Forestry and water yield: the New Zealand example

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Abstract

This article summarises the current state of knowledge with respect to forestry and water yield in New Zealand. The primary mechanism by which tall vegetation affects the water balance is through evaporation of intercepted rainfall, thereby reducing the amount of water available for runoff and streamflow. Generally trees have a high capability for interception due to a large leaf area and high aerodynamic roughness above the canopy. In experimental studies around New Zealand reductions in annual water yield of between 30-80% have been measured following afforestation of pasture. These figures are lower where afforestation has replaced scrub species. The effect of afforestation on peak flows is considerable, particularly for small flood events although there is some evidence that storms with long return periods may also be substantially reduced following afforestation. There is considerable debate whether these effects can be seen at a large catchment scale. The effect of afforestation on low flows is less well studied. Low flows are reduced following afforestation but it appears that in some cases low flows are affected to a lesser extent than annual yield. Public policy on forestry and water yield varies between regions. For example some regional authorities in the South Island have land-use restrictions based on water yield arguments while the Otago Regional Council (also in the South Island) does not.

Introduction

Prior to human settlement New Zealand was largely covered in tall podocarp and southern beech (N*othofagus spp*) forest except for the mountainous regions of the South Island. Settlement and subsequent forest clearance occurred in two phases (Fig 1). Polynesian settlement occurred from around 900 AD onwards with large scale forest clearance, thought to be mainly through burning, particularly in the coastal areas and the South Island. European settlement occurred from 1840 onwards with another phase of forest clearance in order to bring land into agricultural production. The majority of this land use change occurred between 1840 and 1950. Overall New Zealand indigenous has declined from covering around 80% of the country to the current figure of around 23%.

Since around 1900 there has been a significant growth in reforestation, mainly through non-indigenous forestry planting (Fig 2). The main forestry tree type is radiata pine (*Pinus radiata*) which is used for timber, pulp and paper production and chipboard manufacture. In 2002 there was around 1.8 million hectares of non-indigenous commercial forest (approximately 7% of the total land area). Recently the amount of new forest planted has reached a plateau, as the worldwide commodity price of wood has made in a less economic land use.

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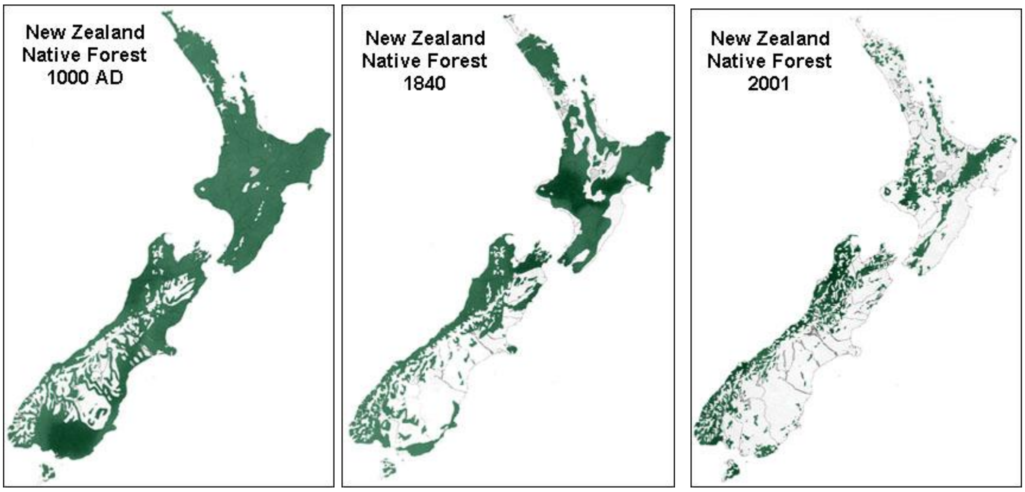

Figure 1: Decline in New Zealand indigenous forest cover since human settlement (from Froude et al 1985).

Figure 2: Current New Zealand topography and land cover. Non-indigenous forestry is shown as the light green colour.

The interaction between forestry and water-users has been a contentious land use issue for a number of years. The issue is essentially a simple one: tall vegetation (e.g. trees or scrub) as a land cover results in less water reaching a stream or underlying aquifer than for short vegetation (e.g. pasture). In practical and policy terms the clarity of the issue is lessened by the variability in hydrological response with a given vegetation cover and also by the important role that tall vegetation plays in improving water quality. This has led to a situation where, in some regions, restrictions on afforestation are put in place with the objective of protecting water yield (e.g. Tasman and Canterbury in the South Island), while in others, restrictions on deforestation are put in place to protect water quality (e.g. Waikato in the North Island).

This article summarises the current state of knowledge from New Zealand studies, with respect to forestry and water yield. It does not cover other water and forestry related areas such as sediment yield and water quality. A recent, more in-depth review of forestry, water yield, sediment and water quality can be found in Fahey *et al.* (2004a). A complete review of the effects of forestry on water yield can be found in a recent series of reports freely available at http://icm.landcareresearch.co.nz/ (follow the WATYIELD link).

How tall vegetation affects water yield

Any analysis of water yield requires consideration of the water balance. This fundamental equation underlying much of hydrology is:

$$Q = P - E \pm \Delta S .$$

For a period of time (e.g. a day or year) Q is a general term for runoff that incorporates streamflow and groundwater movement; P is precipitation; E is evaporation and ΔS is the change in storage. Storage is a term that may account for soil moisture, a snowpack, wetlands, or lake water. The relative importance of each of these is dependent on the time period studied and the geographical location.

Increasing the vegetation canopy cover affects the water balance through an increase in evaporation, thereby reducing the amount of water available for runoff and streamflow. Evaporation can be split between transpiration (dry leaf evaporation) and interception loss (wet leaf evaporation). The ratio of wet to dry evaporation varies between locations and rainfall regimes. Fahey *et al.* (2001) found that during a Canterbury summer/autumn period dry leaf evaporation was twice as high as wet leaf. This contrasts with Pearce & Rowe (1979) who showed that in wetter climates the annual total of wet leaf evaporation can be over twice that of dry leaf evaporation.

If the comparison is being made between pasture and plantation forestry then the ratio between wet and dry leaf evaporation becomes less important. This is because measured transpiration rates (dry leaf evaporation) for pasture and pine forests are very similar, and may be higher for pasture grasses when water supply is unlimited. When we compare short and tall vegetation it is the amount of interception loss (wet leaf evaporation) that is the important difference. For tall vegetation the increased amount of interception loss is due to two factors (see Fig. 3):

- There is a large leaf/needle area for rainfall to be intercepted on and then be evaporated off.
- The top of the forest canopy is aerodynamically rough, which results in turbulence above the canopy and the evaporated water vapour is easily mixed with drier air above. Consequently evaporation rates from wet forest canopies are high.

Of these two factors it is the latter that is most important in accounting for evaporation loss. The high aerodynamic roughness of tall vegetation and consequent excellent turbulent mixing of air leads to very high wet leaf evaporation rates.

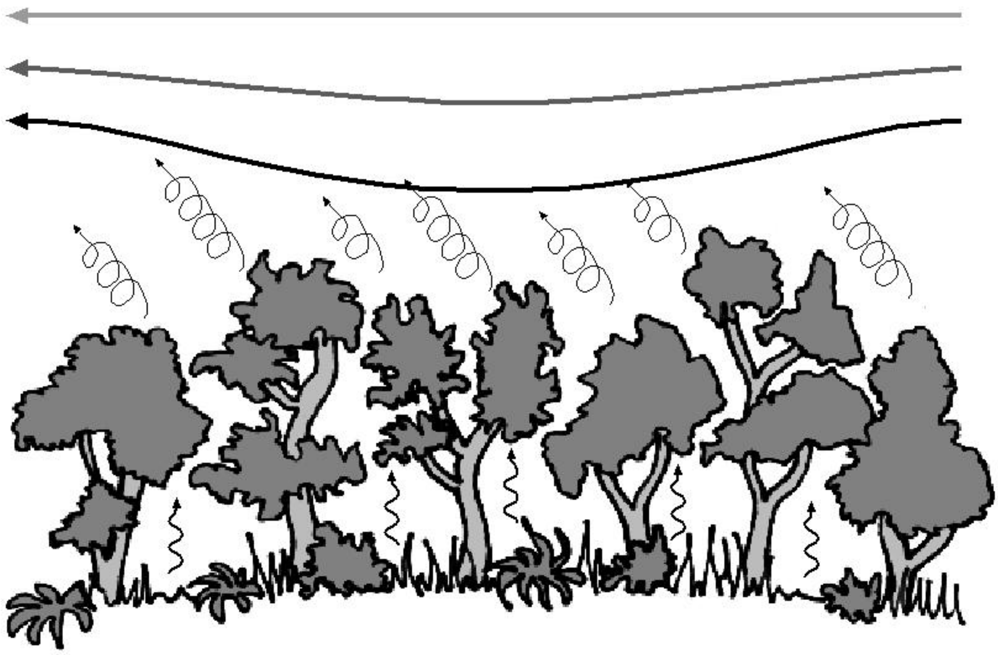

Figure 3: Interception processes. The capacity of the leaves to intercept rainfall and the efficient mixing of water vapour with the drier air above leads to high evaporative losses (so-called interception loss).

It is often stated that because trees have deeper rooting systems than grass and therefore have access to deeper water during dry summer periods, the total dry leaf evaporation is greater than for pasture. Schenk & Jackson (2002) in a worldwide review of rooting depths and distribution show that rooting depths for pasture are less than for forests. However, they go on to show that the depth within which 95% of roots are found is more closely related to climatic variables than to life-form, i.e. all plants adapt their rooting depth according to the climatic regime where they occur.

It is not normally the rooting depth that controls the rate at which water is extracted from the soil by plant roots and transpired by the plant but rather the surface or canopy conductance of vegetation. Canopy conductance refers to the ease with which water vapour escapes through leaf surfaces (Scotter & Kelliher 2004). The canopy conductance of forest is less than that of pasture, due to the ability of most trees to control their stomata when under water stress. If deeper rooting is important it comes into play late in the drying of the soil, and it only has a role if there is water available deep in the soil, i.e. if the whole profile of the soil was recharged in the preceding winter.

In summary, the major effect that tall vegetation has on water yield is through an increase in interception loss, leading to less water available for stream runoff and groundwater recharge.

Effects of afforestation on total water yield

The majority of studies done in New Zealand have concentrated on annual water yield: the total amount of water leaving a catchment as streamflow over a year. Most of these studies have been carried out in small research catchments (less than 1 km^2) where the total land use has been controlled, i.e. all the catchment has been logged or afforested and the water yield response compared to a control catchment with no alteration. Bosch & Hewlett (1982) summarised these types of experiments from around the world and came up with several important conclusions:

- A reduction in tall vegetation cover causes an increase in water yield, and vice versa.
- With respect to the vegetation type the amount of increased annual water yield per 10% decrease in vegetation cover can be generalised.
- Reductions in vegetation cover of less than 20% of an area cannot be detected by measuring streamflow.

Stednick (1996) confirmed Bosch & Hewlett's last conclusion in a review of data from the USA with respect to deforestation. Stednick (1996) analysed the data using regional generalisation and concluded there were considerable differences based on where the study took place. Rowe (2003) provides analysis of numerous data sets around New Zealand that shows regional differences occur, although no generalisation was possible.

Fig 4 shows the location of various catchment studies in New Zealand where a contrast has been made between plantation forestry and either grass pasture or scrub species. There are two notable absences: Donald Creek (very close to number 4) and the Maimai catchments (immediately west of number 5). Both of these catchment studies were set up to investigate forest management practices, rather than the impact of afforestation/deforestation. Subsequent studies at the Maimai catchments have been important for understanding hydrological processes rather than water yield.

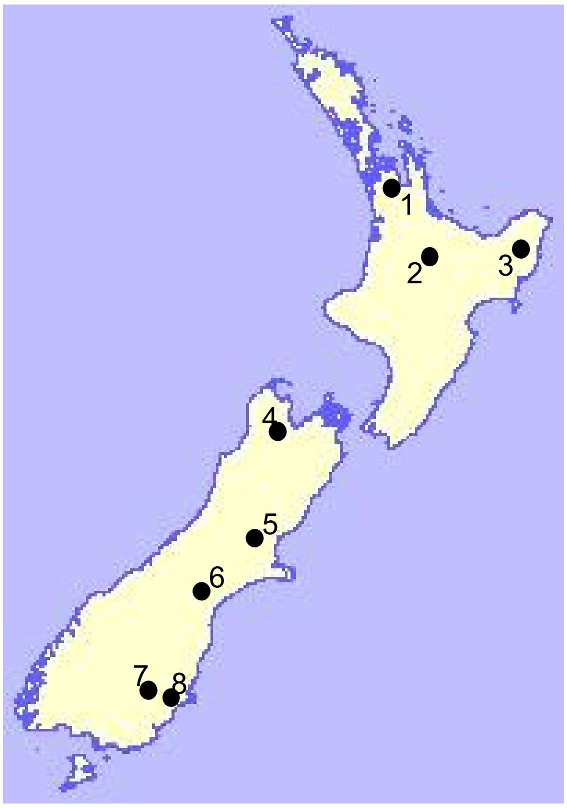

Figure 4: Location of experimental catchments referred to in text. 1 = Moumoukai; 2 = Purukohukohu; 3 = Mangatu; 4 = Moutere; 5= Ashley; 6 = Kakahu; 7 = Glendu; 8 = Berwick.

The reduction in total water yield following afforestation varies according to the nature of the original land use, where the data are collected, and when. For the afforestation of previous pasture land Pearce *et al.* (1987) report reductions of 30% at Mangatu (#3 in Fig. 4); Purukohukohu (#2 in Fig. 4) data analysed by Rowe (2003) show a 30% reduction; Smith (1987) found a 45% reduction at Berwick (#8 in Fig. 4); and Duncan (1995) reports reductions as high as 80% on Moutere gravels (#4 in Fig. 4). For the afforestation of tall tussock at Glendhu (#7 in Fig. 4), Fahey *et al.* (2004a) report a 30% reduction for a 67% afforested catchment that they conclude may equate to a 40-45% reduction for total forest cover.

The effect of afforestation where scrub was the original land cover is less than for pasture. For a site in the Hunua Ranges (#1 in Fig. 4) a 37% reduction in annual yield was found when native scrub was replaced with *Pinus radiata* (Rowe 2003). At Moutere one of two catchments previously covered in gorse showed no distinguishable difference in flows when planted in pines (once the pines were established). The other catchment with the same land-use change showed a 45% reduction in annual water yield (based on data in Duncan (1995)). This is reported in Fahey *et al.* (2004a) as reflecting a 31% reduction in water yield, which compares with the 81% reduction following conversion of pasture to pine at the same location. This reflects the high interception loss found in gorse (Duncan 1995) and the extremely high interception losses found for manuka (Rowe *et al.*, 1999).

The use of percentages to report changes in total water yield is convenient for comparison but may be deceptive. For example, a 10% reduction in annual water yield at a high rainfall site may be considerably less important ecologically than the same percentage reduction at a drier location. It is also important to remember that these are based on averages over time. The period chosen may be important, e.g. has it been a particularly dry spell? This is neatly illustrated for the Ashley data (# 5 in Fig. 4) presented in Jackson (1985) where an average reduction in annual water yield following afforestation is calculated as 62%. Subsequently Jackson & Rowe (1997) calculate the average to be 52%, by including data for 1986, which happened to be a much wetter year.

For the Purukohukohu data set (Rowe 2003) the average reduction in water yield over 19 years following afforestation is 30% but ranges from 22% to 66%. There is a suggestion that there is likely to be a higher percentage change in dry years than in wet years (see Fig. 5). However, the highest percentage change was not recorded during the driest year, nor was the lowest change recorded during the wettest. This suggests that, for this site, the effects of afforestation are more noticeable during dry years than wet, but there is still considerable variability. This variability is probably a result of variations within a year, e.g. a very dry winter followed by a wet spring will have a quite different annual water yield from a wet winter and dry spring, although the annual precipitation may be similar.

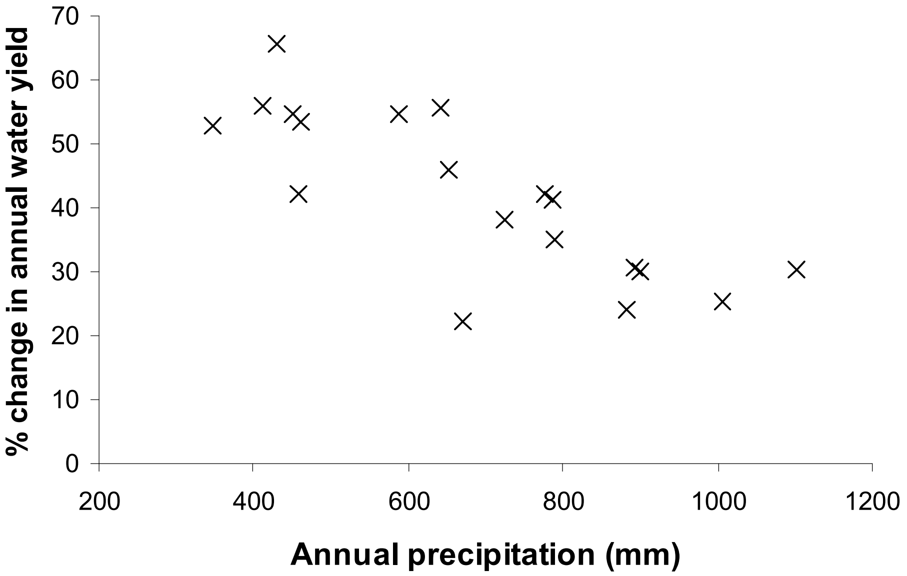

Figure 5: Percentage change in annual runoff following afforestation plotted against the equivalent years annual rainfall total. The data are for the Purukohukohu suite of catchments.

Effects of afforestation on low flows

In contrast to total water yield there is a paucity of data concerning the effect of forestry on low flows. Smakhtin (2001) cites six studies from around the world (including New Zealand) that suggest that following afforestation the percentage change in low flows is greater than the proportional change in annual yield. This differs from the results of Smith (1987) that show a lesser reduction in low flows than in annual water yield for the Berwick site. One of the difficulties in looking at the effects of afforestation on low flows is that in small catchments the lowest flow may be zero, which proves difficult to analyse statistically (Fahey *et al.*, 2004a).

Davie & Fahey (2004) re-analysed four New Zealand data sets (Purukohukohu, Glendhu, Berwick and Kakahu; numbers 2,7,8 & 6 in Fig. 4) looking specifically at whether low flows are affected to the same degree as total water yield. The conclusion was that generally low flows were affected less by afforestation but the actual percentage change depended on which low-flow measure was used (there are numerous different indices and measures that are used) and on the catchment. An explanation of these results could be that low flows are derived from parts of a catchment with high rainfall, wetland storage, and deep groundwater sources; all of which are less susceptible to variation in water balance on hillslopes. The one catchment that showed afforestation having a greater effect on low flows than annual yield (Puruki at Purukohukohu) was the smallest and has very little of these low-flow-generating areas.

In summary forestry does have an effect on low flows, but the affect varies from catchment to catchment and often is to a lesser extent than for the mean annual yield. The extent to which low flows are affected by forestry practices is an area that needs further research.

Effects of afforestation on flood flows

The effect of afforestation on peak flows is considerable, particularly on small flood events. Smith (1987) reports a reduction in annual peak flows of around a third at Berwick and Rowe (2003) reports peak flows reduced by as much as 50% at Purukohukohu. Although it is common to consider that this effect is greatest on small floods (those with an annual return period and less), Duncan (1995) shows that floods with an average 50-year return period are around 50% reduced under pine forest when compared with pasture. Duncan (1995) attributes this difference to the interception occurring during the storm (which may be significant for relatively small storms even if the return period is high) and to the reduction in soil moisture under the forest canopy.

The difference in soil moisture under different vegetation covers highlights the idea that the timing of a peak flood is important. In Fig. 6 the main difference in soil moisture storage under pasture and forest occurs during autumn and early winter. During this rewetting period the reduced rainfall reaching the ground causes a delay in refilling the soil moisture store; any storm occurring then will have a lesser effect in a forested catchment. In the modelled scenarios shown in Fig. 6 up to 60 mm of rain falling in the May-June period could be absorbed by the forest-covered soil that is not available for a pasture-covered catchment. Later in the winter, however, the soil moisture store is the same under either land cover and the difference in stormflow is likely to be considerably reduced.

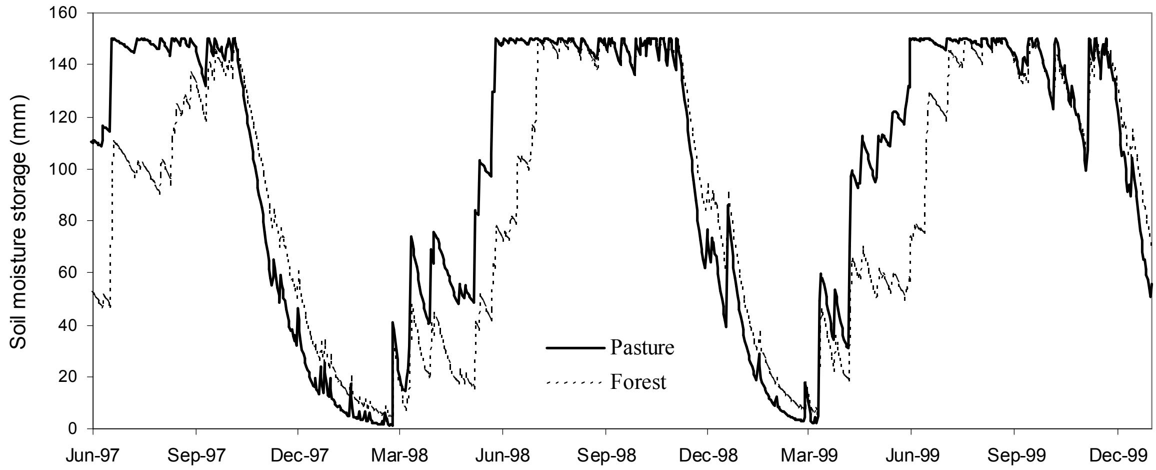

Figure 6: Modelled soil moisture storage beneath pasture and pine forest canopy using soils and rainfall data from Waiwhero (Moutere gravels in Motueka catchment, Nelson). N.B. the modelled values of soil storage agree well with measured values using neutron probes.

The timing of a storm within a forestry cycle will also be important. Davie (1996) showed that any changes in peak flow that result from afforestation are not gradual but highly dependent on the timing of canopy closure. Once canopy closure has been achieved the response of different age forests is relatively uniform.

Effects of afforestation at the large scale

Dons (1986) reports on the effects of afforestation on total water yield at a large scale: the Tarawera catchment (906 km^2) in the central North Island of New Zealand. Approximately 28% of the catchment was afforested with Pinus radiata between 1964 and 1981 which led to a significant reduction in "annual, summer and winter" flows (Dons, 1986). While some of the reduction could be attributed to lower rainfall following afforestation, around 13% of the reduction could be attributed to the land use change. This is "in accord with results of small catchment studies" (Dons, 1986).

In a modelling study of the Motueka catchment (2170 km^2) Davie et al, (2004) compared scenarios of afforestation with Pinus radiata and the indigenous forest, with the current mixed land use situation. Two different models (SWAT and DVHSM) suggested that the largest change in annual yield would be caused by indigenous afforestation; mostly due to a larger land area available to be used. The impact of afforestation on total would be between 3 and 11% but the impact increased to between 9-28% for low flows.

A recent report on forests and flooding (FAO, 2005) has reignited the debate as to whether the effects of afforestation on floods can be detected at the large scale. In the past there has been considerable debate in the literature as to whether this is true. Jones & Grant (1996) analysed data from a series of paired catchment studies in Oregon, USA, and concluded there was clear evidence of changes in interception rates and peak discharges at all scales. Thomas & Megahan (1998) reanalysed the same data and claimed there was clear evidence of changes in peak flows in the small-scale catchment pairs (60-100 km^2) but no change or inconclusive evidence for change in the large catchments (up to 600 km^2). There has followed a series of letters between the authors disputing various aspects of the studies (*Water Resources Research* vol. 37 pp. 175-183). This debate mirrors an overall concern in hydrology over scale: that some processes observed at the hillslope and small-catchment level may not be as important when scaled up to larger catchments.

Public policies on forestry and water yield

In New Zealand environmental regulation and monitoring is carried out at a regional level. Recently the notification of a Natural Resource Regional Plan (NRRP) for Canterbury, in the South Island, has resurrected many water and land-use issues and has been the catalyst for much rhetoric in the media and beyond (e.g. Perley & Weir 2004). Under the provisions of the Canterbury NRRP a resource consent will be required where afforestation in "water sensitive catchments" may cause a greater than 5% decline in mean annual low flow. The definition of "water sensitive" and what area of land in each catchment may cause this decline are set out in the NRRP following hydrological analysis of each catchment (using percentage changes in annual yield and low flow). In theory the area of land affected may be as little as 5% of a farm (referred to as forestry units), although at present the smallest restricted area is 10%. In Tasman District (top of the South Island), following an Environment Court ruling, the restriction in land area is 20% of a land title that may be planted. This only applies in an area deemed as part of the Moutere Groundwater Recharge Zone and it recognises the role of trees in restricting groundwater recharge. The Environment Court explicitly ruled in favour of protecting existing water allocations, in this case groundwater extractors in the Moutere valley. The policy approaches of Tasman and Canterbury were not pursued by the Otago Regional Council (southern South Island) who decided, after public consultation, not to include in its regional water plan policies to control forestry. The Otago decision was largely based on the evidence of other positive benefits of forestry on water (e.g. improved water quality and stream habitats) and the lack of consideration of wasteful practices by existing abstractors (Fahey *et al.* 2004a).

Summary

The main conclusion of Bosch & Hewlett (1982) still applies: increasing scale of vegetation cover (both upwards and outwards) in a catchment does lead to a decrease in water yield, but there is much spatial and temporal variability that needs to be taken into account. The application of simple average percentage decreases on annual streamflow is highly simplistic. It not only ignores the different influences on low and peak flow hydrology but also variations in climate and soils. The development of numerical models, such as WATYIELD (Fahey *et al.* 2004b), TOPNET (He & Woods 2001), SWAT (Cao *et al.* in press) and others, with a capability to investigate effects of land-use change allows detailed analysis of catchments with rainfall and land-use records. These types of models will provide a mechanism for investigating the role of spatial scale and how low flows differ from mean annual yield, although there is still a need for field experimentation to back this up. Murray & Jackson (1998) trace the history of research into the impacts of vegetation change on evaporation and runoff and conclude: “much of the considerable progress since 1948 has resulted from the classical interplay of theoretical and experimental science…”. The science has advanced in recent years but there are no broad-brush rules and answers that can be applied directly into a single policy statement. The inherent variability of natural processes means that scientific results require careful interpreting for each situation before we can fully understand the role of forestry on water yield for a particular site.

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