mm^3/a) for RIs of failure for each of the selected quarternaries and for current and projected future invasions.

State of Invasion	River	Reduction in Yield for RI = 1:70 Years (in Mm^3)						River	Reduction in Yield for RI = 1:2 Years (in Mm^3)					
		Live Storage as % Nat. MAR							Live Storage as % Nat. MAR					
Present		*20*	*50*	*100*	*150*	*200*	*250*		*20*	*50*	*100*	*150*	*200*	*250*
	Mngeni	0.3	0.3	0.4	0.5	0.5	0.5	Mngeni	0.3	0.6	0.5	0.7	0.5	1.2
	Sonend H60B	2	2.9	4.1	5.7	6.4	7.5	Sonend H60B	1.9	2.8	4.2	6.4	4.6	4.4
	Sonend H60K	0.3	1.1	1.3	1.6	1.7	2	Sonend H60K	0.6	1.5	2.6	3.1	3.8	3.9
	Wilge C81A	0.06	0.08	0.2	0.3	0.35	0.36	Wilge C81A	0.1	0.1	0.7	0.3	0.7	0.7
	Wilge C81J	0.1	0.1	0.1	0.1	0.1	0.1	Wilge C81J	0.1	0.2	0.1	0.1	0.1	0.1
	Sabie X31A	5.1	6.8	8.5	8.6	9.4	10.1	Sabie X31A	5.7	9.1	11.1	12.1	12.6	9.9
	Sabie X32G	0	0	0	0	0	0	Sabie X32G	0	0	0	0	0	0
Future														
	Mngeni	0.3	0.3	0.5	0.6	0.7	0.7	Mngeni	0.4	0.8	0.7	0.9	0.6	1.5
	Sonend H60B	1.0	4.5	5.2	6.0	6.0	6.6	Sonend H60B	1.3	5.9	6.9	7.9	10.5	9.0
	Sonend H60K	0.5	1.8	2.1	2.5	2.6	3	Sonend H60K	1.3	2.7	4.3	5.1	5.9	5.9
	Wilge C81A	0.15	0.2	0.4	0.6	0.8	0.8	Wilge C81A	0.1	0.2	1.5	0.6	1.6	1.6
	Wilge C81J	0.1	0.1	0.1	0.1	0.1	0.1	Wilge C81J	0.1	0.2	0.1	0.1	0.2	0.2
	Sabie X31A	6.8	8.8	10.9	11.2	12.3	13.1	Sabie X31A	7.7	12.4	14.7	15.7	16.2	13.6
	Sabie X32G	0	0	0	0	0	0	Sabie X32G	0	0	0	0	0	0



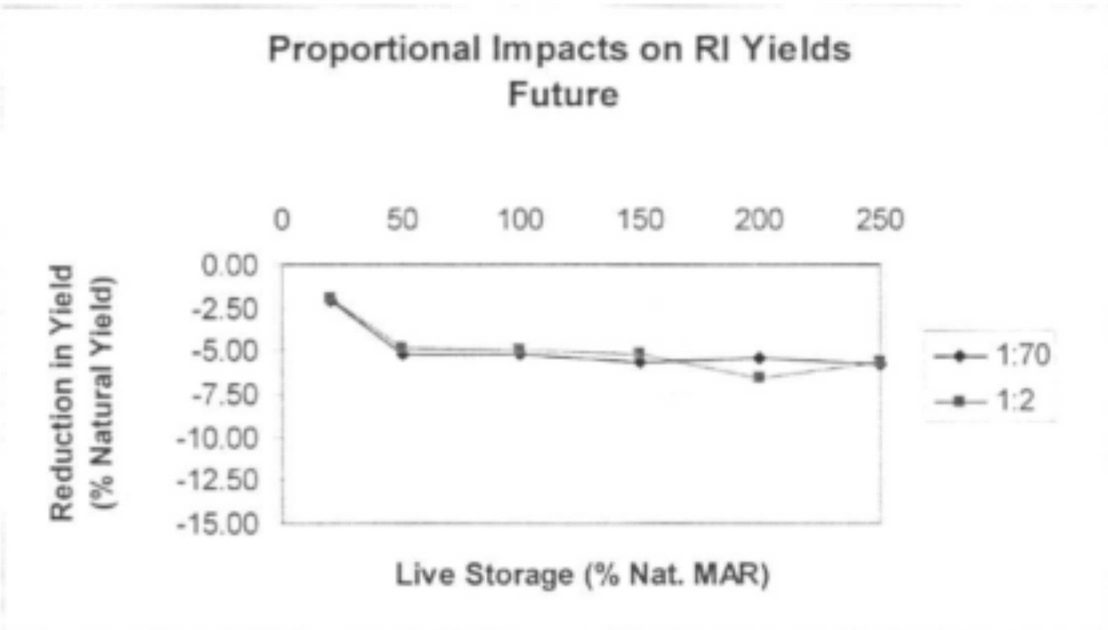
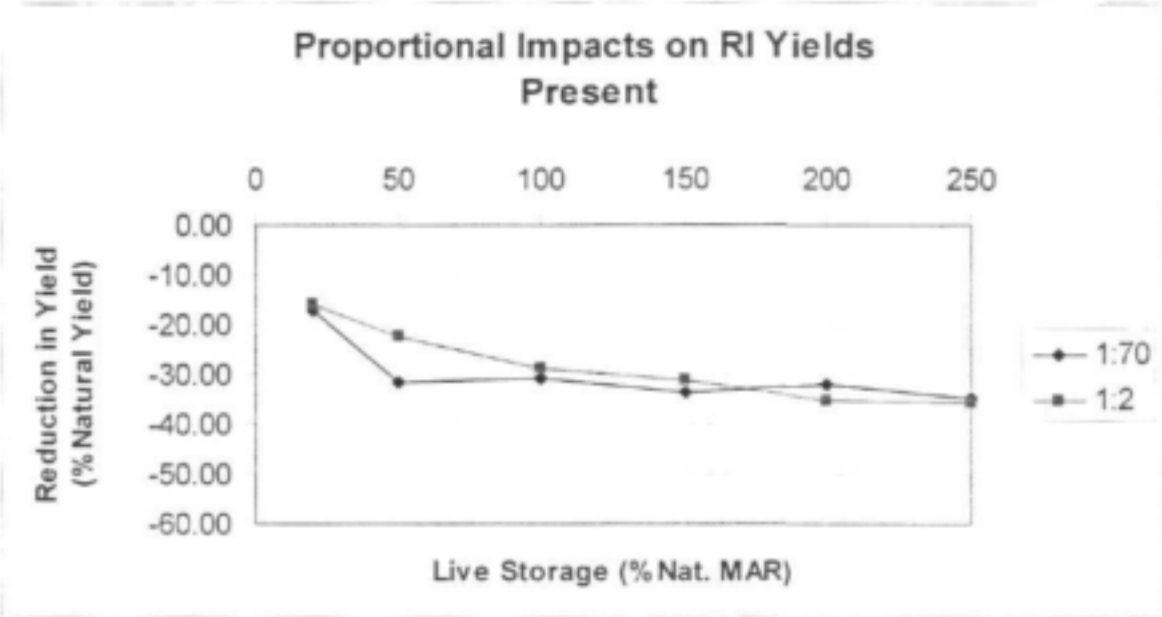


Figure 14: *Proportional* reduction in RI-based yields as a function of maximum live storage, for quaternary Sonderend H60B and for both current and projected future (10 years) invasions



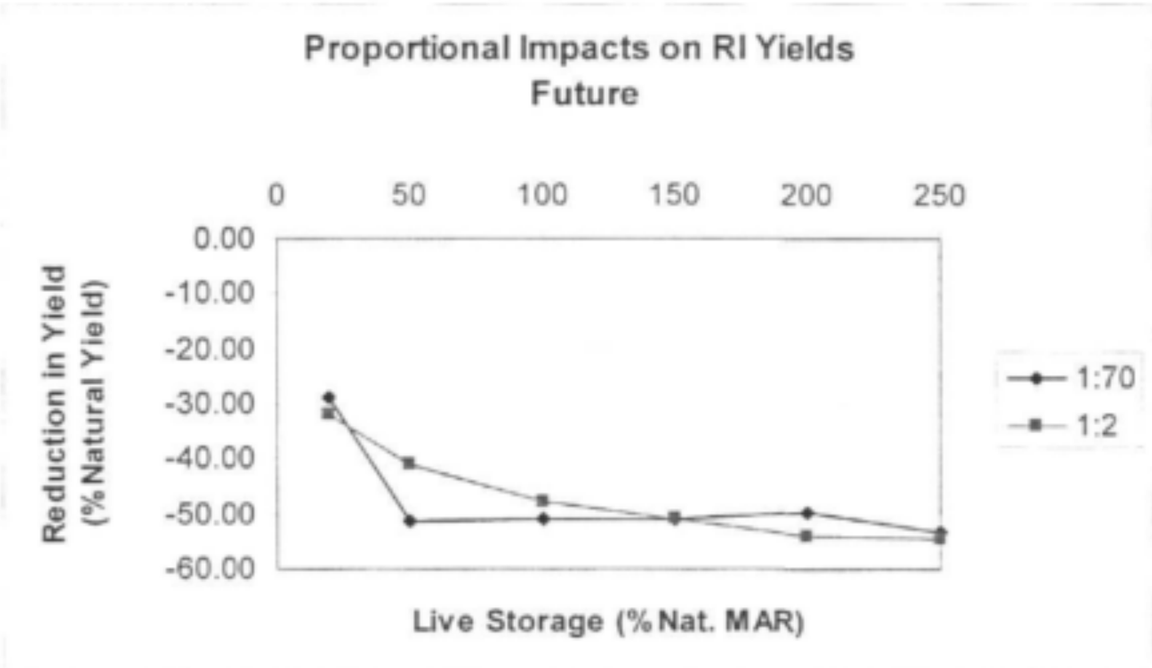
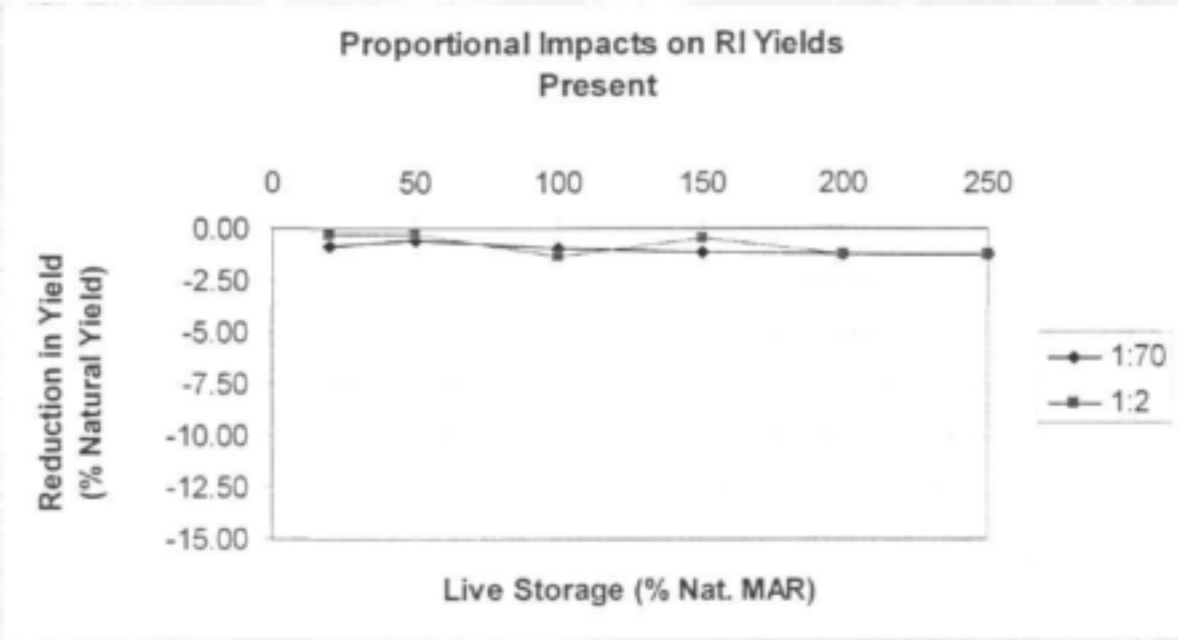


Figure 15: *Proportional* reduction in RI-based yields as a function of maximum live storage, for quaternary Sonderend H60K and for both current and projected future (10 years) invasions.



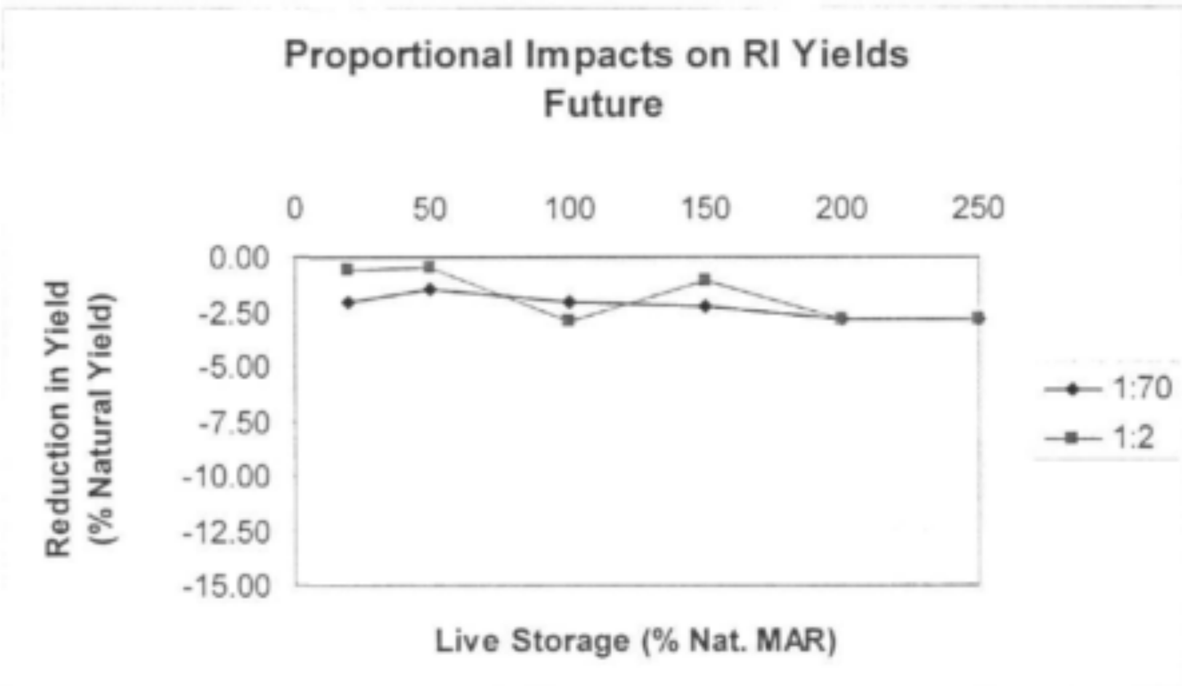
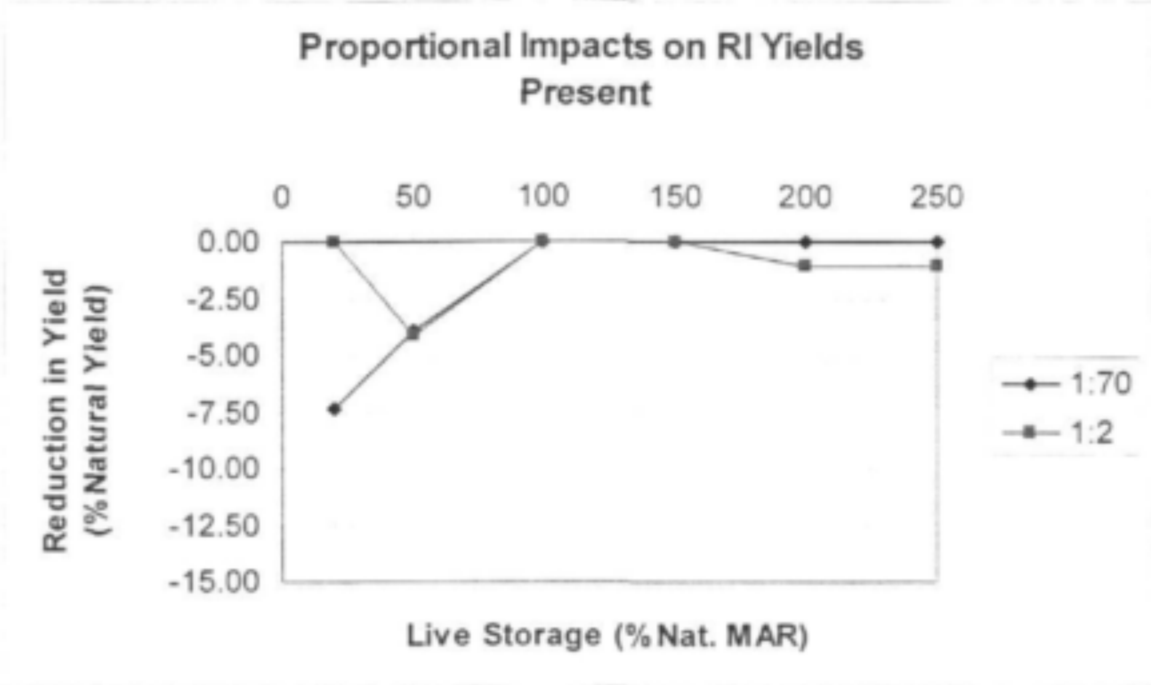


Figure 16: ***Proportional*** **reduction in RI-based yields as a function of maximum live storage, for quaternary Wilge C81A and for both current and projected future (10 years) invasions.**



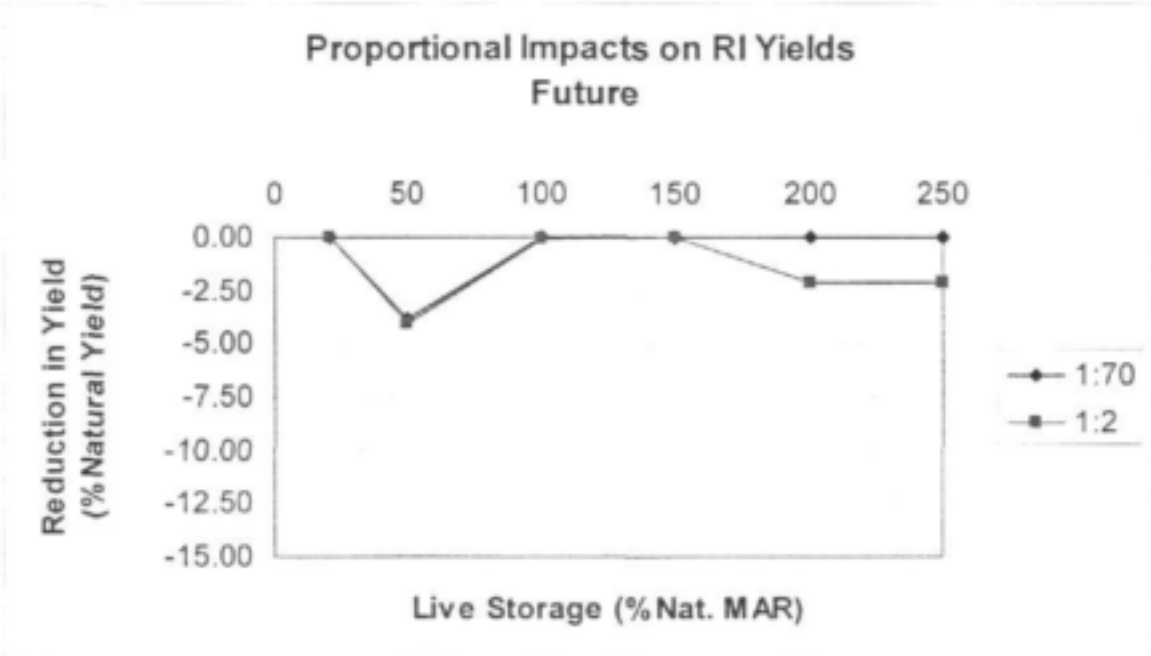
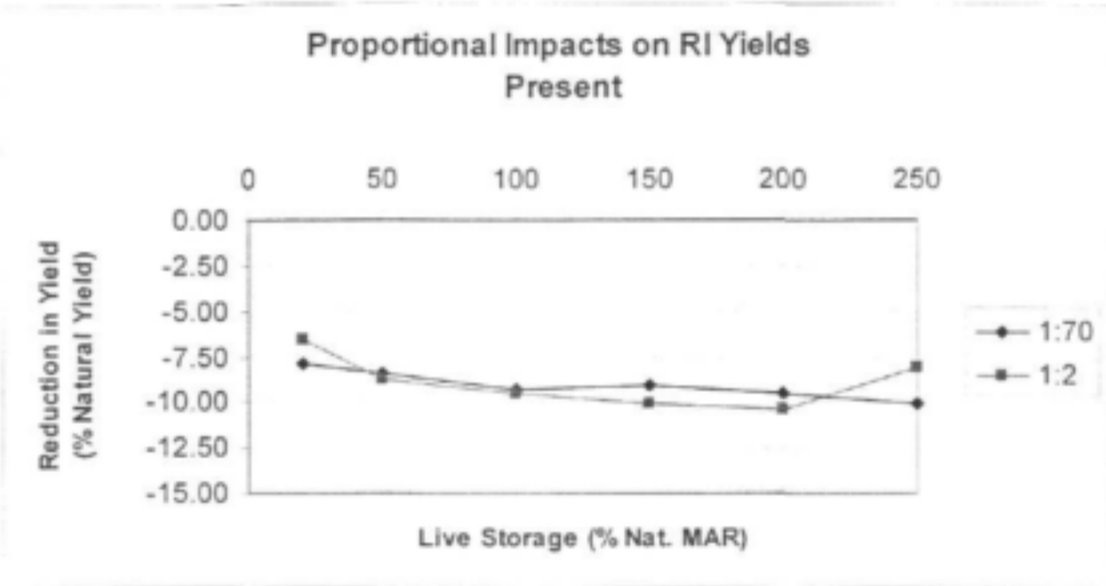


Figure 17: ***Proportional*** **reduction in RI-based yields as a function of maximum live storage, for quaternary Wilge C81J and for both current and projected future (10 years) invasions.**



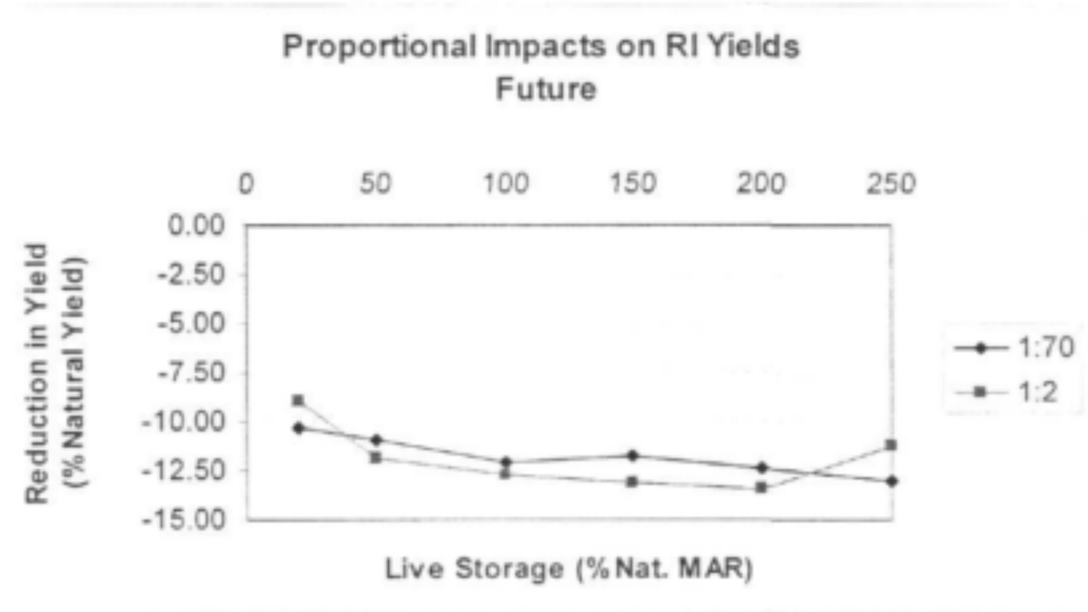
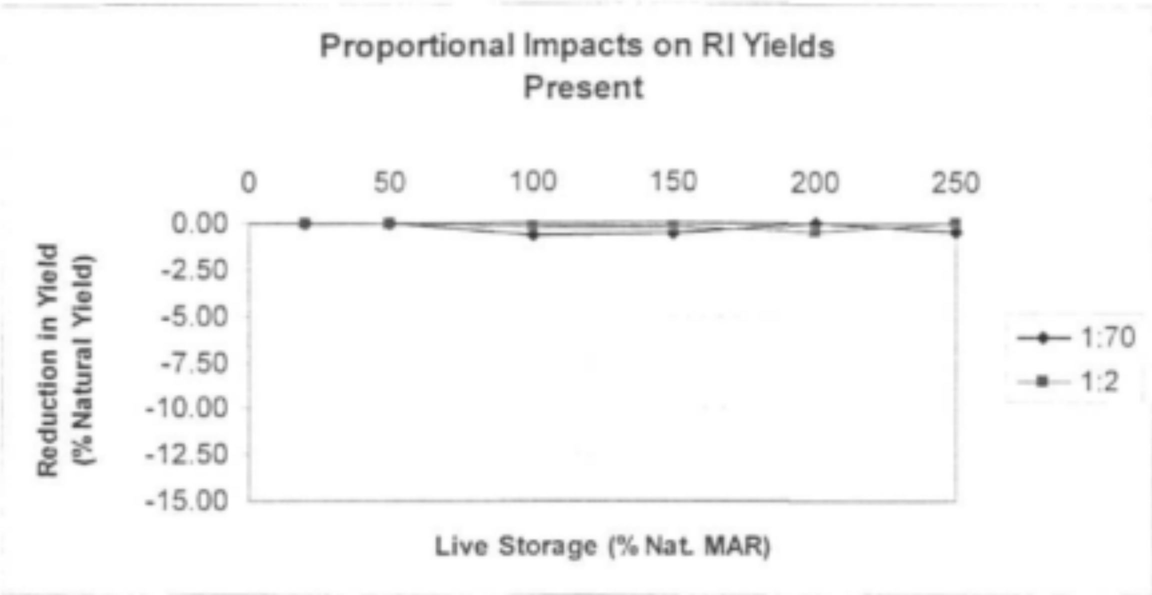


Figure 18: ***Proportional*** **reduction in RI-based yields as a function of maximum live storage, for quaternary Sabie X31A and for both current and projected future (10 years) invasions.**



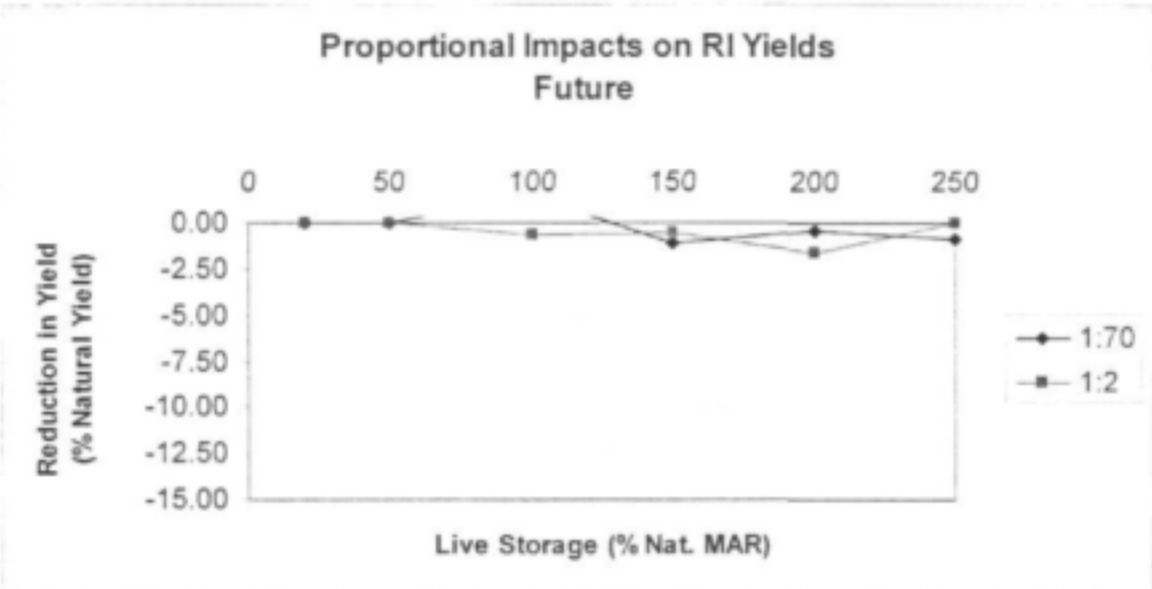


Figure 19: *Proportional* reduction in RI-based yields as a function of maximum live storage, for quaternary Sabie X32G and for both current and projected future (10 years) invasions.

Sonderend H60B (Upper catchment) and H60K (Lower catchment)

A comparison of Figures 14 and 15 illustrates the variation of potential streamflow reduction impacts at local scale that might be encountered in a single river system. The proportional impacts on the upper humid quaternary H60B appears relatively low when compared to the proportional impacts on the lower semi-arid quaternary, which are a factor of 6 – 9 times larger. Although Table 10 shows that in volumetric terms the absolute size of the reduction in yield of the upper quaternary is actually larger, it would be the magnitude of the *proportional* reduction in H60K that might have a significant impact on local aquatic ecosystems. These results suggest that the invasions pose a severe threat to the ecological integrity of rivers in quaternary H60K in the absence of clearing.

Wilge C81A (Upper catchment) and C81J (Lower catchment)

These two sets of results, Figures 16 and 17, show differences in proportional potential reductions between the upper and lower quaternaries, but the small magnitude of the impacts make detailed comparisons relatively meaningless.

Sabie-Sand X31A (Upper catchment) and X32G (Lower catchment)

The variation of potential streamflow reduction impacts at local scale that might be encountered in a single river system is also well illustrated by Figures 18 and 19. Proportionally, the reductions in yield in sub-catchments of the upper Sabie are more than an order of magnitude larger than those in the lower Sand River.

4.6 Perspectives on the representativeness of the findings

For the purposes of economy and speed, the above study was performed against a baseline condition of so-called natural streamflows in the selected river systems. Obviously, current day conditions are far from natural in many parts of all these systems and the current MARs and ambient streamflows of many of the selected quaternaries can be expected to be much lower than those for natural conditions due to the many forms of human-related water use that are present. The implication of this is that the absolute volumes of riparian-related streamflow reductions might be lower under current-day conditions than those estimated here, but, simultaneously, the relative reductions expressed as proportions of MAR will be much higher. In broad terms these estimates of reductions are based on the best invasion data available at present and on natural bioclimatic and hydrological conditions typical of the regions in which each of the selected systems reside. On these grounds it may be proposed that the foregoing results are representative of typical alien invasive-related impacts on utilisable water in South Africa.

5. CONCLUSIONS

(i.) This study has shown that it is feasible to estimate the potential streamflow reduction impacts on utilisable water in South African river systems (expressed as yield from impoundments) for which reasonably reliable data bases on invasion patterns exist.

(ii.) A workable approach has been found to combine empirical long-term streamflow reduction prediction models with monthly time series rainfall-runoff catchment modelling.

(iii.) Both the potential *absolute* reductions (in Mm^3/a) in yield, and the *MAR-standardised* values of those reductions, in the Sabie-Sand and the Sonderend river systems far exceed those in the Upper-Mngeni and Upper-Wilge systems. For example, in the Sabie-Sand system, potential yield reductions can be expected to already exceed 60 Mm^3/a, and to start approaching $100Mm^3/a$ in 10 years' time, if not checked. Such differences may have implications for the prioritisation of alien plant eradication projects.

(iv.) The *proportional* yield reductions in the Sabie-Sand and the Sonderend river systems are considerably more significant than in the other two river systems. For the Sabie-Sand system the proportional yield reductions for dam sizes equal to or greater than 50% natural MAR averages at about 8% (present) and 11% (future). For the Sonderend the proportional yield reductions for dam sizes equal to or greater than 50% natural MAR averages at about 4% (present) and 6% (future).

(v.) On average over the four systems, for a given level of assurance of yield, the proportional reductions are relatively constant for storage sizes equal to or exceeding 50% of the natural MAR.

(vi.) In general, for any give dam size over 50% of the natural MAR, there is relatively little difference in the proportional reductions at different assurances of yield.

(vii.) Potential yield reductions at the scale of specific quaternaries can be very different from the aggregated impact on the full river system. For instance, for current-day conditions, quaternary H60K (Sonderend) shows potential proportional yield reductions of about 30%, while the full system of which it forms part shows potential reductions of about 4%.

6. RECOMMENDATIONS

(i.) The assumption of a sigmoidal relationship between streamflow reductions and biomass *per se* has been questioned recently on the grounds of a number of empirical observations of a strong correspondence between *current annual increment* in biomass and consumptive water use (P. Roberts, pers. com., 2001). It is recommended that data of this nature be assembled and used to review the biomass-based model proposed here.

(ii.) Towards the conclusion of this study the cause of the commonly smaller magnitude of the proportional potential yield reductions for the smallest dam size case of 20% MAR (natural), compared with other dam sizes, was investigated in greater detail. As the yields from small (relative to MAR) dam sizes are known to be particularly sensitive to the low flow regime of a river, there might be concern that the results of this study might be too optimistic in terms of low flows. To investigate this further, a pilot assessment was made on the Sonderend River. The riparian model used here was replaced with the simple assumption that riparian consumptive use would equal that of nett open water evaporation. This change caused the proportional reductions for the 20%MAR dam size to increase from about 2.5% to about 3.5% for the system as a whole, with little change in the reductions for larger dam sizes. It is recommended that this adjustment to the way riparian invasives are treated in the modelling process be further evaluated and, if necessary improved.

(iii.) It is recommended that this investigation be extended to include analyses of multi-land-use, multi-reservoir river systems so that the integrated effects of alien plant invasions on such complex systems may be quantified under current-day development conditions.

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Previous research has shown that there are approximately 10 million hectares, or 8% of South Africa, invaded to some extent by alien woody plants. The invaded area is expanding rapidly, at a rate of perhaps 5% per year, leading to a doubling of invaded area in 15 years. Their impact in South Africa is particularly deleterious, using an additional 3300 million cubic metres of water per year, or 7% of South Africais runoff.

Purpose of This Study

This study investigated ways of achieving efficient use of limited resources. Hence the report presents techniques for estimating

1. How much money will be required to achieve effective control of water using invasive plants in the different provinces in South Africa?
2. How long will it take to achieve significant reductions in water lost due to alien invasion resulting from varying rates of expenditure on control?
3. What impact biological control will have on control costs in the long term.

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Estimation of streamflow reductions resulting from commercial afforestation in South Africa

MB Gush • DF Scott • GPW Jewitt • RE Schulze • TG Lumsden • LA Hallowes • AHM Görgens

The main objective of this project was to verify the *ACRU* model on available streamflow data from experimental or research afforested catchments and thereafter to apply the model to all regions with economically viable afforestation potential. The goal of the project was to produce regional look-up tables providing quaternary catchment scale streamflow reduction estimates, acceptable to a wide group of stakeholders.

This project essentially comprised two simulation phases: the verification phase and the extrapolation phase. Although the one was a planned progression from the other, some fundamental differences existed between the two simulation phases, primarily in connection with the level of detail of input data. These differences were unavoidable, but it is, nevertheless, important not to infer too much accuracy in the extrapolation phase that was not in the verification phase.

The *ACRU* model was verified with acceptable success on the same experimental data ets that were used to produce the CSIR curves. Weaknesses in the model that emerged duringthe verification phase were difficulties in accounting for the full storage capacity of the soil profile and the year-to-year carry over of water storage or usage. Therefore, amounts of water used inevaporation appeared to be limited by current rainfall.

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