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RESEARCH ARTICLE

The Glendhu experimental catchment study, upland east Otago, New Zealand: 34 years of hydrological observations on the afforestation of tussock grasslands

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Abstract

This paper presents results from 34 years of the Glendhu Experimental Catchment Study, established in 1979 by the former New Zealand Forest Service in upland east Otago in New Zealand's South Island to determine the hydrological consequences of converting indigenous tussock grassland to plantation forestry. A traditional paired catchment approach was adopted; after a 2.5-year pretreatment period, one catchment (GH2, 310 ha) was planted over two thirds of its area in *Pinus radiata*, and an adjacent catchment (GH1, 216 ha) was left in tussock as a control. The average annual reduction in water yield from the planted catchment between canopy closure in 1991 and 2013, compared with that in tussock, was 273 mm (33%). Annual water yields from the planted catchment continued to decline relative to the tussock catchment until 2010. Since then, the difference in annual water yields between the two catchments has narrowed. Ripping before planting caused some redistribution of the total streamflow from stormflow to baseflow. Following canopy closure, afforestation has reduced the low flow (Q_{95}) by an average of 26% compared with the tussock catchment. Average peak flows for small events (2–5 L/s/ha) were reduced by 78%, but only by 37% for larger, less frequent storms (>15 L/s/ha), suggesting that peak flows during high magnitude storms are less dependent on the prevailing land cover.

KEYWORDS

afforestation, catchment hydrology, tussock grasslands, water yield

1 | INTRODUCTION

The hydrological effects associated with a change in vegetation cover have traditionally been assessed through the application of paired catchment studies. In North America, for example, experimental catchments were established to investigate the hydrological impacts of forest management at Coweeta in North Carolina (Swank & Crossley, 1988), Hubbard Brook in New Hampshire (Bormann & Likens, 1979), HJ Andrews Forest in Oregon (Harr, 1983), and Casper Creek in north-western California (Ziemer, 1998). In the United Kingdom, the paired catchment approach has been used to investigate the effects of harvesting and afforestation on water yield at Plynlimon in mid-Wales (Kirkby, Newson, & Gilman, 1991), Balquhidder in central Scotland (Calder, 1993), and Llanbrynmair in central Wales (Hudson, Crane, & Robinson, 1997). Elsewhere, Buytaert, Iniguez, and De Bierve (2007) have evaluated the effects of afforestation on water yield in the Andean highlands of Ecuador, and Scott, Le Maitre, and Fairbanks (1998) and Bren and McGuire (2012) present the results of catchment studies in South Africa and Australia, respectively. Reviews of the findings from catchment studies have been conducted by Adams and Fowler (2006), Bosch and Hewlett (1982), Brown, Zhang, McMahon, Western, and Vertessy (2005), Farley, Jobbagy, and Jackson (2005), Hornbeck, Adams, Corbett, Verry, and Lynch (1993), Sahin and Hall (1996), and Stednick (1996).

In New Zealand, the paired catchment approach has been used to assess the hydrological effects of converting pasture to plantation forest at Purukohukohu in the central North Island (Dons, 1987), at Moutere in the Nelson area (Duncan, 1995), and indigenous forest to plantation forest at Maimai near Reefton (Rowe & Pearce, 1994), and at Donald Creek in northwest Nelson (Fahey & Jackson, 1997). The initial effects of converting indigenous tussock grasslands to plantation forest at Glendhu in southern New Zealand have been investigated by Fahey and Watson (1991) and Fahey and Jackson (1997).

The Glendhu study is located in the former Glendhu State Forest in the upper Waipori basin in the southern Lammerlaw Range. Established in 1979, it was designed to determine what effect the afforestation of tussock grassland might have on water yield and assumed special significance because of the presence downstream of hydro-electric-generating plants. It is the longest ongoing catchment study in New Zealand and is recognised nationally for increasing our understanding of the effects of afforestation on the hydrology of the unique tussock grassland environment of the southern South Island (Rowe, Jackson, & Fahey, 2002). Glendhu has also served as a venue for the investigation of evaporation processes and runoff-generating mechanisms in tussock grasslands (Bonell, Pearce, & Stewart, 1990; Bowden, Fahey, Ekanayake, & Murray, 2001; Campbell, 1989; Campbell & Murray, 1990; Fahey, Bowden, Smith, & Murray, 1998, Stewart, 2015; Stewart & Fahey, 2010). In addition, the catchments have been an important source of rainfall and runoff data for the calibration and validation of the WATYIELD water-balance-based hydrological model (Fahey, Ekanayake, Jackson, Fenemor, Davie, & Rowe, 2010), which has been used to assist in the resolution of regional water resource issues (Fahey, Davie, & Stewart, 2011).

Apart from the early results presented by Fahey and Watson (1991), Fahey and Jackson (1997), and some that have appeared more recently in summary form (e.g., Adams & Fowler, 2006; Brown et al., 2005; Farley et al., 2005; Zhao, Xu, & Zhang, 2012), no detailed analysis of the long-term results has been published internationally. This paper seeks to address this gap by presenting the results of over 30 years of observations at Glendhu, a period that covers a complete forest rotation from planting to just prior to harvesting. It begins by describing and comparing the water balance of the two catchments situated in a cool temperate climate that is characterised by a uniformly distributed, moderately high rainfall regime. It then assesses the long-term effects of converting tussock grassland to pine plantation on annual water yield, annual stormflows and baseflows, low flows, flood peaks, flow duration, and baseflow recession characteristics.

2 | STUDY AREA

The Glendhu catchments lie 60 km due west of the city of Dunedin in the headwaters of the Waipori River at the eastern edge of a schist plateau that extends inland from the coast (Figure 1). The tussock catchment (GH1) covers 216 ha and the planted catchment (GH2) 310 ha. They are north-facing and range in elevation from 460 to 680 m a.s.l., with easy rolling interfluves dissected by moderately steep to very steep valley sides, especially in the upper reaches. Wetlands, ranging in area from 0.1 to 3 ha, occupy the headwaters of many of the larger subcatchments.

The climate at Glendhu is dominated by cold fronts moving across the area in the prevailing south-westerly air stream, with intervening anticyclones that are more common in the warmer months. Occasionally, these fronts are preceded by strong, dry north-westerly winds. The nearest climatological station is at Lake Mahinerangi (400 m a.s.l.), 20 km to the east (Figure 1). The mean annual temperature here is 8.6 °C, and the January and July means are 12.7 and 3.6 °C, respectively (New Zealand Meteorological Service, 1983). The mean annual rainfall is 980 mm, and the monthly means range from 62 mm in September to 98 mm in May. Potential evaporation is calculated at 658 mm (112 mm in January and 10 mm in July; unpublished data). Climatic data were also collected between 1991 and 1996 at a site (G4) located between the two catchments at an elevation of 625 m a.s.l. (Figure 2). The mean annual temperature for the period was 7.6 °C, and values ranged from −10 to +30 °C.

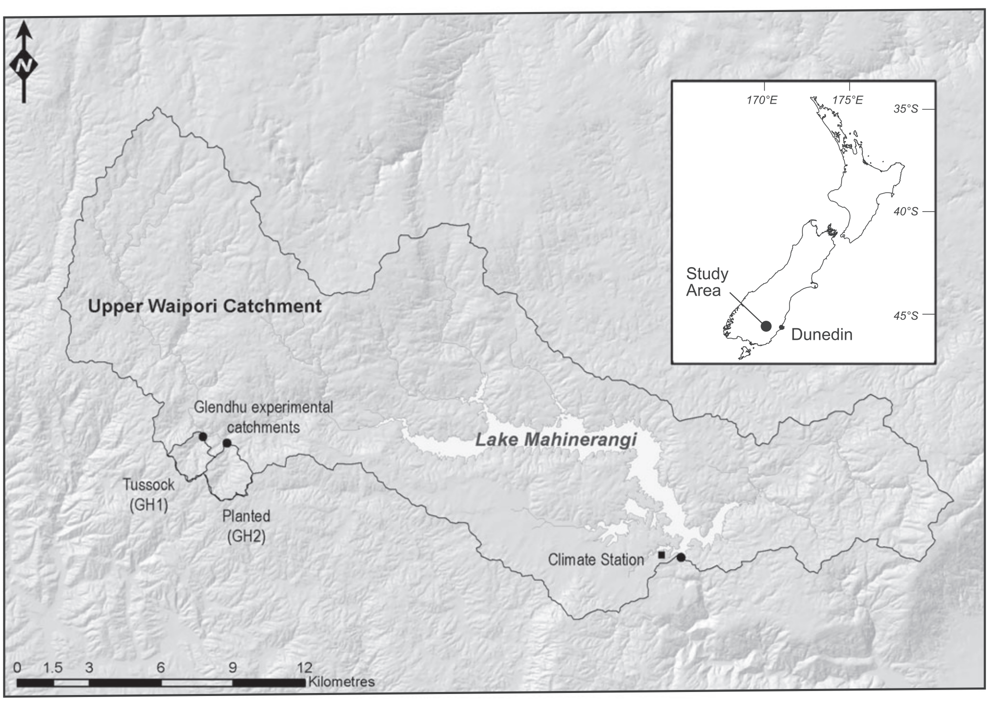

FIGURE 1 Locations of the tussock (GH1) and planted (GH2) catchments in the upper Waipori river basin, Glendhu, South Island, New Zealand

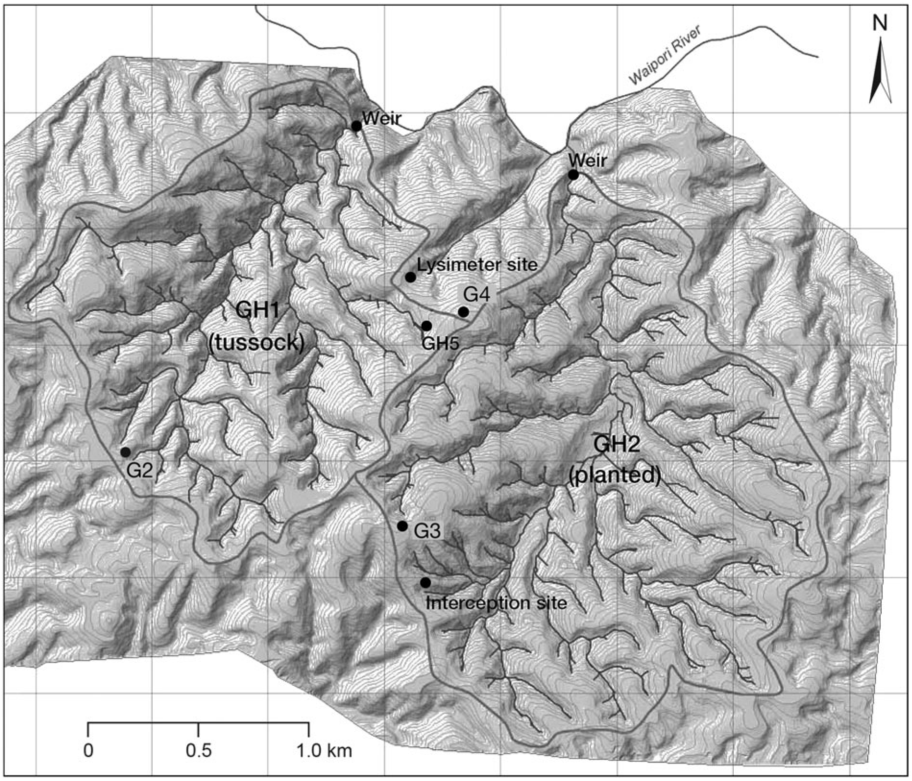

FIGURE 2 The tussock and planted catchments at Glendhu, with instrument sites and other locations referenced in the text

Rainfall at Glendhu is characterised by numerous small events of long duration and low intensity. Snow falls on 10–20 days a year but seldom remains on the ground for more than a week. Low cloud and fog associated with the prevailing south-westerly and southerly winds are common above 600-m elevation. Fog can occur at any time of the year. Its potential for augmenting water yield from midaltitude snow tussock is the subject of an ongoing debate (e.g., Davie, Fahey, & Stewart, 2006; Fahey et al., 2011; Ingraham, Mark, & Frew, 2008) but is believed to contribute no more than 1% to precipitation at Glendhu (Campbell & Murray, 1990).

McGlone and Wilmhurst (1999) described the postglacial vegetation history of the Glendhu area from the pollen record obtained from a 2.5-m core taken from the peat bog occupying the centre of GH5 (Figure 2). Peat began accumulating in valley heads about 7,000 BP, although most of it is <2,000 years old. A montane–subalpine forest dominated by conifers (*Podocarpus bidwillii* and *Phyllocladus alpinus*) became established in the Glendhu area under a cool, moist climate about 7,000 BP. Between 4,000 and 1,300 BP, cooler winters and disturbance by fire led to an expansion of beech forest (*Nothofagus menziesii*), but Polynesian fires from 700 BP reduced this cover to tussock grassland and bracken. The dominant species is narrow-leaved snow tussock (*Chionochloa rigida*), with some introduced grasses. Red tussock (*Chionochloa rubra*) is found in the more poorly drained valley bottoms. In recent years, there has been an expansion of native scrub, notably mānuka (*Leptospermum scoparium*) and some *Coprosma* spp. in the tussock catchment on sunny north- and east-facing slopes. This is a common occurrence throughout the tussock grasslands of Otago, especially where stock grazing is low (Walker et al., 2009).

The schist bedrock is predominantly moderately weathered but ranges from strongly to lightly weathered. Almost everywhere, it is overlain by loess 1–5 m thick. Four soil series were identified on the basis of soil drainage (Webb et al., 1999) in a soil survey of one of the headwater subcatchments (GH5) of the tussock catchment (GH1; Figure 2). Extrapolating these findings to the full catchment, we can expect well-drained Nardoo soils on steep slopes, imperfectly drained Mahinerangi soils on steep footslopes, poorly drained Pioneer soils on toe slopes around bogs, and Bungtown peats in the valley bottoms. On the gentler slopes and associated interfluves, Glendhu soils (a new soil series) prevail. These are well drained and normally have a significant loess component. Under the New Zealand Soil Classification scheme (Hewett, 1998), Nardoo soils are identified as acidic firm (or ortic) brown soils, Mahinerangi soils as mottled acid brown soils, Pioneer soils as typic (or peaty) acid brown soils, and Glendhu soils as typic acid brown soils. The typical profile in the tussock catchment exhibits a highly permeable moss mat and A-horizon overlying a massive, virtually impermeable B-horizon.

Catchment GH2 was contour ripped by bulldozers to a depth of approximately 0.8 m in December 1981 in preparation for planting. Ripping lines were 3.5 m apart. Although disturbance was not excessive, regolith was exposed in some areas (O'Loughlin, Rowe, & Pearce, 1984). The valley bottoms were not ripped. Planting took place in June 1982 with *Pinus radiata* at 1,280 stems/ha, which gave a total planted area of 207 ha. Approximately 34 ha were thinned and pruned to 270 stems/ha in the lower reaches of the catchment in 1989. Both catchments were subjected to light grazing with sheep until 1982. The tussock catchment continued to be grazed at about one sheep per hectare, but all stock has been excluded since 2002. Harvesting commenced in the planted catchment in 2014.

3 | METHODS

3.1 | Rainfall

From 1980 to 1987, rainfall was measured with a network of nine 127-mm manual gauges that were read at least weekly and three Belfort weighing-bucket gauges with Alter shields, located down the altitudinal transect between the two catchments. Four of the manual gauges and the three Belfort gauges were removed at the end of 1987. Tipping bucket rain gauges linked to data loggers were installed near the two weirs (Figure 2) in 1988. Catchment area rainfall from 1980 to 1988 was estimated by constructing Thiessen polygons based on the nine original manual gauges. Pearce, Rowe, and O'Loughlin (1984) found that rainfall for the calibration period (1980–1982) across the two catchments was virtually identical (±2% per annum). Between 1989 and 2013, a revised weighting procedure was applied to the two manual gauges retained at the head of the two catchments (G2 and G3), the one at the meteorological site (G4), and the two recording gauges at the weir sites (Figure 2) to estimate catchment area rainfall. When the area rainfall was calculated for each catchment, the difference between the annual means was <2% of the total for GH1.

3.2 | Streamflow

Streamflow was measured by large, broad-crested, concrete, 120 ° v-notch weirs based on a design described by Holtan, Minshall, and Harrold (1962). No flow is believed to bypass these structures (Pearce et al., 1984). Following volumetric and dye dilution gaugings, ratings for the two weirs were modified slightly from those referenced by Holtan et al. (1962). From 1980 to 1987, water levels in the weir ponds were recorded on Belfort FW recorders located 3 m upstream of the v-notch, and from 1987 to 2005, with oil-filled multiturn potentiometers linked to Campbell Scientific data loggers. These were replaced in 2006 with Dataflow Systems Odyssey capacitance water-level probes. All water-level records are accurate to ±2 mm. Checks made on the rating curve covering 90% of the flow duration led Pearce et al. (1984) to conclude that annual streamflow totals (annual water yields) are accurate to ±40 mm (±5%). Any gaps in the water-level record were filled using graphical procedures available in the data management programme (Hydstra).

The relative contributions to streamflow from storm events (stormflow or quickflow) and from baseflow or delayed flow were estimated with the separation procedure described by Hewlett and Hibbert (1967). They used a line of constant slope (0.0055 L/s/ha/hr) projected from the point on the hydrograph where streamflow begins to rise due to precipitation to the point where it intersects the falling limb of the hydrograph. The latter is defined as the point at which stormflow ceases and baseflow alone is contributing to streamflow.

3.3 | Evaporation

Evaporation is defined here as the sum of actual evaporation from the soil, from plant surfaces as interception loss, and transpiration from plants. Catchment-scale evaporation was calculated as the residual in the water balance.

3.4 | Catchment calibration

The effects on water yield of establishing a plantation of *P. radiata* in the catchment designated for treatment (GH2) were measured as the departure from that predicted by comparison with the catchment left in tussock as the control (GH1). The short 2.5-year calibration period makes it difficult to establish a statistically robust regression equation to predict annual water yields from the planted catchment, assuming that it had been retained in tussock for the duration of the study. Because planting is unlikely to have had an immediate effect on water yield, we examined whether it was feasible to extend the calibration period for a further 4 years to 1986. This appeared justified on the basis that the difference in the mean annual water yields for the two catchments over this period was only 11 mm, which is well within the ±40 mm margin of error for flow measurement at the respective weirs. As a further check, we applied a statistical procedure described by Wilm (1949), which showed that the extended 7-year calibration period was sufficient to give us confidence that any difference that is larger than the measurement error is real and detectable, and not just the result of random chance.

4 | RESULTS

4.1 | Rainfall

The mean annual catchment area rainfall across both catchments for the 34-year period of record was 1,330 mm, with the highest total occurring in 1987 (1,615 mm) and the lowest in 1985 (958 mm). There were no long-term trends apparent in annual rainfall over the period of record (Figure 3). On average, rainfall is evenly distributed throughout the year. Between 1988 and 2013, the highest monthly average for the tipping bucket gauge near the GH1 weir was 128 mm (in January), and the lowest was 83.5 mm (in July). The maximum 24-hr rainfall total (133.4 mm) was recorded at the GH1 weir on April 25, 2006, and the maximum hourly rainfall (57.8 mm) at the GH2 weir was on January 7, 2005. The longest interval with no rain was a 21-day period in the winter of 1989.

4.2 | Streamflow

Mean annual streamflow for the tussock catchment (GH1) for the 34-year period of record was 824 mm, which equates to a mean annual discharge of 58 L/s or 0.27 L/s/ha. The trend line calculated by linear regression in Figure 4 shows an approximate 1 mm/year decline in streamflow from 1980 to 2013. This is within the measurement error with which flow can be measured at the two weirs. Since 1991 (the year of canopy closure at GH2), mean annual water yield was 832 mm (59 L/s or 0.28 L/s/ha) at GH1 and 559 mm (39 L/s or 0.13 L/s/ha) at GH2. Annual streamflow for the tussock catchment was highest in 1983 (1,122 mm) and lowest in 1985 (494 mm). For the planted catchment, the highest and lowest annual streamflows since canopy closure (1991) were 800 mm in 1992 and 385 mm in 1999. These corresponded to the same years for the highest and lowest totals for streamflow from the tussock catchment since canopy closure.

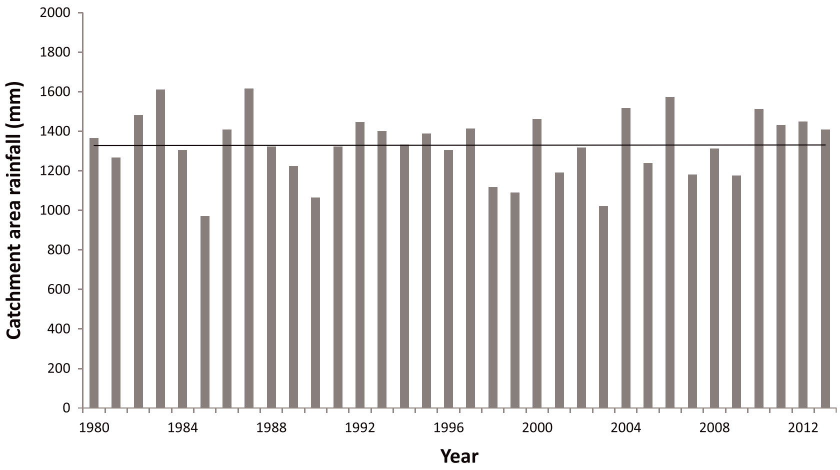

FIGURE 3 Annual catchment area rainfall totals for the period of record (1980–2013). The trend line was fitted using linear regression

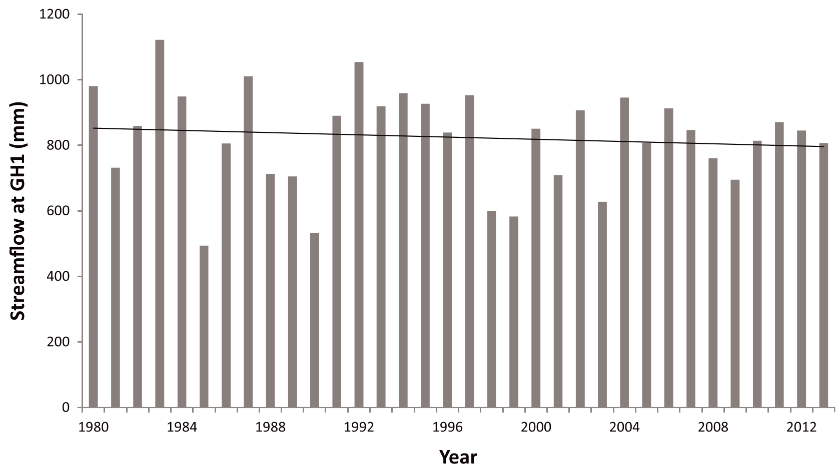

FIGURE 4 Annual streamflow totals for the period of record (1980–2013). The trend line was fitted using linear regression

4.3 | Catchment water balance

The catchment water balance in its simplest form can be calculated from the following:

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

where Q is catchment water yield, P is precipitation, E is evaporation, and ΔS is the change in soil and groundwater storage. For annual periods, the net change in soil and groundwater storage can normally be considered 0. Thus, any change in water yield following a land use change can be assigned to differences in evaporation from the respective vegetation covers.

Water balance calculations are based on average annual catchment area rainfall and water yield for the pretreatment period (1980–1982) and since canopy closure (1991–2013) for both catchments (Table 1). Because the difference in the average annual pretreatment water yields for GH1 and GH2 (17 mm) was well within the measurement of uncertainty of ±40 mm for the weir measurements (Pearce et al., 1984), the average annual water yields are assumed to be the same.

Between canopy closure in 1991 and 2013, the average annual reduction in water yield due to afforestation was 273 mm.

Measurement errors in rainfall and streamflow can be expected at both catchments. It has already been noted that streamflow can only be measured to ±40 mm at both weirs. Errors in precipitation measurements are more difficult to assess. Hudson and Gilman (1993) claim that at Plynlimon in central Wales, the likely random uncertainty in precipitation measurements at the 95% confidence limit can be estimated by doubling the standard error of the mean annual totals caught by the gauges in the network used to calculate catchment area rainfall. Applied to Glendhu, this procedure suggests a small uncertainty of ±56 mm (±4%).

TABLE 1 Average annual water balances (mm) for the tussock (GH1) and planted (GH2) catchments at Glendhu for the pretreatment period (1980–1982) and the period since canopy closure (1991–2013)

Catchment (period)	Cover	Precipitation (*P*)	Total evaporation (*E*)	Water yield (Q)
GH1 (1980–1982)	100% tussock	1,370	513	857
GH2 (1980–1982)	100% tussock	1,370	530	840
GH1 (1991–2013)	100% tussock	1,330	498	832
GH2 (1991–2013)	33% tussock; 67% pines	1,330	771	559

4.4 | Annual water yields

The water balance calculations have shown that the average annual reduction in water yield from GH2 since canopy closure in 1991 was 273 mm. This equates to 33% of the total water yield measured for the tussock catchment for the same period. For a 100% forest cover, the average annual reduction is estimated at approximately 50%. Figure 5 shows the trend in the water yield response to afforestation, derived from the observed minus the predicted values (based on the regression of the 1980–1986 GH1 data against those for GH2). The caption provides details of the regression analysis. By canopy closure in 1991, the annual reduction in water yield had reached 252 mm (28%), with the subsequent trend showing a gradual increase through 2008. Since 2010, there has been a distinct decline in the rate of the reduction.

4.5 | Annual stormflows

The average annual stormflow (that portion of streamflow that is primarily attributed to storm precipitation) during the pretreatment period comprised 32% of the total flow at both catchments. After ripping and planting at GH2 in 1982 and up to canopy closure in 1991, it remained at 32% of the total flow at GH1 but fell to 25% at GH2, indicating that less rainfall was being converted to stormflow. From canopy closure in 1991 until 2013, annual stormflow averaged to 35% and 20% of the total streamflow for GH1 and GH2, respectively, demonstrating that forest management continued to have an impact on the amount of precipitation being converted to stormflow at GH2. The average annual difference in stormflows between the two catchments (GH2 − GH1) from 1983 to canopy closure in 1991 was 75 mm (30%), after which it increased markedly, averaging to 186 mm or 64% annually, compared to GH1 through 2013 (Figure 6).

4.6 | Annual baseflows

Baseflow (water released into the stream from groundwater) contributed on average 68% of the annual streamflow at both catchments over the preplanting period. However, in the year after ripping and planting (1983), annual baseflows increased markedly as a proportion of total streamflow at GH2, averaging to 75% over the 5-year period to 1987. Following canopy closure in 1991, the baseflow component of total flow at GH2 has averaged to 80%, compared with 65% over the same period at GH1.

The average annual difference in baseflow between the two catchments (GH2 − GH1) during the preplanting period was small (<15 mm; Figure 7). Following the increase in the proportion of total streamflow attributed to baseflow at GH2 after ripping and planting in 1982, the difference in baseflow between the two catchments became more pronounced. This situation persisted through to 1987, during which time the difference averaged to 69 mm (12%). Following the overall reduction in streamflow at GH2 in response to the maturing tree crop, the difference in annual baseflows between the two catchments gradually increased through 2004. Since then, however, there has been a distinct but irregular narrowing in the difference (Figure 7).

4.7 | Annual low flows

The daily flow rate exceeded for 95% of the time (Q_{95}) is regarded as a sensitive indicator of low flows (Smakhtin, 2001). In the preplanting period (1980–1982), the Q_{95} flows for the planted catchment were, on average, 0.08 mm/day (9%) lower than those observed for the tussock catchment (Figure 8). Reasons for this are obscure but are probably related to minor differences in the storage characteristics of the respective catchments. In contrast, between 1983 and 1987, the Q_{95} flows for the planted catchment rose above those for the tussock catchment by an average of 0.12 mm/day (14%). By 1988, however, tree growth began to have an effect on low flows, and between canopy closure in 1991 and 2004, there was a gradual but irregular increase in the difference between the two catchments. Following 2004, there has been a marked decline in the difference. Throughout, considerable year-to-year variability was evident. The average difference (reduction) in Q_{95} between the tussock and planted catchment in 23 years since canopy closure was 0.23 mm/day (26%).

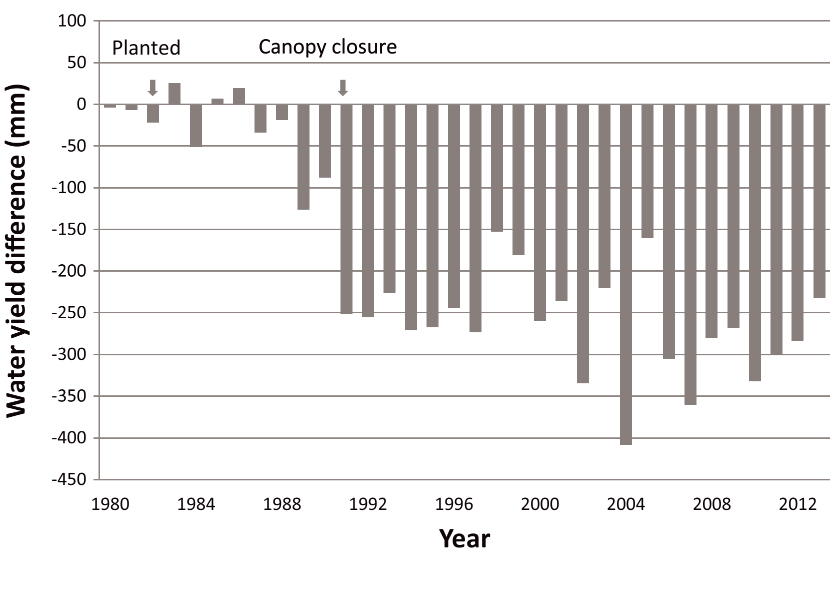

FIGURE 5 Differences between measured annual water yields (1980–2013) from the planted catchment (GH2) and that predicted using the regression equation $y = -40.6 + x1.03$, where y is the predicted water yield and x is the water yield from the tussock catchment (GH1) in millimetre ($r^2 = .985$)

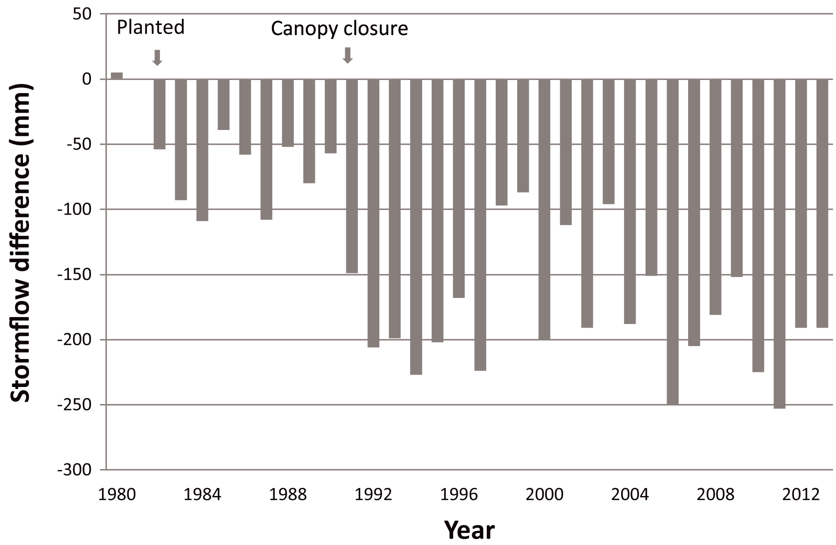

FIGURE 6 Differences in annual stormflows between the tussock catchment and the planted catchment (GH2 − GH1) in millimetre (1980–2013)

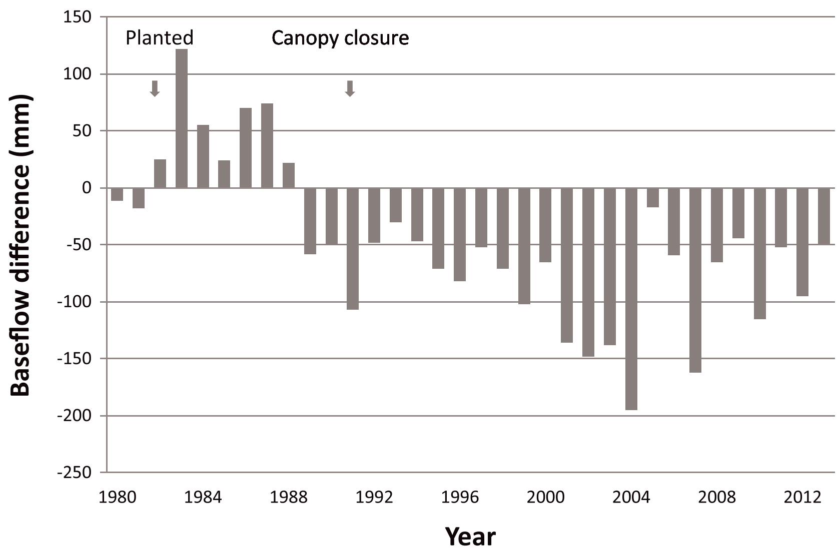

FIGURE 7 Differences in annual baseflows between the tussock catchment and the planted catchment (GH2 − GH1) in millimetre (1980–2013)

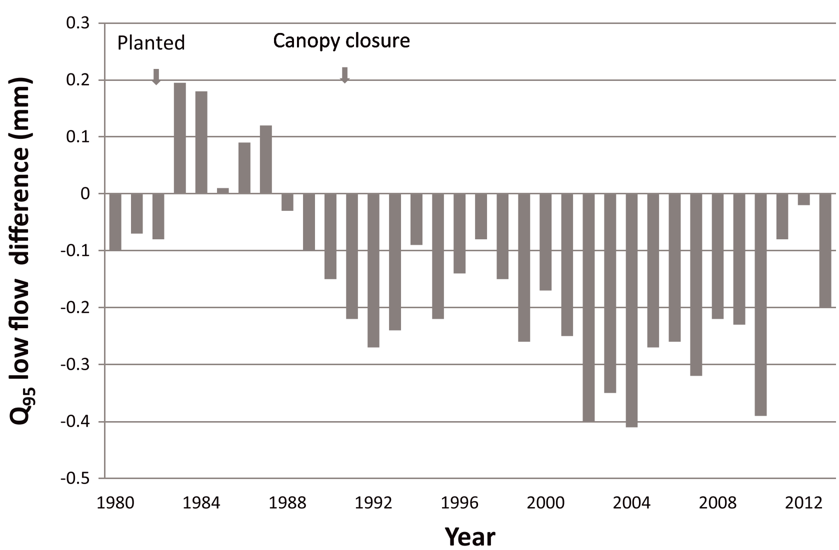

FIGURE 8 Differences in the daily flow rate exceeded 95% of the time (Q_{95}) between the tussock catchment and the planted catchment (GH2 − GH1) in millimetre (1980–2013)

4.8 | Flow duration

Throughout the preplanting period, the flow distributions for the two catchments were virtually identical (Figure 9). The flat slope of the curves towards the high exceedance levels confirms that groundwater is a major contributor to the low flow range of both catchments. For the period 1991–2013, the shape of the flow duration curves was similar, but the planted catchment curve tracked consistently below that

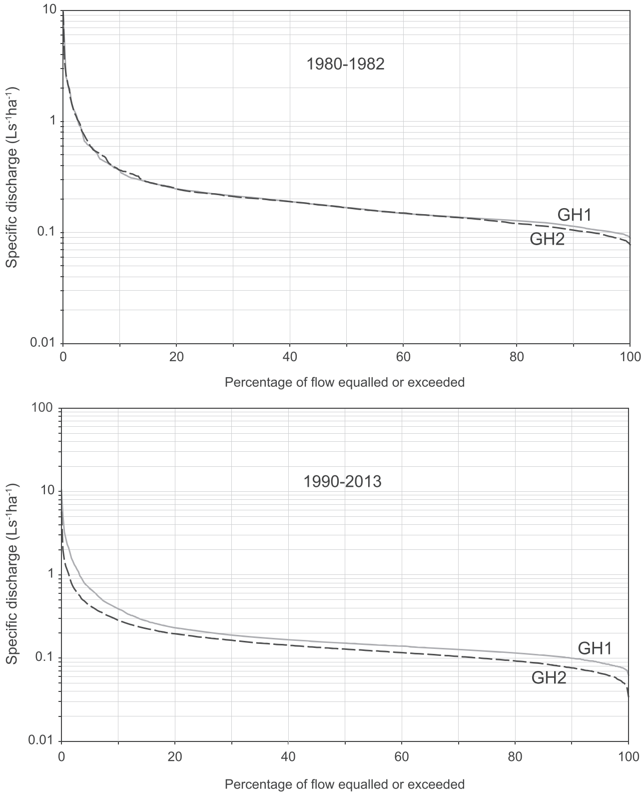

FIGURE 9 Flow duration curves for the tussock catchment (GH1) and the planted catchment (GH2) for the preplanting period (1980–1982), and the postcanopy closure period (1991–2013)

of the tussock catchment. After 23 years of tree growth, the Q_{10}, Q_{25}, Q_{50}, Q_{75}, and Q_{95} percentiles for the planted catchment were lower by 27%, 17%, 16%, 22%, and 26%, respectively, compared with the tussock catchment (Table 2).

4.9 | Peak flows and stormflows

Peak flows were assigned to four size classes according to the return periods of the annual flood peaks for the tussock catchment (Table 3). The means of each size class were calculated for three periods at the tussock catchment: the preplanting period (1980–1982), the immediate postcanopy closure period (1991–1993), and approximately 15 years after canopy closure (2004–2006). The corresponding means for the planted catchment (GH2) were then calculated for the same periods. The differences in the means of peak flows between the tussock and planted catchments for all size classes for the preplanting period were not significant ($p > .3$) but were significant for the two postplanting periods ($p < .04$).

The effects of afforestation on storm peak flows appear as lower means for the planted catchment (GH2) in the 1991–1993 and 2004–2006 periods compared with the tussock catchment (GH1) for the same periods (Table 3 and Figure 10). For example, the mean storm peak flow for the 2–5 L/s/ha size class at GH1 was 3.41 L/s/ha for the 48 storms in that class between 1991 and 1993, whereas the mean for the same storms at GH2 was 1.18 L/s/ha, representing a reduction of 65%. For the 5–10, 10–15, and >15 L/s/ha size classes, the reductions were 59%, 64%, and 54%, respectively. For the period 2004–2006, approximately 15 years after canopy closure, percentage reductions for the 2–5, 5–10, and 10–15 L/s/ha size classes were higher than for the 1991–1993 period (78%, 73%, and 77%, respectively), but the percentage reduction for the >15 L/s/ha size class was substantially lower (37%). This suggests that although the maturing forest may have been having an increasing effect on peak flows associated with small-to-medium size storms, it does not seem to have been influencing peak flows from larger storms to the same extent.

TABLE 3 Mean storm peak flows (±SD) at Glendhu for four size classes of storms (L/s/ha) in the preplanting period (1980–1982), the period immediately after canopy closure (1991–1993), and approximately 15 years after canopy closure (2004–2006) for the tussock catchment (GH1) and the planted catchment (GH2)

Period	Storm class (L/s/ha)	Storm number	Catchment storm peak flow (L/s/ha) Tussock (GH1)	Planted (GH2)	Reduction (%)
1980–1982	2–5	38	3.15 (±0.67)	2.45 (±0.97)	2
	5–10	7	7.19 (±0.15)	6.3 (±1.87)	12
	10–15	4	12.98 (±1.18)	13.7 (±0.83)	0
	>15	4	20.58 (±8.18)	19.7 (±10.22)	4
1991–1993	2–5	48	3.41 (±0.78)	1.18 (±0.47)	65
	5–10	17	6.16 (±1.16)	2.55 (±0.64)	59
	10–15	7	11.83 (±1.06)	4.25 (±2.77)	64
	>15	4	15.35 (±0.34)	6.94 (±1.72)	54
2004–2006	2–5	30	3.27 (±0.95)	0.71 (±0.26)	78
	5–10	12	7.39 (±1.16)	1.99 (±0.57)	73
	10–15	4	11.20 (±0.78)	2.58 (±3.80)	77
	>15	5	23.80 (±5.21)	15.06 (±9.08)	37

TABLE 2 Flow indicators (mm/day) from the flow duration curves for the Q_{10}, Q_{25}, Q_{50}, Q_{75}, and Q_{95} percentiles over the period of record (1980–2013), the preplanting period (1980–1982), and since canopy closure (1991–2013)

Catchment	Period	Q_{10}	Q_{25}	Q_{50}	Q_{75}	Q_{95}
GH1	1980–2013	3.14 (±0.50)	1.84 (±0.35)	1.36 (±0.20)	1.07 (±0.18)	0.88 (±0.14)
	1980–1982	3.19 (±0.22)	1.95 (±0.09)	1.45 (±0.07)	1.23 (±0.06)	0.94 (±0.10)
	1991–2013	3.54 (±0.38)	1.66 (±0.13)	1.37 (±0.15)	0.97 (±0.15)	0.90 (±0.12)
GH2	1980–1982	3.19 (±0.33)	1.93 (±0.02)	1.45 (±0.10)	1.03 (±0.09)	0.86 (±0.09)
	1991–2013	2.59 (±0.48)	1.38 (±0.33)	1.16 (±0.18)	0.76 (±0.22)	0.67 (±0.15)
Difference (GH2 − GH1)[a]		0.95	0.28	0.21	0.21	0.23
Reduction (%)		27	17	16	22	26

Note. Standard deviations are in brackets.

[a]Based on period 1991–2013 for both catchments.

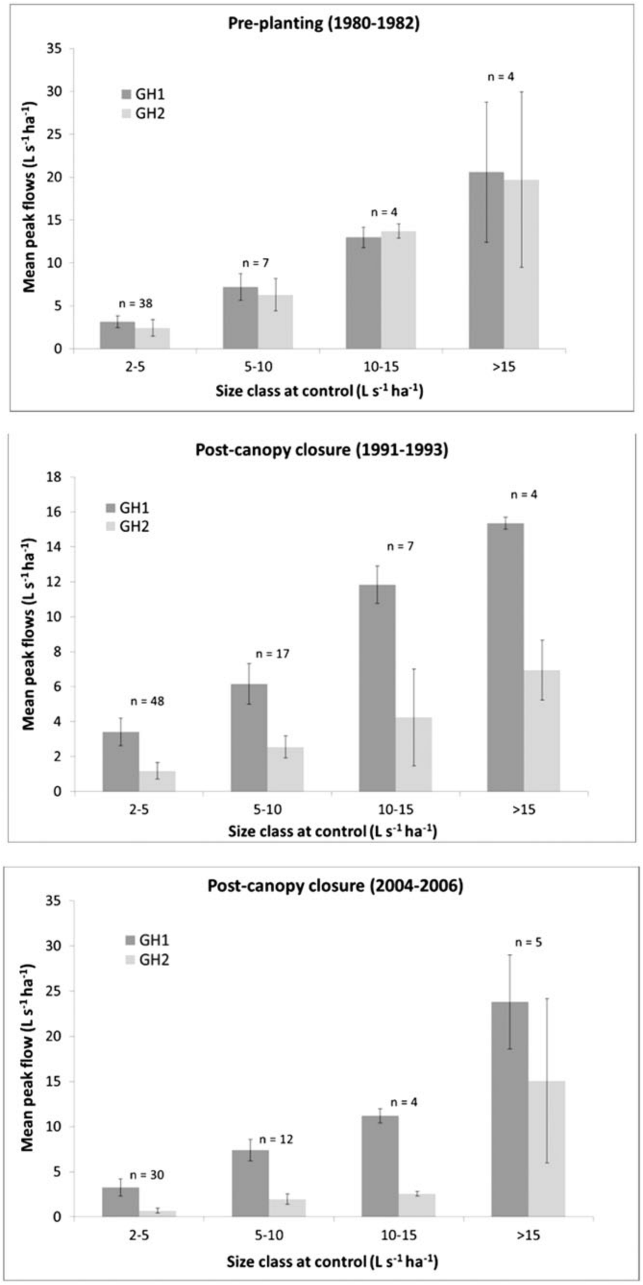

FIGURE 10 Mean peak flows for four size classes of storms in the preplanting period (1980–1982), the immediate postcanopy closure period (1991–1993), and approximately 15 years after canopy closure (2004–2006) for the tussock catchment (GH1) and the planted catchment (GH2). The standard deviation of the sample values is shown in each bar graph where $n \geq 4$

A similar but more subdued pattern of change can be seen in the stormflows (Table 4 and Figure 11). There was no statistical difference in the means for the four size classes of stormflows before planting ($p > .3$), whereas, apart from the largest size class in the early preplanting period (1991–1993), the differences in means were all significant ($p < .007$). Substantial percentage decreases were observed for the smallest size class at GH2 (56% in 1991–1993 and 72% in 2004–2006). There were correspondingly smaller percent reductions with increasing size classes. For the largest size class (>40 mm), the decrease was 36% in the early postplanting period (1991–1993) and 48% in the later postplanting period (2004–2006).

TABLE 4 Mean stormflows (±SD) per event at Glendhu for four size classes of storms (mm) in the preplanting period (1980–1982), the period immediately after canopy closure (1991–1993), and approximately 15 years after canopy closure (2004–2006) for the tussock catchment (GH1) and the planted catchment (GH2)

Period	Storm class (mm)	Storm number	Catchment mean storm flows (mm) Tussock (GH1)	Catchment mean storm flows (mm) Planted (GH2)	Reduction (%)
1980–1982	5–10	22	6.65 (±1.02)	6.22 (±1.31)	6
	10–20	6	13.30 (±3.41)	14.64 (±5.12)	0
	20–40	4	30.64 (±6.77)	29.12 (±7.28)	5
	>40	5	54.50 (±10.66)	51.3 (±8.39)	6
1991–1993	5–10	26	7.04 (±1.05)	3.06 (±1.05)	56
	10–20	23	14.40 (±2.33)	7.42 (±2.48)	48
	20–40	7	25.82 (±5.45)	14.18 (±6.26)	26
	>40	2	46.90	30.11	36
2004–2006	5–10	16	6.97 (±1.29)	1.92 (±1.02)	72
	10–20	17	12.91 (±1.91)	4.39 (±1.06)	66
	20–40	5	27.28 (±5.41)	12.62 (±6.48)	54
	>40	4	58.28 (±14.48)	30.02 (±9.53)	48

4.10 | Maximum peak flows

The maximum storm peak flow for GH1 (36.6 L/s/ha) occurred on February 22, 2012 (Table 5). Two similar-sized storm events were recorded, one on January 17, 1980 (34.8 L/s/ha) and the other on January 7, 2005 (31.0 L/s/ha; Table 5). The peak flow at GH2 for the preplanting event in 1980 (37.2 L/s/ha) exceeded that for GH1, as did the total stormflow. Both peak flow and stormflow at GH2 for the 2005 event were lower by 30% and 23%, respectively, compared with those at GH1. This reduction is comparable to the 37% reduction observed for the five storms with peak flows exceeding 15 L/s/ha between 2004 and 2006 (Table 3). For the February 22, 2012 event, however, peak flow at GH2 (41.0 L/s/ha) exceeded that for GH1 (36.6 L/s/ha). Although this apparent anomaly may be partly attributable to variations in rainfall across the two catchments, or to the comparatively low rainfall intensity, it suggests that peak flows associated with exceptionally high magnitude storm events at Glendhu (approximately 40 L/s/ha) are independent of the prevailing land cover.

4.11 | Flood frequency analysis

A flood frequency analysis using the log Pearson Type III distribution of the GH1 and GH2 storm peak flows for the postcanopy closure period (1991–2013) shows that the presence of a forest cover almost halved the magnitude of the peak flow for a storm with an annual recurrence interval of 5 years (Table 6). However, as the average recurrence interval increases, the difference between the peak flows for the respective catchments decreases. For an annual recurrence interval of 100 years, the calculated instantaneous peak flows are much closer (39.8 and 36.7 L/s/ha for GH1 and GH2, respectively), confirming that the threshold at which instantaneous peak flows for the two catchments converge is approximately 40 L/s/ha.

4.12 | Baseflow recession

Pearce et al. (1984) found that baseflow recession rates were highly uniform and sustained for both catchments. They also noted two

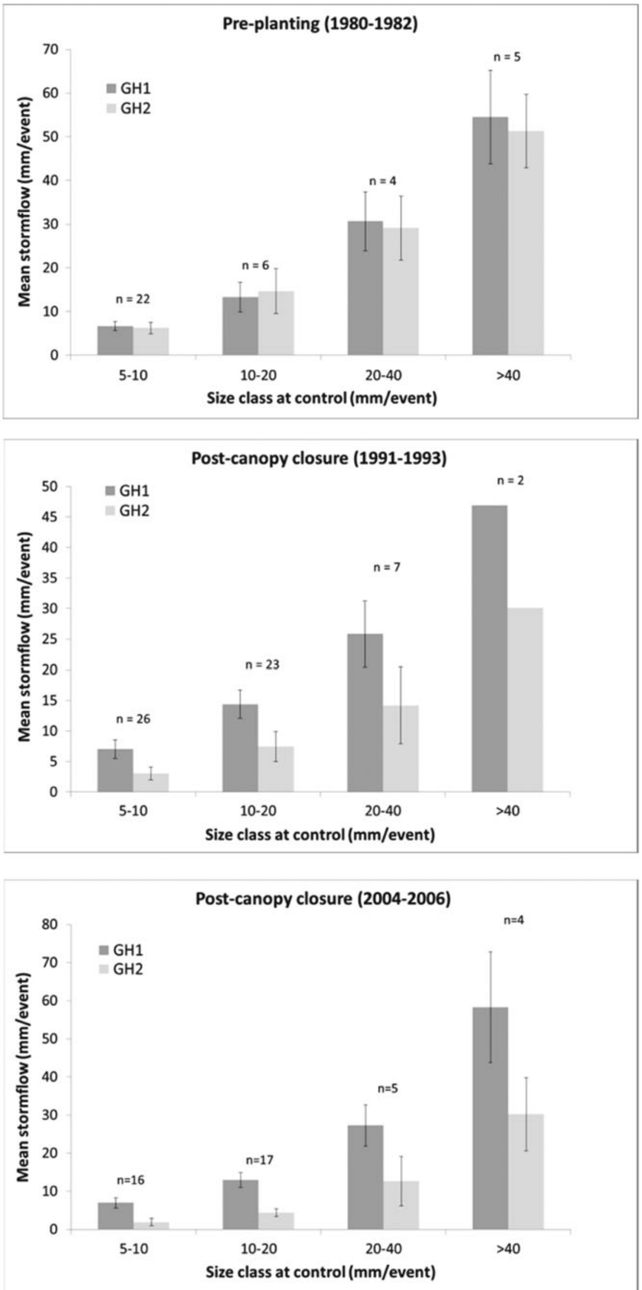

FIGURE 11 Mean stormflows for four size classes of storms in the preplanting period (1980–1982), the immediate postcanopy closure period (1991–1993), and approximately 15 years after canopy closure (2004–2006) for the tussock catchment (GH1) and the planted catchment (GH2). The standard deviation of the sample values is shown in each bar graph where $n \geq 4$

distinct recession segments: a comparatively steep component for the first 12–14 hr followed by a sharp transition to a slower recession once the flow rate reached 0.3 L/s/ha. The flow rate then gradually fell to 0.1 L/s/ha after approximately 17 days (based on the storm with the longest recession period). They attributed the latter response to the release of water stored in the regolith (shallow unconfined groundwater storage).

In contrast, a similar analysis of storm recession data for both catchments in 1995–1996 and 2006–2007 showed a much more gradual transition in the tussock catchment in 1995–1996 from a flow of 0.47 L/s/ha after 12 hr to 0.17 L/s/ha after 5 days and 0.14 L/s/ha after 10 days, and in 2006–2007 an even more gradual change in the rate of the recession after the first 12 hr, falling from 1.2 to 0.15 L/s/ha after 5 days. The trend for the planted catchment in 2006–2007 was similar. At 12 hr, the flow rate from the recession curve was 1.64 L/s/ha, gradually declining to 0.13 L/s/ha after 5 days and 0.10 L/s/ha after 10 days.

5 | DISCUSSION

It is difficult to establish the relative importance of transpiration versus interception loss in accounting for the reduction in water yield from the planted catchment compared with that retained in tussock. According to Farley et al. (2005), transpiration is traditionally considered the more important component, especially in areas of moderate to low annual rainfall (e.g., Bosch, 1979; Scott & Lesch, 1997). However, in higher rainfall zones (>1,000 mm/year), increased interception rather than transpiration is generally regarded as more likely to contribute to the increase in evaporation following afforestation (Calder, 1990; Holmes & Wronski, 1981). Because the average rainfall at Glendhu is about 1,300 mm, we would expect interception loss to be more important than transpiration, and, indeed, in the early stages of the study, there was some evidence for this (Fahey & Watson, 1991).

Pearce et al. (1984) calculated a mean interception loss of 20% of gross rainfall for the tussock catchment from the water balance for extended periods between winter storms of sufficient size to ensure the soil water store was fully replenished at the beginning and end of the period in question. Information on tussock interception was also collected between April 1985 and March 1986 from a large weighing lysimeter containing nine tussock plants located at an elevation of 580 m midway between the two catchments (Campbell & Murray, 1990; Figure 2). Leaf wetness measurements were used to partition evaporation into interception loss and transpiration. Interception loss was estimated at 222 mm (21% of gross rainfall) and transpiration at 400 mm (38%).

Measurements of throughfall made by Davie (unpublished) between July 1998 and June 2000 under a stand of pines in the headwaters of the planted catchment enabled interception loss to be estimated at 30% when compared with gross rainfall from the gauge at G3 (Figure 2). An interception loss of 33% was calculated for pine stands in the planted catchment using the water balance procedure described previously by Pearce et al. (1984). These figures are similar to those listed by Rowe et al. (2002) for interception loss by *P. radiata* elsewhere in New Zealand.

No measurements of transpiration are available at the catchment scale for Glendhu, but Pearce and Rowe (1979) claim that, for catchments with a known interception loss and with accurate long-term rainfall and runoff records, annual transpiration can be estimated as a residual in the water balance. Discrepancies arise at Glendhu, however, when transpiration calculated in this way is compared with that derived from the lysimeter. For example, annual transpiration recorded over 12 months by Campbell and Murray (1990) at the lysimeter (400 mm) was almost twice the annual average of 232 mm estimated for the tussock catchment from the water balance for the period 1991–2013 (assuming an interception loss of 20%). This raises the

TABLE 5 Rainfall and flow information for the three largest storm events at the tussock (GH1) and the planted (GH2) catchments at Glendhu (1980–2013)

	Rainfall (mm)		Peak flow	Stormflow
Storm event	Maximum of 1 hr	Maximum of 24 hr	(L/s/ha)	(mm)
January 17, 1980				
Tussock (GH1)	33.0	89.6	34.8	50.5
Planted (GH2)	33.0	89.6	37.2	55.4
January 7, 2005				
Tussock (GH1)	46.4	82.4	31.0	31.6
Planted (GH2)	57.8	81.4	21.7	24.2
February 22, 2012				
Tussock (GH1)	11.4	86.2	36.6	54.3
Planted (GH2)	12.6	96.1	41.0	40.6

question of whether the lysimeter results can be regarded as representative of the tussock catchment over the long term, particularly because rainfall at the time was well below average. To see what effect this had on the catchment water balance, we calculated transpiration (as a residual) for the same 12-month period as that used by Campbell and Murray (1990). Assuming once again an interception loss of 20%, the resultant figure of 320 mm for transpiration was similar to that quoted previously for the lysimeter, but substantially higher than the 23-year mean of 232 mm. This suggests that any inferences drawn from the lysimeter results with respect to the catchment water balance in the long term should be treated with caution.

The low average annual transpiration for the tussock catchment supports the view expressed by Murray, Jackson, and Fahey (1990) and Davie et al. (2006) that snow tussock is conservative in its water use. If all the planted catchment was in pines, transpiration (calculated as a residual in the water balance, and assuming an interception loss of 30%) is estimated at 498 mm (1.4 mm/day). This is twice the rate estimated for the tussock cover and is consistent with measurements of transpiration rates for *P. radiata* made over short periods elsewhere in New Zealand (Rowe et al., 2002; Fahey, Watson, & Payne, 2001; Whitehead, Kelliher, Lane, & Pollock, 1994; Whitehead & Kelliher, 1991).

The narrowing in the water yield difference between the two catchments since 2010 is believed to be related to the recent spread of mānuka across north- and east-facing aspects of the tussock catchment. Little is known about the water use characteristics of mānuka.

TABLE 6 Storm peak flows, derived from a frequency analysis of the annual maximum series using a log Pearson Type III distribution for the tussock (GH1) and planted (GH2) catchments at Glendhu, associated with different ARIs for the postcanopy period (1991–2013)

ARI (years)	Tussock GH1 (L/s/ha)	Planted GH2
5	18.4	10.6
10	22.0	14.9
25	26.7	21.4
50	30.4	27.2
100	39.8	36.7

Note. ARI = average recurrence interval.

However, transpiration rates and interception losses are likely to be higher than those for tussock (Rowe et al., 2002), which could account for the declining difference in water yield.

As noted earlier, before planting, the proportion of total flow provided by baseflow was essentially the same for both catchments. However, in 1983, annual baseflow as a proportion of total streamflow at GH2 showed a marked increase. This is believed to be due to the destruction of the impermeable B- and C-horizons during contour ripping in 1982. This would have increased the drainage potential of the soil profile across the planted catchment, thereby enabling incident rainfall to reach greater depths instead of being converted to saturated overland flow. A similar response in baseflow to ripping has been observed at Balquhidder in Scotland (Calder, 1993) and at Coalburn in northwest England (Robinson, Jones, & Blackie, 1994).

6 | COMPARISONS WITH OTHER STUDIES

The Glendhu study is the only one in New Zealand dedicated to investigating the hydrological effects of afforesting tussock grasslands. However, other studies have assessed the hydrological changes associated with the conversion of pasture to plantation forestry. For example, Smith (1987) compared streamflow from two catchments in *P. radiata* and two in pasture at Berwick Forest, 30 km east of Glendhu. Average water yield from the catchments in the forest was 43% lower than from those in pasture. Dons (1987) analysed streamflow from catchments comprising the Purukohukohu study in the central North Island and found that 23 years after planting *P. radiata* in one of the catchments annual water yield was reduced by 230 mm (30%). Small catchments (0.07 km^2) in the Moutere Hills near Nelson were planted in *P. radiata*, and their water yields were compared with adjacent control catchments left in pasture (Duncan, 1995). At canopy closure, annual water yields were up to 167 mm/year (80%) less than would have been expected from pasture.

In the United Kingdom, long-term studies at Plynlimon and Llanbrynmair in Wales and at Balquhidder in Scotland have had similar goals and objectives to those at Glendhu (Blackie, 1993; Calder, 1990; Hudson et al., 1997; Kirkby et al., 1991; Whitehead & Robinson, 1993). The results from the Balquhidder study are of most relevance here, given its location in an upland area with ample, evenly distributed precipitation, and plantation forests replacing a cover of heather and bracken. The treated catchment was planted over 41% of its area in pines, half of which was later harvested. The control catchment was predominantly in heather and upland pasture. Water balance calculations and associated modelling showed that afforestation over 14% of the treated catchment would ultimately reduce streamflow by 2% (Blackie, 1993). Increasing the area in forest to 56% would reduce flow by 8%. Taking this reasoning a step further, a 100% forest cover would reduce flow by 14%. This is substantially less than the calculated reduction in water yield at Glendhu for 100% cover (approximately 50%). At Balquhidder, the impact of any increase in interception loss from the presence of a forest was largely matched by the surprisingly high water use by the extensive cover of heather (McCulloch & Robinson, 1993), which may explain the small reduction in water yield compared with that observed at Glendhu.

Elsewhere, Buytaert et al. (2007) investigated the effects of afforesting tall tussock grasslands with *Pinus patula* in the Andean highlands of Ecuador, a region with a similar rainfall climate to Glendhu. The results showed that afforestation reduced annual water yield by 242 mm (50%). Likewise, at Cathedral Peak in the Natal Drakensberg of South Africa (mean annual rainfall 1,680 mm), planting *P. patula* over 74% of a catchment originally in grass caused an average annual reduction in water yield of 257 mm (Bosch, 1979). Also, in South Africa, Scott and Lesch (1997) found that afforesting a 35-ha catchment in *P. patula* reduced annual water yield by 257 mm in the 20th year of the rotation compared with the control catchment retained in grass. From an analysis of 26 catchment data sets (including Glendhu), Farley et al. (2005) concluded that afforesting grasslands and shrublands could lead to a one-third to three-quarters reduction in water yield.

7 | CONCLUSIONS

Between canopy closure in 1991 and 2013, annual water yield from the planted catchment gradually declined relative to the tussock catchment as the trees matured. The reduction in water yield averaged 273 mm (33%) over this period. If all of GH2 had been planted, the reduction would have been approximately 50%. This is comparable with the percentage reduction in water yield following the conversion of pasture to plantation forest elsewhere in New Zealand, and with that following the replacement of tussock grasslands by pines in the Andean highlands of Ecuador, and in South Africa, but it is higher than that observed at Balquhidder in Scotland. Since 2010, the difference in water yield between the two catchments has narrowed. This is believed to reflect the gradual expansion of woody vegetation on sunnier aspects of the tussock catchment, resulting in greater water loss from an increase in interception and transpiration.

In the preplanting period, annual stormflow and baseflow made up 32% and 68%, respectively, of total streamflow at both catchments. Soon after planting, the baseflow component at GH2 increased as a percentage of total flow. This is attributed to improved soil drainage following ripping just before planting. The redistribution of total streamflow from stormflow to baseflow as a consequence of ripping has become a permanent feature of the flow regime of the planted catchment. Afforestation has had no apparent effect on the pattern and rate of baseflow recession. Whereas peak flows and stormflows associated with small storms showed a substantial reduction after canopy closure, the effect of afforestation on high magnitude, low-frequency flood events at Glendhu was much less pronounced, suggesting that as the magnitude of the event increases, the land cover (tussock or pine) becomes less significant in controlling the peak flow response.

The question of the relative importance of transpiration versus interception in explaining the reduction in water yield from the planted catchment has yet to be fully resolved. It is generally recognised that tussocks are conservative when it comes to transpiration, and measurements have shown that at Glendhu, the difference in interception loss between tussocks and pines is comparatively small. These two factors suggest that, following canopy closure, increasing transpiration from the maturing tree crop could explain the observed reduction in water yield. Regardless of which factor is dominant, the afforestation of tussock grasslands in the uplands of east Otago will have a marked impact on water yield from this unique ecosystem.

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