Invasive alien plants and water resources in South Africa: current understanding, predictive ability and research challenges

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Predictions that invasive alien plants would use significant amounts of water were a major factor in the establishment of South Africa's Working for Water programme, which aims to protect water resources by clearing these plants. The predictions were made by combining the results of hydrological experiments, conducted to assess the effects of afforestation with alien trees on water resources, with an ecological understanding of the spread and establishment of invasive trees. The forecasts were then scaled up to arrive at national estimates of the corresponding water consumption. This paper reviews the approaches that have been used to estimate these consequences at different scales. We propose a framework for assessing the process of knowledge generation, and review the approaches used in South Africa at each level of the framework, the current level of understanding arising from the use of these methods, and significant gaps in understanding. The framework has four levels: fundamental observations from which a detailed understanding of biophysical processes can be developed; applied or predictive research from which an understanding of processes can be scaled up to predict generic outcomes; integrative research where a predictive understanding of hydrology can be combined with information from other disciplines to place the outcomes in a wider context; and research on management support, such that the information can be used to improve management and policy decisions. We conclude that much knowledge exists, but that there are also significant gaps in understanding, and challenges associated with scaling up and down to make appropriate predictions. This is especially true at the management support level, where very different kinds of uncertainties operate in the same comparative framework. Existing knowledge needs also to be used more effectively, to help prioritize clearing operations by targeting areas in terms of water-related benefits.

Introduction

This article reviews our understanding of the hydrological effects of invasive alien plants in South Africa, within a hierarchical framework. We survey the scientific basis for the predictions of impacts that have been made for South African ecosystems at different scales, and outline our current levels of understanding as well as significant gaps in knowledge. These gaps can be used to guide a research programme at various levels that will, in turn, help to maximize the water-related benefits of controlling invasive alien plants.

The establishment of the Working for Water programme[1] was based on a novel approach to environmental management. It contended that the invasion of ecosystems by alien plants could have deleterious effects on water yields from catchment areas, and that employing people to deal with the problem could both protect this vital resource and provide employment and upliftment in poor rural communities. The programme has grown in strength over the years, with an annual budget exceeding R400 million in 2002.[2]

The predictions of excessive water use by invasive alien plants dates back to the 1970s[3] and was based on research conducted by the South African Forestry Research Institute on the effects of afforestation on streamflow and water resources.[4] This work provided the basis for initial estimates of the consequences of invasive alien plants[5] and led, in turn, to more widespread assessments.[6–8] In parallel with this work, research funded by the Water Research Commission focused on the development of biophysical models to evaluate the effects of vegetation on water resources.[9] Other efforts concentrated on the estimation of runoff at a catchment level, and were aimed largely at water resource planning. The advent of the Working for Water programme provided a stimulus that brought ecologists, forest hydrologists and engineers together in attempts to combine these approaches, and to understand the role of invasive alien plants in changing the hydrological characteristics of catchments.

The first published estimates of the effects of invasive alien plants on streamflows in South African catchments[10] suggested that invasions by these plants were already having a significant influence in many areas. Since the initial estimates were made, experimental work on water consumption by alien plants, and resultant streamflow reductions, has been commissioned by both the Working for Water programme and the Water Research Commission. Furthermore, the developers and users of the catchment rainfall-runoff models in South Africa (used in water resource planning) have been augmenting existing models to incorporate the surmised effects of invasive alien plants on the hydrological response of catchments.

In this paper, we assess the state of knowledge in the field of hydrology in South Africa, with specific reference to the effects of invasive alien plants. For this purpose we use a knowledge-generation hierarchy[11] to organize existing understanding and gaps in primary knowledge according to four overlapping levels.

A proposed framework for knowledge-generation assessment

The provision of support to decision-making in management is an important goal of research. We understand management to encompass the interactive cycle of information assembly, assessment, policy formulation, planning, option analysis, prioritization, implementation, operation, monitoring, auditing and correction.[12] The quality of support to decision-making by management depends on an understanding of biophysical

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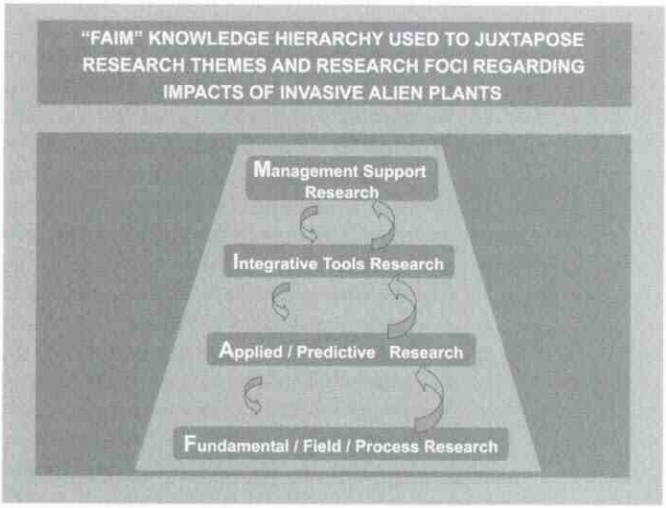

Fig. 1. The FAIM knowledge-generation hierarchy.

processes at different scales, and on the integration of biophysical with other forms of knowledge. These requirements are the keys to an interactive, overlapping hierarchical structure of knowledge and the layers of research, methods and tools that assist knowledge generation. For convenience, this structure is called the FAIM (Fundamental–Applied–Integrated-Management) knowledge-generation hierarchy (Fig. 1).

The FAIM hierarchy provides structure for the analysis and evaluation of knowledge generation in a particular domain as follows:

- Key research or management questions, relevant to each of the levels, can be linked to the knowledge-generation processes at that level.
- Methods and tools used in research, or process quantification, or spatial and temporal extrapolation or impact assessment can be juxtaposed to each of the requisite levels.
- Existing understanding can be recorded and organized in a systematic manner.
- Gaps in knowledge can be located in a holistic understanding of the knowledge-generation process.
- Research needs can be focused at particular levels.

This generic structure can be made specific to the topic of this paper (Table 1), where the research questions relating to the influence of invasive alien plants on water resources are linked to each of the levels and to the generic knowledge-generation processes at that level. In the sections that follow, we deal with the approaches that have been used in South Africa at each of the particular levels.

Studies at the level of fundamental observations

South Africa has a long history of research aimed at developing an understanding of the biophysical processes that underlie water use by alien plants, particularly trees used in commercial forestry.[13] Catchment-scale experiments have formed an important part of this research, with a focus on quantifying changes in streamflow.[14,15] Much less work has been done on groundwater resources, which are an important component of the hydrological cycle affected by invasive alien plants. This section reviews our current understanding at this level.

Table 1. A proposed generic framework for the assessment of knowledge generation, and the key questions for research relating to the effects of invasive alien plants on water resources.

Level of research	Generic knowledge-generation processes	Key questions for assessing the effects of invasive alien plants
Fundamental observations in the field or laboratory.	Gather detailed understanding of individual biophysical processes in specific settings.	What factors and processes govern water use by invasive alien plant species in a particular setting?
	Directly or indirectly measure individual biophysical responses or dynamics in specific settings.	How does water use by invasive alien plant species differ from indigenous (or other baseline vegetation) in a particular setting?
		Which characteristics of the water resource are changed by alien plant invasions or their clearing?
Applied and/or predictive research.	Conceptualize, extrapolate and scale-up from an individual site-specific process or a localized response to the generic process or response.	How should spatial and temporal variability in biophysical factors and processes be accommodated in generalized methods for quantifying some, or all, aspects of water use, streamflow or groundwater impacts?
		By how much, generally, do invasive alien plant species, or their clearing, change individual characteristics of the water resource?
		At what rates, generally, do invasive alien plant types, or their clearing, change the characteristics of the water resource?
Integrative and/or interface research.	Integrate numerous factors, processes and scales in a variety of models to estimate biophysical responses at aggregated scales.	How should changes in streamflow, groundwater and dam yield, following invasion by or clearing of alien plants, be predicted at a catchment or river system scale?
	Interface outputs of predictive biophysical response methods with spatial analysis tools and socio-economic information.	How should predictions of invasive alien plant impacts on water resources be supported by spatial information and juxtaposed with socio-economic information?
Management support research.	Apply integrated models and interfaced information creatively to provide decision support for natural resource management and planning.	Which invaded areas in a catchment, or a whole region, will respond to clearing with greatest hydrological benefit?
	Quantify, describe and prioritize options for natural resource managers.	How important is invasive alien plant water use relative to other anthropogenic impacts on catchment and regional scales?
		How does the benefit-cost profile of clearing projects compare with other water resource augmentation options?
		How should invasive alien plant management decisions influence water and land resource management and planning, and *vice versa*?

Approaches used in South Africa

The primary source of understanding at this level arises from a series of long-term catchment experiments,[16] that have been used in several ways to assess the results of changes in vegetation cover in terms of streamflow. These include comparison of streamflow from catchments under commercial plantations of alien trees with those from unafforested control catchments; comparison of streamflow before and after afforestation with alien trees on the same catchment; measuring increased streamflow, or resumption of previously suspended streamflow, after clear-felling of plantations of alien trees; and performing any of the above with distinct treatment of the riparian zone, as opposed to the non-riparian parts of the catchment.

The above experiments have been supplemented by short- to medium-term field measurements to compare evapotranspiration differentials between alien and indigenous riparian plant communities. These include the determination of sap-flow via heat-pulse velocity measurements (single plants); use of lysimeters (for a small number of plants); Bowen ratio and eddy correlation energy balance modelling (both integrated over small canopies); quasi-empirical prediction, using observed meteorological variables at a plantation scale; and infrared scintillometer measurement of energy balance (integrated over multiple groups of large canopies, that is, of 1-km scale).[17–20] Flow-gauging by movable weirs has also been used under relatively low-flow conditions, upstream and downstream of short (about 500 m) river reaches along which riparian invasive alien plants were being cleared, both before and after clearing.[21–24]

Several medium-term experiments have been used to assess the effects of invasive alien species on groundwater.[25,26] They used various methods involving boreholes, geophysical examination of hydrogeology, and isotope techniques. Observations of changes in groundwater levels after clearing of invaded areas have been of relatively short duration and the persistence of any putative increases over the long term needs to be confirmed. Experiments aimed at assessing the effects of clearing on groundwater have not been adequately integrated with other components of the hydrological cycle in a way that allows integrated modelling of groundwater dynamics.

Understanding water use by invasive alien plants

Research to date has clearly demonstrated that tall alien trees, such as pines, eucalypts and wattles, generally reduce total annual and low-season streamflow,[16,27,28] and increase evapotranspiration[17] compared to the indigenous vegetation that they replace. Reductions in the long-term mean annual runoff have been in the order of 100–300 mm/yr, but all the experimental catchments on which this finding is based were in high-rainfall zones (>1100 mm/yr). Water use by particular invasive alien plant species is dependent on the leaf area of the plants (which correlates roughly with age and biomass), but water use by different invasive alien plant species in the same setting can vary markedly.[19] After clearing of dense and extensive stands of alien trees, it may take several years before streamflow recovery approaches pre-planting levels,[15] indicating that soil water resources can be depleted and need replenishment.[13] Evapotranspiration by riparian alien woody plant communities is markedly greater than by indigenous plant communities in the same setting.[18,20] Experimental clearing of riparian zone invasives during the low-flow season has led to marked streamflow increases in both winter and summer rainfall regions, with values ranging from 9 to 31 m^3 per day per ha cleared.[20–23] It is not known if these increases were sustained beyond the single study season in each case.

Less is known about impacts on groundwater resources. Groundwater storage in certain shallow coastal sand dune aquifers has appeared to increase in response to the experimental clearing of woody alien vegetation (various *Acacia* species).[25] Shallow to medium-depth aquifers in the karoo and arid savanna regions can be accessed by the roots of woody invasive trees, such as mesquite (*Prosopis* species),[26,30] potentially depleting groundwater.

Gaps in knowledge at the level of fundamental understanding

Because the South African catchment experiments were in high rainfall (>1100 mm) areas, there is less confidence in predictions of water use by alien plants in areas with lower rainfall, which are based on extrapolation. The catchment experiments did not include measurements of changes in interception, evapotranspiration, soil water balance, stormflow patterns and groundwater dynamics. Consequently, the experiments did not yield a deeper understanding of the processes leading to streamflow reductions (currently, there is only one such integrated experiment being undertaken in South Africa[31]), and no methods exist for scaling up individual and site-specific measurements of evapotranspiration in both space and time. The observations of increases in streamflow after clearing alien plants from riparian strips have been of short duration and the persistence of such increases over the long term, as indigenous vegetation returns to the cleared areas, needs to be confirmed.

Our understanding is also restricted to relatively few species. Although long-term reduced streamflow by trees has been demonstrated, the experiments included only certain species of pines and eucalypts[14,15] (and, more recently, wattles).[28] The influences of other invasive alien species in these genera, or of other invasive genera (including shrubs and herbaceous plants), have not been measured. Researchers in the forestry industry contend that differences in the water use by alien trees are greater within than between genera and that genus-based streamflow reduction models might be premature. Measurement of these within-genus differences has been limited and still requires substantiation. In addition, water use by alien plants has to be compared with that by indigenous vegetation in order to determine impacts. Water use by indigenous vegetation has been determined in only a limited number of locations and plant communities,[32–34] which further impedes our ability to assess consequences.

In general, the correspondence between measured evapotranspiration and resulting streamflow reduction has not been studied; the scale differential between the energy balance techniques used for the former and the aggregated manifestation of the latter is a formidable obstacle. Despite a good understanding of issues such as rainfall interception and plant water use for some species, there are many processes that affect streamflow generation in a landscape and remain poorly understood.

South African studies of the effect of invasions by alien plants on groundwater have in most cases suffered from a poorly developed, or absent, conceptual model of the totality of processes that might affect the outcomes, and no results have yet been published. Consequently, the monitoring approach has left much to be desired and these studies may not be conclusive in their findings.

Studies at the level of applied or predictive research

To predict the effects of invasive alien plants on water resources, it was necessary to develop models based on an understanding of biophysical and ecological processes. For invasive alien plants, these models were developed mainly from an understanding of water use by alien trees used in forestry, and by fynbos shrubland vegetation.[5] This has been combined with an understanding of the ecology and population dynamics of invasive plants, mainly in the fynbos biome. This section reviews our current understanding at this level.

Approaches used in South Africa

Models of the effects of invasive alien plants on water resources relied in part on a description of the spread of these plants into catchment areas. Several spread models have been used in studies to date.[4,5,35] These models are crude, and have been devised to simulate the spread of invasive alien trees and shrubs (mainly pines and hakeas) in fire-prone fynbos ecosystems. Pines and hakeas are killed by fire, and they spread from seeds released after fires—the occurrence of fires was used to trigger plant spread in the models, which simulate the extent of infestations, and the growth of the plants between fires.

Almost all estimates of streamflow reductions due to invasive alien plant infestations[4,5,8,35] have been made using the 'age–biomass–streamflow reduction model',[5] which allows biomass to be estimated separately for tall trees, medium-sized trees and tall shrubs. Streamflow reduction is driven by the estimated biomass and distinguishes between riparian and non-riparian streamflow reduction conditions. More recently, other approaches have been used to quantify the effects of invasive alien plants,[28] but such studies are still rare.

Our ability to predict

Our ability to scale up from knowledge of a specific site is based on principles that are reasonably well understood. Riparian plant communities dominated by alien woody plants generally cause markedly greater streamflow reductions than similar non-riparian plant communities.[18,22–24] Streamflow reductions and evapotranspiration for particular invasive plant species are also known to be dependent on geo-climatic site conditions.[16,18–20] Proportionally, the observed reduction in low (or dry season) flows due to the influence of tall alien trees, such as pines and eucalypts, is generally more severe than that in higher (or wet season) flows.[16] We also know that streamflow reduction due to invasive alien trees increases sigmoidally with age to a plateau value, but declines as trees mature.[16]

Gaps in knowledge at the level of predictive research

The biomass-driven models on which many of the predictions of the effects of invasive alien plants on streamflow are based are unsophisticated, and were assembled to make rapid estimates of hydrological impacts.[5] Biomass models have little direct physiological justification. The main controller of water loss is leaf area, which correlates broadly but non-linearly with biomass. While these models were useful in conceptualizing the problem of reduced streamflow, and demonstrating some of the likely outcomes of invasions, they have drawbacks. These include the fact that they are based on measurements in high rainfall areas, on a limited number of species, and that they do not take fundamental understanding of plant water use into account. Better models are needed. The models of plant spread are also of limited application, as they are based on non-sprouting tree and shrub species whose seeds are wind-dispersed after fire. Many other important invasive alien species have very different modes of spread, and these cannot currently be simulated.

The general effects of different invasive alien species, the distance from river channels, rehabilitation, or variations in soil and climatic conditions on the resultant streamflow reductions have not been studied with a view to developing predictive power for riparian zones. Measurements of altered streamflow after the planting or clearing of alien trees have been made at fine scales, and it is not certain that these measurements adequately reflect changes at larger scales.

The limited measurements of impacts have not necessarily addressed all the characteristics of a water resource. The nature of the potential changes that invasions cause in the recharge processes of perched or permanent aquifers, both dispersed recharge and preferential recharge, as well as in the consumptive use from aquifers, is not understood. Without adequate understanding of these modifications of recharge pattern and consumptive uses, quantification of the consequences for groundwater levels and borehole yields will remain a 'black box' exercise.

Finally, little research has explicitly focused on the effects of upstream invasions on the ecology and dynamics of wetlands and estuaries. The links between changes to hydrological processes resulting from invasion of upper catchments are not quantified, and the potentially significant implications for these important ecosystems cannot be predicted.

Studies at the level of integrative research

At an integrative level, researchers face the problem of scaling up from site-specific observations, and models based on these, to the level of a large catchment with a variety of different land-cover types. Such predictions will ultimately be as good as the understanding and models on which they are based, and the way in which models are linked. The previous two levels of the FAIM framework have largely been the domain of ecologists and forest hydrologists, and until recently it has been water resource engineers who have traditionally focused their research at the integrative level in South Africa. In this section, we review approaches that have been used, or are currently being developed, at this level.

Approaches used in South Africa

Models have been developed[35] to produce monthly estimates of streamflow (as influenced by alien plants) at a catchment level, by juxtaposing non-riparian and riparian invaded zones. In these models, the Pitman monthly rainfall-runoff model[36] is combined with the age–biomass streamflow reduction model.[5] The hydrological effects of most other water uses such as irrigation diversions, return flows, farm dams, afforestation and urbanization can also be accommodated in this system.

A daily catchment modelling system (known as ACRU — the developers were based at the Agricultural Catchment Research Unit),[9] has been used to estimate daily consumptive soil moisture use by invasive plants using potential transpiration for crops, interception losses, root distributions, age-based leaf-area-index functions, and daily 'capacity-limited' soil moisture budgeting.[37] ACRU allows quasi-realistic juxtaposition of non-riparian and riparian invaded zones. The hydrological effects of most other water uses such as irrigation diversions, return flows, farm dams, afforestation, rain-fed cultivation and urbanization can also be accommodated in this system.

Various emerging international modelling approaches are also being investigated for suitability under South African conditions. These belong broadly to two classes. The first uses plant growth models at the plantation stand scale, and depends on a mechanistic representation of tree growth based on physiological principles, carbon assimilation, energy partitioning, growth allocation and 'rate-based' soil moisture budgeting. These models have intensive site-specific data requirements, but the ultimate intention is that remotely-sensed conditions should be used to predict growth and, therefore, water use via a GIS platform. The 3-PG (Physiological Principles in Predicting Growth) tree growth model[29,38] has been applied in a commercial afforestation setting in KwaZulu-Natal with sound results and offers potential for use with woody invasive alien trees. The second approach involves the use of catchment-scale models that are explicitly designed to be sensitive to land-use and land-cover changes via the phenological characteristics of vegetation, and that incorporate a degree of topographical control on the hydrological responsiveness of the model. The Soil and Water Assessment Tool (SWAT) model,[31] which operates on the basis of hydrological response units that are defined according to the topography and dominant land-uses and soils in the catchment, has seen a promising application in KwaZulu-Natal. It is sensitive to land-use and land-cover changes by tracking the phenological development of vegetation, which is based on the heat unit theory, with the growing season being defined by date or accumulated heat units. Potential evapotranspiration is estimated for all land covers using the Penman-Monteith formulation.

Our current ability to integrate

Two important questions have been addressed at this level with regard to invasive alien plants in South Africa. These studies have shown, in theory at least, that the clearing of invasive alien plants can have significant outcomes at the scale of larger catchments. The first[39] related to whether or not clearing invasive alien plants (and thereby generating additional runoff) would have any substantial effect on yield from dams (which effectively buffer the impacts of reduced streamflow) over a number of years. 'Yield' is the maximum annual volume of water that can be withdrawn from a given maximum storage capacity at a specific reliability. 'Reliability' (often called assurance) is the probability (for instance, 98%) of *not* ending up with an empty dam in any given year. The second[35] related to whether or not clearing of invasions could be justified as a cost to municipalities engaged in the construction or augmentation of new or existing water supply schemes.

Reductions in dam yields due to invasive alien plants were shown to be significant. For the Sabie-Sand River system the estimated yield reductions for plausible dam storage sizes averaged 8% (year 2000 invaded areas) and 11% (year 2010 projected invasions without clearing). For the Sonderend River the equivalent figures were about 4% (2000) and 6% (year 2010), respectively. The study showed that estimated yield reductions due to invasive alien plants at the scale of specific quaternary catchments can be very different, in proportional terms, from the aggregated impact on a full river system. For instance, for present-day invasions, a quaternary catchment in the downstream part of the Sonderend River system showed potentially devastating reservoir yield reductions of 30%, while yield reductions of only 4% were indicated for the full Sonderend River system. The second study considered water augmentation schemes to supply the town of George. In this case, modelled potential reductions in annual yields from dams due to projected invasions over the period 2000–2015 were found to average 13%.

Gaps in knowledge at the level of integration

At this level, the results of different conceptual approaches have to be merged, and these lead to scaling problems. The shortcomings of using the age–biomass–streamflow reduction models here include the fact that streamflow reduction for a particular invaded cell in the model correspond to a type of monthly abstraction; that is, the soil water budgeting of the invaded areas in that cell is not affected directly.[35] A refined version of this approach is needed properly to simulate streamflow reduction as a result of increased interception loss, enhanced consumptive use of soil water and reduced groundwater recharge.

Ideally, scaling experiments should be used to explore the dynamics of invasions or clearing on the hydrological characteristics of catchments. Spatial and temporal scaling experiments are often not practical, and may be best achieved through the juxtaposition of a range of models that cover various spatial scales and time resolutions. Quantification of the consequences of invasive alien plants via the various available models is not possible without significant uncertainty. This uncertainty needs to be systematically mapped out as has been done for the National Streamflow Reduction Tables for commercial afforestation.[42] The outcomes of alien invasives on the yield–reliability characteristics of large multi-demand, multi-resource, multi-reservoir river systems, and on run-of-river and small off-channel storage schemes for rural water supplies require more systematic analysis.

No catchment modelling scheme in general use in South Africa yet provides a satisfactory recharge interface between groundwater and percolation from the upper soil horizons. Consequently, groundwater responses to alien plant invasions (or clearing) in these models cannot be regarded as adequate in terms of recharge or direct water use by alien plants. The large-scale results of invasions on groundwater are currently included in resource-related decision-making and is a potential weakness in water management.

There are many components of the widely used ACRU approach that require further refinement. These include the need to develop crop coefficients, interception storage/leaf-area relationships, plant-water-uptake stress functions, and simulations of groundwater dynamics. The model lacks a distinction between aquifer dynamics of discrete localized riparian groundwater bodies and larger-scale groundwater dynamics, and realistic representations of topographic realities. The model also needs to be verified in invaded catchments for which adequately gauged streamflow data are available. This has already occurred in part through verification against catchment afforestation experiment results; however, these verifications were not convincing in all cases.

Studies at the level of management support research

Policy decisions around catchment management and water resource allocation require answers at a broad scale, incorporating diverse considerations. Our ability to deal with higher-level impacts of invasive alien plants on water resources in South Africa is addressed below.

Approaches used in South Africa

A number of broad-brush approaches are used at this level. Conventional network optimizing or cascading models[35] have been used to simulate the distribution of water across a multi-user, multi-resource system on a monthly basis according to prescribed operating 'rules'. The reductions in water yield from the system caused by widespread invasions can be determined with such models if the monthly streamflow reduction time series for all component sub-catchments of the system are first simulated via either of the monthly or daily catchment models mentioned above.

In addition, large-scale, long-term water balance models[40] have been adapted to accommodate the impacts of invasive alien vegetation as a quaternary sub-catchment 'water use'. This has been done by introducing average annual streamflow reductions (in mm), which are based on age–biomass curves, to assess the status of water resources along with other conventional water uses such as domestic, industrial and irrigation water requirements.

The latest generalized streamflow reduction quantification tool used by the Department of Water Affairs and Forestry for first-order decisions about afforestation licences is a set of so-called National Streamflow Reduction Tables generated by ACRU models on a quaternary catchment basis.[42] This information is also progressively being used in other types of water resource management decision-making. However, given that decisions relating to the streamflow reduction effects of invasive alien plants are usually quantified via the age-biomass model, which is much more generalized than the ACRU-derived estimates, two very different sets of uncertainties are at work in the same comparative decision framework. This has implications for the reliability and equity of such water resource management decisions.

How much water do alien plants use?

The initial estimate of water use by invasive alien plants nationally[7,10] put the annual reduction at 3300 million m^3. This approximation was made by aggregating estimates at a quaternary catchment scale, using the age–biomass–streamflow reduction model.[5] However, South Africa's recently published draft National Water Resources Strategy[41] gave the estimate at 1400 m^3. The more than twofold difference between these estimates is striking, and the process used for arriving at the second quantity is not given in the draft report.

The situation with regard to commercial forestry provides a useful comparison in this regard. Water use by forestry has been the subject of considerable debate,[44,45] largely due to the legal requirements for forestry to 'pay' for streamflow reductions in terms of the new Water Act. A recent comprehensive study[42] attempted to reconcile the differences in estimated water use that resulted from two different approaches—the ACRU model on the one hand and the streamflow reduction curves, based on experimental catchment work, on the other. This study calculated the national average reduction in mean annual runoff attributable to plantations of pines, gums and wattles, using the ACRU model, for 843 quaternary catchments with mean annual rainfall above 650 mm. By assuming that all of the catchments were fully afforested, water use was found to be about 70 mm/yr for non-riparian settings, or 20 889 million m^3 annually. However, given that plantations cover only 1 518 138 ha (5.1% of the 843 quaternary catchments involved),[46] the estimated annual water use by forestry plantations should be reduced to 1065 million m^3. On the basis of the above, the forest industry have negotiated[45] with government to set the estimated annual water use by plantations at 60 mm, reduced from the previously suggested 100 mm based on the results of catchment experiments.

The above comparison highlights two things. First, water use by invasive alien plants has probably been underestimated in the current draft National Water Resources Strategy. The approximate area covered by invasive alien plants is 6.5 times greater[7] than that devoted to forests, which suggests that water use by aliens should be several times that by forestry, even if many of the invasive alien plants are not large trees. Second, it is clear that our ability to scale up to a national level, and to make assessments of water use at this scale, is impeded by a lack of understanding. As a result, important policy decisions will remain controversial.

The Working for Water programme had cleared almost 1.2 million ha of invasive alien vegetation (of varying density) by the end of 2003. By application of the age–biomass–streamflow reduction curves the water benefits of such clearing has been estimated[41] at between 50 and 130 million m^3/yr. Economic analyses of planned water resource augmentation schemes have also shown that the clearing of heavily invaded catchments may enable the postponement of large capital investments by several years.[8,35] The clearing of alien invasive plants can potentially increase yields of reservoirs at a competitive or lower unit cost when compared with conventional augmentation schemes based on impoundment or diversion.[35] All of these studies have suggested that clearing invasive alien plants is cost-effective in terms of water resources.

Many of the economic activities in areas invaded by mesquite (*Prosopis* species) in the arid parts of South Africa rely largely or completely on groundwater. As water use by these invaders is estimated to exceed 134 million m^3 annually,[10,30] it could have a significant impact on the ability of these groundwater resources to continue to meet human demands in these arid regions of South Africa, including the 'basic human need' as required in terms of the reserve in the National Water Act.

Gaps in knowledge at the level of integration

Although streamflow reductions and dam yield reductions by invasive alien plants are now routinely considered in water resource planning and evaluation, at both national strategic and local scheme levels, there is a lack of consistency in approach and quantification methods across the spectrum of water resource management.

The influence of alien plant clearing programmes on the economics of hydrological planning appears to be favourable. However, studies to date have not included the social, land-care and ecological benefits, in estimates of total economic value.[47] Such studies would undoubtedly improve the assessment of benefits. Improved mapping (at fine enough scales) of infestations, in adaptive GIS-linked database environments, is also needed to support such research. Incorporation of estimates of streamflow reduction in criteria that inform the National Water Resource Strategy is currently not definitive and requires review and refinement. A hierarchy of strategic criteria that should drive the selection and location of clearing projects by the Working for Water programme has been suggested,[43] but has not been exhaustively tested and verified. This hierarchy recognizes the need for improved understanding of water-stressed catchment components as well as the location of invasive alien plant communities in catchments that are surmised to have the highest susceptibility.

The way forward

This review has highlighted the complex nature of accurately estimating the effects of invasive alien plants on water resources at a range of levels. While considerable knowledge exists, there are significant gaps in our understanding, and challenges associated with scaling up and down to make predictions at the appropriate scale, and to answer questions at the appropriate level. Nonetheless, research has shown that invasive alien plants can and do have undesirable consequences for water resources, and many of the existing control programmes can be justified on this basis alone. Existing knowledge needs to be more effectively used to prioritize clearing operations by selecting areas for clearing in terms of water-related benefits, something which has not yet been done effectively.

The Working for Water programme proposes to use the FAIM framework to develop a strategic approach to funding research in the field of invasive alien plants and water resources. In this endeavour, it collaborates closely with the Water Research Commission, which will manage the funds earmarked by Working for Water for hydrological research. In addition, the Water Research Commission will ensure that its own research complements that funded by Working for Water.

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