55th Annual Conference, Australian Agricultural & Resource Economics Society
8-11 February 2011, Melbourne, Victoria, Australia

Disposition of precipitation: Supply and Demand for Water Use by New Tree Plantations

T.L. Nordblom[1 2 4 †], J.D. Finlayson[3 4], I.H. Hume[1 2 4]

[1] NSW Department of Industry and Investment (I&I NSW), New South Wales, Australia
[2] EH Graham Centre for Agricultural Innovation (I&I NSW and Charles Sturt University), Wagga Wagga Agricultural Institute, Pine Gully Road, Wagga Wagga, NSW 2650
[3] Formerly, I&I NSW, Orange, NSW; presently School of Agricultural and Resource Economics, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009
[4] Future Farm Industries Cooperative Research Centre (FFI CRC) Australia

[†] Corresponding author, tel: 0269381627 em: tom.nordblom@industry.nsw.gov.au

Abstract:

As the greatest rainwater users among all vegetative land covers, tree plantations have been employed strategically to mitigate salinity and water-logging problems. However, large-scale commercial tree plantations in high rainfall areas reduce fresh water inflows to river systems supporting downstream communities, agricultural industries and wetland environmental assets. A bio-economic model was used to estimate economic demand for water by future upstream plantations in a sub-catchment (the 2.8 million ha Macquarie valley in NSW) of the Murray-Darling Basin, Australia. Given four tree-product values, impacts were simulated under two settings: **without** and **with** the requirement that permanent water entitlements be purchased from downstream entitlement holders before establishing a tree plantation. **Without** this requirement, gains in economic surplus from expanding tree plantations exceeded economic losses by downstream irrigators, and stock and domestic water users, but resulted in reductions of up to 154 GL (gigalitres) in annual flows to wetland environments. **With** this requirement, smaller gains in upstream economic surplus, added to downstream gains, could total $330 million while preserving environmental flows. Extending downstream water markets to new upstream tree plantations, to equilibrate marginal values across water uses, helps ensure water entitlements are not diminished without compensation. Outcomes include better economic-efficiency, social-equity and environmental-sustainability.

Keywords: forest; environmental services; catchment; water sources; interception; entitlement; supply; demand; market; economic surplus; evapo-transpiration; urban water; irrigation; wetlands.

Acknowledgements

This paper draws on Economic Research Report No. 43 (Nordblom *et al*., 2009a), a product of the project "Developing environmental service policy for salinity and water" supported by the Department of Industry and Investment NSW (I&I NSW, formerly NSW Dept of Primary Industries), Charles Sturt University (CSU) through the EH Graham Centre for Agricultural Innovation (I&I NSW and CSU), Future Farm Industries CRC, the Rural Industries Research & Development Corporation, the Murray Darling Basin Authority, Victoria Department of Primary Industries and the University of Western Australia. An early version (Nordblom et al., 2010b) was presented at the *Economics and Environment Network Symposium 2010*, Australian National University, Canberra. The authors wish to thank Fiona Scott, Melanie Weckert, Ron Hacker, Rajinder Singh and Peter Orchard (I&I NSW) for critical comments. Responsibility for any errors resides with the authors alone. Assumptions, observations, results and interpretations in this study do not necessarily represent the policies of I&I NSW nor any other agency or institution.

1. Introduction

The Intergovernmental Agreement on a National Water Initiative (COAG, 2004; Duggan *et al*., 2008), which includes a focus on interception of water by tree plantations, is an important context of this work. A recent study (SKM, CSIRO & BRS, 2010) estimated that existing tree plantations across Australia reduce annual river flows by a volume of water equal to about two cubic kilometres (or 2,000 gigalitres, GL). Such a volume may be compared with the lower and upper (3,000 and 4,000 GL) targets for additional annual water flows sought to sustain environmental assets in the Murray Darling Basin (MDBA, 2010, p. xxi).

The purpose of the present study is to demonstrate simultaneous quantitative projection of the consequences (in terms of upstream and downstream economic efficiency, social equity and sustainability of environmental water) in a catchment, given different levels of incentives for new tree plantations under two contrasting policy settings: (1) where permanent water entitlements must first be purchased from downstream entitlement holders to compensate for expected reductions in stream flow, and (2) where permanent water entitlements are not required for the establishment of new plantations. The latter is presently the case in all Australian states and territories except South Australia (SKM, CSIRO & BRS, 2010, pp.59-60).

The economic and social benefits of forest industries (see *Plantations for Australia: The 2020 Vision*) must be considered. A number of recent studies have focused on the prospects for expanding commercial plantations given the capacity of trees to sequester carbon while improving water quality (Grieve *et al*., 2008; Johnson and Coburn, 2010; Oliver *et al*., 2005; Wood *et al*., 2008), and given different carbon prices (Lawson *et al*., 2008; Crossman et al., 2010; Sohngen, 2010). These studies recognised the fact that expanding tree plantations requires land which may be used in other ways, thereby incurring opportunity costs. Not fully dealt with was the point that forest carbon sequestration requires not just land but, as with any other large-scale biomass production, large amounts of water (Galiana and Green, 2010, p.299); in this case, rainwater at the source of rivers. Indeed, mean annual increments of wood production (i.e. m^3/ha/year) are water-limited and water used in evapo-transpiration for tree growth is no longer available for downstream uses. Reduced water flows, due to plantations, have in some cases imposed external costs on downstream water consumers and/or stress to environmental wetland assets. One study, which focused on 'managed investment schemes' for carbon sequestration, did note that potential distortions in agricultural land and water use may arise where tax benefits attract expanding plantation investments that reduce water flows into streams and rivers (Ajani, 2010). Crossman et al. (2010) explicitly estimated the opportunity costs of displaced land uses given four carbon sequestration forest options and six carbon prices under four commodity price scenarios across South Australia. They also calculated reductions in water yield under the various forest options and carbon prices. However, their study did not attempt to estimate the subsequent economic losses by downstream consumptive water users, though noting a requirement to purchase water entitlements as foreseen by the National Water Initiative would have a negative impact on plantation expansion. None of the studies mentioned in this paragraph explicitly quantify the external costs that may be imposed by tree plantations on local downstream community, industry or environmental interests in water volumes.

Jackson et al. (2005) noted that carbon sequestration strategies around the world promote tree plantations without considering their full environmental consequences, including substantial, predictable losses in stream flow.

Schrobback *et al*. (2009), in Australia, likewise concluded:

> "Large scale forest plantations in the Murray-Darling Basin may be embraced as a carbon sequestration mechanism under a Carbon Pollution Reduction

> Scheme. However, increased tree plantation will be associated with reduced inflows to river systems because of increased transpiration, interception and evaporation. Therefore, an unregulated change in land management is most likely to have a dramatic impact on the water availability."

High level policy debate has touched upon water shortages associated with tree plantations:

> "A large switch in land use toward production forestry would have additional consequences that might be negative (such as impacts on water supply) or positive (for example, mitigating dryland salinity and assisting with habitat restoration), depending on the type of forestry and the land use it replaces. These externalities should be addressed through the creation of market-based instruments for other ecosystem services, such as water quantity and quality, biodiversity, air filtration, and abatement of salinity and erosion." (Garnaut, 2008, p.551).

The *World Development Report 2010, Development and Climate Change* adds:

> "By not properly accounting for certain uses (such as plantation forestry and natural vegetation) or for changes in user behaviour, the schemes in Australia and Chile assigned rights for more water than was available" (World Bank, 2010, p.142).

Trees are able to use water that otherwise leads to water-logging of soils or rising water tables, which in turn mobilise salts causing dryland salinity and/or salination of rivers (Wood, 1924; Stirzaker *et al*., 2002; Vertessy *et al*., 2003; Nuberg *et al*., 2009). Studies to calculate the least cost changes in land use to reduce salt loads exported from catchments (Nordblom *et al*., 2006; 2007, 2010a; Cresswell *et al*., 2009; Finlayson *et al*., 2010) all include tree planting among the options. These studies considered only the minimisation of landowner costs for changing land uses to decrease by specified targets the annual salt loads flowing from their farms to streams (Pannell and Roberts, 2010), but did not explicitly include the external costs imposed on downstream water users due to reduced water availability. The present study attempts to address this gap by simultaneously including water demands by upstream and downstream economies and, as a starting point, considering water entitlements are held by the downstream water users.

The economic demand for water by new tree plantations in the highest rainfall parts of the 2.8 million hectare Macquarie Catchment of New South Wales is estimated for different tree product values. In the present study tree plantations displace other land uses in the upstream watersheds and reduce river flow to downstream communities, industries and wetland areas. Economic gains are calculated for the upstream areas of new plantations as well as the uncompensated losses borne by downstream agricultural industries and wetland environments. We also calculate economic surpluses for both upstream and downstream water users as the consequence of requiring purchase of permanent water entitlements to permit establishing tree plantations.

In each case, the areas of new tree plantations are estimated by considering the value of tree products per hectare, the direct costs of tree establishment and the opportunity costs of displacing current land uses in each watershed. In the cases where water entitlements must be purchased to permit establishment of tree plantations, demands for water are brought into market equilibrium among the upstream plantations and the downstream entitlement holders. A novel approach developed in this study is the expression of all upstream benefits and costs of establishing plantations in terms of dollars per GL of water used, as are downstream demands for water and supply of water entitlements.

The biophysical bases of the present study are summarised in 'Zhang curves' that relate land covers (forest, permanent pasture, rotations of permanent pastures with annual crops, and continuous annual cropping or annual pasture) and mean annual rainfall to water outputs (yields) of catchments (Zhang *et al*., 2001). The large body of field research backing this up is briefly reviewed in Section 2.

Section 3 presents a brief summary of the physical, biological and economic conditions in the Macquarie Catchment's watersheds, and methods used to frame the economic analysis of upstream and downstream water use. Section 4 presents a summary of results for the cases of each of four values of tree products (stumpage values \$40, \$50, \$60 and \$70/m^3) given two policy settings: without and with the requirement to purchase water entitlements in line with the annual water use by trees in particular rainfall zones. Results are given in terms of (a) changes in water uses in upstream watersheds and by downstream irrigators, stock and domestic users and wetland environmental assets, (b) new areas of tree plantations and (c) changes in economic surpluses by each sector. Discussion is provided in Section 5 and conclusions offered in Section 6.

2. Sources of rivers and the role of vegetative land cover

That a cloud-burst or torrential rain is the cause of a flash-flood may only be apparent to those witnessing or notified of the rain event. Floods may occur so far from the rainfall source that the causal relation is not suspected. Did the ancient Egyptians, who depended so heavily on the annual Nile floods, have a clear understanding of the distant sources in the East African equatorial lakes and Ethiopian highlands? The ancient Greeks knew from direct observation that rivers are sustained in the summer by springs emerging from dry ground. People observe that rivers flow from forested areas. This reinforces the common belief that forests attract more rainfall to an area than would be received without the forest. Only in the 17th century did Perrault and Mariotte discover that annual rainfalls measured over the catchment area of the Seine account for volumes of water far in excess of the river's volume. Edmond Halley's experiments measuring water evaporation from the sea showed this represents sufficient volumes of water to account for rainfall. This discovery of the atmosphere's role completed the first accurate description of the hydrologic cycle (Whitehead and Robinson, 1993; McCulloch and Robinson, 1993).

Except in cases of fog or tropical montane cloud forests, which are rare or absent in the Murray-Darling Basin of Australia, the popular notion that forests increase rainfall is seriously questioned. Rather, forests generally consume large quantities of water (FAO, 2003, Jackson et al., 2005). "Though vegetation may affect the disposal of precipitation, it cannot affect the amount of precipitation to be disposed" (Penman, 1963, p.8).

An early long-term study of streamflows from two Swiss catchments, showed 11% lower annual water yield from the forested catchment than one which was only 31% forested with the remainder in pasture (Engler, 1919). That study was subsequently criticised for its inability to exclude other possible causes of the differences in water yields, such as topography or underlying geology (Zon, 1927; Penman, 1963; Keller 1988).

Bates and Henry (1928) describe how daily precipitation, temperature and streamflow of two forested catchments in Colorado, chosen for their similarities, were monitored from 1911 through 1919. Then one of the catchments was cleared, and the 'control' catchment left forested. Meteorological and streamflow observations were continued in both catchments until October 1926.

That experiment produced stronger evidence that cleared land yields greater annual stream flows than forested land. Hibbert (1967) reviewed this and 38 other studies, comparing forest treatment effects on water yields under widely different conditions. Some of the studies measured the effects of afforestation (decreasing water yields) while others dealt with harvesting areas of forest (increasing water yield) and allowing regeneration. Hibbert, however, found the amounts of these responses "highly variable and, for the most part, unpredictable." (p. 535).

Bosch and Hewlett (1982) reviewed 55 new catchment studies in addition to Hibbert's 39, for a total of 94. They concluded: (1) no experiments in deliberately reducing vegetative cover caused reductions in water yield; (2) nor had any deliberate increases in forest cover caused increases in water yield; and (3), in contrast to Hibbert (1967), who had not considered mean annual precipitation as an explanatory variable, they found responses to deforestation and afforestation are largely predictable.

One study seemed to contradict these generalisations, reporting a decrease in water yield after a 163 km^2 mature stand of Mountain Ash (*Eucalyptus regnans*) was burned in 1939. But the fire had created conditions for such vigorous forest regrowth that evapotranspiration (water use) exceeded that of the old forest. The 35 GL shortfall in annual water yields from the area represented a 10% reduction in Melbourne's water supply in the1944-1964 period (Langford,1976, p.112). Presumably, had the vigorous forest regrowth been prevented, the burned area would have yielded far more water than the mature forest.

Wicht (1967) reported controlled catchment studies in South Africa in response to concerns in 1935 that policy encouraging afforestation could lead to drying up local water supplies. Based on subsequent experimental results, and motivated by the needs of towns and irrigation areas experiencing water shortages, the Forest Act (Act No. 72 of 1968) established an Afforestation Permit System (APS) in South Africa (van der Zel, 1995). The first 22 years of experience with the system are summed up:

> "The APS has not been popular with either foresters or environmentalists. Foresters thought it a severe restriction, while environmentalists think it not comprehensive enough. It has, however, accomplished much, such as restrictions in respect of riparian zones, eradication of wattle jungles and inclusion of many aspects of an Environmental Impact Assessment. It also is the

> instrument which achieves cooperation between the country's official forestry, agriculture, water and nature conservation agencies. It saved and improved the image of forestry on many crucial occasions" (van der Zel, 1995, p.49).

Drysdale (1981) reported marked reductions in water yields for a hydro-power water supply dam in Fiji when shrub vegetation in the catchment was replaced with *Pinus caribaea* to develop a wood-based industry (Gregerson *et al*., 1987; Brooks *et al*., 2003; Rauto, 2009). Awareness of this Fiji experience helped the Beijing Water Conservancy Bureau alter its plans to replace Chinese locust and shrubs with pine in the Miyun Reservoir catchment area, a key municipal water source for Beijing (Shuhuai *et al*., 2001; FAO, 2003).

Holmes and Sinclair (1986) summarised quantitative relations linking forest and grass land covers and evapotranspiration to rainfall in 19 Victorian catchments by fitting equations for each land cover, expressed as the proportion of land under tree cover (C) and under herbaceous cover (1-C). Similarly, Turner (1991) fitted equations for US catchments showing that annual precipitation and land cover explained 76% of variation in mean annual evapotranspiration. These meta-models integrated the results from a number of catchment experiments. Cornish (1989), Lesch and Scott (1997) and Scott and Smith (1997) demonstrated delayed, but pronounced, reductions in stream flow with afforestation as the trees grow; in contrast to the rapid increases in stream flow following removal of forest cover.

The biophysical bases of the present study relate land cover (land use as forest, permanent pasture, rotations of permanent pastures with annual crops, and continuous annual cropping or annual pasture) and mean annual precipitation to water use and water yield from catchments (Schofield and Ruprecht, 1989; Sahin and Hall, 1996; Croke and Lane, 1999; Nambiar and Brown, 2001; Zhang *et al*., 2001, 2003, 2007; Gerrand *et al.*, 2003; Benyon and Doody, 2005; Barratt *et al.*, 2007; Parsons *et al*., 2007; Gilfedder *et al.*, 2009). These recent studies have integrated the larger body of earlier field research and provided site specific examples on the relations of land cover and annual precipitation to water yield.

Zhang *et al*. (1999) developed a statistical framework, extending those of Holmes and Sinclair (1986) and Turner (1991), demonstrating the effects of vegetation cover and annual precipitation on water yield. Combining results from over 250 catchments in 28 countries they showed that for a given proportion of forest cover there is a solid relationship between long-term average evapo-transpiration and precipitation (Zhang *et al*., 2001). Their study used information on catchment area, proportions of various vegetative land covers, annual precipitation and water yield from each catchment. The strength of the response curves of Zhang *et al*. (2001) derives from the large number and diversity of catchments considered (see Figure 1).

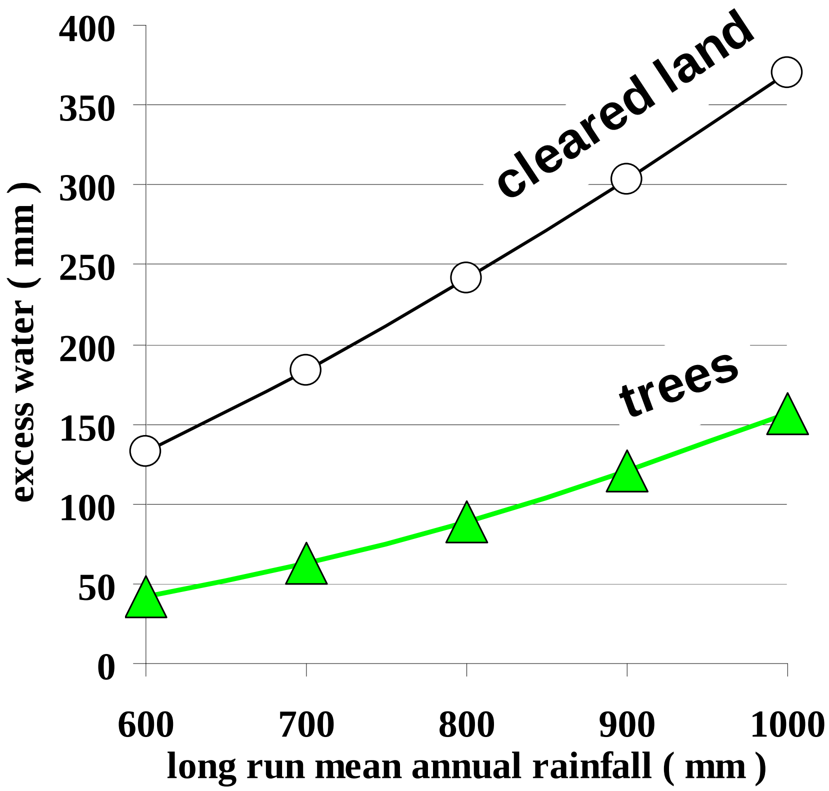


Figure 1. Excess water (catchment water yield) as a function of precipitation and annual evapotranspiration for different vegetation types (based on Zhang, Dawes and Walker, 2001)

Herron *et al*. (2002, 2003) used these relationships to simulate water yield reductions in the case of hypothetical forest expansions in the Macquarie Catchment of NSW. Most recently SKM, CSIRO & BRS (2010) have used the 'Zhang curves' to estimate the additional interception of water by existing commercial tree plantations across Australia assuming these plantings occurred on land which was not forested at the time. The impacts of commercial forestry on regional water resources in the lower South East of South Australia have been the subject of new legislation (SE-NRMB, 2007; DW-GSA, 2010) requiring water entitlements to be obtained before establishment of a new tree plantation is permitted. To date, no limitations on tree plantation use of water are yet in place in other States or Territories of Australia (SKM, CSIRO & BRS, 2010, pp.59-60).

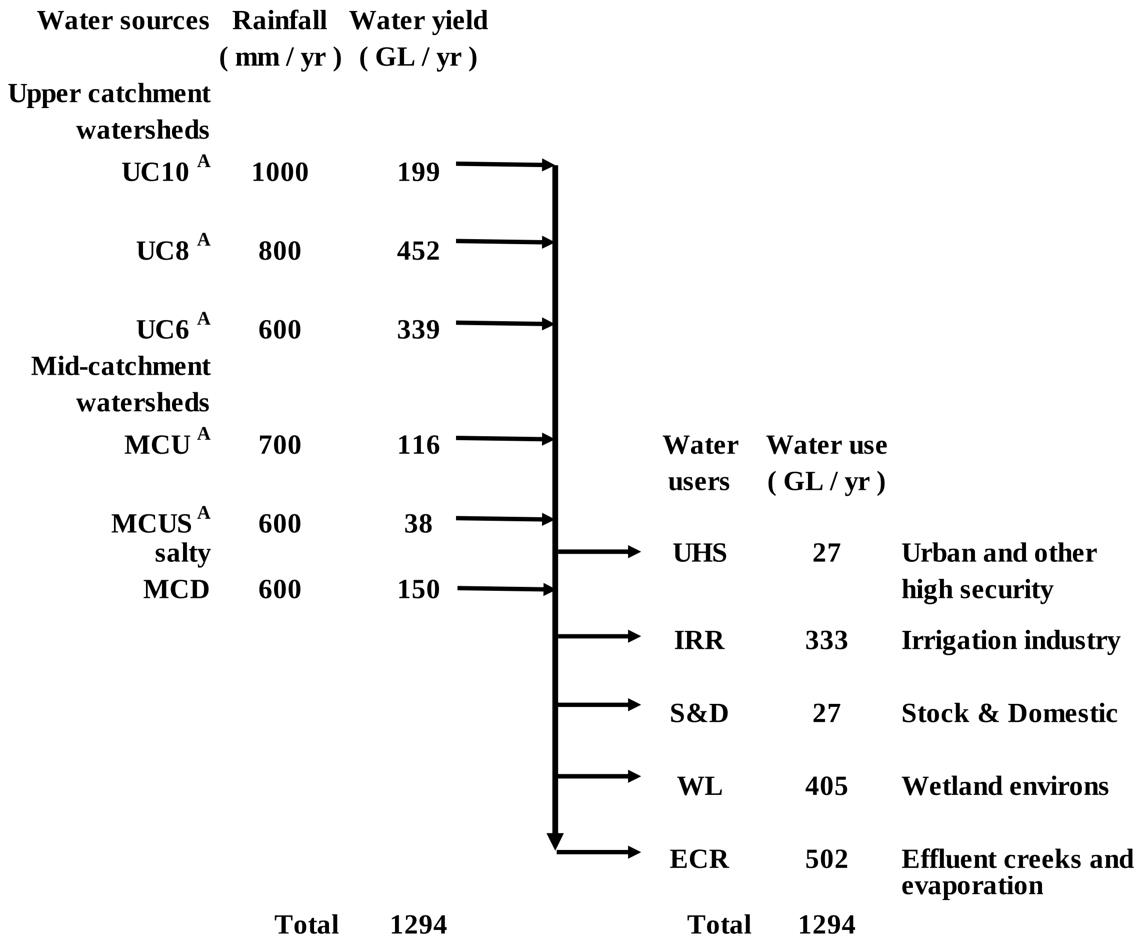
3. Water sources, sinks and economy in a study catchment

3.1 Catchment characteristics

In this section a brief summary of the physical, biological and economic conditions is developed for the 2.8 million ha Macquarie Catchment in New South Wales, Australia. A schematic map of the catchment (Figure 2) identifies the relative locations of the six watershed economies and downstream sectors that interact in the present analysis and quantifies key characteristics of these sectors (annual rainfall, water yield and water use).

3.2 Productivity of additional water use by tree plantations

Quantitative assumptions on water use per hectare of tree plantations beyond the water use of current land covers are needed for the present analysis (Table 1). For the scenarios presented in this paper, the units of trade are permanent entitlements to one GL of annual water flow. These translate to differing land areas under tree plantations depending on the mean annual rainfalls of the respective sub-catchments. We assume wood yields increase in direct proportion to water use and both are linear functions of mean annual rainfall over the range of 600 to 1000 mm (Table 1). Given these values, 774 ha of new tree plantation in the 1000 mm rainfall zone reduces water-yield to the river by one GL. This compares to 1675 ha of new trees per GL reduction in streamflow from the 600 mm zone.



[A] water yields of the upper and mid-catchment tributaries upstream of UHS were divided by a factor of 1.328 such that deliverable values shown are net of transmission and evaporative losses

Figure 2. Schematic map of Macquarie catchment identifying key water sources by rainfall zone and location with respect to key groups of river water users. The indicated water yields and water use levels are considered the 'initial conditions' in this study.

Table 1. Parameters for wood production and additional forest water use by rainfall zone

Mean annual rainfall (mm)	MAI* in wood product (m^3/ha)	Additional water use (ML/ha) by new tree plantation**	Land / Water use ratio of plantation (ha/GL)
600	8.0	0.597	1675
700	10.5	0.784	1276
800	13.0	0.970	1031
900	15.5	1.157	864
1000	18.0	1.343	744

* MAI = mean annual increment, an increasing function of mean annual rainfall in the study area
** values for 600-700mm areas approximated from South Australia's Approval Process For Plantation Forestry under the Natural Resources Management Act 2004 (DW-GSA, 2010).
Note: where a tree plantation displaces perennial pastures or perennial shrub growth the additional water use will be lower than if trees are established on cleared land.

The present value (PV) per hectare of tree plantation benefits is taken to be the MAI in a particular rainfall zone times the stumpage value per m^3 of tree product, times 30 years, discounted at 7%. The stumpage value is that received by the plantation owner after all harvest, transport and other charges are subtracted from the wood value at the mill. For illustration here (Figure 3), stumpage values of $40 to $70/$m^3$ are shown.

The PV of tree plantation benefits per GL of water may be calculated for each rainfall zone by multiplying the above estimates of PV of plantation benefits per hectare ($/ha) by the land / water use ratio of tree plantations (ha/GL) for each rainfall zone (Table 1). The assumptions made here on water use and productivity are balanced such that the PV of new tree plantation benefits per GL of water used are constant across the ranges of water use and across rainfall zones. From the gross PV of benefits for land owners per GL of water for tree products, must be subtracted their direct and opportunity costs of establishing tree plantations.

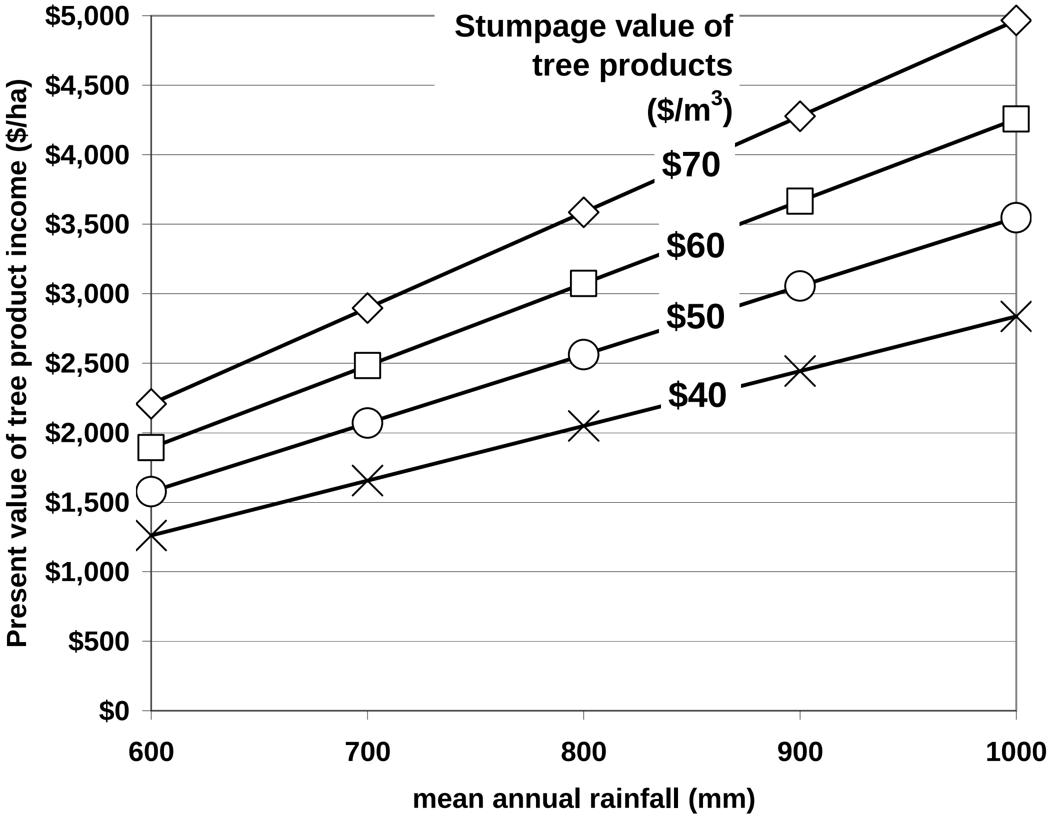


Figure 3. Present Value (PV) of tree product income ($/ha) by rainfall zone without establishment or opportunity costs or purchase costs of water entitlements

'Direct costs' include those of land preparation, rooted tree stock for planting, the planting operation itself, material and application costs of fertiliser, insecticide and weed control as necessary, and fencing; these costs are assumed to total $1,200/ha.

3.3 Estimating marginal values of water for tree plantations: benefits per GL used minus opportunity costs and direct costs

'Opportunity costs' are the net income losses due to giving up the current use of the land on which a tree plantation is to be established (Crossman et al., 2010; Sohngen, 2010). Where it is poor grazing land the opportunity cost will be lower than for good grazing land or highly productive farm land; these costs need to be considered as a newly established tree plantation excludes other productive uses (Figure 4). In this study the expression of all upstream benefits and costs of establishing plantations is in terms of dollars per GL of water used. This novel approach allows a direct connection with downstream demands for water and the supply of water entitlements held by irrigators and other water users.

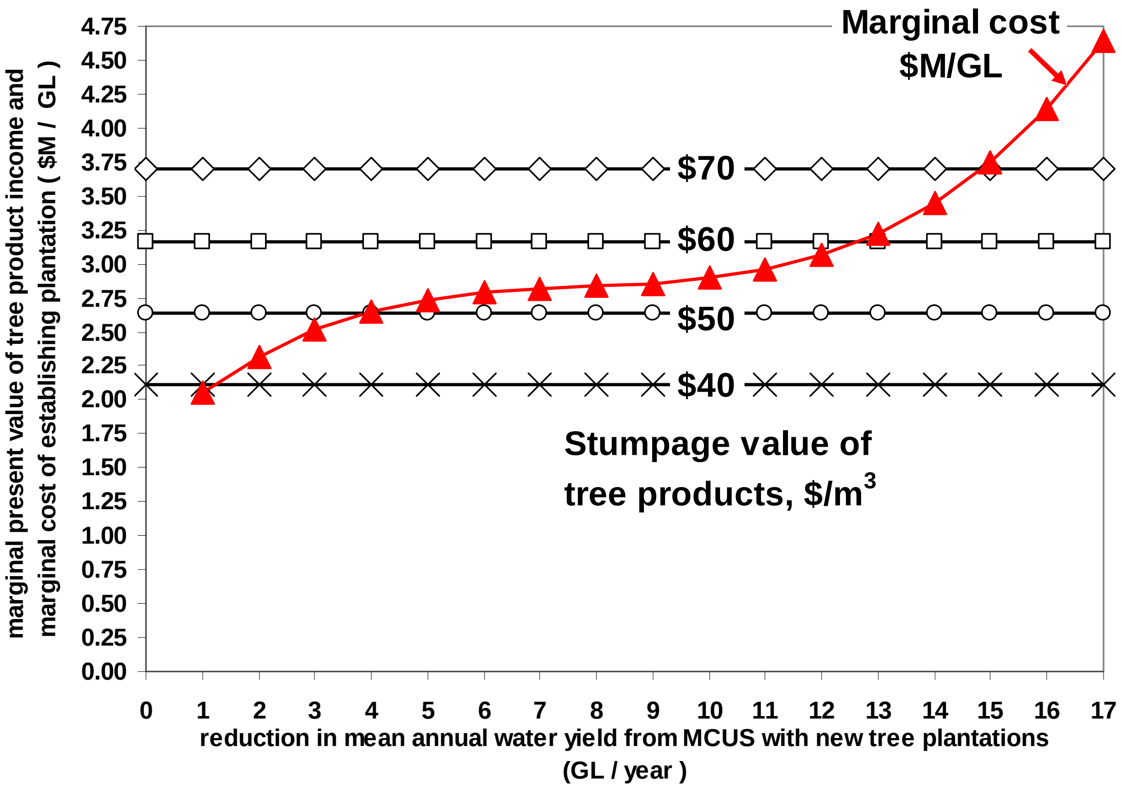


Figure 4. Marginal PV of tree product income ($M/GL) given stumpage values, before opportunity and establishment costs or purchase costs of water entitlements. **MC** = marginal opportunity and establishment costs of tree plantations in MCUS ($M/GL).

The marginal opportunity cost (change in opportunity cost of giving up current land uses by establishing tree plantations) may be expressed as cost to the landowner for incremental GLs of additional water used by the trees. These were derived by summing the water-yields and salt-loads of subcatchments of Little River Catchment by Evans *et al.* (2004). A linear programming analysis was used to solve for least-cost land use changes to meet specified targets for changes in water and salt yields of three classes of salt-source land (Nordblom *et al.*, 2009a). That analysis assumed all present forest areas would be retained while new forest plantations, even if not profitable in themselves, could be established to use water strategically for salinity mitigation. While it is technically feasible to increase water-yields and salt loads by shifting land use away from trees and perennial pastures and expanding annual pastures and cropping, our analysis focuses only on the water yield-reducing effects of tree plantations.

Nordblom *et al.* (2006; 2007; 2010a) explored the idea of minimising the direct and opportunity costs of reducing salt loads in streams through strategic changes in land use. A conclusion of that work is that the least-cost pathway for reducing salt-load entering a stream from a catchment reaches a lower limit with new tree plantations replacing other land uses.

New linear programming analyses of Little River Catchment in the Macquarie Valley, NSW, project sequences of least-cost land use changes (see Figure 3 in Nordblom *et al.* 2009a) to deliver decrements in salt-loads (and water-yields) entering the river. The associated sequences of increasing marginal opportunity costs of land use changes were smoothed by fitting a cubic function. This quantifies the proposition that new tree plantations will first be located where they are most profitable, followed by parts of the catchment with greater opportunity costs.

The direct and opportunity costs of tree planting depend on the land uses being displaced. Satellite images of upstream areas were compared with Little River, a well-studied sub-catchment (Evans *et al*. 2004; Finlayson *et al*., 2010, ; Hall *et al*., 2002; Murphy and Lawrie 1998; Nordblom *et al*. 2006, 2007) allowing rough estimates of various proportions of land uses in the other sub-catchments. These land use proportions appeared sufficiently similar to allow a simple scaling of the plantation cost curve (Figure 4) to match the ranges of water yield change in the other sub-catchments. The plantation cost curve, based on the lowest (600mm) rainfall zone, was adjusted downward for the higher rainfall zones, which need fewer hectares of plantation per GL of water used (Table 1).

For example, we assume only 744 ha of new plantation in UC10 (the 1000mm rainfall zone) reduces water-yield one GL below the base level from that area, while in 600mm rainfall zones (UC6, MCUS or MCD) 1675 ha of new plantation would have this effect (Table 1). The UC10 plantation cost curve, therefore, is reduced by a constant equal to the cost of the first GL unit from MCUS minus 744/1675 of that same cost. The cost curves for the 800 and 700 mm zones (UC8 and MCU) are likewise adjusted downwards by constant amounts according to the areas of new tree plantations in each to reduce water-yields by one GL relative to that of MCUS.

The analysis assumes the first GL of water used by new plantations in MCUS will have direct and opportunity costs on the order of $2M/GL while the highest-cost plantations will exceed $4.5M/GL in direct and opportunity costs (Figure 4). The latter cost figure is well above the highest PV of plantation benefits considered, so the cost curve will exceed or cut the benefit line from below in every case, providing a hard limit to the expansion of such water use. However, in some cases this limit is very high.

Subtracting the minimum (opportunity and direct) cost sequence of adding tree plantations to the landscape (Figure 4) from the benefits of plantations (horizontal lines) to landowners in this 600 mm rainfall area allows expressing the marginal values of water used by plantations; that is, their demand for water in $M/GL (Figure 5). For this, the horizontal axis may be labelled “additional water use by new plantations in MCUS, GL/year” with the vertical axis being “marginal value of water to plantation owners in MCUS, $M/GL”. The MCUS sub-catchment, with its 600 mm annual rainfall, is among the places in the catchment where tree plantations will be least profitable in their own right.

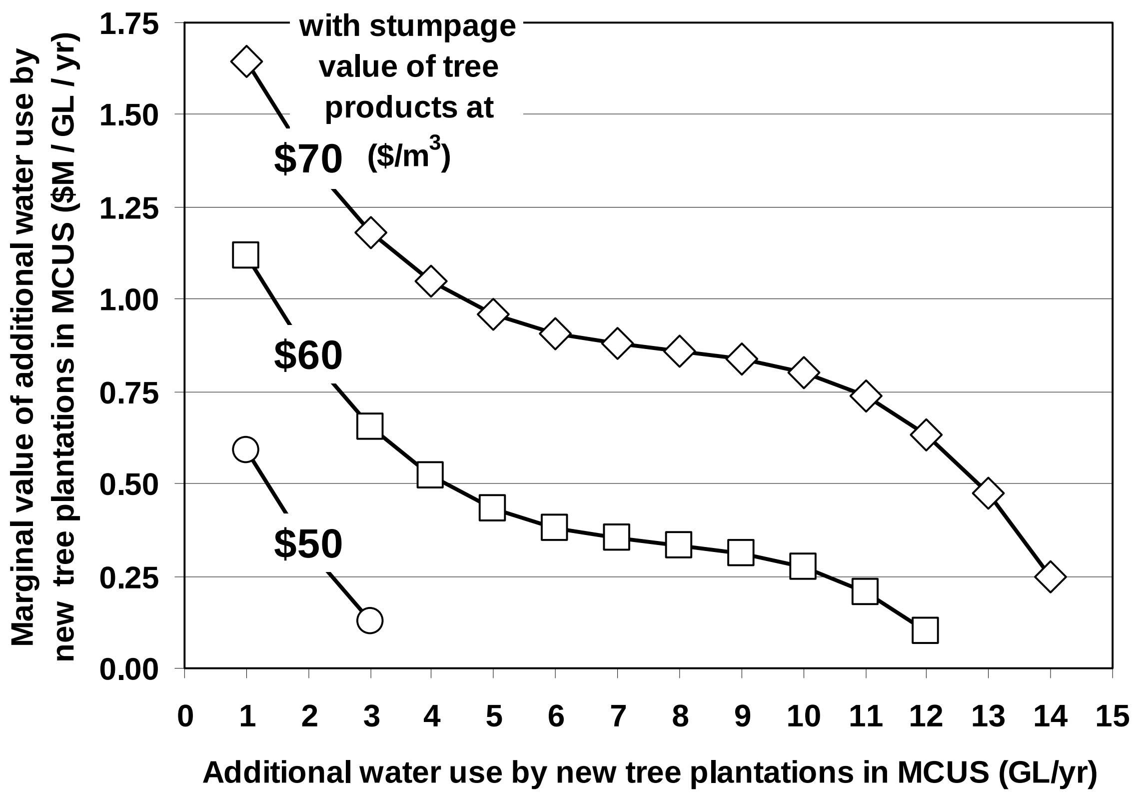


Figure 5. Demand for new tree plantation water given different values of tree products in MCUS

Of particular interest in this study are the lands of the upper catchment where tree plantations will be most profitable in their own right. The best example of this is UC10, an area with 1000 mm annual rainfall. By considering only tree product values and the direct and opportunity costs of new tree plantations in UC10 (Figure 6), not counting the external costs of water yield reduction, we can estimate the limits of plantation expansion in the absence of a requirement to first purchase water entitlements.

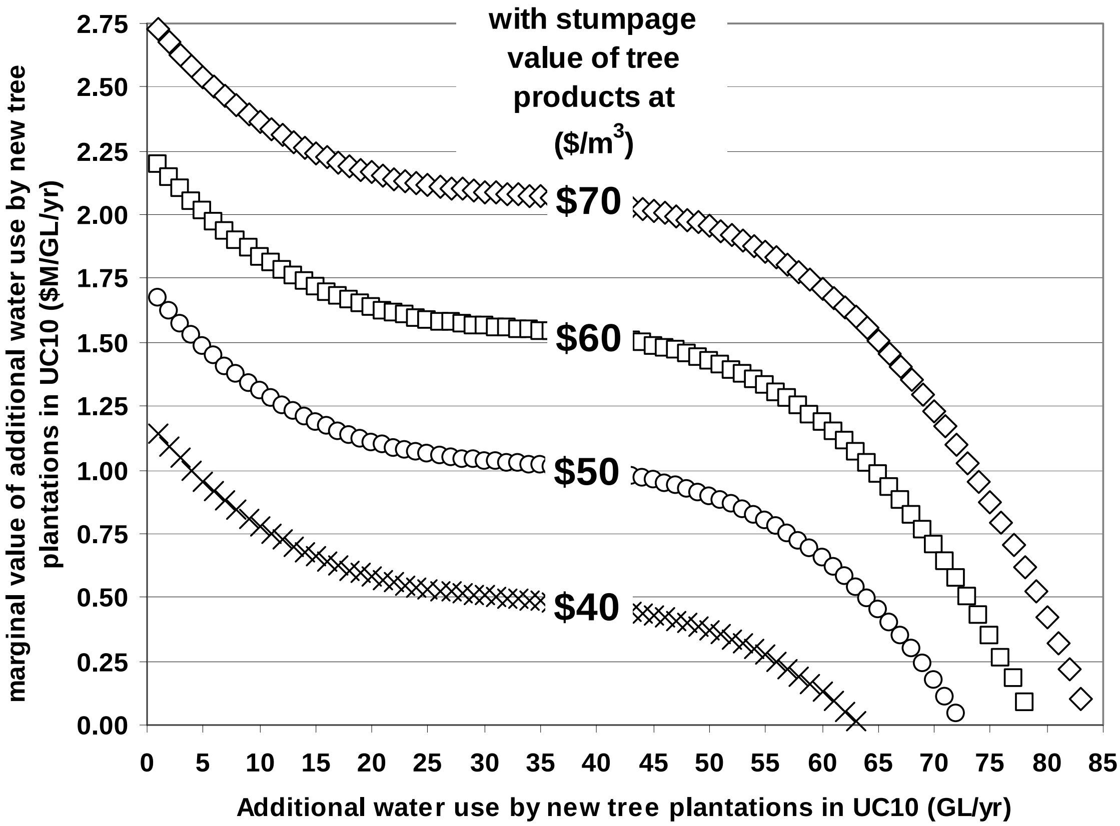


Figure 6. Demand for additional water use by new tree plantations in UC10 given different values of tree products

Without the requirement to purchase entitlements to the additional water used by new tree plantations in UC10, the latter may be expanded profitably to the point where the marginal value of water equals zero. That is, consumption of up to 63 GL given $40/m^3 tree stumpage value to land owners; 72 GL at $50/m^3; 78 GL at $60/m^3; and 83 GL at $70/m^3. The latter represents a massive occupation of UC10 by tree plantations and a large reduction in water yield from the sub-catchment. Extra water consumption of 83 GL by new plantations in UC10 would reduce the water-yield of this sub-catchment by about 40%.

A requirement for new tree plantations to purchase water entitlements would mean finding a price equalising the marginal values of water among all the players in the market. This means including the marginal values of water from the perspectives of downstream entitlement holders as well as all the upstream land owners who may wish to establish tree plantations.

The price of water in such cases could be determined in a competitive market given the marginal values of those wishing to purchase water and those of the downstream water entitlement holders. We now need to construct estimates of the marginal values of water among the downstream entitlement holders.

3.4 Marginal values of water use by downstream irrigators and stock and domestic water users starting with recent prices of permanent water entitlement trades

The marginal values for water by IRR and S&D sectors may be visualised as downward-sloping demand curves passing through the value of $1.2M/GL, a recent price for permanent trades, at the initial entitlement levels of 333 and 27 GL, respectively (Figure 2, Figure 7). This construction supposes that IRR and S&D would be willing to purchase more water at lower prices (e.g., 100 and 10 GL, respectively at $0.4M/GL) and to sell water at higher prices than current. It also supposes the WL sector, representing the government's environmental interests would offer to purchase up to 15 GL of water at a fixed price of $1.33M/GL (that is slightly above recent prices of permanent trades), but not be willing to sell any of its entitlements for less than $3.86M/GL, just above the price at which IRR would be willing to sell its last unit of entitlement. This high reserve price by WL could be taken as that at which offsetting alternative wetland assets could be secured and developed. These scenarios also assume full 100% allocations of these entitlements with no year-to-year variations, and that all entitlements are held by these downstream interests and UHS which has a fixed entitlement of 27 GL. We also assume UHS is not interested in selling water or buying water for its own use. These assumptions, being somewhat arbitrary in marginal rates, are anchored to historical values of the downstream water market and comprise a simple and transparent scenario with which we may consider physical and economic interactions with the upper catchment water sources.

This construction, with downstream sectors holding all available entitlements, puts these sectors in the position of the only potential suppliers of water entitlements in the case that a requirement is in force for upstream land owners to purchase water entitlements to permit the establishment of tree plantations. Alternatively, if widespread establishment of new tree plantations takes place in the absence of such a requirement, the downstream entitlement holders will suffer losses as their allocations of water are reduced. We assume such losses (in GL) would be in proportion to their respective initial shares of the aggregate entitlements, just as general security percentage allocations are reduced by shortfalls in droughts. And their economic losses would be valued by them according to their marginal value (demand) lines (Figure 7).

In the case that downstream entitlement holders are the only suppliers of water entitlements, we have assumed only IRR and S&D would be involved in selling water according to their marginal values (in their demand lines). That is, each would agree to sell only at prices greater than or equal to their marginal values, just as they would purchase water only at prices lower than or equal to their marginal values.

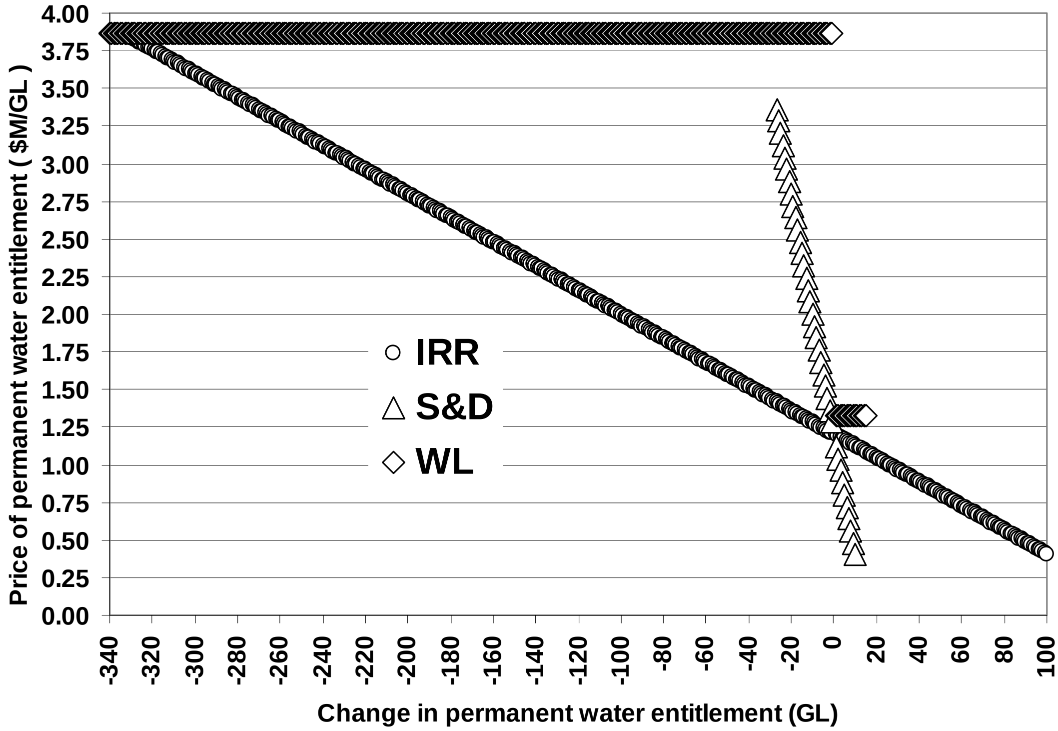


Figure 7. Assumed demand for changes in permanent entitlements to water by downstream IRR, S&D and WL sectors initially holding 333, 27 and 405 GL entitlements, respectively.

3.5 Framework for estimating the distributions of water use and economic surpluses given supply and demand for water among sectors

The parts of the picture developed above allow considering aggregate demand for water coming into equilibrium with aggregate supply in the cases of eight scenarios: four tree product prices, and the presence or absence of a requirement for tree plantations to acquire water entitlements in line with the water they are expected to use according to rainfall zone.

Aggregate demand for water for new upstream tree plantations may be expressed as the horizontal sum of the individual sub-catchment demands (as in Figure 8). The irregular 'wavy' character of these demand curves is due to the natures of their constituent watershed curves (i.e., Figure 5 and Figure 6). Assembling the marginal value arrays of the constituent sectors in a spreadsheet column with a paired column identifying sector names, allowed sorting the values in descending order by their marginal values, creating the 'horizontal sum' to represent the demand curve. This was repeated to produce an aggregate demand curve corresponding to each of the four stumpage values to construct Figure 8.

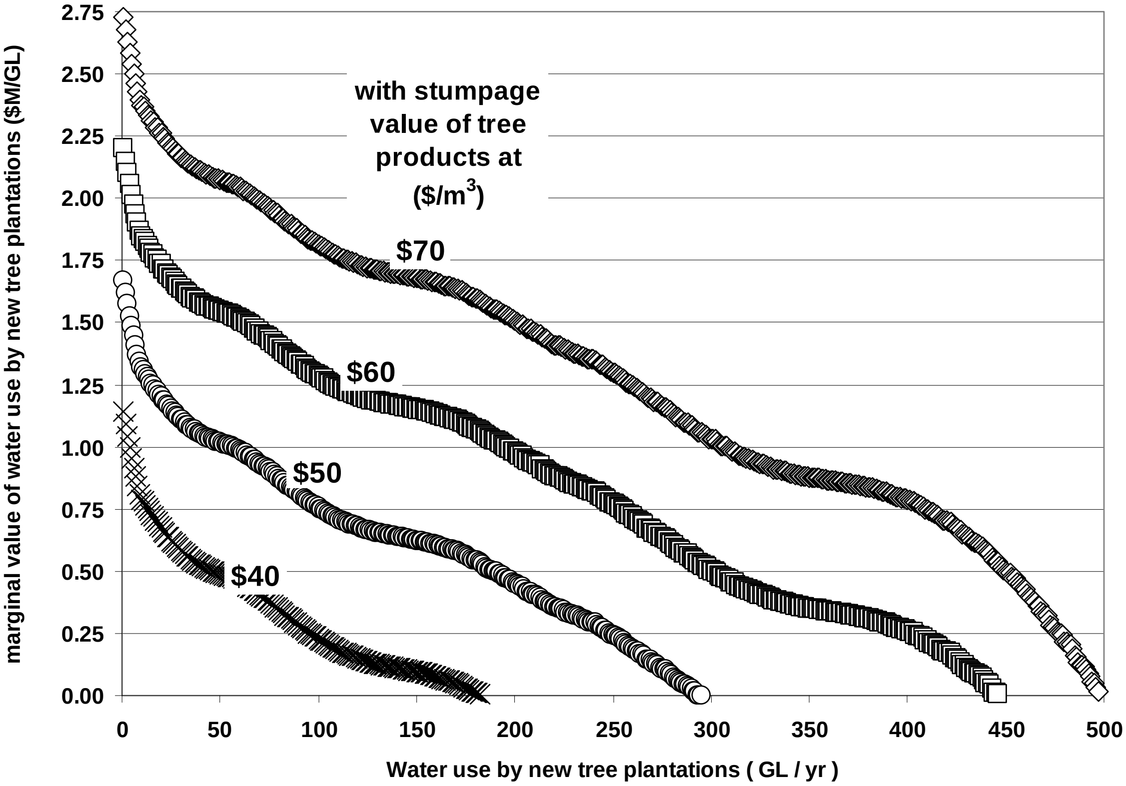


Figure 8. Aggregate demand by upstream watersheds (UC10, UC8, UC6, MCU, MCUS, and MCD) for water entitlements given different values of tree products

The aggregate supply curve for permanent water entitlements is similarly constructed in Figure 9 as the horizontal sums of the marginal values of the downstream entitlement holders, IRR, S&D and WL, which may interact with the upstream aggregate demand for water.

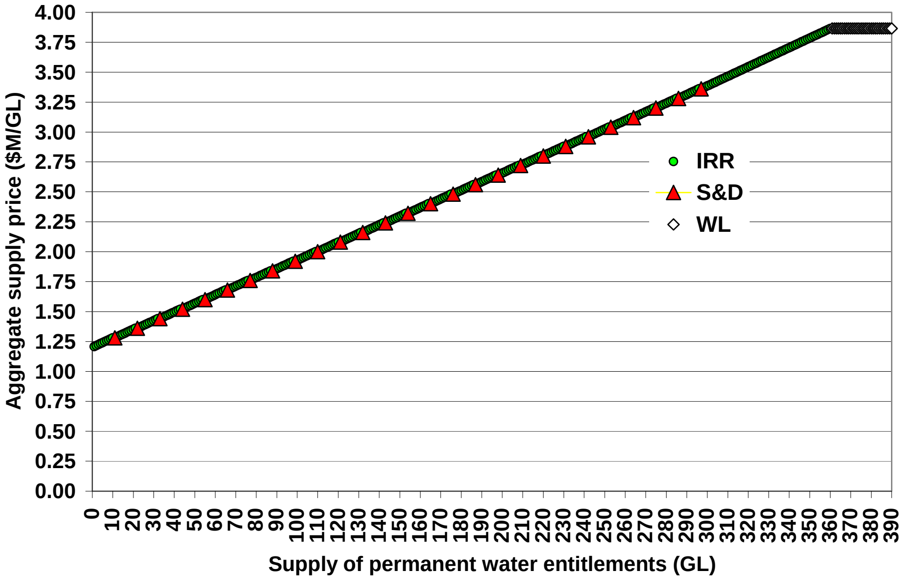


Figure 9. Aggregate supply of downstream water entitlements… of interest in the presence of a requirement that upstream landowners need to purchase water entitlements to permit establishment of new tree plantations

Values of the aggregate supply curve (Figure 9), ranked in ascending order, are matched against the demand columns to find the points of equilibrium supply and demand values… the market prices. Then, up to these equilibrium points, the demand and supply arrays are each sorted by sector. This process results in simultaneous discovery of equilibrium prices, new water use distributions and economic surplus distributions among the upstream and downstream sectors.

4. Results

4.1 Aggregate supply and demand results

Without the requirement to purchase water, the price upstream landowners pay for using water for new plantations is **zero** and they may profitably expand plantations to the point where their direct and opportunity costs of doing so are just covered by the value of their tree products. Referring to the lowest ends of the aggregate water demand curves for new tree plantations (Figure 8), with $40/m^3 for tree products they could reduce water-yields by a total over 150 GL; at $50/m^3 by nearly 300 GL; at $60/m^3 nearly 450 GL; and at $70/m^3 nearly 500 GL. These are extreme estimates of additional water consumption by new trees established by upstream landowners unaware of the large reductions in river flow and large economic losses suffered by the downstream sectors. The losses are assumed to be distributed among the downstream sectors according to their shares of water-use and valued by them according to their marginal values (Figure 7).

In contrast to the large the upstream gains and downstream losses in water use described above, where there is no requirement for new tree plantations to purchase water entitlements, are the more balanced cases where the requirement holds.

Where new plantations must purchase water entitlements, the downstream water market is effectively extended upstream. Downstream demand for additional water beyond the initial entitlements (Figure 7) is added to upstream demand to arrive at aggregate demand for water (Figure 10). Notice the demand by WL for 15 GL at $1.33M/GL is reflected as horizontal steps at that price in the aggregate demand curves. The upward sloping aggregate water supply line in Figure 10 was derived in Figure 9. Notice how this cuts each of the four aggregate demand curves from below to define equilibrium quantities of water traded and the prices discovered in these trades, given the four stumpage values. These results are summarised in Table 2.

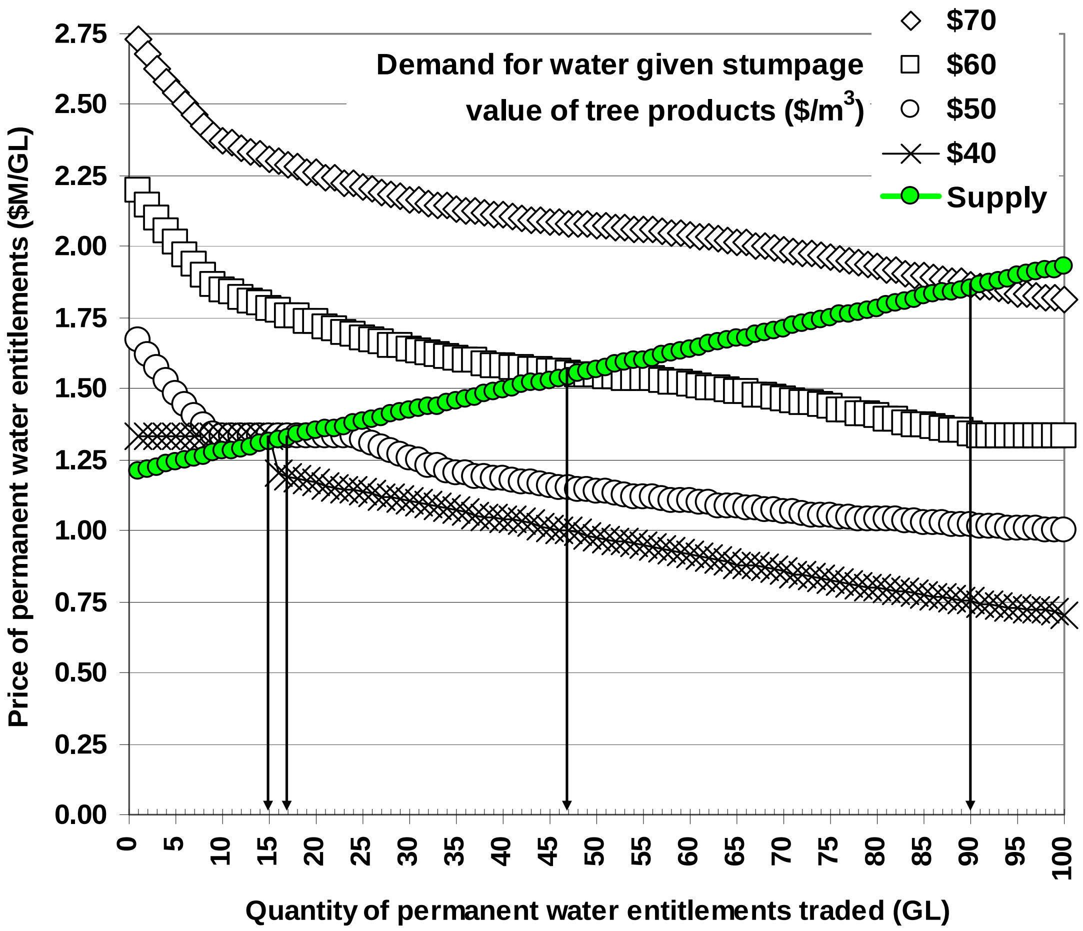


Figure 10. The aggregate supply curve and four aggregate demand curves determine equilibrium prices and quantities of permanent water entitlements traded, given the four tree product values.

Table 2. Equilibrium water prices with trade in permanent entitlements between upstream watersheds establishing new tree plantations and downstream irrigation and S&D sectors, see Figure 10 for solutions

Given stumpage value of tree products ($/m^3)	Equilibrium quantity of water traded (GL)	Equilibrium water price discovered ($M/GL)
$40	15	$1.33M
$50	17	$1.33M
$60	47	$1.55M
$70	90	$1.89M

The aggregate supply and demand solutions (Table 2, Figure 10) were found with a model combining the marginal values of water for new tree plantations by landowners in the six watershed areas and the marginal values for water by downstream IRR, S&D and WL sectors. Each GL increment in water use by a sector carried a marginal value and the name of the sector. When the aggregate array of marginal values was ranked from highest to lowest, the sector names accompanied the marginal values. This made it possible to 'deconstruct' the aggregate results at the overall trade quantity where aggregate marginal demand values equal aggregate marginal supply values. The marginal values in the aggregate market solution were simply sorted by sector name. This allowed counting the quantities and calculating the gains and losses in water entitlements (Figure 11), and in economic surplus (Figure 13), expected for each watershed and downstream sector. New tree plantation areas in the different watersheds (Figure 12) were calculated with the GL of water used for new trees in a watershed (Figure 11) times the land/water use ratio for the annual rainfall appropriate to that watershed (Table 1).

4.2 Disaggregated results: changes in water use, new tree plantation areas and changes in economic surplus for each watershed and downstream sector

In the aggregate results shown above in which the market equilibria were found, one cannot see the very different parts played or impacts felt by the constituent watersheds or downstream sectors. We only see the combined effects as the results of their individual marginal values for water were simultaneously resolved in the economic model, without and with a requirement for new tree plantations to purchase water entitlements.

Changes in the volumes of permanent water (GL) used in each sector, changes in areas of new tree plantations in the six watersheds, and changes in economic surpluses ($M) in each sector, are plotted in Figures 11, 12 and 13, respectively. In each of these figures, results for the scenarios without a requirement for new tree plantations to obtain water entitlements are presented in the top panels. The bottom panels indicate the results for scenarios with the requirement for purchasing water on the market to permit planting trees.

As seen in the aggregate analyses, results for the various watersheds and downstream sectors contrast strongly between the cases without and with a requirement for new tree plantations to purchase water entitlements. Readers are referred to the schematic map (Figure 2) for names of the watersheds and downstream sectors used in Figures 11 – 13.

Without a requirement for new tree plantations to purchase water entitlements, the highest increases in water use for new tree plantations and highest gains in economic surplus (top panels in Figures 11 and 13) are expected for watershed UC8, largest of the higher rainfall parts of the upper catchment.

Also, with increasing stumpage values, water use by new plantations increases at decreasing rates while economic surpluses increase at increasing rates. The accompanying reductions in water flow to the downstream sectors are reflected in large reductions in their economic surpluses (Figure 11 and Figure 13 top panels). Increasing stumpage values induce large expansions in tree areas in the model where there is no requirement to obtain water entitlements (Figure 12 top panels).

Where water entitlements must be purchased from downstream sectors the expansion of plantation areas is attenuated, as reflected in subdued increases in water use and economic surpluses (bottom panels of Figures 12, 11 and 13, respectively).

The downstream consequences of increasing tree stumpage values, where there is no requirement for new tree plantations to purchase water entitlements, include large uncompensated reductions in river flows (Figure 11 top panels) to the downstream sectors and wetland assets and large losses of economic surpluses by the downstream sectors (Figure 13 top panels).

Where there is a requirement for new tree plantations to purchase water entitlements, model results show downstream sectors selling permanent water entitlements (Figure 11 bottom panels), that have marginal values to these sectors below the price being offered, resulting in increased economic surpluses for them (Figure 13 bottom panels).

For the economic agents (land owners in all the watersheds and the IRR and S&D sectors) their ‘bottom lines’ are the expected changes in economic surpluses (Figure 13). For the environmental water users (WL and ECR), their “bottom lines” would be matched to the water flows reaching them, though not linearly because of possible threshold levels below which functionality may be destroyed.

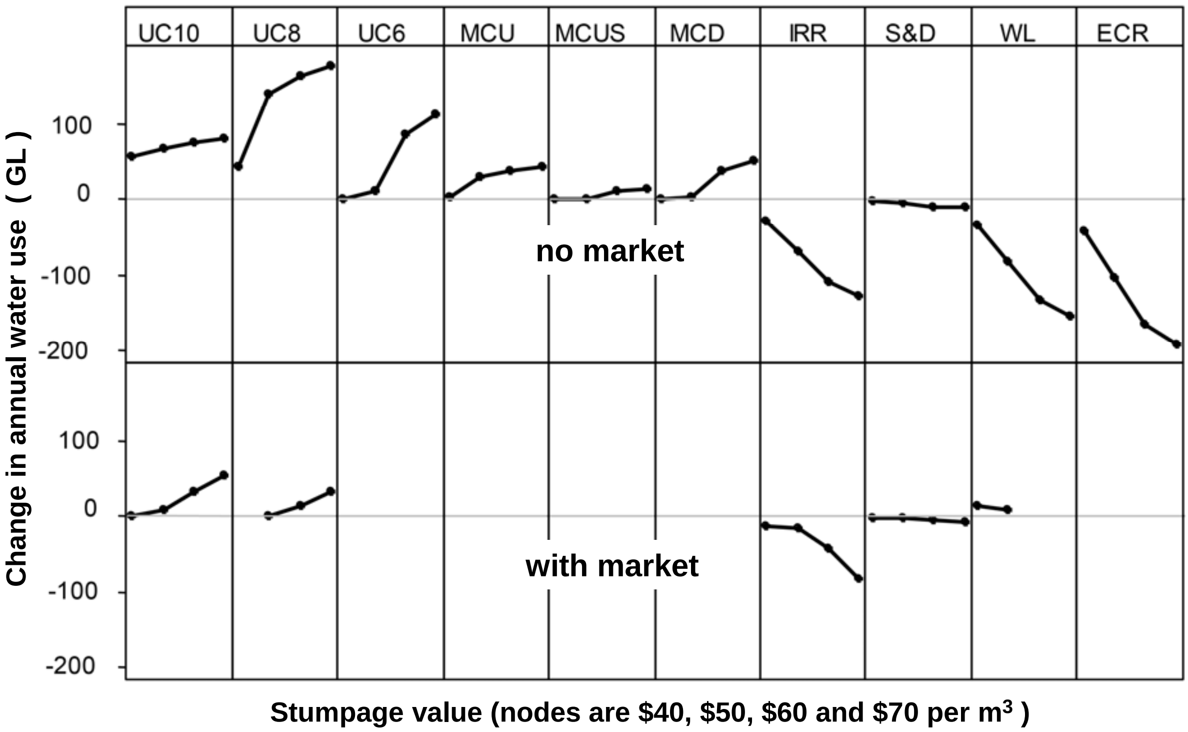


Figure 11. Changes in water use sector by sector, where there is no requirement for those establishing tree plantations to account for their water use (top panels), and where new tree plantations are only permitted after permanent water entitlements have been purchased from downstream entitlement holders (bottom panels). The four nodes shown for each sector are results reflecting the four stumpage values for tree products.

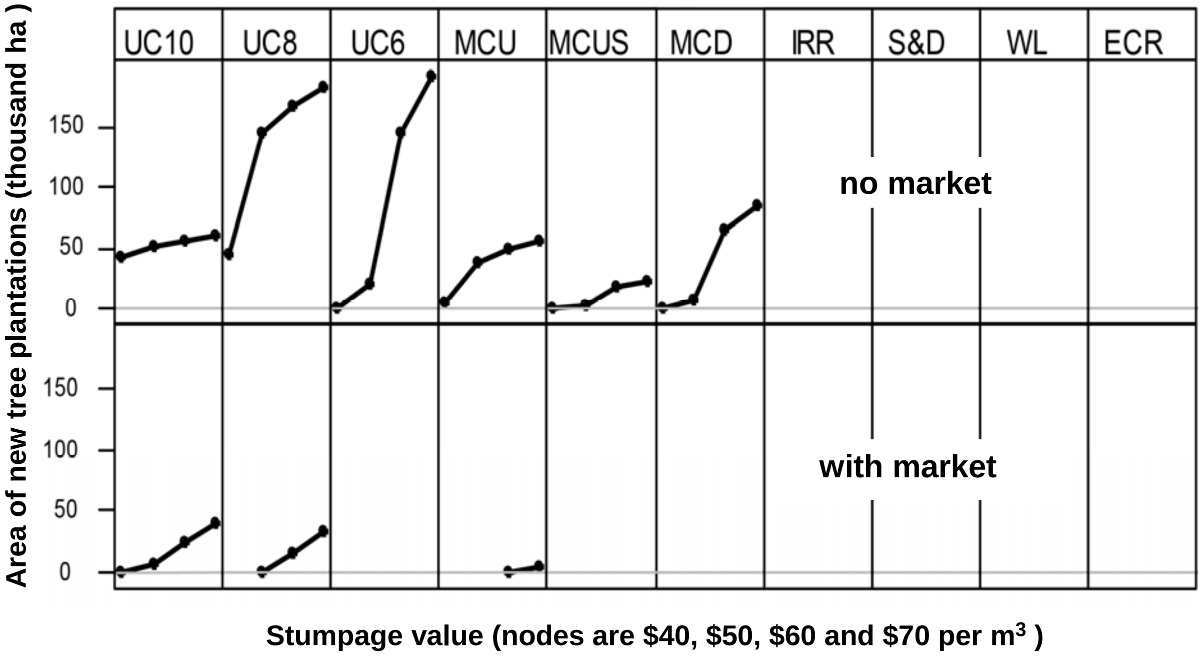


Figure 12. Changes in new tree plantation areas with conditions as described in Fig. 11

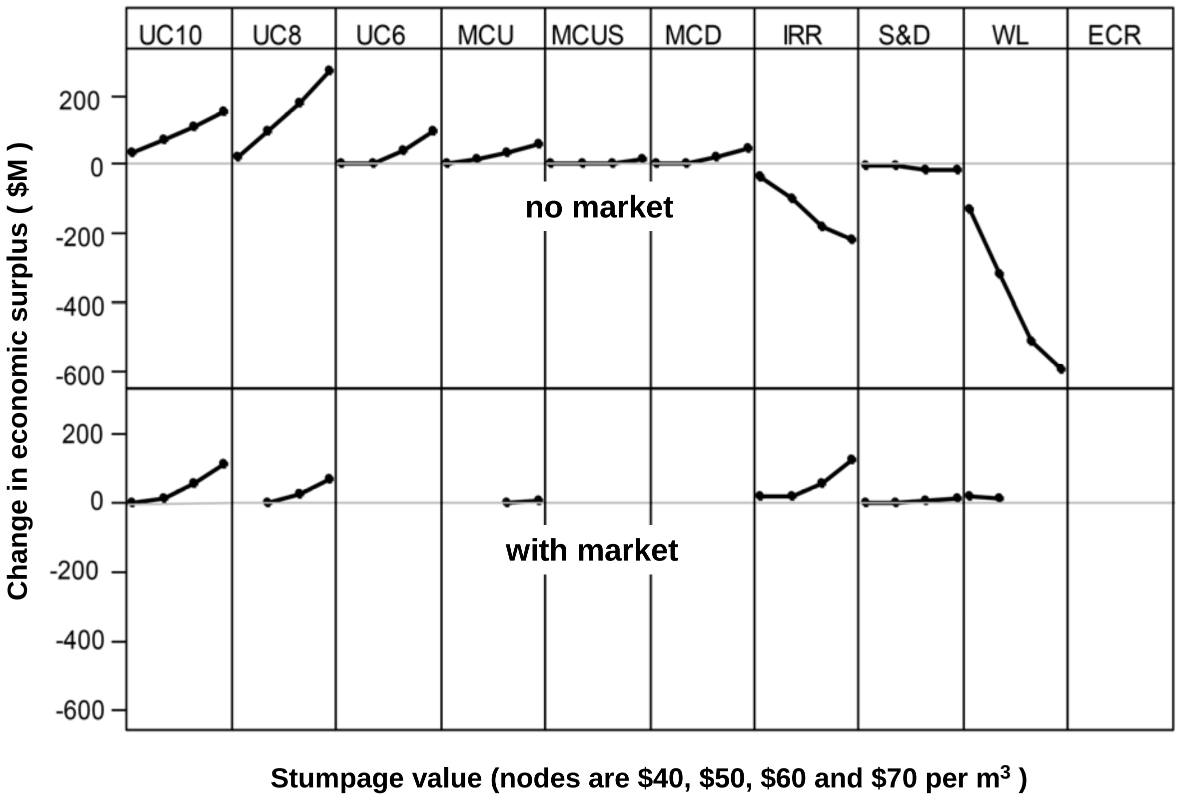


Figure 13. Changes in economic surpluses with conditions as described in Fig. 11

5. Discussion

5.1 The 'No market' scenarios (top panels)

Where landowners in the watersheds are free to establish tree plantations without paying for the water flow reductions caused (top panels of Figure 11), the areas of new trees planted (top panels of Figure 12) will be limited only by their estimates of tree product values minus the direct and opportunity costs of establishment (top panels of Figure 13). Landowners in each watershed simply (and unconsciously) take as much water as they want by planting trees. Plantations would expand to the maximum area that is profitable in each watershed independently, gaining the most in terms of their economic surpluses and, coincidently, using the maximum amounts of water. In contrast, the downstream parties (IRR and S&D) would face maximum uncompensated economic loses, which are unrelated to the gains achieved upstream. They and the environmental assets (WL and ECR) would face significantly reduced river flows, assuming all downstream sectors share water reductions in equal proportions to their flow entitlements.

5.2 'With market' scenarios (bottom panels)

Where new plantations are first required to purchase entitlements from the water market, smaller areas of trees will be planted in fewer watersheds (Figure 12), much less water will be used by trees (Figure 11), but the trees planted will be profitable (Figure 13) and the downstream interests will also have profited by selling some water entitlements for more than its value to them. In the 'with market' scenarios it was assumed that water for the environmental flows, as the case of water for UHS, is quarantined only for their use. Only the remaining amounts of water are allocated by the market.

The present study has developed a theoretical model and calculated equilibrium prices and quantity response at the aggregate whole-catchment level, and sector by sector distributions of water, tree plantations and economic surpluses. An economic experiment, using human subjects and the same marginal value structure, with the same watershed and downstream sectors assumed in the present study, has been staged in laboratory settings (Nordblom *et al*., 2009b). The experiment was run as a series of continuous double auctions, with three replications. Similar quantitative results to those of the present study were found. However, fewer units were traded in the experiment than predicted in the present study.

Of course environmental service markets are not automatic panaceas, but require careful deliberation, design and support (Landell-Mills and Porras, 2002). A market that deals only with water in a given catchment, though more straightforward and manageable than a global carbon market, will still have many challenges. Not least of these would be year to year variations in rainfalls. Likewise, property rights in water, which are presently over-allocated to many downstream jurisdictions and undefined in many upstream watersheds (Adamson *et al*., 2007, 2009).

The water modelling used in the present paper smooths over a great deal of complexity found in any real world application. For example we assume that water yields are a simple function of mean annual rainfall and land use, which at best may account for better than 70 percent of variation in mean annual water yields. We have not directly accounted for different soils, different geological and topographic placements of tree plantations or their aspect of slope with respect to the sun. Neither have we accounted for different options in plant species (of trees, pastures, crops), nor how any of these are managed with regard to land preparation, pest control, planting, thinning, etc. (Van Dijk *et al*., 2004).

Some system of regulations, taxes and subsidies to balance and distribute water use can be imagined as an alternative to markets, but may lack efficiency and result in cutting off valuable opportunities (Young and McColl, 2009). Indeed, given the complexity of the real world landscapes, economics and weather mentioned above, it is hard to see how a system of regulations alone could allocate water efficiently among all its competing uses without including a market mechanism that allows adjustments year to year and over time for bigger changes; for example, technological breakthroughs or climate change (DECCW, 2010).

6. Conclusions

That forest lands exhibit lower annual water yields than permanent pastures, and the latter have lower water yields than annual crops or pastures in the same location, given the same annual rainfall above 600mm, is supported by a large body of scientific literature, briefly reviewed in the paper. Trees (conifers in particular) intercept rainfall well, as water wetting the canopy evaporates and water reaching the ground is taken by the roots and later transpired to the air, so a small share of the received water eventually reaches a river. Other plant species allow greater shares of the rainfall to reach a river. Where river water has important economic, social and/or environmental values, the high water use of tree plantations may be an important consideration in plans to subsidise or otherwise promote the latter in fresh-water source watersheds of the river. This is recognised in contemporary Australian thinking (COAG, 2004; Water Act 2007; SKM, CSIRO & BRS, 2010).

The present analysis developed a simplified bio-economic model of a single large catchment in NSW (the 2.8 million ha Macquarie valley). It illustrated extreme scenarios of plantation expansion in the upper watershed without regard to downstream economic and environmental losses. It also illustrated scenarios in which an extension of the water market from downstream entitlement holders to upstream interests in plantations result in balanced use of water among economic interests and preserved allocations of water to wetland environmental assets.

- Where new tree plantations are not required to purchase water entitlements from downstream entitlement holders, in proportion to river flow reductions, several economic consequences are projected. If tree products have stumpage values of $70/m^3, the model estimates 600,000 ha of new tree plantations would be established to earn economic surpluses of $639 million, but transpire 483 GL more water annually, which would become unavailable for downstream uses. The model apportions this loss of annual flow as 137 GL to agriculture, 154 GL to wetlands and 191 GL in riparian flow and evaporation. Estimated loss of agricultural PV, due to lost water, is $233 million. A lower stumpage value of $40/m^3 for wood products limits forest expansion to 94,000 ha, earning an economic surplus of $53 million and reducing river flow by 106 GL. Downstream agriculture's share of this loss would be on the order of 30 GL of water for a $40 million reduction in economic surplus; the remaining loss of water would amount to about 76 GL not reaching the wetlands and creeks.
- Requiring new upstream tree plantations to buy water entitlements from downstream entitlement holders resulted in no permanent trade of water upstream given tree stumpage values of only $40/m^3. However, if tree products are valued at $70/m^3, the model estimates 90 GL of permanent water entitlements would be purchased to support 78,000 ha of new forest upstream earning economic surpluses of some $192 million, while downstream agricultural sectors would gain $138 million in economic surplus from this sale of water; a total gain in economic surpluses of $330 million, with no reductions in water flows to the environmental assets.

- This study has, for the first time in NSW, quantitatively projected the economic, social (distributional) and environmental benefits that may be associated with requiring new upstream tree plantations to purchase water equivalent to water lost thereby from the flows reaching downstream holders of water entitlements.

References

Adamson, D., Mallawaarachchi, T. and Quiggin, J. (2007). Water use and salinity in the Murray–Darling Basin: A state-contingent model. *The Australian Journal of Agricultural and Resource Economics,* 51: 263–281.

Adamson, D., Mallawaarachchi, T. and Quiggin, J. (2009). Declining inflows and more frequent droughts in the Murray–Darling Basin: climate change, impacts and adaptation. *The Australian Journal of Agricultural and Resource Economics,* 53: 345-366.

Ajani, J. (2010). *Climate change policy distortions in the wood and food market*. Paper, 54th Annual Conference, Australian Agricultural and Resource Economics Society, February 10-12, 2010, Adelaide, Australia. http://purl.umn.edu/58877

Barratt, D., Parsons, M., Welsh, W. and Nation, E. (2007). *Investigating land use-change-scenario impacts: potential effects of reforestation on water yield in the Upper Murray River Basin*. Water 2010 Technical Paper 5. Bureau of Rural Sciences. GPO Box 858, Canberra, ACT 2601 http://adl.brs.gov.au/water2010/Publications/Water2010_Paper5.pdf

Bates, C.G. and Henry, A.J., (1928). Forest and streamflow experiments at Wagon Wheel Gap, Colorado. *U.S. Weather Bureau Monthly Weather Reports*, Suppl. No. 30. pp.79- 97. http://ams.allenpress.com/perlserv/?request=get-toc&issn=1520-0493&volume=56&issue=3

Benyon, R. and Doody, T. (2005). *Regional scale, spatially explicit quantification of plantation forest water use*. Forest & Wood Products Research & Development Corporation. Project no. PN04.4010. http://www.ruralrdc.com.au/WMS/Upload/Resources/FWPRDC%20CSIRO.pdf

Bosch, J.M. and Hewlett, J.D. (1982). A review of catchment experiments to determine the effects of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55: 3-23.

Brooks, K,N., Ffolliott, P.F., Gregersen, H.M. and DeBano, L.F. (2003). *Hydrology and the management of watersheds* (3rd edition). Iowa State University Press, a Blackwell Publishing Company, Ames, Iowa.

COAG. (2004). *Intergovernmental Agreement on a National Water Initiative, Between the Commonwealth of Australia and the Governments of New South Wales, Victoria, Queensland, South Australia, the Australian Capital Territory and the Northern Territory.* http://www.nwc.gov.au/resources/documents/Intergovernmental-Agreement-on-a-national-water-initiative.pdf

Cornish, P.M. (1989). *The effects of Radiata pine plantation establishment and management on water yields and water quality - a review*. Forestry Commission of NSW, Technical paper, No. 49. (53pp)

Cresswell, H.P., Hume, I.H., Wang, E., Nordblom, T.L., Finlayson, J.D. and Glover, M. (2009). *Catchment response to farm scale land use change*. CSIRO Land and Water, and NSW Department of Industry and Investment. Canberra and Wagga Wagga. http://www.csiro.com.au/files/files/psy9.pdf

Croke, J. and Lane, P. (eds) (1999). *Forest Management for the Protection of Water Quality and Quantity*. Proceedings of the 2nd Erosion in Forests Meeting, Warburton, Victoria, 4–6 May 1999. Cooperative Research Centre for Catchment Hydrology, Report 99/6. 107pp. http://www.catchment.crc.org.au/pdfs/technical199906.pdf

Crossman, N.D., Summers, D.M. and Bryan, B.A. (2010). *Opportunities and Threats for South Australia's Agricultural Landscapes from Reforestation under a Carbon Market*. CSIRO Client Report. Final Report – March 2010. CSIRO Sustainable Ecosystems. http://www.csiro.au/files/files/pviu.pdf

DECCW (Department of Environment, Climate Change and Water NSW) (2010). *NSW Climate Impact Profile*, *The impacts of climate change on the biophysical environment of New South Wales*. DECCW, Sydney, NSW, Australia. 168 pp. ISBN 978 1 74232 259 9 http://www.environment.nsw.gov.au/resources/climatechange/10171climateimpactprof.pdf

Drysdale, P.J. (1981). *Status of general and forest hydrology research in Fiji*. Working paper. In Country papers on the status of watershed forest influence research in Southeast Asia and the Pacific. Honolulu, Hawaii, USA, East-West Center.

Duggan, K., Beavis, S., Connell, D., Hussey, K. and MacDonald, B. (2008). *Approaches to, and challenges of managing interception*, Waterlines Occasional Paper No. 5, February 2008, National Water Commission. http://www.nwc.gov.au/resources/documents/approaches-interception-body-waterlines-0208.pdf

DW-GSA (Department for Water, Government of South Australia). (2010). *Approval Process for Plantation Forestry under the Natural Resources Management Act 2004*. Government of South Australia, Department for Water. http://www.waterforgood.sa.gov.au/wp-content/uploads/2010/06/Plantation%20commercial%20forestry/ForestryFSUpdatejune08.pdf

Engler, A. (1919). *Experiments showing the effects of forests on the height of streams*. Transactions of the Swiss Central Institute for Forestry Research. 12: 1-626. (Engler, A. 1919. *Untersuchungen über den Einfluss des Waldes auf den Stand der Gewässer*. Mitteilungen der Schweizerischen Zentralanstalt für das forstliche Versuchswesen. 12: 1-626).

Evans, W.R., Gilfedder, M. and Austin, J. (2004). *Application of the Biophysical Capacity to Change (BC2C) Model to the Little River (NSW)*. CSIRO Land & Water Technical Report No. 16/04. March 2004. http://www.clw.csiro.au/publications/technical2004/tr16-04.pdf

FAO (2003). *Sustainable use and management of freshwater resources: the role of forests. FAO State of the Worlds Forests.* Food and Agriculture Organization. United Nations. http://www.fao.org/DOCREP/005/Y7581E/y7581e09.htm#TopOfPage

Finlayson, J.D., Bathgate, A., Nordblom, T., Theiveyanathan, T., Farquharson, B., Crosbie, R., Mitchell, D. and Hoque, Z. (2010). Balancing land use to manage river volume and salinity: Economic and hydrological consequences for the Little River catchment in Central West, New South Wales, Australia. *Agricultural Systems* 103: 161–170.

Galiana, I. and Green, C. (2010). Technology-led climate policy. Chapter 7 In Lomborg, B. (ed.) (2010). *Smart solutions to climate change, comparing costs and benefits*. Cambridge University Press, Cambridge. ISBN 978-0521-13856-7 pp. 292-339

Garnaut, R. (2008). *The Garnaut Climate Change Review: Final Report*, Commonwealth of Australia. http://www.garnautreview.org.au/index.htm

Gerrand, A., Keenan, R.J., Kanowski, P. and Stanton, R. (2003). Australian forest plantations: an overview of industry, environmental and community issues and benefits. *Australian Forestry* 66 (1): 1-8

Gilfedder, M., Walker, G.R. Dawes, W.R. and Stenson, M.P. (2009). Prioritisation approach for estimating the biophysical impacts of land-use change on stream flow and salt export at a catchment scale. *Environmental Modelling & Software* 24: 262–269.

Gregerson, H.M., Brooks, K.N., Dixon, J.A. and Hamilton, L.S. (1987). *Guidelines for economic appraisal of watershed management projects*. FAO Conservation Guide 16. Food and Agriculture Organization of the United Nations. Rome.

Grieve, A., Wood, S. and Cowie, A. (2008). *Carbon Trading and Catchment Management Authorities: Realising the revenue potential of environmental plantings under the New South Wales carbon market*. Rural Industries Research and Development Corporation (RIRDC) Publication No 08/136, RIRDC Project No CGA-2A. ISBN 1 74151 725 7, ISSN 1440-6845. August 2008. https://rirdc.infoservices.com.au/downloads/08-136.pdf

Hall, N., Watson, W. and Oliver, M. (2002). *Farm Economic Analysis: Little River Catchment, Integrated Catchment Assessment and Management (iCAM) Centre Report No. 2003 TARGET 6*, prepared for the TARGET project, Australian National University, Canberra. http://www.dnr.nsw.gov.au/salinity/science/pdf/fea_final_report-little_river.pdf

Herron, N., Davis, R. and Jones, R. (2002). The effects of large-scale afforestation and climate change on water allocation in the Macquarie River catchment, NSW, Australia. *Journal of Environmental Management* 65, 369-381.

Herron, N., Davis, R., Dawes, W. and Evans R. (2003). Modelling the impacts of strategic tree plantings on saltloads and flows in the Macquarie River Catchment, NSW, Australia. *Journal of Environmental Management* 68, 37–50.

Hibbert, A.R. (1967). Forest treatment effects on water yield. In Sopper, W.E. and Lull, H.W. (eds). 1967. *Forest hydrology*. Proc., National Science Foundation Advanced Science Seminar, Penn. State University, University Park, PA. Aug 29 – Sept 10, 1965. Pp. 527-543.

Holmes, J.W. and Sinclair, J.A. (1986). *Streamflow from some afforested catchments in Victoria*. In: Hydrology and Water Resources Symposium, Griffith University, Brisbane, 25–27 November 1986. The Institution of Engineers, Australia, Preprints of papers, pp. 214–218.

Jackson, R.B., Jobbágy, E.G., Avissar, R., Roy, S.B., Barrett, D.J., Cook, C.W., Farley, K.A., le Maitre, D.C., McCarl, B.A. and Murray B.C. (2005). Trading water for carbon with biological carbon sequestration. *Science* 310, 1944-1947.

Johnson, I. and Coburn, R. (2010). *Trees for carbon sequestration*. Primefact 981. Primefacts for profitable, adaptive and sustainable primary industries. NSW Department of Industry and Investment. ISSN 1832-6668. http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/317559/Trees-for-carbon-sequestration.pdf

Keller, K. M. (1988). European experiences in long-term forest hydrology reserach. In Swank,W.T. and Crossley, D.A., Jr. (eds.) 1988. *Forest Hydrology and Ecology at Coweeta*. pp 407-414. Springer-Verlag.

Landell-Mills, N. and Porras, T.I. (2002). *Silver bullet or fools' gold? A global review of markets for forest environmental services and their impact on the poor*. Instruments for sustainable private sector forestry series. International Institute for Environment and Development, London. http://pdf.wri.org/ref/landell-mills_02_silver.pdf

Langford, K.J. (1976). Change in yield of water following a bushfire in a forest of *Eucalyptus regnans*. *Journal of Hydrology* 29: 87-114.

Lawson, K., Burns, K., Low, K., Heyhoe, E. and Ahammad, H. (2008). *Analysing the economic potential of forestry for carbon sequestration under alternative carbon price paths*. Australian Bureau of Agricultural and Resource Economics, GPO Box 1563 Canberra 2601 Australia. www.treasury.gov.au/lowpollutionfuture/consultants_report/downloads/Economic_Potential_of_Forestry.pdf

Lesch, W. and Scott, D.F. (1997). The response in water yield to the thinning of *Pinus radiata*, *Pinus patula* and *Eucalyptus grandis* plantations. *Forest Ecology and Management*, 99: 295-307.

McCulloch, J.S.G. and Robinson, M. (1993). History of forest hydrology. *Journal of Hydrology* 150: 189-216.

MDBA (Murray-Darling Basin Authority) (2010). *Guide to the proposed Basin Plan: overview*. Murray-Darling Basin Authority, Canberra. ISBN (online) 978-1-921557-73-6 http://download.mdba.gov.au/Guide_to_the_Basin_Plan_Volume_1_web.pdf

Murphy, B.W. and Lawrie, J.W. (1998). *Soil landscapes of the Dubbo 1:250000 sheet (Dubbo,Wellington, Gulgong, Mudgee).* Department of Land and Water Conservation of NSW, Sydney. (Research Centre, P.O. Box 445, Cowra, NSW 2794).

Nambiar, E.K.S. and Brown, A.G. (eds) (2001). *Plantations, Farm Forestry and Water*. Proceedings of a National Workshop, Melbourne, 21–22 July 2000. RIRDC Report No. 01/20. https://rirdc.infoservices.com.au/items/01-020

Nordblom, T., Hume, I., Bathgate, A. and Reynolds, M. (2006). Mathematical optimisation of drainage and economic land-use for target water and salt yields. *Australian Journal of Agricultural and Resource Economics*, 50 (3): 381-402.

Nordblom, T., Hume, I., Cresswell, H., Glover, M., Hean, R., Finlayson, J., and Wang, E. (2007). *Minimising costs of environmental service provision: water-yield, salt-load and* *biodiversity targets with new tree planting in Simmons Creek Catchment, NSW, a dryland farming/grazing area*. Paper presented at the Annual Conference of the Australian Agricultural & Resource Economics Society, 13-16 Feb, Queenstown, New Zealand http://purl.umn.edu/10357

Nordblom, T.L., Finlayson, J.D., Hume, I.H., and Kelly, J.A. (2009a). *Supply and Demand for Water use by New Forest Plantations: a market to balance increasing upstream water use with downstream community, industry and environmental use?* Economic Research Report No 43, NSW Department of Primary Industries, Wagga Wagga. CRC for Future Farm Industries. http://www.dpi.nsw.gov.au/research/areas/biosecurity/economics-research/reports/43

Nordblom, T., Reeson, A., Finlayson, J.D., Hume, I.H., Whitten, S. and Kelly, J.A. (2009b) *Experiments with regulations and markets linking upstream tree plantations with downstream water users*. Paper for AARES 2009, 10-13 Feb. Cairns, QLD. http://purl.umn.edu/47945

Nordblom, T.L., Christy, B., Finlayson, J., Roberts, A. and Kelly, J. (2010a). Least-cost landuse changes for targeted salt-load and water-yield impacts in south-eastern Australia. *Agricultural Water Management*. 97 (6): 811-823.

Nordblom, T.L., Finlayson, J.D. and Hume, I.H. (2010b). *Supply and demand for water use by new forest plantations*. Invited paper, Economics and Environment Network Symposium 2010. 22-24 Nov 2010, Australian National University, Canberra. Presented Monday, 22 Nov, see: http://www.crawford.anu.edu.au/research_units/eerh/workshops/network_symposium/program.php

Nuberg, I., George, B. and Reid, R. (eds). (2009). *Agroforestry for natural resource management*. CSIRO Publishing, Collingwood, Victoria.

Oliver, I., Ede, A., Hawes, W. and Grieve, A. (2005). The NSW Environmental Services Scheme: Results for the biodiversity benefits index, lessons learned, and the way forward. *Ecological Management & Restoration*, 6(3): 197-205.

Pannell, D.J., Roberts, A.M. (2010). Australia’s National Action Plan for Salinity and Water Quality: a retrospective assessment. *Australian Journal of Agricultural and Resource Economics* 54 (4): 437–456.

Parsons, M., Frakes, I. and Gerrand, A. (2007). *Plantations and water use*. *Science for Decision Makers*. Department of Agriculture, Fisheries and Forestry. Bureau of Rural Sciences. http://www.plantations2020.com.au/assets/acrobat/Aug2007_plantationsandwateruse.pdf

Penman, H.L. (1963). *Vegetation and hydrology*. Tech. Comm. 53, Commonwealth Bureau of Soils, Harpenden, 124 pp. Commonwealth Agricultural Bureaux

Plantations for Australia: The 2020 Vision. (no date, accessed 8 October 2010) http://www.plantations2020.com.au/index.html

Rauto, M. (2009). Low dam level threatens power supply. *Fiji Times Online*. Saturday, Nov 21, 2009. http://74.125.155.132/search?q=cache:IIV6a_u36e4J:www.fijitimes.com/story.aspx%3Fid%3D134022+%22Monasavu+Dam%22+%22Viti+Levu%22+Fiji&cd=4&hl=en&ct=clnk

Sahin, V. and Hall, M.J. (1996). The effects of afforestation and deforestation on water yields. *Journal of Hydrology* 178: 293-309.

Schofield, N.J. and Ruprecht, J.K. (1989). Regional analysis of stream salinization in Southwest Western Australia. *Journal of Hydrology* 112:19-39.

Scott, D.F. and Smith, R.E. (1997). Preliminary empirical models to predict reductions in total and low flows resulting from afforestation. *Water South Africa*, 23 (2), 135-140. http://researchspace.csir.co.za/dspace/bitstream/10204/2112/3/scott_1_1997.pdf

Schrobback, P., Adamson, D. and Quiggin, J. (2009). *Turning Water into Carbon: Carbon sequestration vs. water flow in the Murray-Darling Basin*. Australian Agricultural and Resource Economics Society Conference (53rd), February 11-13, 2009, Cairns, Australia. http://ageconsearch.umn.edu/bitstream/47616/2/Schrobback.pdf

SE-NRMB (South East Natural Resources Management Board). (2007). Accounting for and managing plantation forest impacts on groundwater. Information Sheet 7, Nov 2007. Government of South Australia. http://www.senrm.sa.gov.au/LinkClick.aspx?fileticket=VFF62WAnIVo%3d&tabid=619&mid=2469

Shuhuai, D., Zhihui, G., Gregersen, H.M., Brooks, K.N. and Ffolliott, P.F. (2001). Protecting beijlng's municipal water supply through watershed management: an economic assessment. *Journal of the American Water Resources Association* 37 (3): 585-594.

SKM, CSIRO & BRS (Sinclair Knight Merz, CSIRO and the Bureau of Rural Sciences). (2010). *Surface and/or groundwater interception activities: initial estimates Waterlines report*. National Water Commission, Canberra. Waterlines Report Series No 30, June 2010 http://www.nwc.gov.au/resources/documents/Surface_and_or_groundwater_interception_activities_23June.pdf

Sohngen, B. (2010). Forestry carbon sequestration. Chapter 3 in Lomborg, B. (ed.) (2010). *Smart solutions to climate change, comparing costs and benefits*. Cambridge University Press, Cambridge. ISBN 978-0521-13856-7 pp. 114-132.

Stirzaker, R., Vertessy, R. and Sarre, A. (eds). (2002). *Trees, water and salt: an Australian guide to using trees for healthy catchments and productive farms*. Joint Venture Agroforestry Program, RIRDC publication number: 01/086 https://rirdc.infoservices.com.au/downloads/01-086.pdf

Turner, K.M. (1991). Annual evapotranspiration of native vegetation in a Mediterranean-type climate. *Water Resour. Bull*., 27 (1): 1-6.

van der Zel, D.W. (1995). Accomplishments and dynamics of the South African afforestation permit system. *South African Forestry Journal* 172, 49–57.

Van Dijk, A.I.J.M., Austin, J., Theiveyanathan, T., Benyon, R. and Hairsine, P.B. (2004). *Representing plantation scenarios in hydrological modelling: Requirements and limitations in representing Commercial Environmental Forestry scenarios in stream flow and salinity modelling*. CSIRO Land and Water. Commercial Environmental Forestry report CLW/02. http://www.clw.csiro.au/publications/consultancy/2004/Representing_Plantation_Scenarios_in_Hydrological_Modelling.pdf

Vertessy, R.A., Zhang, L. and Dawes, W.R. (2003). Plantations, river flows and river salinity. *Australian Forestry* Vol. 66 (1): 55–61.

Water Act 2007 (2007). Act No. 137 of 2007 as amended. Prepared on 5 March 2010 taking into account amendments up to Act No. 8 of 2010. Office of Legislative Drafting and Publishing, Attorney-General's Department, Canberra, Australia. http://www.austlii.edu.au/au/legis/cth/num_act/wa200783.txt

Wicht, C.L. (1967). Forest hydrology research in the South African Republic. In Sopper, W.E. and Lull, H.W. (eds). 1967. *Forest hydrology*. Proc., National Science Foundation Advanced Science Seminar, Penn. State University, University Park, PA. Aug 29 – Sept 10, 1965. Pp.75-84.

Wood, W.E. (1924). Increase of salt in soil and streams following the destruction of native vegetation. *Journal of the Royal Society of Western Australia.* 10 (7): 35-47.

Wood, S., Cowie, A. and Grieve, A. (2008). *Carbon Trading and Catchment Management Authorities: Predicting above-ground carbon storage of plantations*. Rural Industries Research and Development Corporation (RIRDC) Publication No 08/191, RIRDC Project No CGA-2A. ISBN 1 74151 780 X, ISSN 1440-6845. December 2008. https://rirdc.infoservices.com.au/downloads/08-191.pdf

World Bank. (2010). Managing land and water to feed nine billion people and protect natural ecosystems. Chapter 3. *In World Development Report 2010*, The International Bank for Reconstruction and Development / The World Bank. 1818 H Street NW. Washington DC 20433. ISBN: 978-0-8213-7987-5. DOI:10.1596/978-08213-7987-5.

Whitehead, P.G. and Robinson, M. (1993). Experimental basin studies - an international and historical perspective of forest impacts. *Journal of Hydrology*, 145: 217-230.

Young, M.D. and McColl, J.C. (2009). Double trouble: the importance of accounting for and defining water entitlements consistent with hydrological realities, *Australian Journal of Agricultural and Resource Economics*, 53, 19-35. doi: 10.1111/j.1467-8489.2007.00422.x

Zhang, L., Dawes, W.R. and Walker, G.R. (1999). *Predicting the effect of vegetation changes on catchment average water balance,* CRC for Catchment Hydrology Technical Report 99/12. http://www.catchment.crc.org.au/pdfs/technical199912.pdf

Zhang, L., Dawes, W.R. and Walker, G.R. (2001). Response of mean annual evapotranspiration to vegetation changes at catchment scale, *Water Resources Research* 37 (3): 701-708.

Zhang, L., Dowling, T. Hocking, M., Morris, J., Adams, G., Hickel, K., Best, A. and Vertessy, R. (2003). *Predicting the Effects of Large-Scale afforestation on Annual Flow Regime and Water Allocation: An Example for the Goulburn-Broken Catchments*, Cooperative Research Centre for Catchment Hydrology, Technical Report, 03/5. Monash University, Victoria, Australia. http://www.catchment.crc.org.au/archive/pubs/1000121.html

Zhang, L., Vertessy, R., Walker, G., Gilfedder, M. and Hairsine, P. (2007). *Afforestation in a catchment context: Understanding the impacts on water yield and salinity.* Industry Report 01/07. CSIRO. Land and Water Science Report Number 01/07. eWater Cooperative Research Centre, Canberra. http://www.ewatercrc.com.au/documents/Afforestation%20in%20catchments.pdf

Zon, R. (1927). *Forests and water in the light of scientific investigation*. In: U.S. National Waterways Commission, Final Report, Appendix V, 203-302. Washington, DC: U.S. Government Printing Office. http://chla.library.cornell.edu/cgi/t/text/text-idx?c=chla;idno=2863561