ARTICLES

The effect of plantation forestry on water yield in New Zealand†

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ABSTRACT

This paper discusses the hydrological consequences of converting land in native forest, scrub, tussock grassland, and pasture to plantation forestry, and the impacts of harvesting and re-establishing a tree crop. Forests influence water yield and associated streamflow responses through increased canopy interception of rainfall. Thus afforestation of pasture may reduce water yield by 30-50% five-ten years after planting. For tussock grasslands the reduction is between 25 and 30%. A similar percentage reduction can be expected in low flows. Storm quickflows and flood peaks can fall by over 50%. Silvicultural practices, such as understorey control and spreading the time of planting, have the potential to augment water yield.

Forest harvesting in moderate-to-high rainfall areas can cause a 60-80% increase in water yield for three-five years after clearfelling. Yields should return to pre-harvesting levels within six-eight years, depending on the silvicultural regime adopted. Mean flood peaks can rise by up to 50%. However, the hydrological impact must be viewed within the context of the area harvested compared with the total forest area. If the former is small in comparison, any local increases in water yield and flood response may be quickly attenuated.

INTRODUCTION

There are about 1.3 million ha of exotic forest in New Zealand (MOF 1994). This resource has contributed substantially to the economic growth of the country over the last 60 years, and is likely to play an even more important role in the future based on projected afforestation rates of over 50,000 ha per year. In addition, the introduction of plantation forests on land previously in pasture has served to protect many unstable areas from further erosion. However, the large-scale conversion of one vegetation type to another has the potential to alter streamflow characteristics, which in turn may have implications for downstream users of the water resource. The hydrological consequences of plantation forestry is a topic that has received considerable attention from foresters, hydrologists, and water resource managers in New Zealand, especially in recent years. This paper discusses the water use by forests from a theoretical and practical standpoint. In particular, it identifies the impact that plantation forests are likely to have on annual water yield, storm flows and low flows. It also examines a number of related issues including the potential effects of forests on groundwater recharge, and whether forest management techniques can assist in reducing forest demands on water.

BACKGROUND INFORMATION

The changes likely to accompany the management of a vegetation cover can best be explained within the context of the water balance, which in its simplest form can be written as:

$$P = R + E + G \pm \Delta S$$

where P = precipitation, R = runoff, streamflow, or water yield, E = evaporation, including transpiration, G = groundwater loss or gain, and ΔS = the change in soil water storage.

Since changes in soil moisture storage and groundwater are likely to be small over the period of a year, changes in runoff after the conversion of one vegetation type to another are normally controlled by changes in evaporation. Thus we can rewrite the water balance equation to highlight the impact of the evaporation component on runoff:

$$R = P - (E_t + E_i + E_u)$$

where the evaporation loss from a forest is derived from transpiration (water removed from the soil by roots, transpired via stems and branches to leaves, and evaporated from the dry canopy, E_t), interception loss (evaporation of intercepted water from wet canopies during and immediately after rainfall, E_i), and evaporation loss from the understorey vegetation and soil, (E_u).

In areas where the canopy is wetted frequently, or remains wet for long periods, E_i may exceed E_t. Indeed, field studies here and overseas (e.g. Calder, 1976; 1977; Pearce and Rowe, 1979) show that E_i can be 70% of total evaporation for forest. In addition, while E_t rates for different tree species may be quite different, total E_t rates for plantations of different conifer species in Britain did not differ substantially with location or climate, suggesting that the range of E_t losses among forest types is narrow (Pearce and Rowe, 1979). Thus water yield changes in areas with medium-to-high annual rainfalls are likely to be dominated by changes in interception loss. Because E_i varies little from species to species differences in water use between forest types should be small.

Understorey transpiration rates can contribute substantially to total water loss from a forest (Kelliher *et al.* 1989). Roberts *et al.* (1982) found that understorey removal can increase transpiration rates of individual trees leading to increased photosynthesis and basal area increment.

ASSESSING THE IMPACTS OF LAND-USE CHANGE

Much of our knowledge of the impact of changes in forest cover on water resources has been derived from experimental catchment studies in which the results of a controlled change or modification in vegetation cover in one or more catchments are compared with an adjacent control catchment, or by direct comparison of nearby catchments with different vegetation covers. An analysis of time trends in a single large catchment can also provide useful insights into land-use effects on streamflow.

IMPACTS OF AFFORESTATION ON WATER YIELD

Pasture Conversion to Pines: The conversion of land pre-

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viously in pasture to *Pinus radiata* should lead to a marked decline in water yield because of the higher wet and dry canopy evaporation rates for forest. At Berwick Forest in east Otago (mean annual rainfall 1000 mm), runoff from four catchments, two in *P. radiata* forest and two in pasture, was compared (Smith, 1987). Catchment areas ranged from 100 to 300 ha. Average runoff from the forested catchments was 172 mm (45%) less than that from the pasture catchments. In wet years runoff from a small *P. radiata* catchment in Ashley Forest, north Canterbury was about 100 mm less than that from an adjacent catchment in pasture (Jackson, pers. comm.). Duncan (1980) observed a substantial reduction in annual runoff after five years of *P. radiata* growth in three small (2.7-7.6 ha) catchments near Moutere in the Nelson area (mean annual rainfall 1050 mm) that were previously in either gorse (*Ulex europaeus*) or pasture. In wet years runoff from pasture was 250 mm compared with 120 mm for pines, a 130 mm or 50% reduction. The greatest absolute reduction occurred in winter which led Pearce (1980) to conclude that increased E_i rather than E_t was responsible for the reduction in yield despite the dry climate. At Purukohukohu near Rotorua (mean annual rainfall 1400 mm), average annual runoff from a small catchment was 543 mm. Runoff from an adjacent catchment planted in *P. radiata* 10 years previously was 254 mm, representing a decrease in annual water yield of 289 mm or 53% (Dons, 1987). Pearce *et al.* (1987) found that reforestation of pastoral land at Mangatu Forest near Gisborne reduced annual runoff by about 30%, or by between 200 mm and 450 mm depending on elevation. The decreases in runoff quoted above could be even larger if the soil infiltration characteristics of pasture land had been lowered by compaction from stock before conversion.

Tussock Grassland Conversion to Pines: The hydrological consequences of *P. radiata* establishment on tall tussock grassland has been studied at Glendhu Forest (mean annual rainfall 1300 mm) in the uplands of east Otago since 1982 (Fig. 1). Because of the similarity in wet canopy evaporation rates between tussock and pines, the replacement of one by the other in theory should not have a marked effect on water yield. However, since the tussock cover is normally left intact, the growth of pines adds another tier to the canopy that will also intercept and transpire water. The tussock understorey will continue to intercept some rainfall even after individual tussocks have died. Thus runoff from planted areas should decline as trees grow. The Glendhu data support this conclusion (Fahey and Watson, 1991). After a three-year calibration period one catchment was planted over 67% of its area. Little difference in runoff between the two catchments was observed for six years (Fig. 2). However, in the eighth year (1989) annual runoff from the planted catchment had fallen by 130 mm, representing a decline of 19%. This trend has continued through to 1993 when the difference between the planted and tussock catchment was 228 mm (25%). If all the catchment had been planted the reduction would have averaged 35%. Once the remaining three-quarters of the planted catchment is thinned and pruned, the pattern of a progressive reduction in runoff may be reversed temporarily. However, it is expected that runoff will be 25-30% less than the control catchment when the forest reaches maturity.

Figure 1: View of the planted catchment, Glendhu Forest, east Otago, summer 1993.

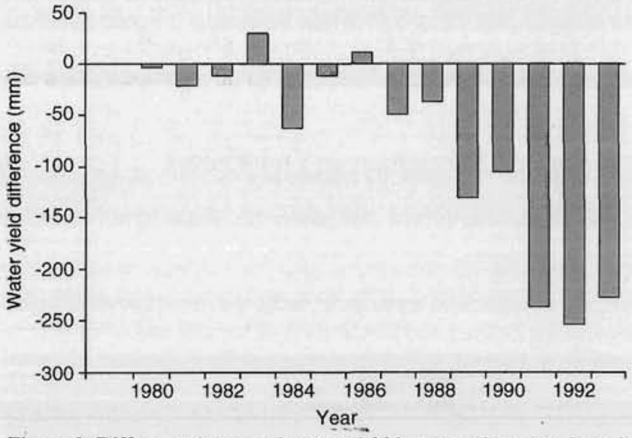

Figure 2: Difference in annual water yield between the control catchment in tussock, and the catchment planted in *Pinus radiata* in 1982, Glendhu Forest, east Otago.

Native Forest Conversion to Pines: Because there is little difference in the interception storage capacity of a mature pine stand compared with a native beech or podocarp stand, the replacement of one with the other should, in the long term, not alter the catchment water yield. At the Maimai experimental catchments near Reefton (mean annual rainfall 2500 mm), water yields returned to pre-treatment levels three-six years after planting in *P. radiata*. Re-growth of bracken and Himalayan honeysuckle was believed to have been important in contributing to water loss in the early years. After year six, annual water yields fell below pre-treatment levels by an average of about 200 mm (Fahey and Rowe, 1992). A similar trend has been observed at the experimental catchments in Big Bush Forest, southwest Nelson, but yields have not fallen as far below pre-treatment levels. Figure 3 shows one of the treated catchments at Big Bush three years after planting.

Scrub Conversion to Pines: Water storage capacities for tall scrub and forest are similar. Thus apart from an increase for the

Figure 3: View looking across catchment DC4, Big Bush Forest, south-west Nelson. The stream outlet is to the right. This catchment was hauler-logged in 1980, and planted in 1981.

first few years after conversion, water yields should not be that much different once the tree crop matures. The final outcome will, however, depend on the scrub species and the thinning and pruning regime adopted for the crop. At Moutere an eight-year-old stand of pine yielded 62% less water than it would have had it been left in gorse (Duncan, 1980). This figure is probably at the upper end of the scale for water yield differences between scrub and pines, given the small size of the Moutere catchments.

Impacts of Afforestation on Low Flows

Low flows are likely to be affected by forest growth because water will be intercepted that otherwise would have infiltrated into the soil under pasture and recharged the groundwater. However, predicting the effects of land use on low flow is much more difficult than for total water yield, since the former is very dependent on the amount and distribution of rainfall and other hydrogeological variables. In many areas of New Zealand, delayed flow from soil and groundwater between storms represents a high proportion of total flow. This is particularly so in the pumice country of the central North Island, and the schist terrain of the South Island, where the impacts of afforestation on low flows will be much the same as those on total flow.

There is some evidence from Glendhu to suggest that summer low flows were reduced by about 30% after eight years of tree growth (Fahey and Watson, 1991). More recent data from the study support this contention. In 1980 (two years before planting) the lowest recorded flow was 21.8 l/s and 31.0 l/s for the tussock and the planted catchment respectively. In 1992 the lowest recorded flows were 21.8 l/s and 21.7 l/s, respectively. These figures suggest that there has been a 30% reduction in instantaneous low flow in the planted catchment after 10 years of tree growth.

At Berwick the reduction in low flows due to the presence of a forest was thought to be about 20% (Smith, 1987). Limited low flow data from the Moutere area (Duncan, 1980) suggest that seven years after planting the duration of zero flow was longer from pines than from pasture.

Impacts of Afforestation on Floods

The effect of afforestation on storm peak flows and associated quickflows (flow during storm events) has been examined for Glendhu (Fahey and Watson, 1991) and is updated here. Changes in peak specific discharge and quickflow were calculated for three size classes of storm based on flow from the tussock or control catchment. Mean peak flows in each size class were similar for the two catchments before planting. After 10-12 years of tree growth mean peak flows had fallen to between 32 and 43% of their initial level (Fig. 4). Quickflows had declined to between 43 and 52% of their original levels. At Berwick, Smith (1987) also found that even during storms with a return period of almost 100 years, the presence of a forest cover prevented much more rainfall being converted to runoff than was the case with catchments in improved pasture. At Moutere, the forested catchments produced lower peak flows than their counterparts in pasture (Duncan, 1980). Eight years after planting for example, the average reduction in peak flows was 73%, with the greatest reduction occurring during smaller storms. Forests can therefore be very effective in reducing both flood peaks and volumes.

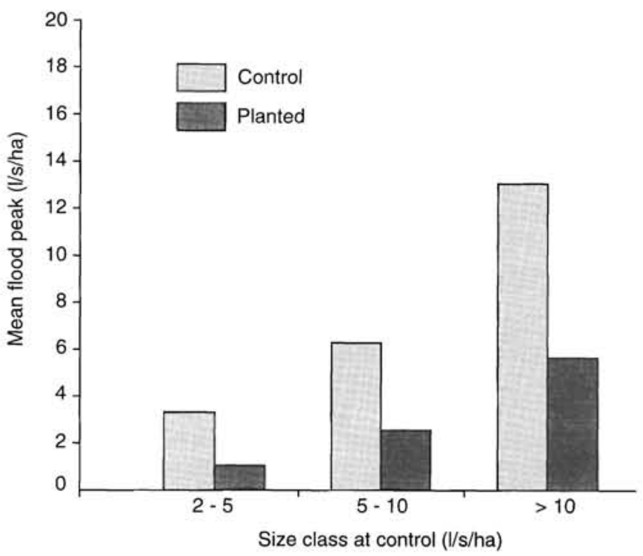

Figure 4: Comparison of mean flood peaks for three size-classes of storms over the post-planting period, 1991-93 for the tussock and planted catchment at Glendhu.

Impacts of Afforestation on Groundwater Recharge

We would expect the results of afforestation studies discussed above to also be applicable to situations where water drains to a groundwater reserve rather than to a stream. Of particular interest here is the Moutere valley south of Motueka where horticulturists are heavily dependent on groundwater for their irrigation requirements. About 14% of the recharge area of the Moutere aquifer is currently planted in pines with the bulk of the remainder in grassland. Fears have been expressed that further afforestation of the recharge zone will lead to a reduction in water supply. From data collected in the Moutere area Duncan (1993) showed that the presence of a full pine canopy in an area already experiencing soil moisture deficits could reduce soil moisture by 30% compared with adjacent pasture sites. Assuming that trees intercept 20% of the annual rainfall (about 1100 mm), this converts to a 220 mm reduction. Duncan concluded that groundwater recharge under pines could be reduced by as much as 70%. We do not know whether this figure is applicable to all areas in the recharge zone. In addition, we know little about the relationship between storms and recharge. However, since annual runoff from small catchments can be lowered by as much as 50% after afforestation there could be a significant effect on the ability of an area under a growing forest to continue to replenish the groundwater resource. Silvicultural practices may lessen the effects of afforestation on groundwater recharge. A reduction in recharge may also result from the expansion of scrub into the pastoral land currently occupying the recharge zone. However, while it may be unwise to promote forestry as a viable land use in areas where existing water allocations are known to approximate the annual recharge, land uses other than forestry are also having an adverse effect on a groundwater store already under stress.

Impacts of Stand Management on Water Yield

Although there is plenty of evidence to show that converting pasture or tussock to plantation forests normally reduces water yield and that clearfelling increases water yield at least temporarily, there is much less certainty about the effects of management such as thinning or understorey suppression on water availability from forests.

Effects of Understorey Manipulation: Conventional management practices in New Zealand call for thinning and pruning at age seven-eight years, leaving a final stocking density of 300 stems per ha. Widely-spaced pruned trees can lead to the development of a thick understorey which may account for up to 50% of the forest evaporation during the summer (Roberts *et al.* 1980; Kelliher *et al.* 1986). Kelliher *et al.* (1989) examined evaporation from two stands of *P. radiata* in Kaingaroa Forest. One stand comprised four-year-old trees in their original stocking density of 2900 stems per ha with an understorey covering 70% of the ground. The other stand was made up of seven-year-old trees thinned at age five to 450 stems per ha with a herbaceous understorey covering only 16%. Slash covered 60% of the ground. In both stands the understorey made a major contribution to total forest evaporation, and occasionally understorey evaporation exceeded tree transpiration. However, the slash cover left over from the thinning and pruning of the seven-year-old stand kept understorey evaporation rates comparatively low at this site. Understorey removal is probably too costly, but selective thinning could increase the total water yield.

Effects of Thinning and Pruning: Whitehead and Kelliher (1991) investigated the water balance of a *P. radiata* stand before and after thinning at Longmile, Rotorua with the aid of a water balance model. The stand was thinned from 754 to 334 stems per hectare at age 11. The results suggested that an extra 200 mm of water, representing an increase of 13%, would be available in the soil after thinning. They concluded that careful timing of the thinning operation could be used as a management tool to increase the water supply at critical times.

In a similar study at Haupapa south of Rotorua, Kelliher *et al.* (1992) examined rainfall interception both above and below the slash layer in a seven-year-old *P. radiata* stand thinned to 450 stems per ha. The tree canopy intercepted 19% and the slash layer 11% of gross rainfall. Thus, although an increase in water yield can be expected after thinning and pruning, the retention of a slash layer can reduce the magnitude of the increase.

Impacts of Forest Harvesting on Water Yield

There is little information in the New Zealand literature on the increases in water yield likely to accompany the harvesting of pines. Interception and transpiration data from a variety of forested areas in New Zealand suggest that differences in water use between indigenous and exotic forests should be small. Therefore the results from the Maimai and Big Bush experimental catchments, although derived from harvesting native forest, should be broadly applicable to plantation forests.

Increases in water yield after harvesting beech-podocarp forest at Maimai (Pearce *et al.* 1980; Rowe and Fahey, 1991), and south west Nelson (Pearce *et al.* 1982; Fahey, Jackson, and Rowe, 1993) are large (350-650 mm) compared with those quoted for similar studies overseas (Bosch and Hewlett, 1982). They are, however, consistent with the high rainfall (1800-2500 mm) and interception losses of 750 mm in wet years (Rowe, 1979). At Big Bush catchment DC1 (8.6 ha) was harvested in 1980 over 83% of its area and the logs removed with skidders. At the same time, catchment DC4 (20.2 ha) was 94% clearfelled and hauler logged. Both were planted in *P. radiata* in 1981.

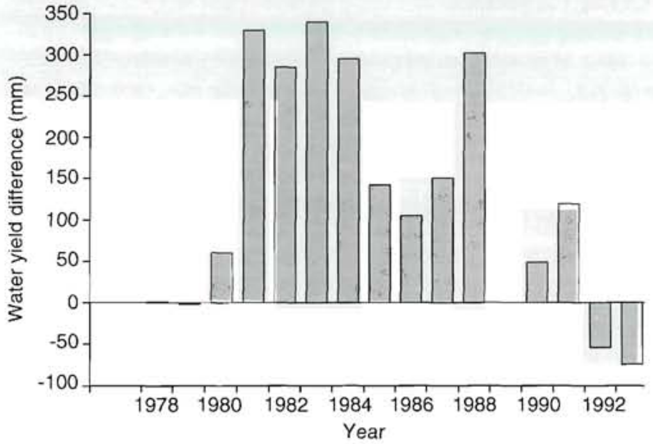

Figure 5: Difference in annual water yield between the control catchment in beech forest (DC2) and the catchment harvested and planted in 1980 and 1981 respectively (DC1), Big Bush, south-west Nelson.

Stream gauging weir in a young radiata pine catchment at Maimai, north Westland.

Catchment DC2 (4.7 ha) was left as a control. At DC1 there was a marked and sustained increase in annual runoff for the next four years (average 313 mm or 66% of the annual yield over the same period for the control catchment), followed by a gradual but intermittent decline to near pre-treatment levels by 1989 (Fig. 5). By 1992, the annual yield had fallen below that of the control, and this was repeated in 1993. However, it is too early to say whether this trend will persist. The pattern of change in water yields after planting at DC4 was much the same as that for DC1, but the average annual increase over the first four years was higher (364 mm). The maximum increase was 488 mm. Annual yields approached pre-treatment levels by 1989, but they have not yet fallen below those of the control. The higher yield for DC4 is believed to be a function of the larger area of the catchment harvested compared with DC1.

Thus, clearfelling of mature pine plantations in moderate-to-high rainfall climates in New Zealand is likely to result in a 300-500 mm increase in runoff for the first three-four years, after which there will be a gradual return to pre-treatment levels as the new crop becomes established.

Impacts of Forest Harvesting on Floods

Once again we must rely on information collected from studies comparing the hydrological response of treated and untreated catchments in native forests to assess the impact of harvesting on floods. At Big Bush, for example, we can use data from the control catchment DC2 in undisturbed beech forest to provide information on natural variations of flood magnitudes, and data from DC1 and DC4 as indicative of logged catchments. The two most useful measures for comparison are peak flows (in l/s/ha) and quickflows (in mm depths per event). Matched data sets from runoff events with flood peaks in selected size classes were used to compare the flood responses of the harvested catchments with that of the control. The mean flood peaks in each size class for the same storms during the pre-treatment period (1977-1980) were similar. However, for the post-treatment period (1981-1986), while the storms at DC2 (the control) have similar means to the pre-treatment storms, those for DC1 and DC4 show a substantial increase. At DC1 for example, the peak flow for the biggest storm in the pre-treatment period was about 15 l/s/ha. In the post-treatment period there were two storms with a mean over twice this amount (38 l/s/ha). When the post-treatment data for DC1 and DC2 are compared, the most pronounced increase is observed for the largest-size class of storm (Fig. 6).

A knowledge of likely increases in flood volumes accompanying a harvesting operation rather than flood peaks is also important to the forest manager. At Big Bush size classes for quickflow events were selected (20-40 mm, 40-60 mm, and > 60 mm) and the data sets matched among the three catchments using the control catchment (DC2) as the base. The mean quickflow amounts and the number of events in each size class were closely similar. For the post-harvesting period average quickflow size and number of events increased. In percentage terms the increase was greatest for the 20-40 mm size class (26% for DC1 and 36% for DC4). For events between 40 and 60 mm, and greater than 60 mm there was less of an increase; in fact at DC4 the mean was slightly below that for DC2, but there were twice as many in that size class at DC4. Thus, relative increases in stormflow after logging are large for small events and small for large events. Most of the increase in storm flow is believed to come from extra rainfall reaching the soil once the canopy is removed, but soil disturbance and compaction may also play a role by increasing surface runoff during storms. The results from Big Bush suggest canopy removal, which is unavoidable, is more important than soil disturbance, which is controllable.

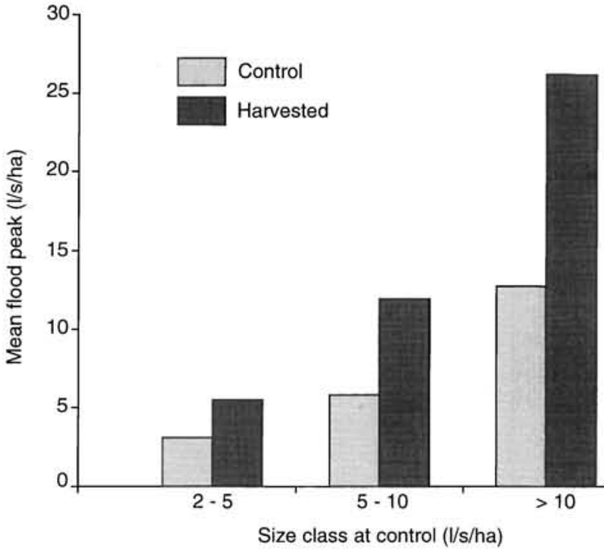

Figure 6: Comparison of mean flood peaks for three size-classes of storms in the post-harvesting period, 1981-86, for catchment DC1 at Big Bush.

Scaling up Results to Larger Catchments

Although the data derived from catchment studies in New Zealand and elsewhere clearly show that afforestation and harvesting can reduce and increase water yields respectively, there is some uncertainty as to whether the resultant changes can be proportionally scaled up to larger catchments. One reason why changes in water yields may be substantially less than those quoted for small-scale experiments is related to forest management. We have seen that the gains in water yield after harvesting quickly diminish after replanting. In large forests only a small proportion (e.g. 100 ha) will be harvested at any one time, and the total increase in water yield may be quite small. If we assume sustainable yield forest management for example, an increase in runoff of 30% from a small-scale experimental catchment may be reduced to a much smaller fraction over an entire forest (Harr, 1983). The nett effect will be dependent on the percentage area harvested; for example, the clearfelling of 100 ha in a 1000 ha forest may only lead to a 2-3% increase in annual runoff. Indeed, an increase of this magnitude may be the same as the error in measuring streamflow in the parent stream (Harr, *et al.* 1982). We do not know to what extent the increase in flood peaks and quickflows accompanying a logging operation will be filtered through a larger forest. However,it is reasonable to assume that the attenuation effect will be in proportion to the increase in water yield.

The only published results covering the impact of large-scale afforestation in New Zealand are those of Dons (1986) for the Tarawera catchment in the central North Island. Between 1964 and 1981 over 250 km^2 or 28% of the 906 km^2 catchment previously in light scrub and native forest was planted in pines. The reduction in flow during this period was 10.9m^3/s (379 mm). Approximately 60% of this total (225 mm) was attributed to a decrease in rainfall, and the remainder (4.5 m^3/s, or 154 mm) to afforestation. Compared with the mean flow of the Tarawera over the calibration or pre-planted period (1949 to 1963), this represents a 13% reduction in water yield. Potentially the mean annual flow could fall by 45% if all the catchment was planted. A reduction of this size is consistent with that observed at Glendhu (25% reduction from a 67% forest cover), suggesting that the results of small-scale afforestation studies are applicable at least in the long term to larger areas.

The lack of information on the hydrological effects of afforestation and harvesting over areas measured in hundreds of square kilometres is disconcerting. While it is not practical to operate experimental catchments at these scales, studies of soil-water-plant relationships in New Zealand and overseas have led to the development of hydrological and biophysical models that could be useful in predicting the consequences of a land-use change or a management option at the regional level (e.g. Whitehead and Kelliher, 1991).

CONCLUSIONS

In moderately wet to wet climates, changes in water yield following vegetation changes are dominated by changes in interception, more so than by differences in transpiration. Experimental evidence and an improved understanding of the biophysical processes of evaporation show that an increase in forest cover will increase interception loss through evaporation from the wet canopy leading to a reduction in flow of water to streams and groundwater storage. The difference in water use between types and species of mature forest is likely to be small, but rainfall climate and stand management may be just as important as species in determining how water yield will change in response to forest establishment. There is a need, however, for more information on water use by plantation species other than *P. radiata*, especially those singled out for planting in water-short areas such as inland Canterbury.

Afforestation will reduce water yields, and the reduction is likely to be greatest in areas of higher rainfall. Tussock grassland conversion to pine plantation is likely to cause a 25-30% reduction, and pasture conversion a 30-50% reduction. Impacts may not be seen in the flow records until 5-10 years after planting, and are likely to be greatest in areas of high rainfall. Other forms of tall vegetation such as gorse, manuka, or bracken will also reduce water yields but not to the same extent as forest establishment. The impact of vegetation change on low flows is much more difficult to quantify, but is becoming an issue of growing importance, especially in water-short areas. The limited information available suggests that a reduction of up to 30% is possible after afforestation. There is a need for more research into the impacts of afforestation on low flows.

Since interception is a physical process, the smaller the canopy coverage the smaller the interception loss, resulting in less water available for runoff and for percolation to groundwater. Thus there is the opportunity to augment water yield by careful stand management, such as increasing tree spacing, understorey control, and spreading the time of planting. A substantial increase in water yield can be expected after thinning and pruning, depending on the proportion of forest thinned in a given year. The timing of these types of silvicultural and harvesting operations in general may be a useful tool in water yield management.

A reduction in forest cover causes annual water yields to increase. The magnitude of the initial increase is dependent on the proportion of the forest cover affected, and will be higher in areas of high rainfall. High annual runoff totals will persist for three-four years after harvesting, after which natural regeneration and growth of new plantings will begin to bring yields back to pre-treatment levels. This should be accomplished within six-eight years, but the temporal pattern of reduced runoff and the final level achieved will reflect stand management practices.

While we are now in a position to predict with some certainty the changes in annual runoff associated with forest harvesting, the response of streamflow to flood events is less well understood. Stormflow volumes and peak flows increase after harvesting, with the magnitude of the increase dependent again on the extent of vegetation removed. A topic requiring further investigation is whether post-harvesting increases in peak flow and quickflow during storms are mostly in response to the loss of canopy protection, or to increased surface runoff from soil compaction and disturbance.

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