HYDROLOGICAL IMPACTS OF INVASIVE ALIEN PLANTS

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Abstract

It is now well recognised that invasive alien species, particularly tree species, often have much increased water usage compared with native vegetation. Perhaps less well understood are the reasons for this increased water use and whether such increases should be expected from all species of invading alien trees under all environmental conditions. This paper examines the reasons for increased water use from trees as compared with short crops. From a knowledge of these reasons and a knowledge of the limiting processes (the Limits Concept) governing alien tree and native tree and short crop water use, (derived from case studies in India and RSA), we suggest that it is now possible to assess under what conditions high water use by aliens may occur. Inverse solutions based on knowledge of growth rates are also suggested as another approach for assessing alien and native tree water use under water limited conditions. We conclude that in dry climates the greatest increase in water use from aliens, in both absolute and percentage terms, may occur in water limited rather than riparian (water unlimited) conditions. Hydrological models which can predict the spatially distributed increase in water use by aliens within catchments, coupled with ecological models which can predict controlled and uncontrolled invasion, can assist the evaluation and design of improved cost effective eradication programmes. Such coupled models, linked with an economic evaluation component, should indicate in what circumstances the value of the extra streamflow released may alone be sufficient to cover the costs of the eradication programme and under what circumstances the ecological (protection of indigenous communities) and other socio-economic benefits also need to be taken into account to justify the costs of the programme.

1. INTRODUCTION

It is now well recognised that invasive alien species, particularly tree species, often have much increased water usage compared with native vegetation, especially where this is short. Perhaps less well understood are the reasons for this increased water use and whether it should be expected from all species of invading alien trees under all environmental conditions. Answers to these questions are important so that financial resources directed at eradication programmes for alien invaders can be used to maximum effect. This paper examines our world-wide understanding of the reasons for increased water use from trees as compared with short crops. It also considers whether, by using this knowledge and from consideration of the Limits Concept (knowledge of the limiting processes governing water use), it may be possible to assess under what conditions excessive water use from aliens may occur. Specific case studies in Karnataka, India and in the Western Cape, RSA are considered from different dryland and wetland (riparian) sites.

2. ESTIMATING WATER USE FROM DIFFERENT VEGETATION TYPES

2.1 Principal reasons for differences in evaporation between short and tall crops

2.1.1 Difference in height

Forests usually evaporate more water than shorter or annual crops. In wet climates, where the surfaces of vegetation remain wet for long periods, interception from forests is higher than that from shorter crops because the very rough surfaces of forests assist the aerodynamic transport of water vapour into the atmosphere. This is analogous to the “clothes line” effect, i.e. wet clothes pegged out on a line will dry quicker than those laid out flat on the ground.

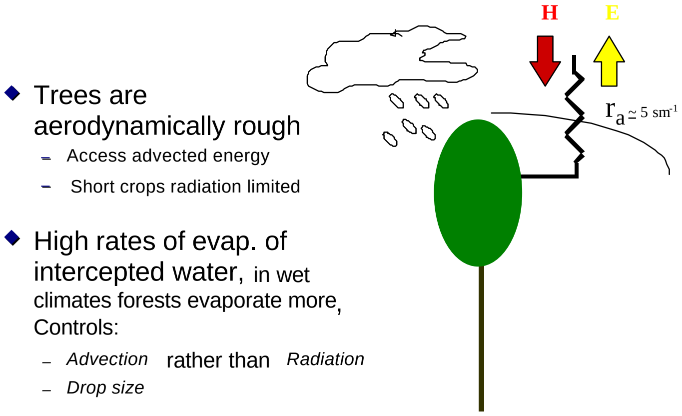


Figure 1. Reasons: trees are tall.

Not only does the increased aerodynamic transport, by reducing the aerodynamic resistance (r_a), increase the rate at which evaporated water molecules leave the surface but it also increases the rate at which heat can be supplied by the atmosphere to the cooler vegetation surface to support the evaporation process. This source of energy, known as advection, is of such significance that annual evaporation rates from forests in wet climates can exceed those that could be sustained by direct radiation from the sun by a factor of two. The difference between the evaporative requirement and the radiant supply is accounted for by the advected energy drawn from the air mass as it moves over the forest.

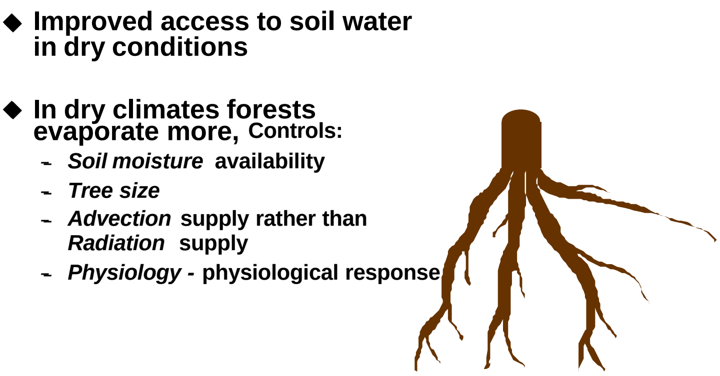


Figure 2. Reasons: trees have deep roots.

2.1.2 Difference in rooting depth

In drier climates, because forests generally have much deeper root systems (Fig. 2) than short vegetation or agricultural crops, forests are able to access and transpire more soil water during dry periods which also leads to higher evaporation rates overall.

2.1.3 Differences in senescence

Most crops and grasslands have a characteristic pattern of development where green leaf area increases rapidly after germination or winter dormancy, and peaks towards maturity before senescing. This pattern may be influenced by soil water availability or low temperature, but is frequently an intrinsic characteristic of the plant. In South Africa it is believed that the senescence of short vegetation, particularly montane grassland is often a major cause of the reduced evaporation from this vegetation type as compared with alien or native forest.

2.2 Limits and controls on water use between different vegetation types

Evaporation equations, based on the concept of the energy balance and the aerodynamic transport equation (Penman, 1948, Monteith, 1965), are central to most of the modern hydrological methods of estimating evaporation from different surfaces, whether these surfaces are natural vegetation, water or man made surfaces such as those of urban areas. These methods have been widely used in models that describe the spatial distribution of evaporation, both in global climate models and in distributed catchment models. Although neither the physical basis nor the potential accuracy of the Penman-Monteith approach is questioned, it has been suggested (Calder, 1996a; Calder, 1998a,b) that for practical applications, and particularly for practical applications in dry, water-limited environments, other, simpler, approaches should also be considered.

Historically, the energy balance-based evaporation models best reflected the wet temperate climates, because they are essentially first order meteorological demand estimation models with second order moderating functions, which take account of physiological and other supply limiting controls. However, in dry environments, evaporative systems are limited more by supply, and where demand greatly exceeds supply, detailed measurement or modelling of the meteorological demand in the evaporative equations becomes largely irrelevant.

The conventional estimation of water use from different vegetation types growing in different parts of the world has required detailed and expensive measurement programmes to measure either the evaporation directly or indirectly. An alternative “Limits approach” is much less data intensive, focussing on processes which are known to be limiting evaporation in a particular situation. This approach could be regarded as taking a more holistic or systems perspective on the processes controlling evaporation. It is less concerned with estimating evaporation as some simple or linear function of atmospheric demand, and is more willing to consider the availability of water supply and what scaling (emergent) properties of the vegetation are relevant for estimating evaporation.

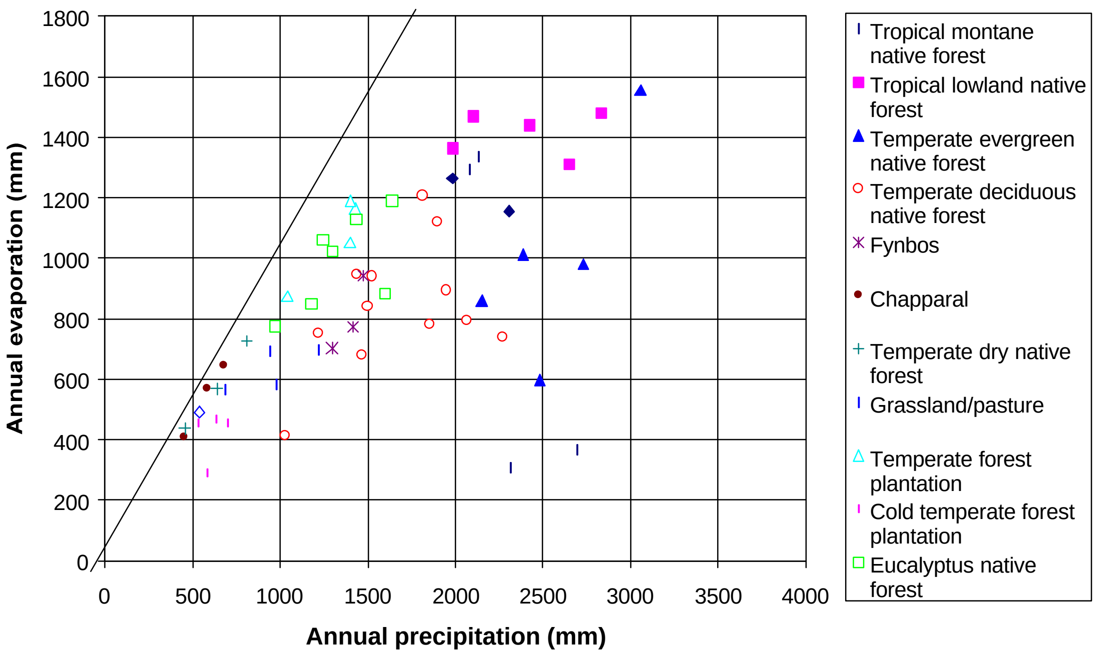


Figure 3. **Annual evaporation plotted against annual precipitation for different vegetation types from different regions of the world (Vertessy and Dye, 2000).**

The effects of demand and supply limitations are illustrated by the results from catchment studies that have been carried out in different parts of the world (Fig.3, Vertessy and Dye, 2000). In dry climates evaporation is usually controlled primarily by the availability of soil moisture and is ultimately limited by the supply of rainfall. In wetter climates atmospheric evaporative demand, the ability of the atmosphere to supply radiant or advective energy to the evaporative surface is the principal limit. Fig. 3 also illustrates the large variability of evaporation rate within a particular climatic regime, which is a reflection of the particular physical and physiological evaporative properties of the vegetation type. Least evaporation occurs from grasslands, deciduous forests and high altitude vegetation where green leaf area dynamics, short growing seasons, cool temperatures and high humidity can inhibit evaporation. Highest evaporation is associated with well-developed evergreen forests characterised by dense stands of physiologically vigorous trees. The potential range in annual evaporation increases with increasing rainfall. Over a range of annual precipitation associated with most forest plantations in South Africa (600 – 1600 mm), the net difference in evaporation can vary from approximately 0 to 600 mm.

From the results emerging from catchment studies and process studies world-wide it has been suggested (Calder, 1996a) that the results carried out in the wet and dry climates of both the temperate and tropical regions can be interpreted in terms of six types of controls and limits on the evaporation process: *advection, radiation, physiological, soil moisture, tree size* and *drop size*, Table 1.

Table 1. Principal limits and controls on evaporation for different land uses in different climates.

PRINCIPAL LIMITS ON EVAPORATION TEMPERATE CLIMATE		
Land use	**DRY**	**WET**
Tall crop	***Physiological*** ***Soil moisture***	***Advection***
Short crop	***Soil moisture*** ***Radiation***	***Radiation*** ***Physiological***

PRINCIPAL LIMITS ON EVAPORATION TROPICAL CLIMATE		
Land use	**DRY**	**WET**
Tall crop	***Soil moisture*** ***Tree size***	***Drop size*** ***Radiation***
Short crop	***Soil moisture***	***Radiation***

The extent to which this approach may be of value for assessing broadly the increase in water use that might be expected when alien tree species replace native vegetation is investigated here. The limits and controls determining water use from alien and native vegetation in wet and dry conditions are considered in relation to the results from process studies carried out in RSA, India and the UK.

3. ALIEN WATER USE, LIMITS AND CONTROLS

3.1 T Temperate wet climates – *advection*

The results from studies carried out at the Plynlimon experimental catchments in mid Wales, the Balquhidder experimental catchments in central Scotland and at the Crinan Canal catchments in west Scotland, illustrate some of the important controls on evaporation from vegetation growing in these wet temperate climates. The Plynlimon 'natural' plot lysimeter, which contained a mixture of "alien" Sitka and Norway spruce trees, hydraulically isolated by containing walls and impermeable clay subsoil, clearly demonstrated the importance of the interception process for upland forest. Annual forest interception losses, determined by large plastic-sheet net-rainfall gauges, were about twice those arising from transpiration. The total evaporative loss, from both transpiration and interception, required a latent heat supply, which was supplied by large-scale advection, which exceeded the radiant energy input to the forest. The uplands of the UK, subject to a maritime climate typified by high rainfall, a high number of raindays per year and high windspeeds, are an example of a situation where large scale advection of energy routinely occurs from moving air masses as they pass over wet forest canopies. In the UK uplands *advection* can probably be regarded as not only a major source of energy for forest evaporation but as the principal limit on the evaporative process, Table 1. For short "native" vegetation, grassland or heath, evaporation is limited primarily by *radiation* and *physiological* controls (Calder 1996a). In the wet uplands of the UK, the evaporation from fast growing alien conifers is typically about twice that of short native vegetation. Few studies have been carried out on native conifers but it would not be expected, for the reasons discussed below, to be very much less than that from alien conifers.

3.2 Tropical wet climates – *drop size,* and *radiation* limits

In tropical wet-climates, interception usually remains a major if not, as for temperate wet-climates, the major component of the annual forest evaporation. The reduced interception losses, in both absolute and percentage terms, from tropical as compared with temperate climates, probably arise because of two limiting processes; those governed by *drop size*, and *radiation* limits.

<u>Drop size controls</u>

From studies carried out in rain forest in Indonesia (Calder *et al*., 1986), the importance of rain drop size in determining interception losses from tropical forest was first realised. Application of a stochastic interception model, which explicitly took into account drop size, was required to describe the interception process in these conditions. This model shows that up to ten times as much rain may be required to achieve the same degree of canopy wetting for tropical convective storms, with large drop sizes, than would be necessary for the range of smaller drop sizes usually encountered for frontal rain in the temperate UK. There are also results from studies using rainfall simulators, which show that the final degree of canopy saturation also varies with drop size, being greater for drops of smaller size, Fig 4.

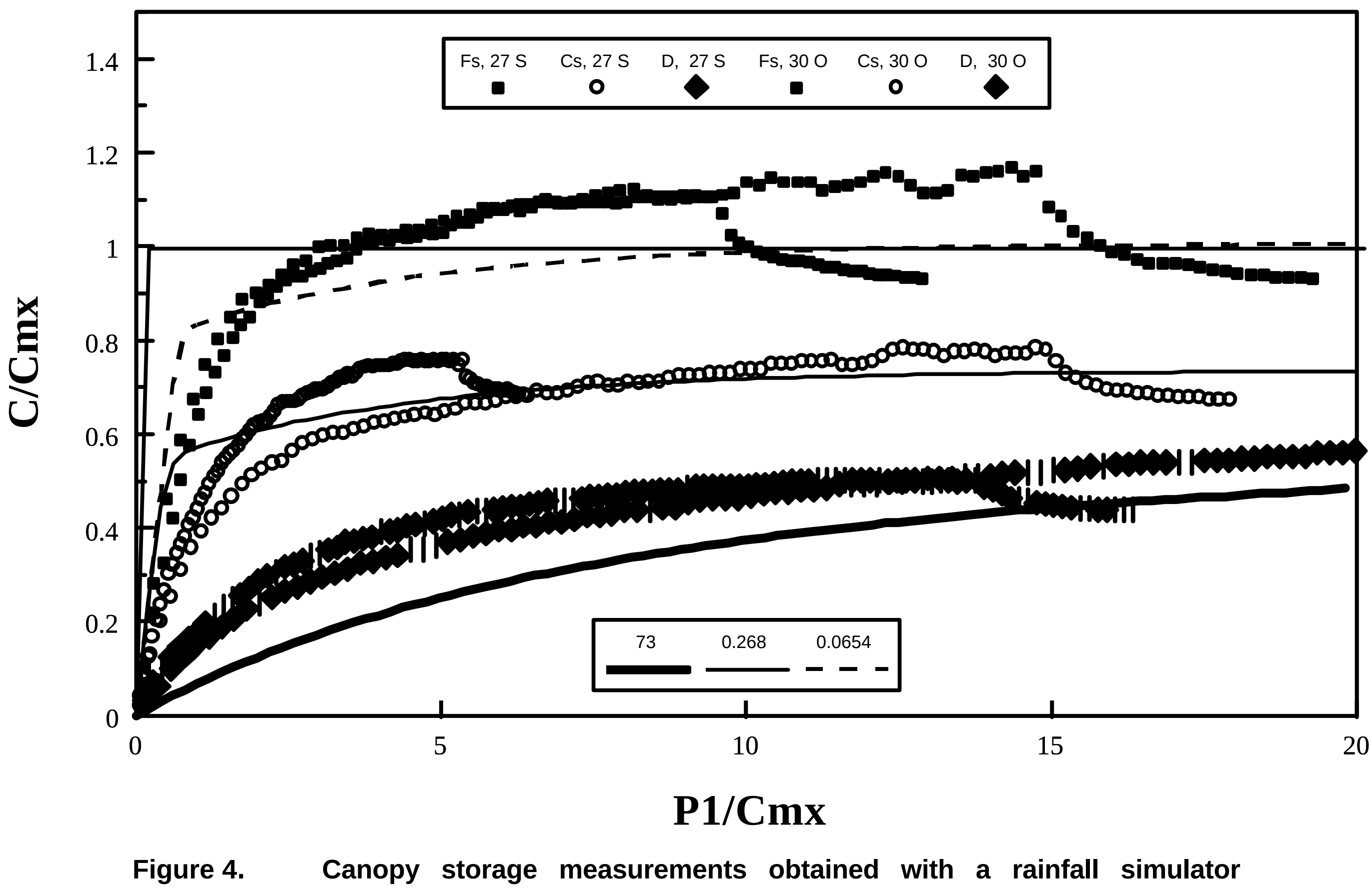


Figure 4. Canopy storage measurements obtained with a rainfall simulator showing that the final degree of canopy saturation is much greater when wetted with drops of smaller size. The storage of water on the sample, *C*, is shown normalised by the maximum storage obtained with

fine drops, C_{mx}, and the depth of simulated rainfall applied, P_1, is also normalised by C_{mx}. The wetting functions predicted by the stochastic interception model for these drop sizes are shown as continuous lines. Also shown, as straight lines, is the wetting function implicit in conventional interception models of Rutter type. From Calder *et al.* 1996.

Vegetation canopies also influence the drop size of the net rainfall as it falls through the forest canopy. Deeper layers in the canopy will be more influenced by the modified drop size spectrum falling from canopy layers above, than by that of the incident rain. Studies have shown that different vegetation canopies have very distinct canopy spectra, Fig. 5, (Hall and Calder, 1993). For canopies with a low leaf area index the interception characteristics would therefore be expected to be related more to the drop size of the incident rain, whereas for canopies with a higher leaf area index the characteristics would be less dependent on the drop size of the rainfall (Calder 1966b).

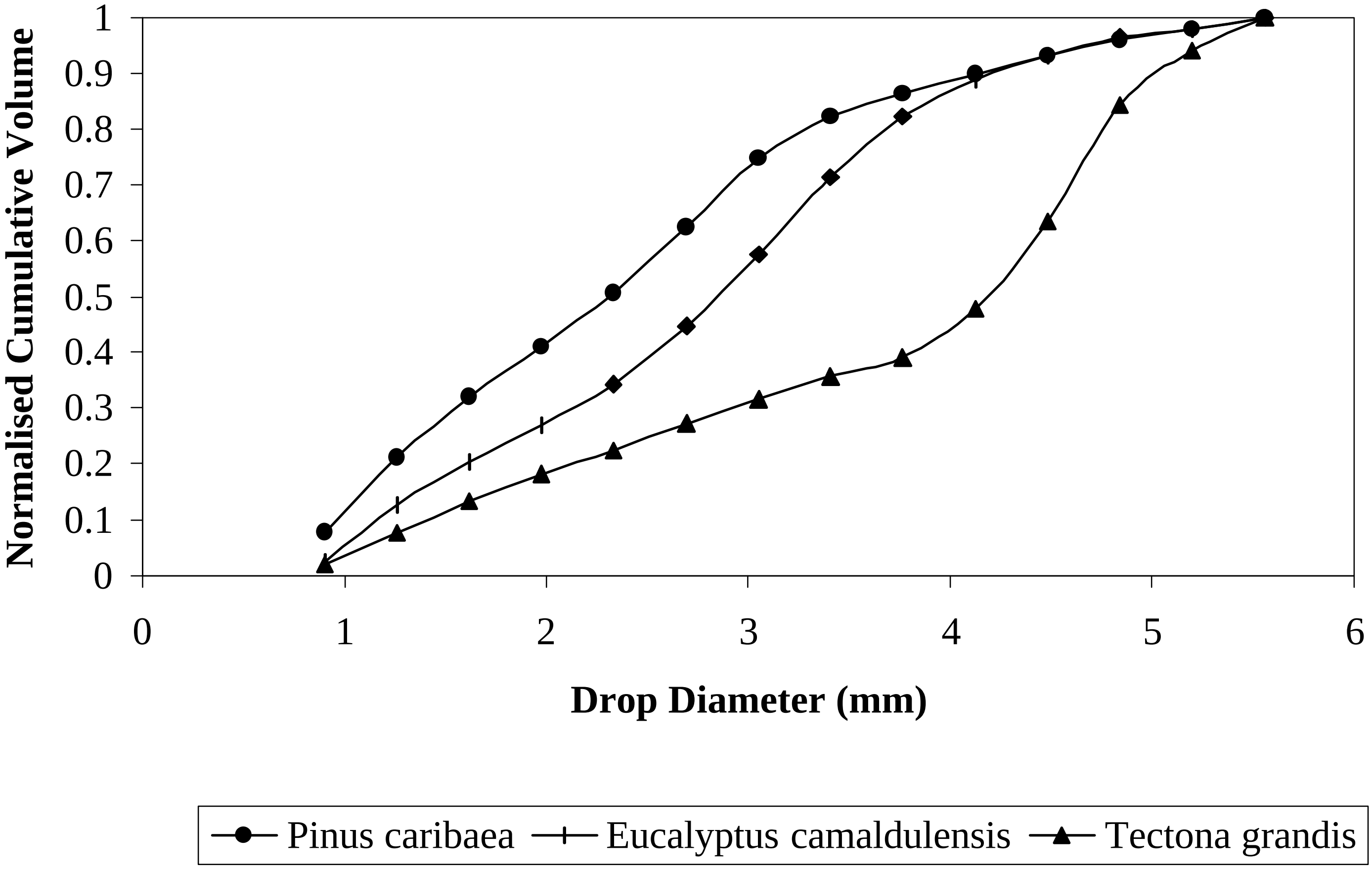


Figure 5. **Characteristic net-rainfall drop-size spectra for *Pinus caribaea, Eucalyptus camaldulensis* and *Tectona grandis* (from Hall and Calder, 1993)**

The drop size dependence of canopy wetting provides part of the reason why forest interception varies so much world-wide, and why interception losses from coniferous temperate forests are so much higher than from tropical forests. Canopy wetting will be achieved most rapidly and maximum canopy storage will be highest, leading to high interception losses overall, when the volume of individual raindrops and drops draining from the canopy, are both small. These conditions apply for coniferous forests in the low intensity, small rain drop size climate of the uplands of the UK. By contrast, when both individual raindrop volumes and leaf drop volumes are large, canopy wetting will be achieved much more slowly, the final degree of canopy saturation will be less, and interception losses are likely to be much reduced. This situation is typified by tropical rainforest experiencing high intensity convective storms of large drop size.

Radiation limits

The wet evergreen forests of the tropics represent a situation where climatic demand is likely to limit forest evaporation. However climate circulation patterns in the tropics do not generally favour large scale advection of energy to support evaporation rates and here evaporation rates are likely to be closely constrained by the availability of solar radiation. Whereas in the wet temperate, maritime climate of Plynlimon in Mid-Wales, the energy requirements of the total evaporation far exceeds the supply of radiant energy to the forest, in continental humid tropical forest the evaporation rates are likely to be much more closely constrained by the supply of *radiant energy* requirements, Fig.1. An exception may be that in tropical wet **maritime** climates such as tropical islands, circulation patterns may also favour large-scale advection. Brujzneel (unpublished manuscript) presents results suggesting very high interception losses from forests in these conditions.

3.3 Temperate dry climates – *Physiological* and *soil moisture* limits

Included within the British Government's 1995 White Paper on Rural England was a proposal to double the area of forests within England by the year 2045. The combination of this proposal, together with Government recognition of the real possibility of climate change resulting in hotter drier summers and wetter winters, raised questions concerning the possible impacts on UK water resources and the water environment of the combined effects of climate change and such a large change in land use. The Department of the Environment Transport and the Regions (DETR) commissioned a modelling exercise using the HYLUC97 model (based on the limits concept) to assess the range of the possible water quantity impacts of afforestation on one of the UK's most important aquifers: the Nottinghamshire Triassic sandstone aquifer (Calder *et al.* 1999). The model predicted increased evaporation from conifers as compared with broadleaf forest, both of which were significantly greater than grassland, Fig.6. Using these the calculated average reduction in recharge plus runoff from the Greenwood Community Forest which partially overlies the sandstone aquifer, as a result of a planned three times increase in forest cover, from the existing 9% to 27%, would be 14 mm, equivalent to an 11% reduction in the long term recharge.

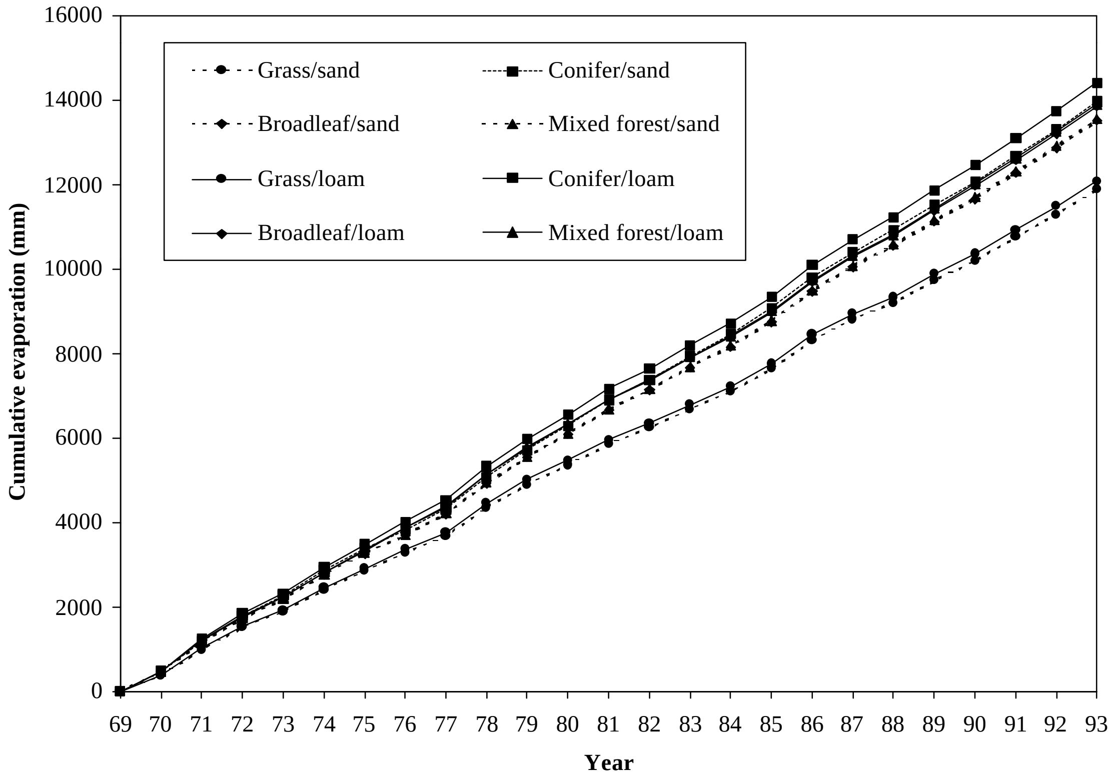
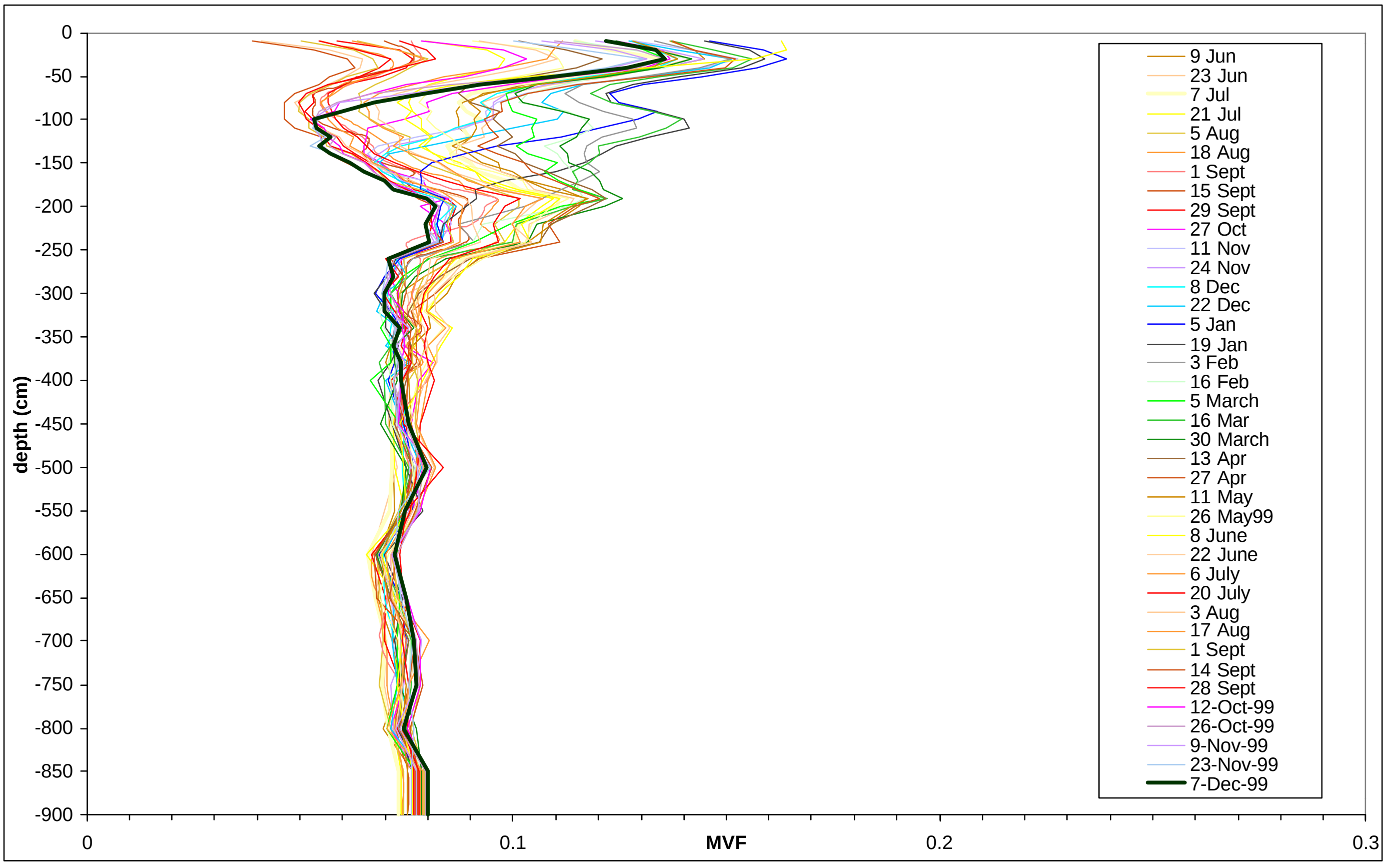


Figure 6. Model predictions of cumulative evaporation for conifer, broadleaf, mixed forest and grassland at Clipstone, the Midlands, UK, from Calder *et al.* 1999

A follow-up field study, to improve the parameterisation of the model, is currently underway which involves detailed soil moisture measurements under Corsican pine, oak, heath and grass vegetation, together with heat pulse sap flow measurements and water quality sampling. These studies are not complete and it is planned to carry out felling treatments to remove any possible influence of site differences in the soil properties. However, the preliminary indications are that over the measurement period (Feb 1998 -Dec 1999), there has been no wetting of the soil profile beneath the “alien” Corsican pines, whereas wetting fronts were observed to penetrate the whole depths of the profile under both the “native” oak and “native” heath vegetation, Fig. 7.



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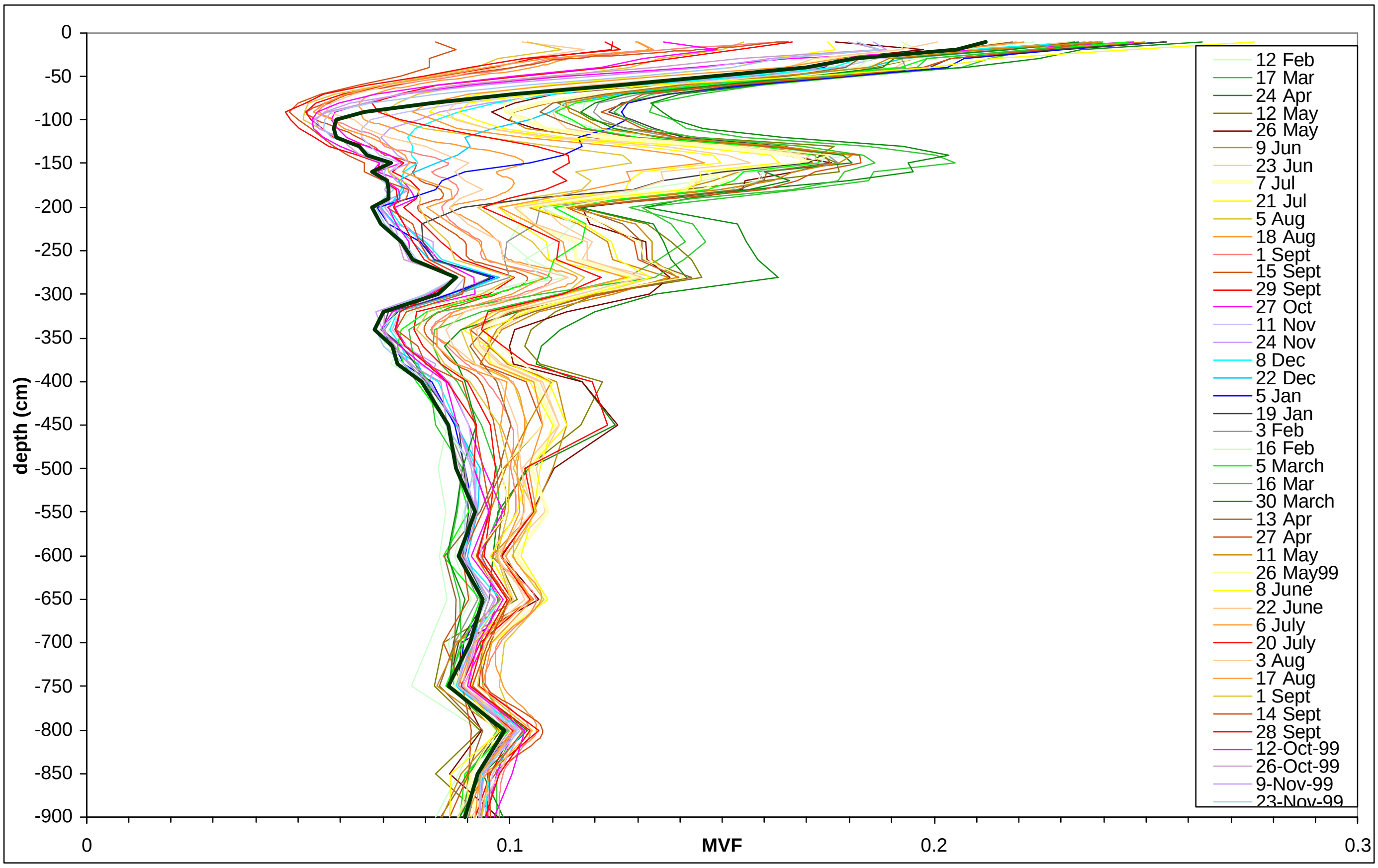

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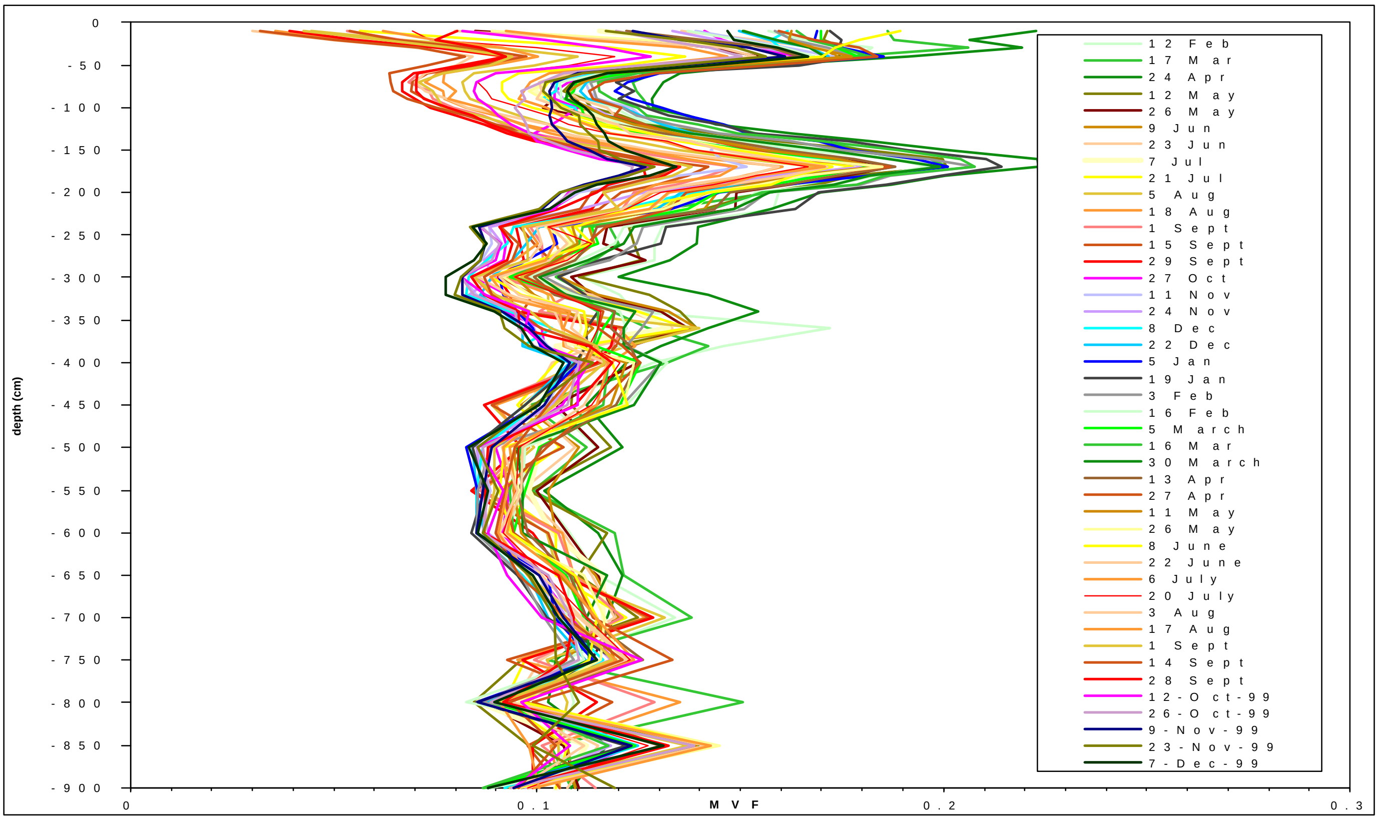


c)

Figure 7. **a, Soil moisture profiles recorded under "alien" pines , b, "native" oak and c. heath at Clipstone, the Midlands, UK.**

On the sandy soils at Clipstone *soil moisture* controls represent a major limitation on evaporation for all vegetation types. For heath and grassland it is generally recognized that *radiation* controls also represent a limitation on evaporation rates. If the follow up studies confirm the preliminary indications that there is no recharge occurring under the "alien" pine, even under years of average rainfall, this will have important implications for plans for further afforestation in the area.

3.3 Tropical dry climates – *tree size*, *advection* and *soil moisture* limits Southern India, *soil moisture* and *tree size* limits

<u>*Soil Moisture*</u> As part of a study to investigate the hydrological impact of eucalyptus plantations in the dry zone of Karnataka, in southern India, comparative studies were carried out on the evaporative characteristics and soil moisture deficits under "alien" eucalyptus plantation, indigenous forest, "native" commercial tree species and agricultural crops. At one of the sites, Hosakote, the soil was a very deep (>8m) laterite; at the other sites, Puradal and Devabal, the soil profile comprised a 2-3 m depth of red soil overlying a basement bedrock.

The main water use findings of the study were:

1. In the dry zone, the water use of young "alien" Eucalyptus plantation on medium depth soil (Puradal and Devabal) was no greater than that of the "native" indigenous dry deciduous forest.
2. At these sites, the annual water use of eucalyptus and indigenous forest was equal to the annual rainfall (within the experimental measurement uncertainty of about 10%).
3. At all sites, the annual water use of forest was higher than that of annual agricultural crops (about 2 times higher than finger millet).

4. At the dry zone deep soil (Hosakote) site, the water use of “alien” eucalypts, over the three (dry) years of measurement, was greater than the rainfall. Model estimates of evaporation were 3400 mm as compared with 2100 mm rainfall for the three-year period. These results were later confirmed by an experiment carried out on an adjacent "farmer’s field" where measured soil moisture depletion patterns under eucalyptus, from the date of planting, were shown to be much greater than those under both the agricultural crop, Fig. 8., and under other tree species, Fig. 9. They indicated that eucalypt roots were penetrating the soil at a rate exceeding 2.5 metres per year, about twice the rate of “native” species, and were able to extract and evaporate an extra 400 to 450 mm of water in addition to the annual input of rainfall.

For all the sites where investigations were undertaken, *soil moisture* availability was therefore found to be a major limit on evaporation for both agricultural crops and trees. For the annual agricultural crop studied, (finger millet, *Eleusine coracana)*, the rooting depth was less than two metres and the total available water was found to be 160 mm. This compares with 390 mm total available water for eucalypts and indigenous forest at the medium depth soil sites of Puradal and Devabal.

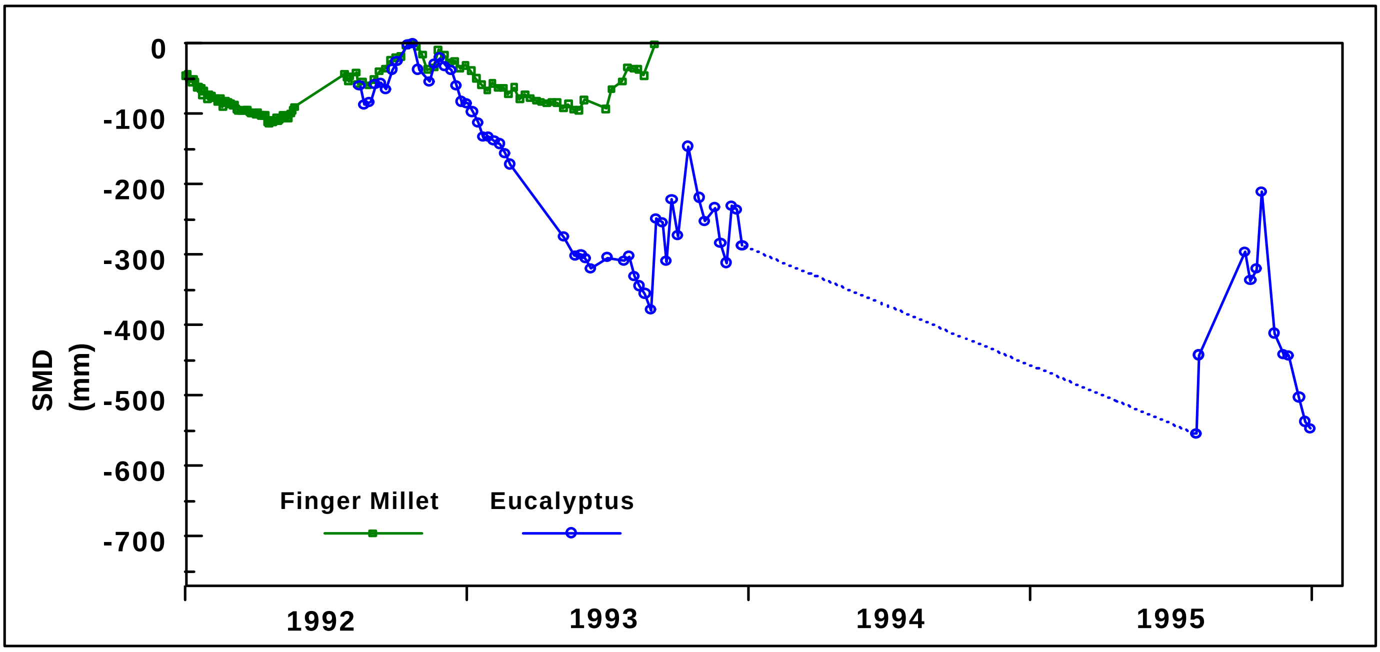


Figure 8. Soil moisture deficits recorded beneath *Eucalyptus camaldulensis* and *Eleusine coracana*, finger millet at the Hosakote site, India.

The Hosakote studies demonstrate the large increase in water use that can occur when fast growing “alien” species are not subject to the same limits on evaporation as other species. Here the eucalypts, through deep rooting, clearly have much greater access to *soil moisture* and consequently both water use and growth rates are higher than native species. However at none of the sites was there any evidence of eucalypts extending their roots to sufficient depth to abstract from the water table.

The deep rooting behaviour of *Eucalyptus* species has also been reported in South Africa. Dye (Dye *et al.* 1997) found root abstraction from a depth of 8m taking place from 3-4 year-old *Eucalyptus grandis.* The ability for deep rooting may be a feature of other fast growing alien tree species.

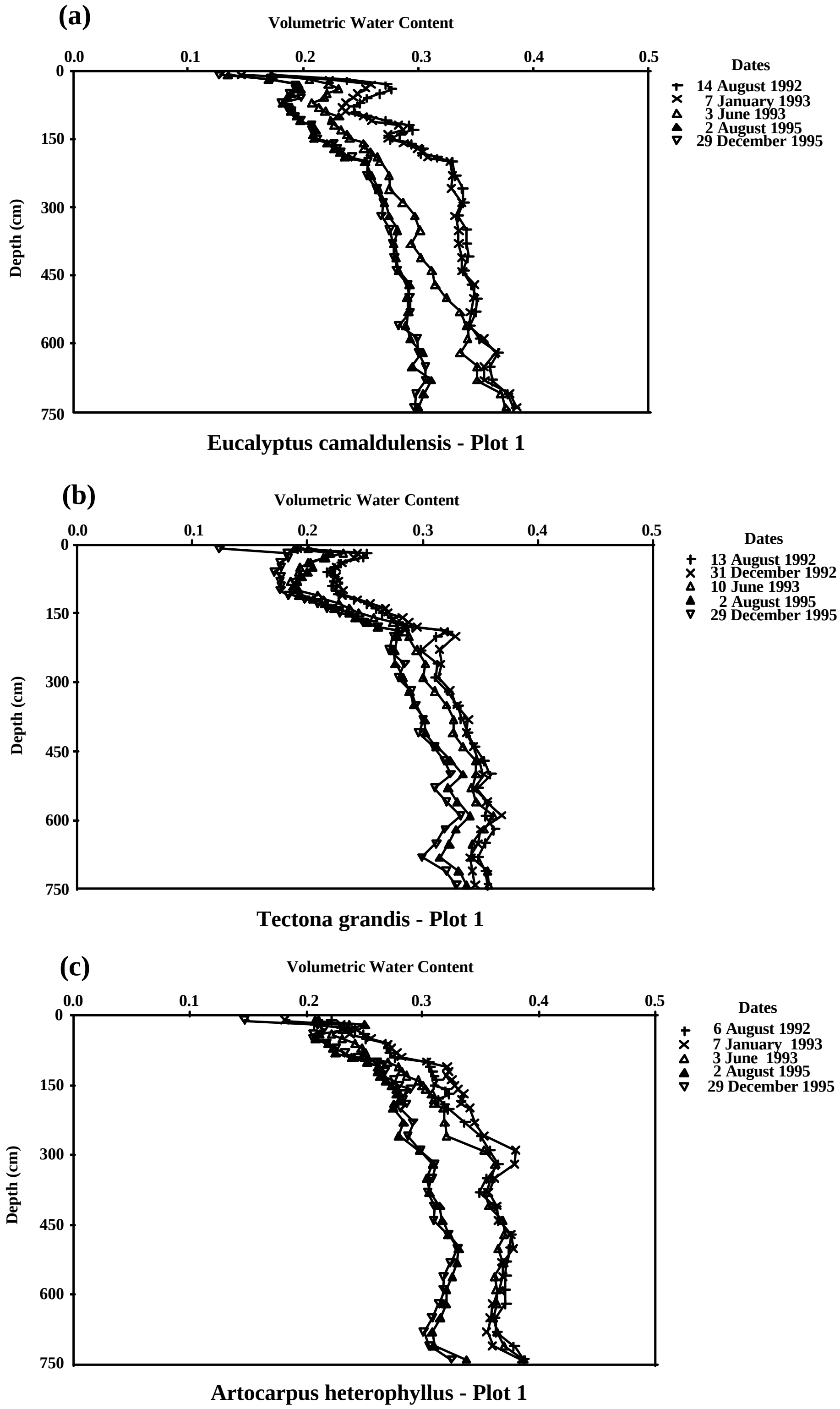


Figure 9. **Volumetric water content profiles to 7.5m depth recorded beneath the *Eucalyptus camaldulensis, Tectona grandis,* and *Artocarpus heterophyllus* plots, "farmer's field experiment", Hosakote, India: planting date: August 1992, from Calder *et al*., 1997a.**

Tree size These Indian studies also demonstrated, for the relatively young plantation trees used in the study (less than 7 years old) not only the importance of *soil moisture* but also t*ree size* as a limit on water use. Tracer studies established a linear scaling relationship between transpiration rate and basal cross-sectional area for these young trees, Fig. 10. This linear relationship held in both conditions of relatively unlimited *soil moisture* availability during and immediately after the monsoon (November 1989) when transpiration rates were greatest, and in the pre and post monsoon conditions when *soil moisture* availability, and water use was much reduced. The Indian studies also showed that in these generally *soil moisture* limited conditions, the growth rates of the eucalypts, expressed in terms of stand volume increment was essentially linearly related to the volume of water transpired. This allowed the development of a simple water use and growth model (WAG), (Calder 1992) based on not only knowledge of the linearity between growth rate and water use, but also of knowledge of the *soil moisture* and *tree size* limits and controls. The possibility of using this type of model to derive estimates of tree water use based on knowledge of growth rates is discussed later.

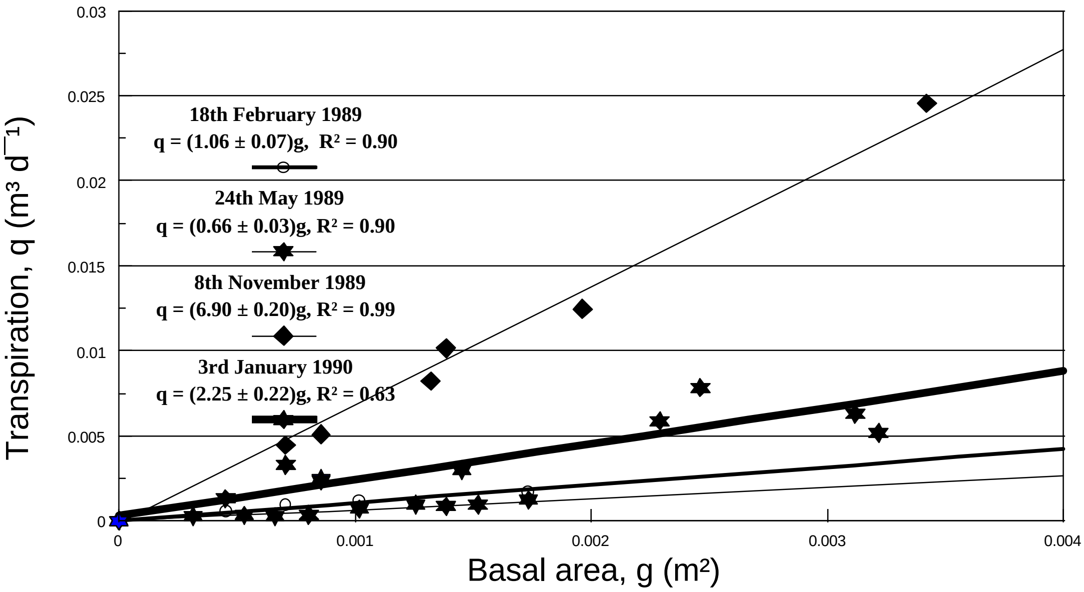


Figure 10. **Measured transpiration rates as a function of tree basal area (g) at the Puradal site prior to and after the monsoon (Jul - Sep) 1989 from Calder, 1992.**

South Africa, *tree size* and *advection* limits

In a recent study of the comparative water use of riparian wattle thickets and riparian fynbos (Dye and Moses, 1999), hourly sap flow was recorded in six sample trees representing different size classes of tree in a dense wattle thicket near the town of Wellington, Western Cape. Measurements were continued over a seven-month period. Daily sap flows in all six sample trees were found to be highly correlated to the product of mean daily vapour pressure deficit and the number of daylight hours (Fig. 11). Daily sap flow was correlated to tree basal area, the relation being linear over the smaller trees, but curvilinear overall because of lower water use per unit basal area in the largest trees (Fig. 12). Annual evaporation was estimated to be 1503 mm.

Comparative evaporation measurements were made above a riparian "fynbos" plant community in the Jonkershoek valley, Western Cape, using the energy balance Bowen ratio technique. Daily evaporation from the 0.75 m high canopy was highly correlated to total daily solar radiation (Fig. 13). Annual evaporation at this site was estimated to be 1332 mm.

At both these sites, there was no evidence of physiological control on evaporation rate due to soil water deficits. Annual water use by wattle trees was somewhat higher than the short fynbos, by a factor of 1.13. The absence of a larger difference in water use between wattle thicket and fynbos is attributed to non-limiting soil water at these sites, and the evergreen nature of the fynbos plant community in this habitat.

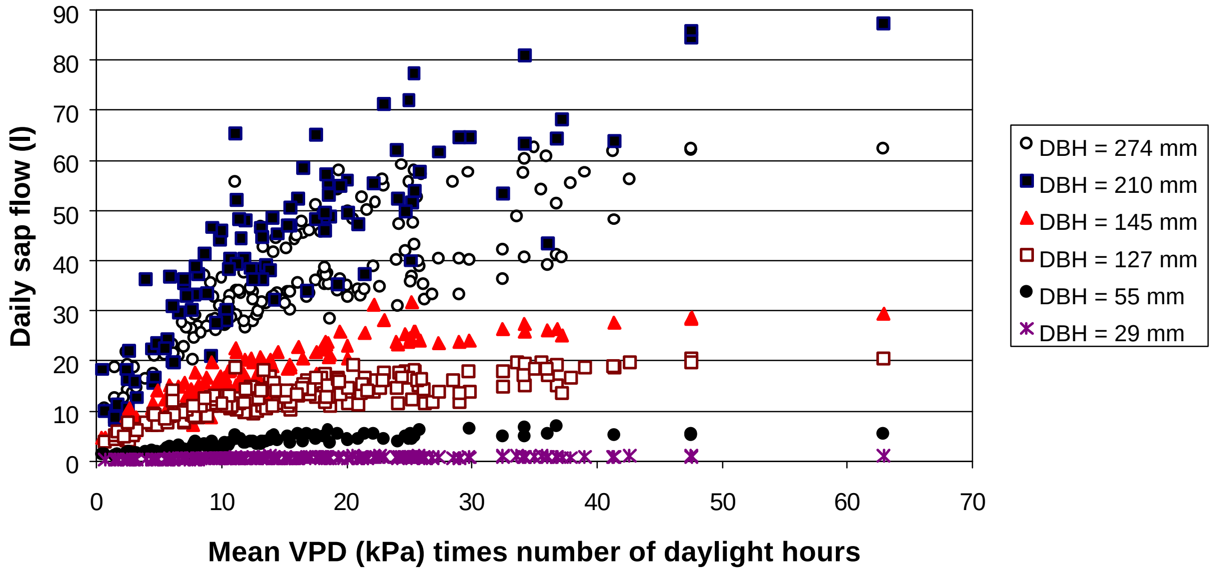


Figure 11. **The relation between daily sap flow and the product of mean VPD and the number of daylight hours, illustrated by all available daily data recorded in the six A. mearnsii sample trees at the Wellington riparian site.**

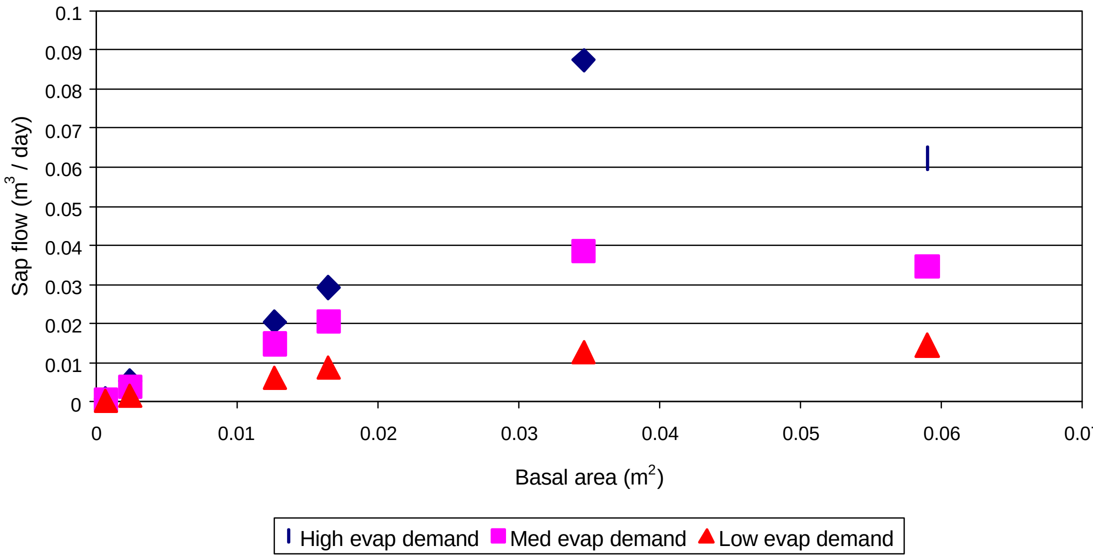


Figure 12. **The relation between basal area and daily transpiration recorded on three days of high, medium and low evaporative demand, in six riparian *Acacia mearnsii* trees.**

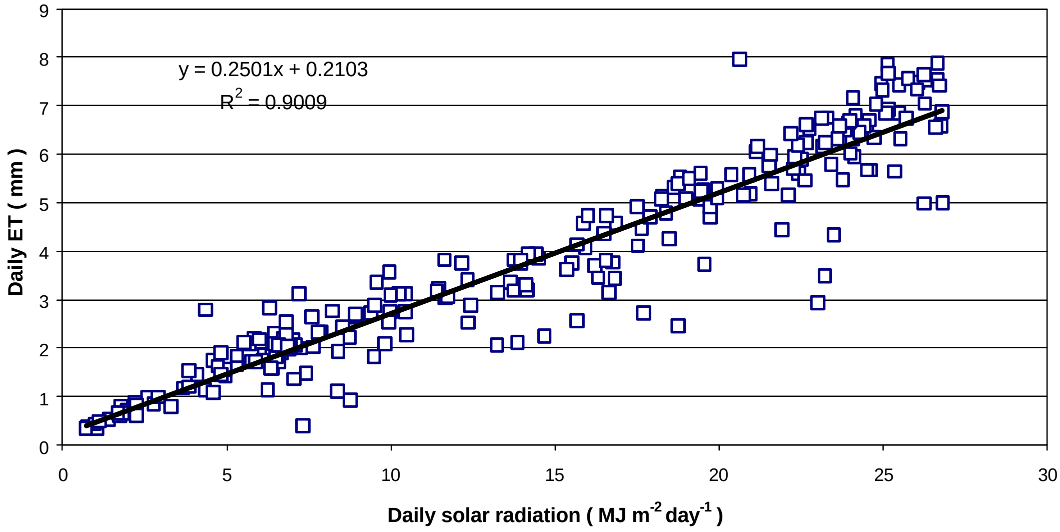


Figure 13. **The relation between total daily solar radiation (MJ m^{-2} day^{-1}) and total daily ET (mm) recorded at the Jonkershoek riparian fynbos site.**

4. Relevance of the limits approach for assessing water use by alien and native plants in South Africa

Increased catchment water yield is a major justification for the cost of clearing alien plants in water-scarce South Africa. It is therefore important to be able to predict the net change in evaporation following alien clearance and recovery of a stable native plant community, to assess the cost-benefit of the conversion, and assist in prioritising invaded areas for clearing. Fig. 14 indicates that high-rainfall catchments show the greatest potential streamflow enhancement, as indicated by the evaporation difference between the forest and grassland trends calculated by Zhang (1999).

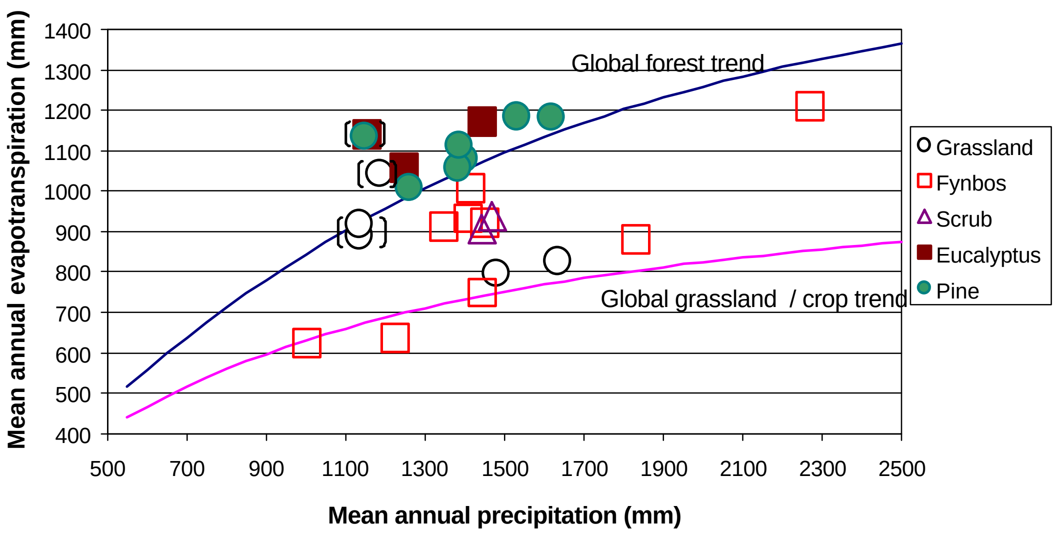


Figure 14. **The relation between mean annual precipitation and mean annual evapotranspiration for a selection of South African research catchments. The symbols in brackets indicate the Mokobulaan catchments that are believed to leak significantly. Global trends are those calculated by Zhang, (1999).**

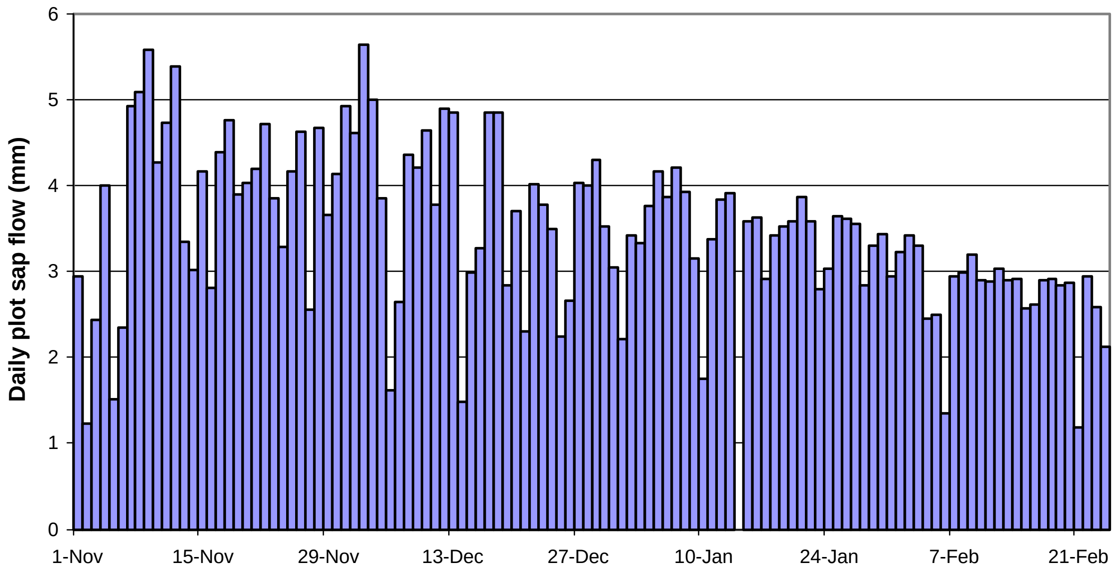
Assessing the hydrological impact of alien removal programmes is, however, greatly complicated by the following considerations:

- There is commonly great variation in the density of alien plants within catchments (especially trees). Highest density is often seen along riparian zones, with considerably lower densities elsewhere in the catchment. Fire history and previous land use patterns often cause a patchy distribution of alien plants. It is mostly necessary, therefore, to assess evaporation on a **site** basis rather than a whole-**catchment** basis.

- Alien plants include a wide range of species, many with properties intermediate between grassland and forest. Problem species such as Lantana (*Lantana camara*), Mauritius thorn (*Caesalpinia decapetala*) and Triffid weed (*Chromolaena odorata*) are likely to fall in this category. A species may occur in stands of very different ages, differing markedly in height, leaf area and rooting depth. Likewise, native vegetation is diverse, and may cover the entire range from grassland to forest. Fynbos may show short crop characteristics immediately after a fire, but progressively assume the characteristics of a forest as growth and succession proceed over subsequent years (Fig. 14). Clearly, the net difference in evaporation between alien and native vegetation can cover a wide range.

- Prediction of soil water availability at a site is made highly complex by uncertainties such as rooting depth, soil water holding capacity, lateral soil water movement and rainfall distribution. Dye monitored sap flows in *Acacia mearnsii* trees growing alongside an ephemeral channel in the Stellenbosch area, and recorded a marked decline in sap flow in the second half of summer as soil moisture became limiting (Fig. 15). This soil water limitation to the water use of trees growing in an apparently riparian site could not have been predicted from a site evaluation, owing to the extremely rocky soil profile, unknown water storage capacity, and unknown recharge of soil moisture during periods of channel flow. The use of remote sensing for estimating the onset of soil moisture stress and reduced water use by vegetation is believed to be a potentially useful tool

Figure 15. Daily plot sap flow based on five *Acacia mearnsii* sample trees growing



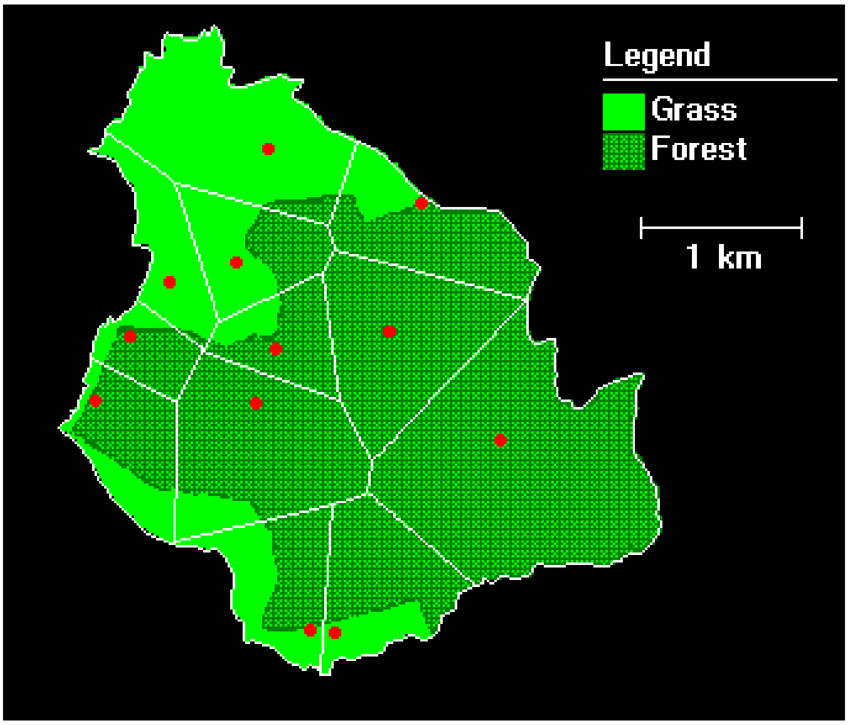
along an ephemeral stream channel in the Stellenbosch area.

There is unfortunately no existing practical methodology for spatially estimating the incremental (additional) water use of alien species that meets the needs of land managers. The few South African research catchments and evaporation studies that have yielded water use data so far are too few to provide an adequate foundation for the countrywide estimation of evaporation in invaded regions. A simple model based on an observed relationship between biomass and streamflow reduction has been developed from Western Cape catchment data, and applied countrywide (*Le Maitre et al*., 1996). While adequate for providing a preliminary assessment of alien hydrological impacts (especially in the Western Cape), there is enough worldwide information to suggest that the relation is not universally applicable, and that there is a need for more refined and generally applicable models. Further measurements of annual water use over a wide range of alien and native vegetation are seen as a prerequisite for developing such models. The scope for this kind of work is limited, however, by the following constraints:

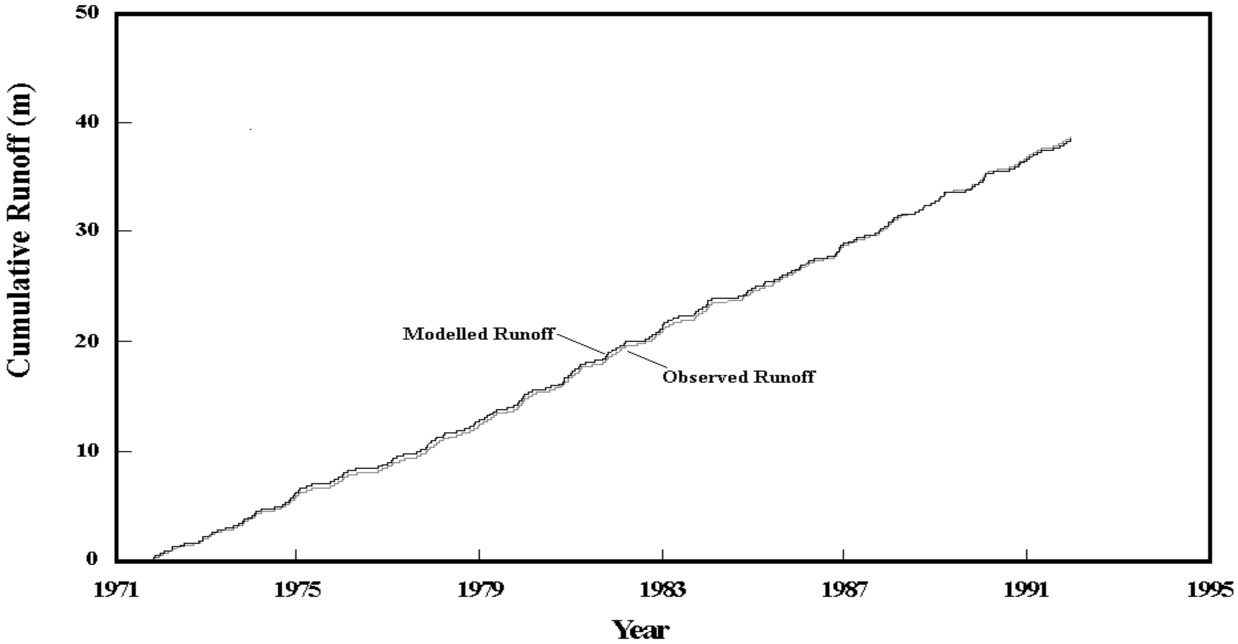
- The cost of instruments and manpower in sustaining measurements over a full year
- Significant risks in maintaining field equipment (theft, floods, fire)
- The very large number of alien and native plant communities requiring study
- Results needed now, rather than later, when many areas will have already have been cleared

We propose a strategy of undertaking short term, intermittent readings at different times of the year, to supplement existing knowledge of the major limits to evaporation, experienced by different alien and native plants growing in different environmental conditions. Knowledge of these limits can then be utilized to model evaporation over a complete year, or longer time periods. In this way, the time and cost of gathering water use estimates for a wide range of alien and native vegetation can be greatly reduced.

Table 2 summarises the principle limits on water use by alien and native vegetation that have been discussed in this paper.

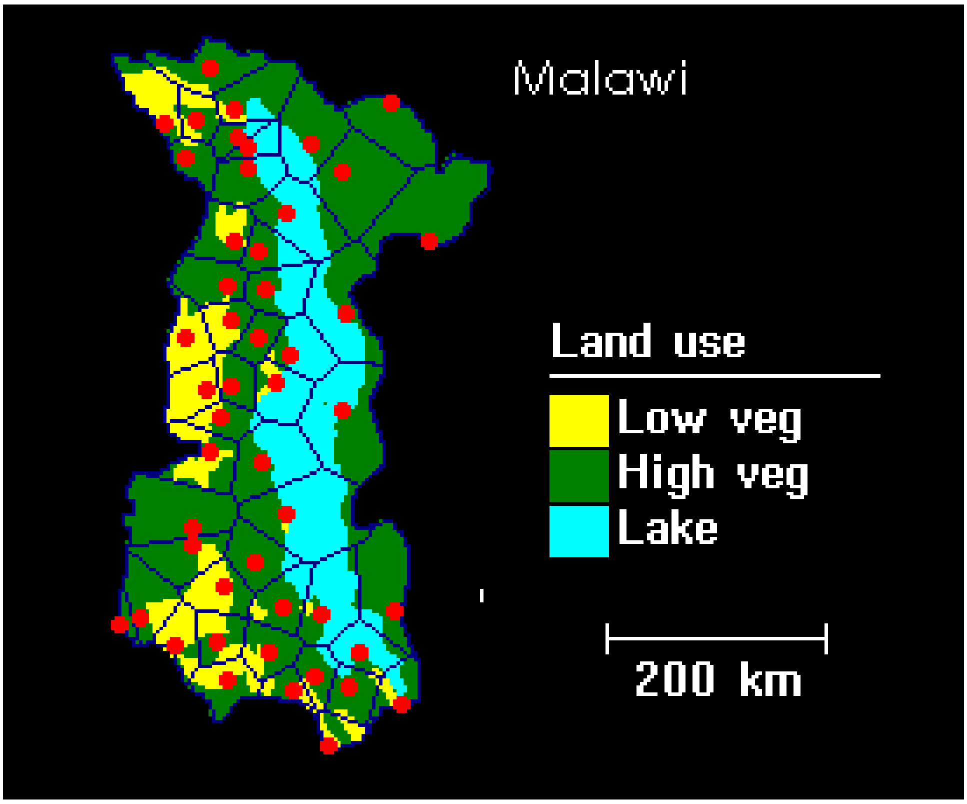


a)

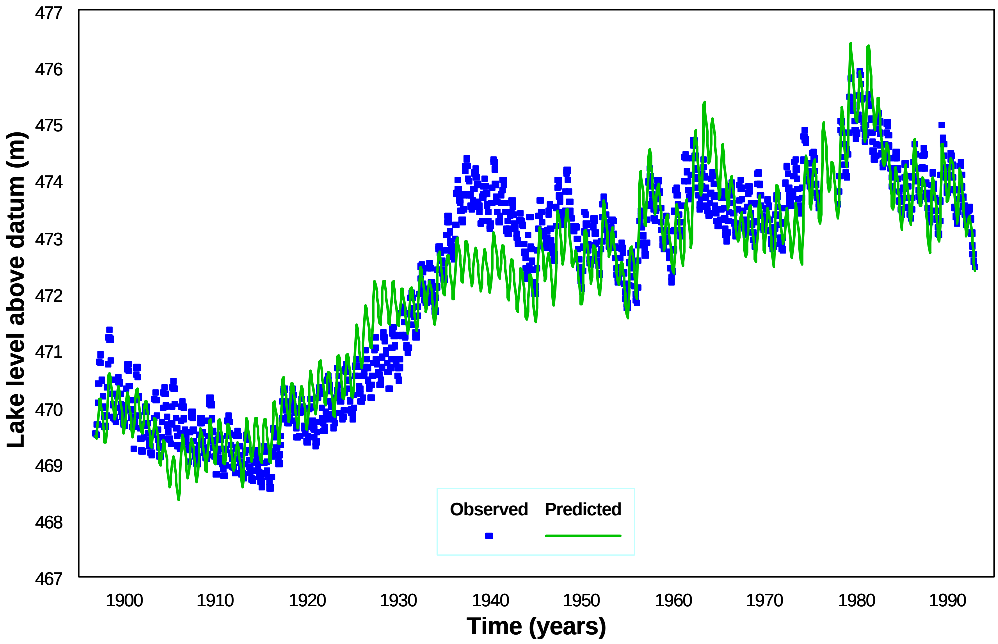


b)

Figure 16. **Application of the HYLUC, limits approach, model to investigate the impact of the change in forest cover on runoff from the Plynlimon experimental research catchments; a) GIS of land cover for the catchments showing location of raingauges; b) modelled and predicted runoff (Calder, 1999).**



a)



Forest cover declining from 64% in 1967 to 51% in 1990

b)

Figure 17. **Application of the HYLUC, limits approach, model to investigate the impact of the change in forest cover on the level of Lake Malawi; a) GIS of land cover for Malawi showing location of raingauges, b) modelled and predicted lake level (Calder *et al*., 1996).**

Examples of water use models based on limiting processes include the following:

- Water use and growth of alien Eucalypts in India *soil moisture, tree size* (Calder 1992).
- Pine plantations in New Zealand *advection, tree size* (Calder 1996a).
- Research catchment scale studies in the uplands of the UK, conifer, grassland, (Calder, 1999).
- Large catchment (whole country) studies of the impacts of land use change on the level of lake Malawi (Calder *et al.*, 1996).
- Oak and pine water use in the midland of the UK and Denmark, *advection, soil moisture* (Calder *et al.* 1999).
- Stands of riparian trees - *tree size*, *advection* (Dye and Moses, 1999)
- Riparian short evergreen fynbos - *radiation* (Dye and Moses, 1999)
- Montane grassland (LAI_{green}, *radiation*) (Everson *et al*., 1998)

With information of this kind, alien hydrological impacts could be assessed using a suite of GIS-linked "limits models" applied spatially to areas of concern. The possibility of incorporating such an approach within a forthcoming DFID-funded project in KwaZulu-Natal is currently being investigated.

Table 2. **Principal limits and controls on water use from alien and native vegetation established for certain conditions in the UK, India and RSA.**

SITE - SPECIES	PRINCIPAL LIMITS	INFER
Upland sites, UK		
Alien Spruce	*advection*	Evaporation from alien spruce exceeds that from
Native grass	*radiation*	"native" grassland by **2X**
Clipstone, sand soil, UK		
Alien Pine	*soil moisture*	**No recharge** for average year
Native oak	*soil moisture*	Some recharge for average year
Clipstone, sand soil, UK		
Alien Pine	*soil moisture*	**No recharge** for average year
Native grass	*soil moisture, radiation*	Considerable recharge for average year
Puradal, 2m soil depth, India		
Alien Eucalypts	*soil moisture, tree size*	Aliens and natives equally soil moisture limited
Native forest	*soil moisture*	**same** water use
Hosakote, deep soil, India		
Alien Eucalypts	*soil moisture, tree size*	Aliens, deep roots, **greater** water use & growth
Native trees	*soil moisture, tree size*	Natives, shallower roots, less water use & growth
Hosakote, deep soil, India		
Alien Eucalypts	*soil moisture, tree size*	Aliens, deep roots, **2 X** greater water use
"Native" short crop	*soil moisture, radiation*	Natives, shallow roots, much less water use
Jonkershoek, riparian, RSA		
Alien Acacia	*tree size, physiology, advection*	Aliens and natives have no soil water limitations
Native short crop, fynbos	*radiation*	Aliens have **1.13 X** greater water use
KZN midlands,dryland, RSA		
Alien Acacia	*tree size, physiology, soil moisture*	Aliens have greater soil water availability
Native grassland	*physiology, radiation, soil moisture,*	Grasses seasonally dormant, less water use

4.2 Integrated hydrological, ecological and economic modelling

The modelling approach of Le Maitre and colleagues (Le Maitre *et al*., 1996; Van Wilgen *et al*., 1997), in which ecological models describing the colonisation of aliens are linked with hydrological models which predict water use, provides an excellent and innovative framework for assessing the hydrological impact of alien invasion. We concur with Versfeld *et al.* (1998) that this framework could be developed and refined further to assist the design and execution of spatially targeted eradication programmes by:

1. The inclusion of improved hydrological models which may be able to take account better of the water use from aliens and natives spatially, particularly as this relates to riparian and dryland conditions.
2. The inclusion within the ecological modelling scheme of spatially related alien growth rates and colonisation opportunities, linked to water availability and water use.
3. The inclusion of an economic modelling scheme that calculates the costs of spatially directed eradication programmes in relation to the value of the various socio-economic and economic benefits, ecological benefits and the value of the extra water released by the programme.

Although the authors are not aware of such a coupled ecological /hydrological/economic modelling scheme being applied to the problem of alien control, such linked schemes have been developed for other purposes.

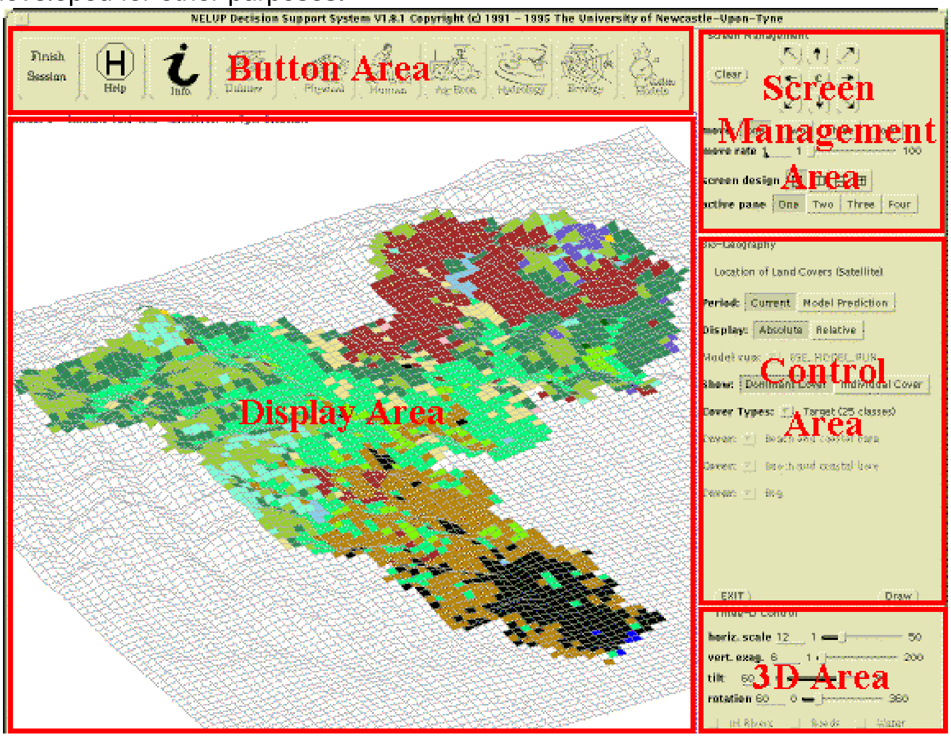


Figure 18. Screen display of the NELUP Decision Support System that assists land use decision making by calculating the ecological, hydrological and economic impacts of land use change.

One such scheme is the NELUP Decision Support System (O'Callaghan, 1996). This was developed under the UK's Natural environment and Economic and social research councils Land Use Programme. The DSS allowed the investigation, using different modelling methodologies, of the interactions between land use, water resources, economics and ecology within a spatial context, Fig 18. In principle, the concepts behind such a scheme could also be applied to alien invasion control.

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