Plantations, river flows and river salinity

Robert A. Vertessy, L. Zhang and W.R. Dawes

Cooperative Research Centre for Catchment Hydrology, CSIRO Land and Water,
GPO Box 1666, ACT 2601, Australia
Email: rob.vertessy@csiro.au

Revised manuscript received 20 December 2002

Summary

Large-scale plantation development will exert additional pressure on a water resource system that is already under considerable stress. Tree planting will reduce river flows and recharge to groundwater and, in certain circumstances, may lead to short-term worsening of river salinity prior to any improvement. Reductions in flow will be particularly problematic during dry spells, when water resources are sorely stretched. Most of the likely hydrologic impacts of afforestation can be predicted using current catchment models, but new field data are needed to test and improve their accuracy. Reductions in river flow induced by afforestation can be minimised with careful planning, and various strategies to minimise impact are recommended. It is argued that a regulatory framework needs to be erected to control the development of new plantations in order to complement other policies to preserve water resources, such as the cap on diversions in the Murray-Darling Basin and recently introduced legislation on farm dams. Given the future need to allocate additional river flows to the environment, new allocations of water to plantations should be offset by up-front transfers of water from other uses. We argue that water use by plantations should be factored into the water economy of catchments.

Keywords: forest plantations; water yield; stream flow; salinity; saline water; water allocation; water management; runoff; land use

Introduction

In a recent paper, Calder (2002) notes that there is a significant disparity between public and scientific perceptions of the hydrological role of forests and plantations. Some old myths such as ‘forests generate rainfall’ and ‘forests increase runoff’ abound, as do some more contentious (and usually incorrect) assertions such as ‘forests regulate flows’. The Australian public is probably better informed than most about such issues, yet even in the natural resources management sector several unproven assertions about the virtues of plantations are regarded as truths. For instance, we commonly hear that ‘plantations will reduce river salinity’ and ‘plantation impacts on water yield are small relative to farm dam impacts’. Despite the importance of these matters to land-use sustainability in Australia, data to address them are scarce.

According to the latest National Plantation Inventory report, a further 86 000 ha of plantations were added to the national estate in 2001, a growth of 6% (National Forest Inventory 2002). Most of the recent expansion has been in hardwood plantations in Victoria, Western Australia and Tasmania. These figures reveal that Australia is indeed well on track to achieving the shared industry and government vision of trebling our plantation area by the year 2020 (DPIE 1997). Increasingly, those observing these developments are giving consideration to the hydrologic impacts of such dramatic land-use change. A stimulating and productive national workshop was devoted to this topic in July 2000 (Nambiar and Brown 2001). Presenters at that meeting gave diverse perspectives on afforestation impacts from the standpoints of water resource assessment, salinity remediation and catchment management in general. These perspectives were complemented by regional case studies that highlighted the relative importance of different issues. On the basis of the papers published and the workshop discussions held, one can conclude that there is a rapidly maturing understanding of the hydrologic consequences of plantation development in Australia.

This paper recapitulates the state of knowledge and discusses the latest developments in our understanding of how plantation development affects the water and salt balances of catchments. We attempt to be as quantitative as possible, so as to provide a sound basis for estimating the environmental impacts of afforestation. For sake of reference, comparisons are made with the estimated hydrologic impacts of farm dam development. Finally, we make recommendations on how to limit the hydrologic impacts of afforestation, and argue the case for erecting a regulatory framework to control the expansion of the forestry sector.

A recapitulation of the state of knowledge

Several recent Australian publications have summarised how mean annual runoff in catchments would be affected by afforestation (Vertessy 1999, 2001). The foundations of these studies are two sets of curves known as the Holmes and Sinclair (1986) and Zhang *et al.* (1999) curves. Both sets of curves relate mean annual rainfall to mean annual evapotranspiration (and, by difference, mean annual runoff) in forested and grassland-covered catchments (Fig. 1). The Holmes and Sinclair (1986) curves are purely empirical, based on hydrometric data from 19 catchments in Victoria. The Zhang *et al.* (1999) curves are derived from a process-based model, albeit a simple one. Both sets of curves are

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This paper was presented at a conference, ‘Prospects for Australian Forest Plantations 2002’, held on 20–21 August 2002 at Canberra, ACT.

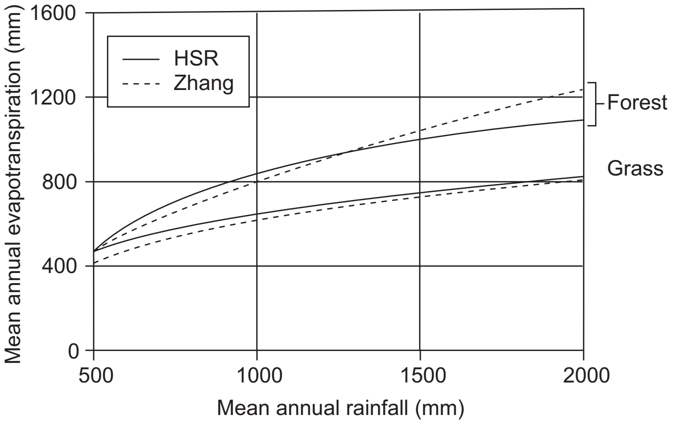

Figure 1. Relationship between land cover, mean annual rainfall and mean annual runoff, as predicted by the Holmes and Sinclair (1986) relationship (HSR) and the Zhang *et al.* (1999) model. Source: Vertessy (2001).

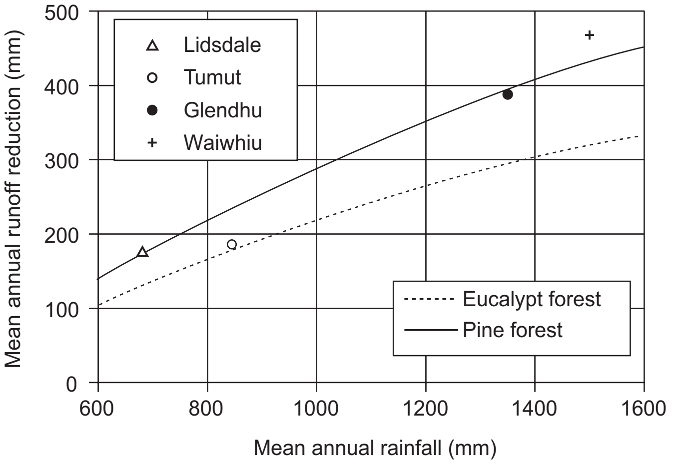

Figure 2. Potential reduction in mean annual runoff estimated to result from afforestation of grasslands with eucalypts and pines. Also shown (as symbols) are field data from four pine afforestation experiments in Australia and New Zealand. Source: Vertessy (2001).

quite similar, differing significantly only for the case of forests in high-rainfall areas (>1200 mm y^{-1}). These curves have been tested locally and overseas and have been shown to be robust estimators of mean annual runoff for grassland and forest catchments (Vertessy and Bessard 1999; Bradford *et al.* 2001; Zhang *et al.* 2001, 2003).

Vertessy (2001) demonstrated how to use the Holmes and Sinclair (1986) curves to deduce reductions in mean annual runoff that would arise from pine and eucalypt afforestation of grassland (Fig. 2). For areas with 800 mm mean annual rainfall, grassland catchments are assumed to yield a mean annual runoff of 210 mm y^{-1}. After complete afforestation of these areas, mean annual runoff may decline by up to 165 mm under eucalypt forest and up to 210 mm under pine plantations. For areas with mean annual rainfall of 1200 mm, grassland catchments are assumed to yield a mean annual runoff of 493 mm y^{-1}. After complete afforestation of these areas, the mean annual runoff reductions may be as great as 265 and 350 mm. Vertessy (2001) showed that pine afforestation experiments in Australia and New Zealand revealed mean annual runoff reductions similar to those predicted by the Holmes and Sinclair curves (Fig. 2).

Latest developments

Mitigating factors

Several of the above-mentioned studies on changes in mean annual runoff have cited the maximum possible impacts (Vertessy and Bessard 1999; Bradford *et al.* 2001). In the real world, variations in site characteristics and plantation management exert a moderating and dynamic influence on the potential hydrologic impacts of afforestation. Factors that would mitigate against the maximal hydrologic impacts discussed above include the fraction of area planted, the planting position, and variations in the stand age and site productivity. These factors are elaborated on below.

Catchments are rarely completely afforested because some land is usually reserved for other uses. The classical forest hydrology literature suggests that the magnitude of catchment runoff response is linearly proportional to the fraction of the catchment cleared (Bosch and Hewlett 1982; Stednick 1996). Hence, in the case of plantations, one could assume that if only half of a grassland catchment is afforested then the estimated reduction in mean annual runoff would be half of the maximum reduction predicted by Figure 2 for a given isohyet. This implies that plantation position does not influence catchment response. Unfortunately, few data are available on the effect of plantation position on catchment water balance. However, one would expect that the further away from the stream the plantation is established, the smaller the hydrologic impact would be. This notion is predicated on the assumption that the further away one gets from a stream, the smaller the probability that net rainfall will contribute to streamflow (Barling *et al.* 1994; Nandakumar *et al.* 1994).

These ideas have been tested in numerical modelling experiments using the Topog catchment model (Vertessy *et al.* 1996), and lend support to the notion that plantation position could affect catchment runoff response (Fig. 3). In those experiments we predicted the changes in runoff that would occur for 0, 10, 20, …, 100% levels of afforestation, starting from the top of a catchment and progressively planting downslope. We compared these against model predictions for the same levels of afforestation starting from the bottom of the same catchment and progressively planting upslope. Figure 3 shows the predicted response curves for the ‘bottom up’ and ‘top down’ planting cases. They meet at the 0 and 100% afforestation levels but diverge in between. These curves indicate that planting the lower 30% of the catchment has a much greater hydrologic impact than planting the upper 30%. The reason for this is that valley bottoms are the prime areas for producing runoff for the catchment, and trees tend to grow better (and thus evapotranspire more) in lower parts of the landscape. Such effects are likely to be most pronounced in catchments with low lateral connectivity (low to medium net rainfall, high potential evapotranspiration, gentle slopes).

We believe that there is much to be gained from optimising plantation position to minimise the hydrologic impacts. Process-based, distributed-parameter hydrologic models such as Topog (Vertessy *et al.* 1996) and Macaque (Watson *et al.* 1997; Watson *et al.* 1999; Peel *et al.* 2000) can be used to assess how different planting strategies would affect catchment flow regimes. Whilst such models are difficult to set up and apply, the effort is surely worthwhile given the level of investment that goes into planning any significant afforestation initiative.

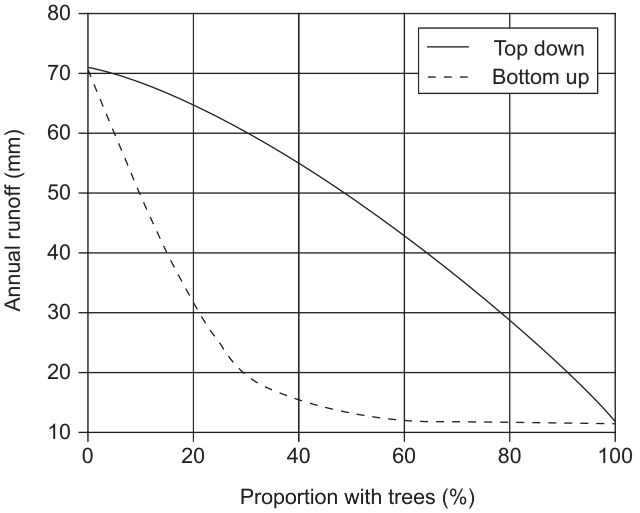

Figure 3. Results from a numerical modelling experiment conducted using the Topog model. This shows two sets of predictions of annual runoff response to afforestation for a catchment with 700 mm annual rainfall in central New South Wales. The upper curve (solid line) shows changes in annual runoff with varying levels of afforestation, starting at the top of the catchment and progressing downslope. The lower curve (dashed line) shows the comparative response when afforestation starts at the bottom of the catchment and progresses upslope. Source: unpublished data, CSIRO Land and Water.

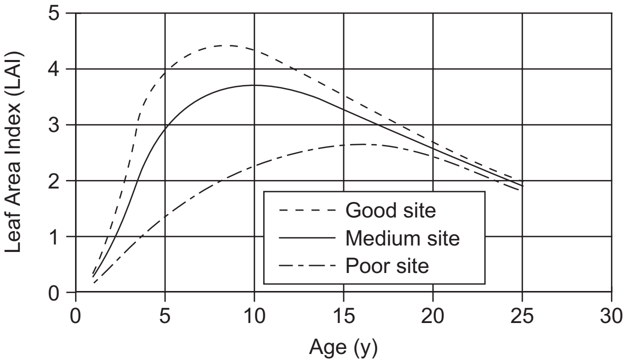

Figure 4. Variations in leaf area index (LAI) across the Goulburn-Broken catchment, predicted using the 3-PG Spatial model. Such variation would have significant effects on patterns of evapotranspiration and runoff. Source: Zhang *et al.* 2002.

The phasing of afforestation within a catchment is another important factor that would mitigate against the maximal hydrologic impacts being realised. Plantings within a catchment are usually made over a period of years, leading to a mixture of stand ages. In most situations, the full hydrologic effect of plantations is not attained until the stand has reached about 8–15 y of age. Hence, any catchment containing a significant proportion of young stands will not exhibit the maximum hydrologic effects of afforestation. There is also some evidence to indicate that evapotranspiration rates in mature forest stands are lower than in vigorously growing ones, with decreases starting to become apparent after 30–35 y. Of course, such effects would not be felt in short-rotation systems.

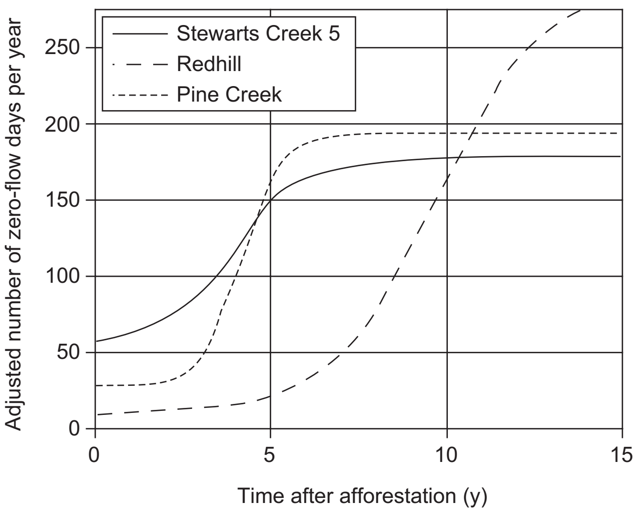

Figure 5. Adjusted number of zero-flow days per year in three small (18–320 ha), fully afforested catchments in Victoria and New South Wales. The runoff data used have been adjusted for climate, so the effect shown is fully attributable to changes in land cover. Source: Lane *et al.* (*pers. comm.*).

Finally, variations in site productivity also affect the magnitude of hydrologic change ensuing from afforestation. If plantation growth rates are low, evapotranspiration rates will be lower, leading to smaller reductions in runoff after afforestation. However, if stand productivity were enhanced by the application of fertiliser, then evapotranspiration would also be enhanced, leading to larger-than-expected reductions in runoff. Zhang *et al.* (2003) have recently incorporated estimates of plantation productivity into their assessments of the hydrologic impact of future bluegum plantation development in the Goulburn-Broken catchment. As Figure 4 shows, they estimate significant variation in leaf area development across that catchment. This would result in variation in evapotranspiration and changes in runoff. However, one would assume that plantations are most likely to be established on the most productive sites, resulting in maximal hydrologic impacts. Figure 4 also suggests that runoff impacts would set in earlier in productive sites where growth rates are higher.

Changes to low-flow hydrology

Probably of greatest concern to catchment managers assessing the hydrologic consequences of afforestation are changes in the magnitude and persistence of low flows. It is vital to understand how low flows will be affected by plantations, because water security becomes problematic during dry times. Unfortunately, relatively little has been published on the hydrologic impacts of plantations on low flow (Vertessy 2001; Best *et al.* 2003).

P. Lane *et al.* (CRCCH, *pers. comm.*) have examined the duration of changes in flow in ten catchments subjected to varying levels of afforestation. They report on a method for separating out the effects of climate in hydrologic records (via a de-trending technique), so that flow reductions can be attributed *solely* to change in land cover. The vital contribution of this work is that it makes a simple method available for estimating how flows of different magnitude will change following afforestation. Their analysis shows that the ten different catchments considered respond to afforestation in different ways, with some having their

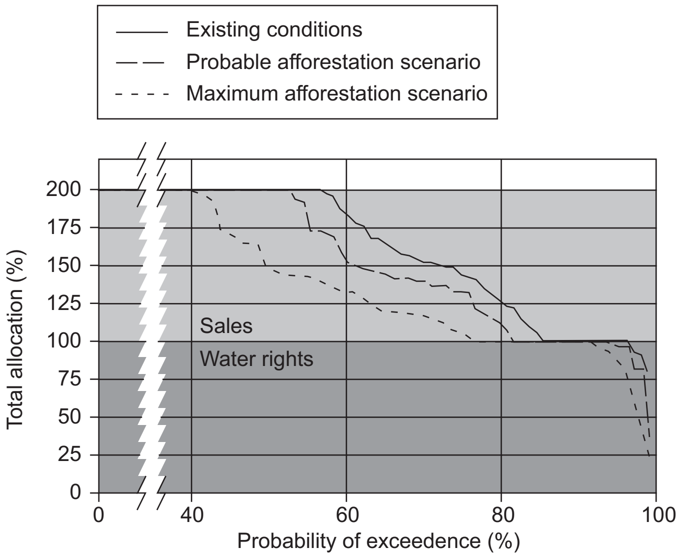

Figure 6. The predicted effects of two bluegum afforestation scenarios on the reliability of water allocations in the Goulburn-Broken system. Note that allocations are committed to a 200% level under the Victorian system, with the first 100% representing allocations against water rights, and the remainder against sales. Source: Zhang *et al.* (2002).

high flows altered more and others having their low flows altered more. However, flows of all magnitudes clearly decrease as a consequence of afforestation. They show how the number of zero-flow days can be expected to increase after plantations are established in small catchments (Fig. 5). Impacts of this magnitude are far less likely in large catchments, because (1) the larger the catchment, the more perennial the flow usually is, and (2) the larger the catchment, the less likely it is to be fully afforested. Nevertheless, their results indicate that water security during dry times is an important issue to be considered when planning plantation development.

Implications for the allocation of water resources

The methods developed by Lane *et al.* were used by Zhang *et al.* (2003) to predict changes in flow regime associated with two bluegum afforestation scenarios in the Goulburn-Broken catchment. Under the ‘maximum’ afforestation scenario, 21% of the land above Goulburn weir was afforested with bluegum plantations, resulting in a 14% reduction in mean annual flow. Under the ‘probable’ scenario, 6% of the land was afforested, resulting in a 4% reduction in mean annual flow. Zhang *et al.* (2003) input predictions of altered curves for flow duration into the REALM water allocation model, to estimate the impacts of various afforestation scenarios on reliability of flows (Fig. 6). The allocation model simulates the operation of the Goulburn-Broken water supply system using historical inflow and climatic data for the period 1891–1993.

Irrigation customers in the Goulburn system have access to two separate water products. The first is the so-called ‘Water Right’ component, which is provided with a high reliability. The second is the ‘Sales’ component, which is made available in varying quantities when there are sufficient water resources available to provide the Water Right in the following season under minimum inflow conditions.

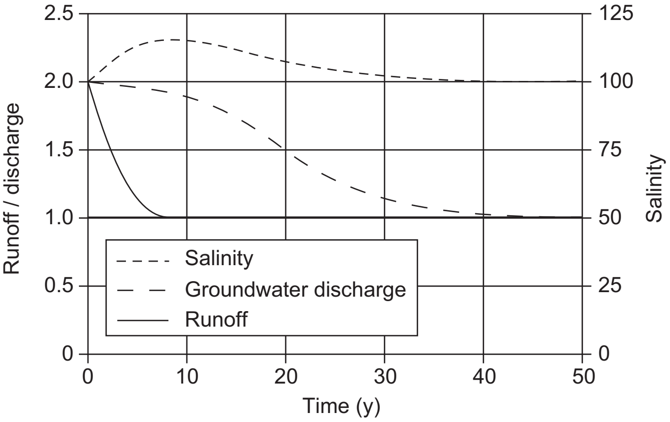

Figure 7. Long-term effects of halving runoff and recharge in a catchment, showing equilibration of stream salinity to previous level. Runoff and groundwater discharge are expressed in non-dimensional units, relative to a base case at time zero. Salinity is expressed in percentage units relative to a base case at time zero. Source: Unpublished data derived from the BC2C model, CSIRO Land and Water.

From a water security perspective, a key statistic is the fraction of time water allocations are less than 100% (in other words, when the high reliability entitlements cannot be met). Figure 6 shows that this is predicted to increase from 3% of the time under existing conditions, to 7% of the time as a result of the maximum afforestation scenario considered by Zhang *et al.* (2003). Another important metric is the minimum available allocation during the simulated period. Figure 6 shows that this reduces from 75% of the entitlement under existing conditions, to 28% under the maximum afforestation scenario. As for the Sales component, Figure 6 shows that the capacity of the system to deliver the full 200% allocation would decline from about 55% of the time under existing conditions, to about 40% of the time under the maximum afforestation scenario.

Impacts on river salinity

There is now a fairly convincing body of evidence in Australia to show that tree clearing leads to increases in river salinity (here defined as the concentration of salt in streamflow). Unfortunately, there are comparatively few field data available to show how river salinity changes after afforestation. However, recent modelling experiments conducted using CSIRO’s Biophysical Capacity for Change Model (BC2C) reveal that a broad spectrum of responses in river salinity can be expected to afforestation. They show that, contrary to popular perception, tree planting will not necessarily lead to immediate decreases in river salinity. In some cases, river salinity might well worsen before improving.

The response of surface water to afforestation is much quicker than the response of groundwater flow. If the concentration of salt in each pathway is constant, then a reduction in runoff and groundwater discharge can lead to transient increases in river salinity via a ‘dilution flows effect’ (Fig. 7). This would happen if the salt concentration in the groundwater was higher than that in surface runoff (a fairly safe assumption), and if the proportion of flow passing through both pathways remained constant following afforestation (probably not a bad assumption for the first few decades after afforestation). The type of response shown

Table 1. The effect of farm dam development on mean annual flow (MAF)[a]

Study	Catchment	Area (km^2)	Dam volume (ML)	Dam volume (% of MAF)
SKM (2000)	Ten Mile Ck	46	26	0.3
	Arthurs Ck	105	150	1.5
	Mt Cole Ck	158	366	3.1
	Running Ck	126	106	0.3
	Woori Yallock Ck	322	678	0.7
Schreider *et al.* (2002)[b]	Yass River	388	6650	32.3
	Broadwater Ck	108	3600	60.0

[a]Estimated by the SKM (2000) and Schreider *et al.* (2002) studies

[b]Alternative values shown for catchments in Schreider *et al.* (2002) pertain to estimates derived using alternative methods

[c]Reductions in MAF are expressed as ML per ML of farm dam development

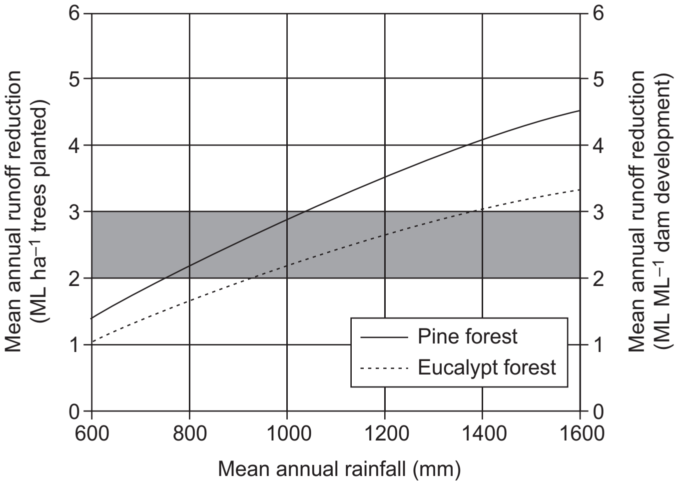

Figure 8. Comparative effects of afforestation and farm dam development on mean annual runoff. The curves pertain to afforestation (as per Fig. 2) and indicate the reduced annual runoff for each hectare of trees planted in a catchment. The shaded band denotes the mode of estimates cited in the SKM (2000) and Schreider *et al.* (2002) studies, and indicates the reduced annual runoff for each megalitre of farm dam storage established in a catchment.

in Figure 7 is plausible for catchments of moderate size (say 10–100 km^2) with local groundwater flow systems (as defined by Coram 1998). In such situations the flow paths for surface water and groundwater are likely to be directly coupled to the river. In Figure 7, runoff reaches a new level 8 y after afforestation, but groundwater takes about 40 y to re-adjust to a new steady state. As a consequence of this, river salinity declines markedly in the first ten years and gradually returns to pre-afforestation levels within about 30 y. If the proportion of groundwater flow to surface runoff declined beyond this point, then river salinity would decrease further, leading to a net improvement in water quality.

Relative impacts of afforestation and farms dams

In recent times, various Australian State governments have enacted legislation to control the further development of farm dams. In the past, farm dams could be established with minimum, or no, formal approval. Rapid intensification of farm dam development over the last three decades, however, has put additional pressure on scarce water resources, leading to the formulation of policy to limit future impacts.

Two recent Australian studies provide a good summary of the impact of farm dam development on catchment runoff (SKM 2000; Schreider *et al.* 2002). SKM (2000) examined five catchments in Victoria subjected to varying amounts of farm dam development. Schreider *et al.* (2002) examined 12 catchments throughout the Murray-Darling Basin, but detected hydrologic impacts from farm dam development in only two of these. Table 1 provides background data on each of the catchments examined, and shows that farm dam development has led to reduced mean annual runoff. The magnitude of flow reduction is mainly between 2 and 3 ML y^{-1} for each ML of farm dam storage established.

Figure 8 compares reductions in mean annual flow from afforestation and reductions expected to ensue from farm dam development. For sake of reference, a typical small farm dam built for stock and domestic purposes has a volume of about 0.5–3 ML. Figure 8 shows that at the 1000 mm isohyet, a 100 ha pine plantation would reduce mean annual flow by about 300 ML. This reduction is equivalent to the impact of 100 small farm dams, assuming an average dam volume of 1.2 ML and an average flow reduction of 2.5 ML ML^{-1} of dam storage. A conventional irrigation dam has a volume of about 50 ML and would therefore reduce mean annual runoff by 125 ML. At the 1000 mm isohyet, this is equivalent to planting 42 ha of pines.

Whilst the above comparisons are based on ‘rule of thumb’ calculations, they do illustrate that the hydrologic impacts of afforestation are significant in relation to those expected to arise from farm dam development.

Discussion

With careful planning, it is possible to minimise the hydrologic impacts of afforestation. Here are four suggested strategies:

1. Plant in regions with less than 800 mm annual rainfall, where yield reductions are lower and salinity is more of a problem.
2. Plant in mosaics to spread out the impact. Catchments with less than 20% area planted exhibit little effect on water yield.
3. Phase plantings so as to generate a wide spread of stand age classes. Evapotranspiration rates normally peak between stand ages 8 and 15 y.
4. Plant away from drainage lines in areas likely to lie outside the main runoff-producing zones.

The returns from such strategies are, however, limited, and any significant expansion of the plantation resource will demand policy action to protect water resources. For instance, Goss (2001) notes that water allocations are extremely tight in the Murray Darling Basin, with over 96% of the allocation going to an irrigated agriculture industry worth \$4.5 billion y^{-1}. The government policy response to this problem has been (i) to place a cap on water extractions, (ii) to introduce water trading aimed at stimulating the transfer of water to more efficient and higher-value enterprises, and (iii) to enact legislation to control further farm dam development. Concurrently, Commonwealth and State governments are seeking to allocate more water to the environment. Given these efforts, it is surprising that no regulatory framework exists to control the water resource pressures that are exerted by plantation forestry. Whilst some State governments (notably South Australia) have the legislative issue firmly on their agenda, the Commonwealth seems primarily focused on identifying impediments to the roll out of the *2020 Vision* (DPIE 1997). For instance, the terms of reference for the current Senate Inquiry into Plantations talk about 'maximising' the environmental benefits, and not at all about minimising adverse impacts on water resources.

South Africa appears to be the only country with a policy and legislative framework in place to tackle the water resource pressures from plantations (Versfeld 1996). Afforestation-induced reductions in streamflow were reported by South African farmers as early as 1915. Water shortages reached crisis point in the mid-1960s drought, resulting in the establishment of committees to assess the link between plantations and water supply. The findings of these committees provided the basis for the Forestry Act of 1968. After a series of amendments to this Act, plantation forestry in South Africa came to be regulated by the 'Afforestation Permit System' or 'APS' (van der Zel 1995). The primary focus of the APS is the protection of natural water resources.

Given the future need to allocate more water to the environment and the need to provide water security to water users, it would seem prudent to implement some kind of system whereby new allocations of water to plantations are off-set against trades of water away from other land uses. One might argue that, given the beneficial environmental services offered by plantations (e.g. biodiversity and carbon sequestration), trades of water into plantations should be subsidised. This issue, and the impacts of plantations on water resources, should be considered in the formulation of a rational policy and legislative framework to manage plantation development.

Acknowledgements

We thank Geoff Adams (Goulburn-Murray Water), Rae Moran (NRE), Pat Lane (Forest Science Centre), Rory Nathan (SKM), Alice Best, Klaus Hickel and Trevor Dowling (CSIRO Land and Water) for their contributions to the studies described herein. Dan Figucio kindly prepared all the diagrams for this paper. We thank Peter Hairsine for his thoughtful review of a draft of this paper, and Tanya Jacobson for a good deal of editorial refinement.

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