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RESEARCH ARTICLE

The stream hydrology response of converting a headwater pasture catchment to *Pinus radiata* plantation

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ABSTRACT

The planting of degraded land with tree plantations may be effective at improving land use sustainability and profitability but it can also have significant effects on stream hydrology. In this paired catchment study, we report the stream hydrological response to partial (62%) afforestation of a steep pastoral catchment in the western Waikato Region, North Island, New Zealand. We comprehensively analyse the hydrological regime changes over a 23-year period (including eight years before pine planting) with reference to a native-forested 'control' catchment. Our results show that afforestation has markedly affected stream hydrology. Seven years after planting, the total annual runoff was 380 mm lower than predicted for the catchment in pasture. Two phases of plantation thinning resulted in the difference between measured and predicted runoff reducing to only 129 mm. Peak flows reduced by ~50% while total stormflow reduced by ~30% – which we attribute to canopy interception attenuating and delaying water yield. The impact of plantation establishment on low flows is not so clear, although afforestation appears to have reduced low flows by ~25%. This study provides information on the hydrological impact of afforestation within a hitherto poorly-represented New Zealand environment (i.e. high rainfall, sedimentary lithology-based, North Island hill country).

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Catchment hydrology; plantation; land use change; forestry thinning; water yield; canopy interception; integrated catchment management; paired catchment study; BACI

Introduction

The conversion of steep, erosion-prone pastoral land to plantation forestry is often expected to improve the environmental condition by removing unproductive/unsustainable land uses (Pearce et al. 1987; van Dijk and Keenan 2007). Pastoral land uses in New Zealand, established in the nineteenth century, have resulted in large-scale land degradation (Page and Trustrum 1997; Glade 2003), with consequent offsite damages due to sediment mobilisation and degradation of water quality and aquatic habitat. While the planting of degraded land with tree plantations may be effective at improving land use sustainability and profitability it can also have significant effects on stream hydrology, with ramifications for water abstraction and stream habitat. This is a particularly pertinent issue given the New Zealand Government's current goal to double the current tree planting rate (both plantation and native forests) between 2018 and 2028 through the One Billion Trees Programme (FNZ 2018).

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The impact of afforestation on stream hydrology is traditionally, and arguably most effectively, assessed with a paired catchment approach whereby the hydrological response of an experimental catchment is directly compared to a nearby control catchment, ideally in a before-after, control-impact (BACI) design. A number of such studies have been carried out internationally, although the nature of the afforestation and the land cover prior to afforestation, plus catchment features, in these studies varies considerably. Many of these paired catchment studies are included in the review by Brown et al. (2005). This review identified four broad paired catchment study types:(i) afforestation experiments, (ii) regrowth experiments, (iii) deforestation experiments and (iv) forest conversion experiments. Brown AE et al. (2005) noted that regrowth experiments make up the majority of international studies.

There are a small number of published paired catchment stream hydrology studies from New Zealand. The nature of these studies varies considerably, with several directly comparing the difference in hydrology between forested and nearby non-forested headwater catchments (Dons 1987; Smith 1987; Beets and Oliver 2007). Of those studies that have monitored the hydrological impact of a change in land cover, the only long-term studies that report the hydrological impact of converting pasture to plantation forestry are by Duncan (1995) and Beets and Oliver (2007). Duncan (1995) reported the hydrological response over 29 years of converting pasture and gorse-dominated catchments near Nelson City to *P. radiata*. Beets and Oliver (2007) described the hydrological effect of converting pasture to *P. radiata* in pumice-based catchments at Purukohukohu (near Rotorua) over a 32-year period. The Glendhu experimental catchments (east Otago) have also been the focus of much research into the conversion of grasslands to *P. radiata* forest (e.g. Fahey and Watson 1991; Fahey and Jackson 1997; Fahey and Payne 2017). The Glendhu catchments differed, however, in that the land cover prior to forestry conversion was native tussock grassland as opposed to the other land conversion studies from grazed pasture dominated by introduced grasses. Other relevant studies include those of Fahey and Jackson (1997) and Rowe and Pearce (1994) who investigated the stream hydrology response to clearing of native forest catchments and re-establishment with *P. radiata* plantations at Big Bush (near Nelson) and Maimai (Westland), respectively. Information on the change in water yield following conversion to plantation forestry is presented in Rowe (2003) from a number of other sites as well as those cited above. Most of these studies, however, were not true paired catchment (control-impact) studies with information before-, as well as after-, vegetation change (BACI designs), and no hydrological regime information other than changes in water yield, such as flood size or low flows, is presented.

Most published New Zealand studies of the effect of land cover change on stream hydrology have been in the South Island. With over 70% of all plantation forestry located in the North Island (Yao et al. 2013), there is a need to increase our understanding of the stream hydrology impacts at lower latitudes and typically warmer climates. The only published data from a North Island site is from a catchment (i.e. Purukohukohu) within the pumice-dominated Taupo Volcanic Zone. While the rapid infiltrating pumice-lands represent a very important plantation forestry area (Yao et al. 2013), there is a need to extend our understanding of the hydrological response of tree planting in the high rainfall, steep deeply-weathered sedimentary lithology-based catchments that are typical of much of the rest of the North Island. The stream hydrology response of the establishment of pine plantations within such catchments may differ from other previously investigated sites. The combination of high rainfall, steep terrain and poorly drained clay-based soils may mean that the establishment of forest cover will have a disproportionately large impact on stream hydrology. The poor representation of a range of New Zealand environments (particularly high rainfall steep-lands) by previous hydrological studies was also recently highlighted by Meason et al. (2019).

In this study, we assess the stream hydrology response to partial afforestation with *P. radiata* of a steep pastoral headwater catchment in the western Waikato Region, North Island, New Zealand. We comprehensively analyse the hydrological regime changes, including storm flows, flood size, and low flows, as well as water yield, over a 23-year period (including eight years before pine planting) with reference to a native-forested 'control' catchment in a classic BACI design. Such long-term studies with a meaningful period of 'before' intervention data provide the opportunity to assess the impact of a range of forestry activities, including planting, thinning and harvest. Other studies have been carried out over similar (or longer) time periods (e.g. Duncan 1995; Beets and Oliver 2007; Fahey and Payne 2017). However, unlike these previous studies, the data record from this study is both continuous (i.e. no data gaps) and has an extensive period of pre-plantation data (i.e. eight years).

The primary objective of this paper is to determine the change in stream hydrology in response to the establishment of pine plantation in a steep, high rainfall, sedimentary lithology-based New Zealand catchment. This information will allow us to better assess the role of physiography in determining the magnitude of the change in stream hydrology regime in response to the catchment-wide establishment of pine plantations.

Methods

Study area

The paired catchments in this study are located in the Waikato region of the North Island of New Zealand (Figure 1; Table 1). The experimental Mangaotama catchment is located within the former Whatawhata Research Station (WRS). A control catchment (Whakakai) is located within a native forest reserve immediately adjacent to the former WRS. The Whakakai catchment has been largely undisturbed by human activities for over 90 years, since fires, used for land clearance, swept through the original old-growth podocarp-broadleaf forest. The catchments are dominated by hilly to steep terrain, comprised of Mesozoic sedimentary sandstones and siltstones (greywacke and argillite) with strongly weathered yellow brown earth soils. Residual areas of Pleistocene volcanic ash drape the more gently-sloping parts of the catchments. The climate is humid-temperate with a mean annual rainfall of 1695 mm (1994–2016; NIWA, unpublished data for WRS climate station) and a mean average temperature of 13.7°C. Quinn and Stroud (2002) give a more detailed description of the study area.

Catchment afforestation

Prior to 2001 the Mangaotama catchment was ~99% ryegrass-clover pasture and was rotationally grazed by a mix of sheep and beef cattle at 9 Stock Units ha^{-1} (Dodd, Thorrold et al. 2008). In 2001 an integrated catchment management (ICM) plan was implemented.

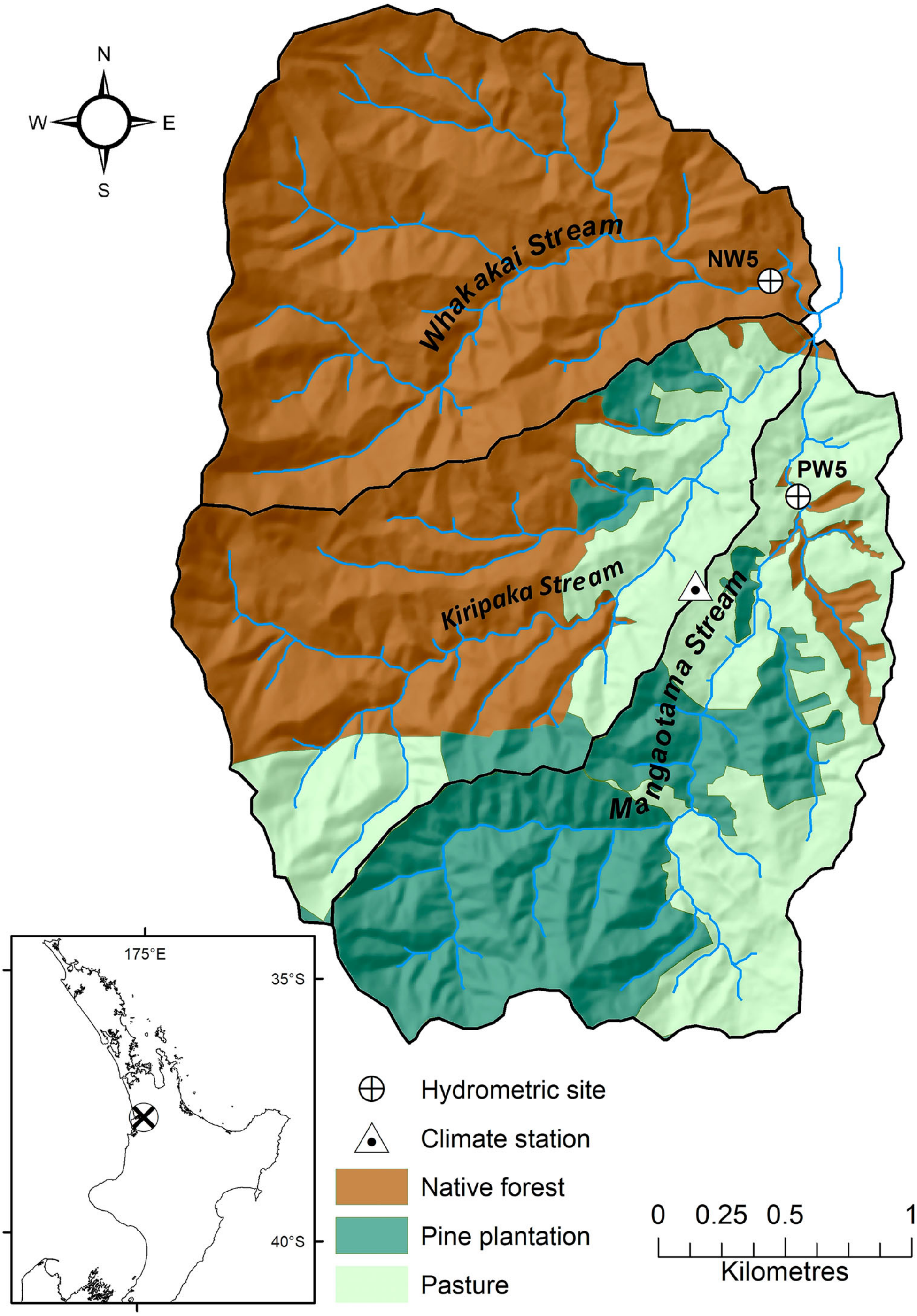

Figure 1. Location map of study area showing hydrometric sites and post-integrated catchment management plan (2002–16) land cover.

Table 1 Characteristics of the Mangaotama and Whakakai catchments.

Catchment	Site name	Area (km^2)	Mean slope (°) (±1sd)	Elevation range (m)	Circularity ratio	Pre-ICM land cover: %pasture: %pine: %native	Post-ICM land cover: %pasture: %pine: %native
Mangaotama	PW5	2.68	22.5 ± 8.9	62–338	0.41	99:0:1	38:58:4
Whakakai	NW5	3.11	23.8 ± 7.7	62–371	0.57	0:0:100	0:0:100

The goal of the ICM plan was to improve both the farm's profitability and environmental performance (Dodd, Thorrold et al. 2008; Quinn et al. 2009). Land use changes implemented as a result of the ICM plan included planting of riparian buffers and/or the exclusion of cattle from riparian areas, and planting poplar trees (*Populus deltoides*) adjacent to eroding stream banks. The native riparian planting augmented pockets of remnant native forest and increased the total catchment area under native forest from ~1% to ~4%. However, the most significant land use/cover change in the catchment was the planting of *Pinus radiata* during August 2001. As a result of the ICM plan, by the end of 2001 ~58% of the Mangaotama catchment above the hydrometric station (PW5; Figure 1) was planted in *P. radiata* – mostly in a steep and physically degraded sub-catchment. The plantation was initially planted at a stem density of ~1250 stems ha^{-1} – except for a 10 m riparian set-back along stream channels. This was intended to avoid 'catastrophic' bank erosion (including loss of plantings) as channels attempt to widen to a 'forest' (shady) morphology as observed in nearby 15-year-old pine plantations by Davies-Colley (1997). The pines underwent two thinning operations: a first phase of thinning (August–December 2009) reduced stem densities to ~700 stems ha^{-1}, and the second (January–March 2011) further reduced stem densities to ~340 stems ha^{-1}.

For the purpose of the data analysis in this study, we have classified the period up to the end of 2001 as the 'pre-planting' period, while the 2002–16 period is classified as the 'post-planting' period.

Flow and rainfall monitoring

Stage height has been measured (at 15 min intervals) near the outlets of both catchments since February 1994 at Whakakai, and since December 1992 at Mangaotama, (NW5 and PW5 hydrometric sites, respectively on Figure 1). Stage height was measured by NIWA Hydrologger water level recorders (1 mm resolution). The Mangaotama Stream (PW5 site) has a composite rectangular weir at its outlet while the Whakakai Stream (NW5 site) has a bedrock control immediately upstream of a small waterfall. Both sites have stage/discharge ratings that have been determined by manual gaugings (approximately four per year) over a range of stage heights. Over the study period, due to changes in channel/bed conditions, a new stage/discharge rating was applied on seven occasions at Whakakai and on 10 occasions at Mangaotama.

Rainfall was measured by an OTA tipping bucket rain gauge (0.2 mm bucket capacity) at 10-min intervals within an intermediately-located catchment (Kiripaka; Figure 1).

Data analysis

Flow data management and statistical analysis were carried out using TIDEDA hydrological management software (Thompson 2000) and Microsoft Excel. Data presentation and hydrological statistical analysis in this study followed a similar approach to other similar studies (e.g. Rowe and Pearce 1994; Duncan 1995; Fahey and Jackson 1997; Fahey and Payne 2017).

A number of statistical analyses are available to assess the impact of the plantation forest through time on both flood events and low flows. We carried out flood frequency analyses for both the pre-planting and post-planting periods. Flood frequency analysis is a statistical approach used by hydrologists that relate the magnitude of flood events to their frequency through the use of probability distributions (Rao and Hamed 2000). Flood frequency analysis here was carried out assuming a Gumbel distribution. The Gumbel distribution has been found to be suitable for most New Zealand rivers (Fahey and Jackson 1997).

A number of methods are available for characterising stream low flows, including specifying the 7-day mean annual low flow (7-day MALF) or the flow exceeded 95% of the time (Q95) (Smakhtin 2001). The 7-day MALF is the 7 day period that has the lowest average flow for a given calendar year. Fahey et al. (2004) suggest that 7-day MALF is a good indicator of the effect of land use on low flows. Accordingly, we have estimated 7-day MALF (expressed as water depth (mm)).

We constructed flow duration curves for three periods (pre-planting (1994–2001), pre-thinning (2002–2009), and post-thinning (2010–16)) for both sites. A flow duration curve is a cumulative frequency plot that displays the proportion of the time a particular discharge is equalled or exceeded for a given period. As such, a flow duration curve provides information on the flow characteristics of a stream over a range of discharges (Searcy 1959). Flow duration curves for the pre-planting, pre-thinning and post-thinning periods allow the impact of planting and thinning to be determined over a wide range of stream discharges.

The impact of afforestation on peak flows was assessed by comparing mean peak flows for the pre-planting period with a post-canopy closure period. Event peak flows (normalised to catchment area, units: $\mathrm{l\,s^{-1}\,km^{-2}}$) at Whakakai were assigned to four size classes. The mean and standard deviation of event peak flows at Whakakai were calculated for each class for the 8-year (1994–2001) pre-planting period and the 8-year period (2009–16) after 8 years of plantation forest growth. The period from 2009 to 2016 was selected to match the record length of the pre-planting period, because 2009 (8 years from planting) is around the time of canopy closure as indicated by previous New Zealand studies (e.g. Fahey and Payne 2017; MPI 2018). The mean and standard deviation of peak flows for the corresponding events at Mangaotama were also determined for the same periods. To avoid the inclusion of the many, frequent very low magnitude events, peak flow analysis was limited to events that produced at least $200\,\mathrm{l\,s^{-1}\,km^{-2}}$ within the control Whakakai catchment.

To assess the impact of afforestation on total stormflow the mean and standard deviation of stormflow volumes (water depths; mm) at Whakakai were calculated for four stormflow size classes for the same pre- and post-planting periods described above for the peak flow data. The mean and standard deviation of stormflows for the corresponding events at Mangaotama were also determined for the same periods. Stormflow in this study was calculated by summing all the flow generated during a runoff event. As with peak flow analysis, to avoid the inclusion of the many, frequent very low magnitude events, we only included events that produced at least 5 mm of runoff within the control Whakakai catchment.

Results

Annual rainfall and runoff

The total annual rainfall and total annual runoff for the Mangaotama and Whakakai sites (1994–2016) are illustrated in Figure 2. The annual rainfall during the study period ranged between 1445 and 2056 mm. Mean annual rainfall for the 1994–2016 period was 1695 ± 188 mm (±1 SD). Annual runoff ranged between 627 and 1270 mm at Mangaotama and between 630 and 1328 mm at Whakakai. The annual runoff co-efficient (ratio of runoff to rainfall) ranged between 0.40 and 0.62 at Mangaotama and between 0.41 and 0.64 at Mangaotama.

To determine the effect of afforestation on annual runoff, runoff for the Mangaotama catchment, if it had remained in pasture, was predicted. This was done by developing a regression relationship between annual runoff at Mangaotama and Whakakai for the pre-planting period (1994–2001) (Figure 3). This relationship was then applied to the post-2001 annual runoff data from Whakakai to provide predictions of pasture-based runoff. Figure 4 shows the difference between measured and predicted annual runoff within the Mangaotama catchment. Figure 4 shows that from 2003 the measured runoff at Mangaotama was consistently lower than predicted. Between 2003 and 2008, when the pine trees were growing vigorously (e.g. as recorded by shade along a reach of the Mangaotama within the pine plantation – Figure 2 of Davies-Colley and Hughes 2020), there was a gradual increase in the difference between measured and predicted runoff, with a peak at 380 mm in 2008 (seven years after forest planting). At the time of the first thinning (2009) the difference reduced to between 263 and 303 mm and then reduced again to 129 mm after the second thinning. In the five years since the second phase of thinning the difference between measured and predicted runoff increased again with the mean difference in measured and predicted runoff between 2012 and 2016 of 203 mm.

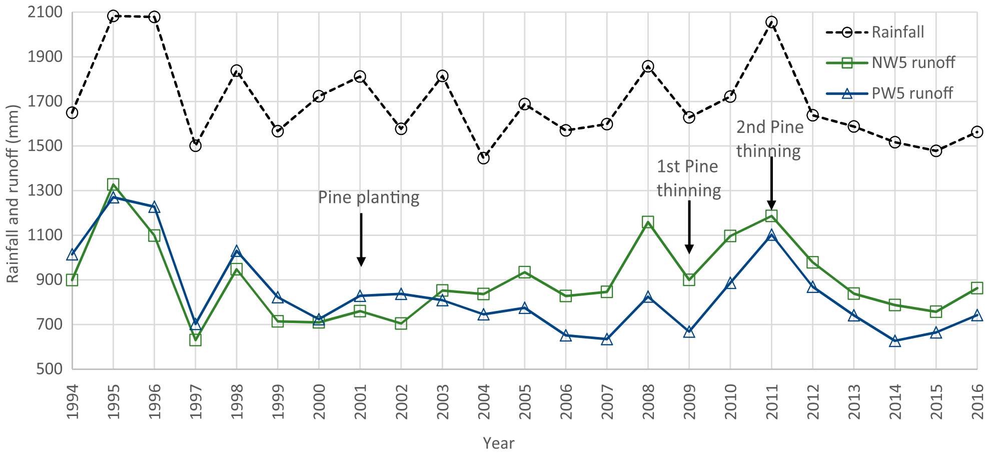

Figure 2. Total annual rainfall and total annual runoff from Mangaotama (PW5) and Whakakai (NW5) between 1994 and 2016. Rainfall was measured in the adjacent Kiripaka sub-catchment (Figure 1).

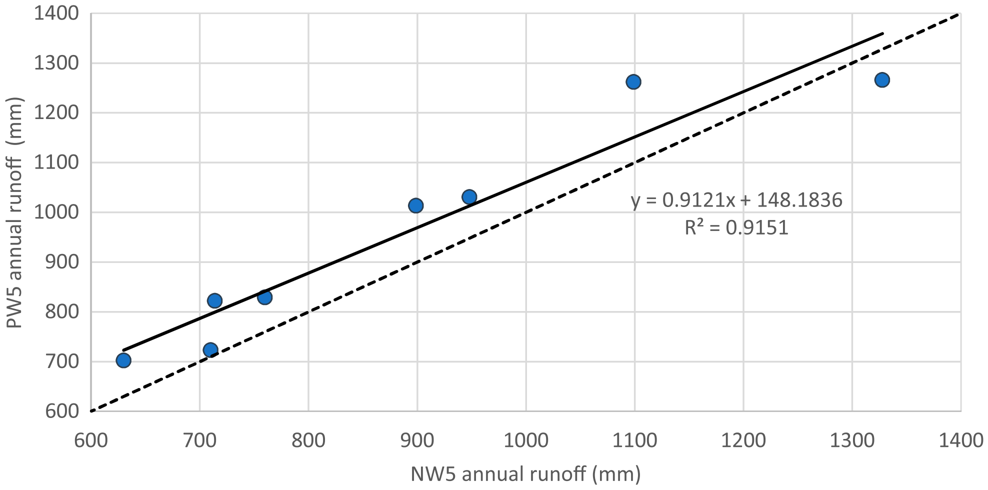

Figure 3. Relationship between annual runoff at Mangaotama (PW5) and Whakakai (NW5) for the 8-year pre-planting period (1994–2001). Dashed line is the 1:1 line.

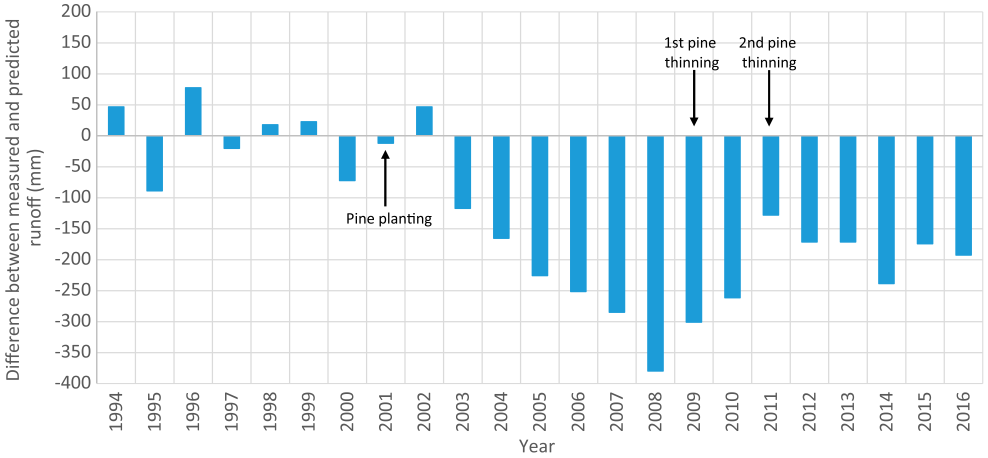

Figure 4. Difference between measured and predicted annual runoff for the Mangaotama catchment. The predicted runoff was determined using the regression relationship illustrated in Figure 3.

Annual stormflows

A similar pattern to the change in total runoff can be seen in the stormflow data (Figure 5), albeit with more 'noise' than would be expected. During the pre-planting period (with the exception of 1995) the stormflow produced by both catchments was generally similar. The impact of afforestation on storm flow is apparent, with Mangaotama consistently producing less stormflow than Whakakai from 2003 inclusive. From 2003 to 2016 the Mangaotama catchment generated an average of around 180 mm year^{-1} less stormflow than the Whakakai, amounting to an average reduction of ~37%.

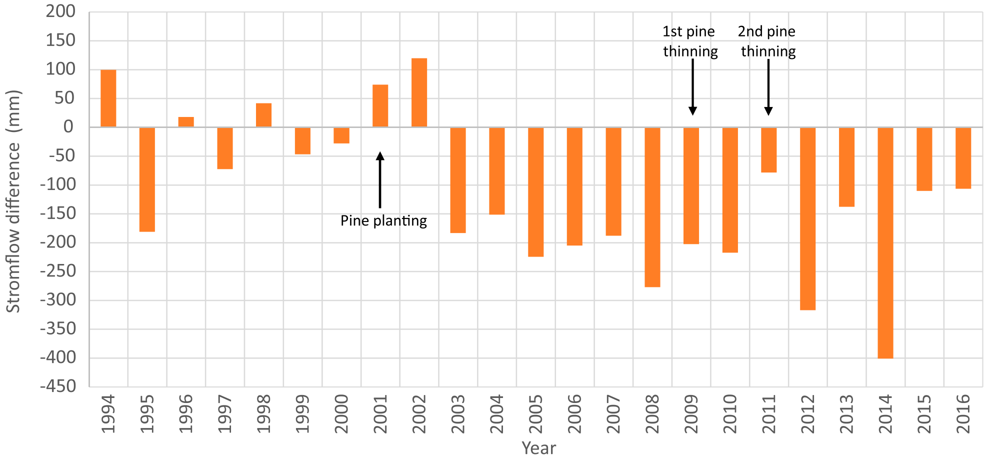

Figure 5. Difference in annual stormflow between the Mangaotama and Whakakai catchments (PW5–NW5) for the 1994–2016 period.

Flow duration analysis

Flow duration curves were calculated for three periods: (i) pre-planting (1994–2001), (ii) post-planting (2002–2009), and (iii) post-thinning (2010–16) (Figure 6). Both sites exhibited some changes in the flow distributions between these periods. The Mangaotama catchment exhibited an appreciable decline in flow between the pre-planting period and the post-planting period (before any stand thinning), with the 10th, 50th and 90th percentile flows decreasing by 28.7%, 19.6% and 13.5%, respectively – suggesting a pattern of greater relative effect on high flows than low flows. This trend reversed partly between the post-planting and post-thinning periods, with flow at each percentile increasing at all but the highest percentile flows (e.g. 10th and 50th percentiles increased by 19.5% and 9.4% respectively, while the 90th percentile decreased by a further 6.4%). Over the same periods, the flow distribution at the Whakakai forested control catchment remained essentially unchanged, as expected, perhaps excepting high percentiles (low flows).

Prior to the forest planting, the Mangaotama catchment yielded more water than Whakakai for flow rates that were exceeded for 50% of the time. However, for the higher percentiles (i.e. lower flows) the largely pastoral Mangaotama catchment produced slightly less flow per unit area than the native-forested Whakakai catchment. The planting of trees, mainly pines, within the Mangaotama catchment resulted in large proportional decreases in water yield across the frequency range. After thinning, the difference between the catchments reduced, but the Mangaotama catchment continued to yield less water than the forested Whakakai catchment across the frequency range.

Low flow analysis

The Mangaotama catchment generally produced lower 7-day MALFs than the forested Whakakai catchment over the entire study period (Figure 7). During the pre-planting period (1994–2001) the difference between the 7-day MALF at Mangaotama and

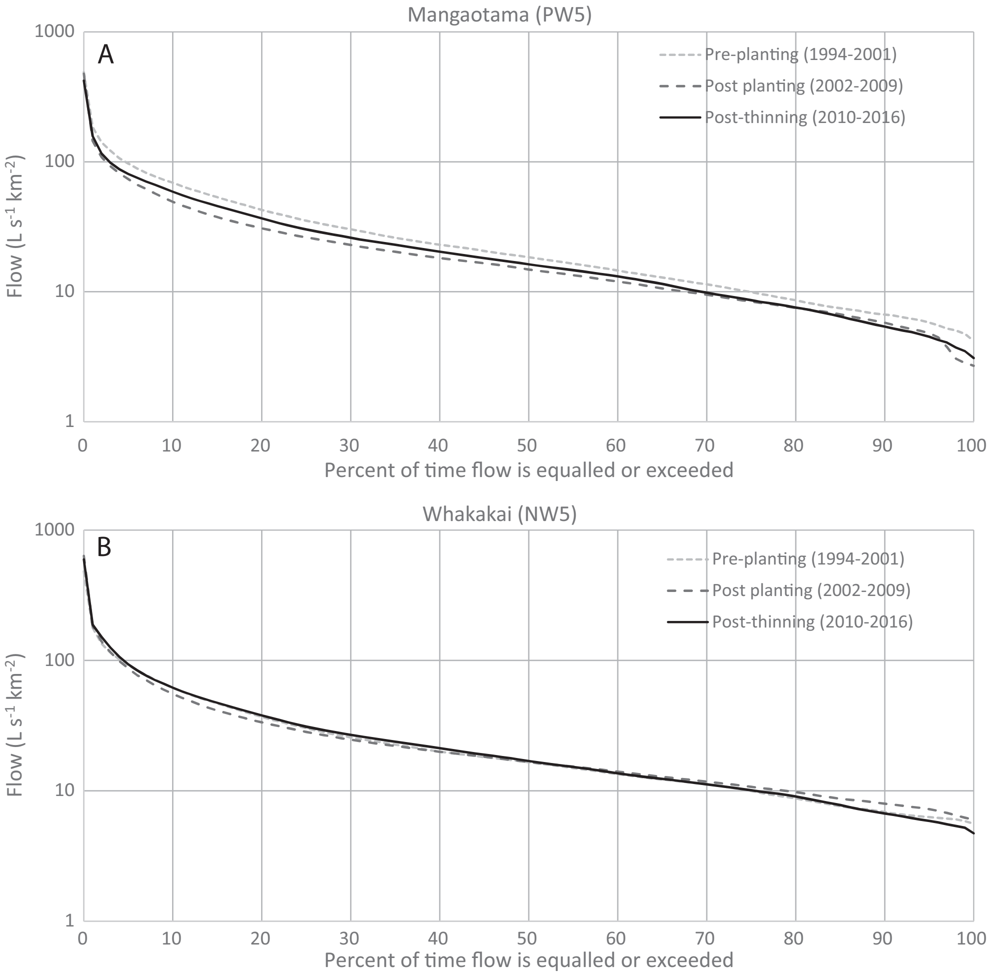

Figure 6. Average daily flow duration curves for **A** the Mangaotama (afforested) catchment, and **B** the Whakakai native-forested (control) catchment. Pre-planting (1994–2001) – dotted curves; post-planting (2002–2009) – dashed curves; and post-thinning (2010–16) – solid curves.

Whakakai was quite variable. Between 1996 and 1998 Mangaotama produced (marginally) more low flow than Whakakai, while in the remaining pre-planting years the Mangaotama produced substantially less low flow than the Whakakai. Over this pre-planting period, the median difference between the Mangaotama and Whakakai catchments was 0.09 mm day^{-1}. During the post-planting period (2002–2009), the Mangaotama consistently yielded less water at low flow, and the difference increased by ~50% to a median of -0.17 mm day^{-1} (the peak difference in 7-day MALF was -0.33 mm day^{-1} in 2007). During the post-thinning period (2010–16) the difference reduced to near pre-plantation forest levels (0.11 mm day^{-1}). Overall, the pattern of low flow differences between the Mangaotama ‘impact’ and Whakakai ‘control’ catchments in Figure 7 was similar to that for stormflows (Figure 5) and annual runoff (Figure 4).

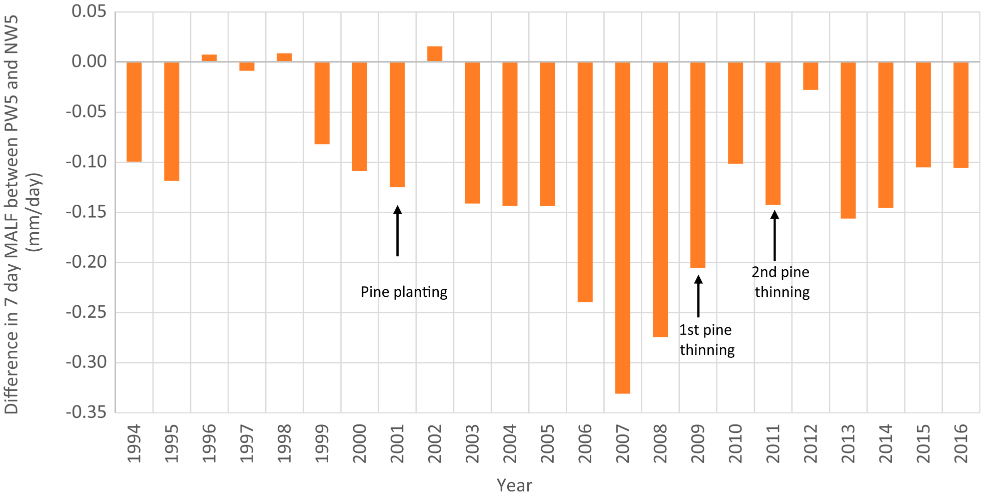

Figure 7. Difference in mean annual 7-day low flow between the Mangaotama catchment (PW5) and the Whakakai catchment (NW5) for 1994–2016.

Flood frequency analysis

Flood frequency analyses for both the pre-planting and post-planting periods for PW5 and NW5 are presented in Figure 8 and Table 2. For this analysis, the pre-planting (pre-ICM) period for Whakakai ranged from 1994 to 2001, but was one year longer at Mangaotama, with the record commencing in 1993. In the Whakakai forested control catchment, there was little difference between the flood peak magnitude (for a given annual exceedance probability) between the pre-planting and post-planting periods. The flood peaks were between 16% and 24% larger in the post-planting

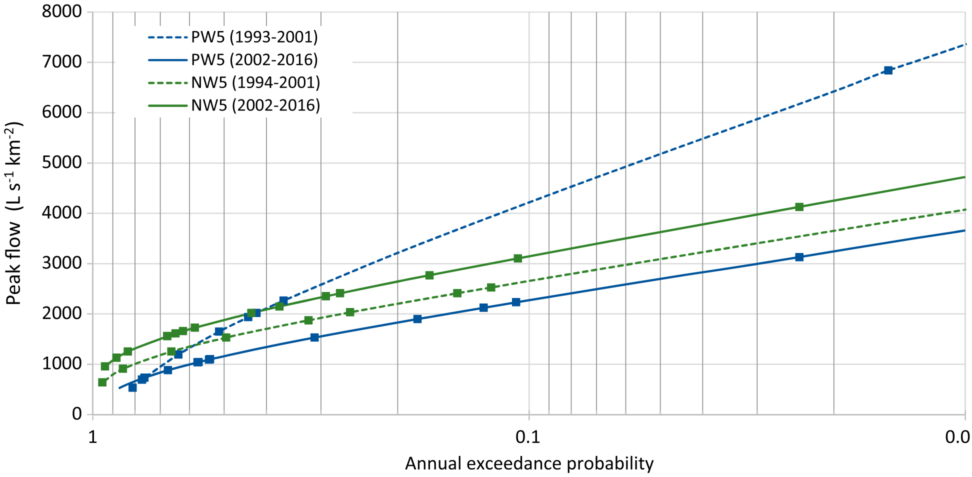

Figure 8. Flood frequency curves for the Mangaotama (PW5) and Whakakai (NW5) catchments for the pre-planting (1993/1994–2001) and the post-planting (2002–16) periods. The curves are derived from a frequency analysis of the annual maximum series assuming a Gumbel distribution.

Table 2. Event peak flows for a range of annual exceedance probabilities (AEP) for the pre-planting period (1993/1994–2001) and the post-planting period (2002–16) for Whakakai (NW5) and Mangaotama (PW5).

	NW5			PW5		
AEP	Pre-planting (1994–2001) peak flow (l s^{-1} km^{-2})	Post-planting (2002–16) peak flow (l s^{-1} km^{-2})	Difference (%)	Pre-planting (1993–2001) peak flow (l s^{-1} km^{-2})	Post-planting (2002–16) peak flow (l s^{-1} km^{-2})	Difference (%)
0.01	4102	4766	16	7371	3694	−50
0.02	3636	4244	17	6354	3236	−49
0.05	3020	3554	18	5008	2629	−48
0.1	2554	3031	19	3991	2171	−46
0.2	2088	2509	20	2973	1712	−42
0.5	1472	1819	24	1628	1106	−32

period over the range of annual exceedance probabilities (AEP). The shape and trajectories of the Whakakai catchment flood frequency curves are similar between the pre- and post-planting periods, indicating no marked difference in peak flood magnitude for a given AEP.

In contrast, in the Mangaotama catchment, the flood frequency pattern was markedly different pre- versus post-ICM planting. The post-ICM flood frequency pattern (with partial catchment afforestation) was similar in shape to that for the Whakakai native-forested control, but with somewhat lower peak flood size for a given AEP. The tree planting within the Mangaotama catchment decreased the magnitude of the peak flows overall AEPs, but more markedly for more extreme floods (at low AEPs) – with the 0.01 AEP event (100 year return period), for example, being halved in magnitude.

Event peak flows

The mean and standard deviations of event peak flow for four event size classes for Mangaotama and Whakakai for the 8-year pre-planting period (1994–2001) and for an 8-year post-canopy closure period (2009–16) are illustrated in Figure 9. Despite the strongly contrasting land covers of the two catchments during the 1994–2001 period, the mean peak flows for each size class are similar. Statistical analysis using paired sample t-tests ($\alpha = 0.05$) failed to detect a significant difference between the mean peak flows between the two sites for all size classes.

Afforestation in the Mangaotama greatly reduced (~50%) mean peak flows for each size class during the 2009–16 post-planting period. Paired sample t-tests ($\alpha = 0.05$) indicate that these differences are all statistically significant. As expected, mean peak flows for each size class within the Whakakai native-forested control catchment remained almost unchanged between the pre- and post-planting periods.

Stormflows

The mean and standard deviations of stormflow volumes for four event size classes for Mangaotama and Whakakai for the 8-year pre-planting period (1994–2001) and for an 8-year post-canopy closure period (2009–16) are illustrated in Figure 10. The mean stormflows for each size class were similar at both sites during the pre-planting period. Paired

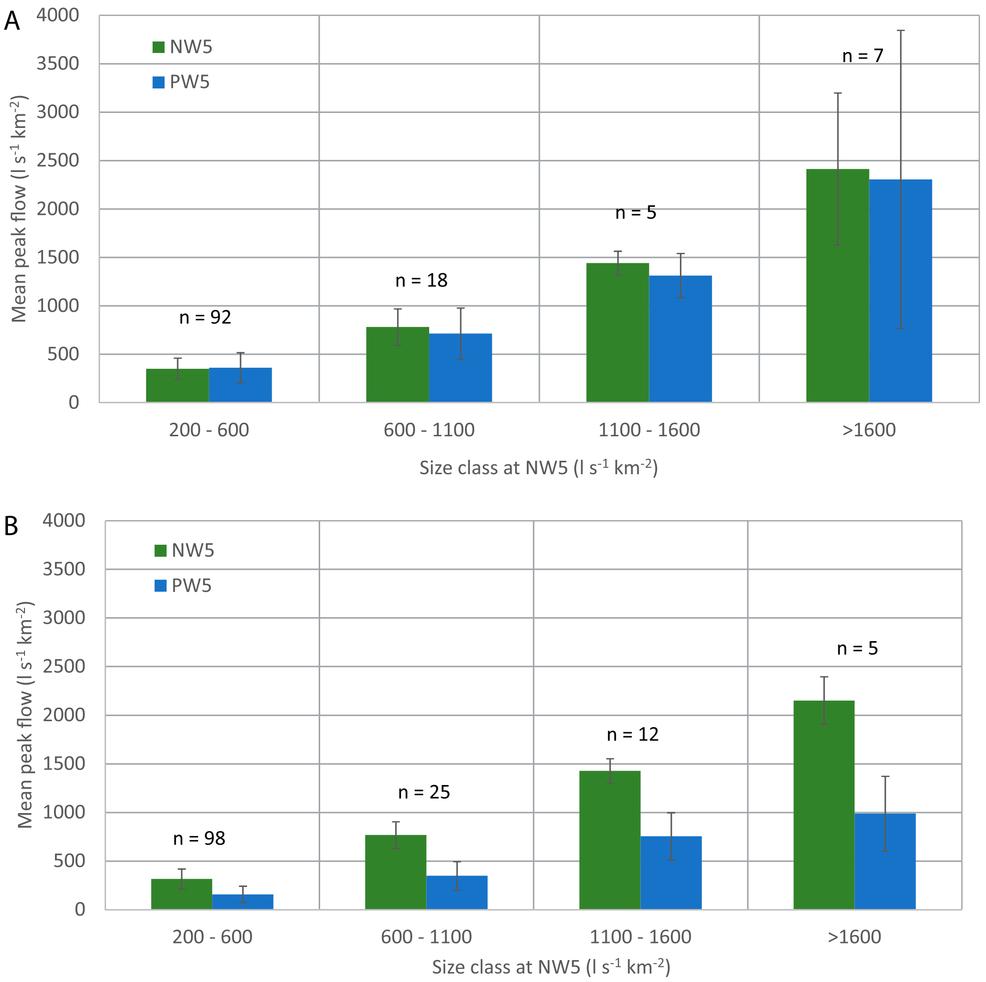

Figure 9. Event peak flows (mean ±1 standard deviation) for four event size classes for **A** the 8-year pre-planting period (1994–2001) and **B** for the 8-year post-planting period after 8 years of plantation forest growth (2009–16) for the experimental catchment (Mangaotama; PW5) and the reference native forest catchment (Whakakai; NW5).

sample t-tests ($\alpha = 0.05$) only detected a significant difference between the mean stormflows at Mangaotama and Whakakai for the 5–10 mm/event size class.

Afforestation reduced mean stormflows in the Mangaotama for each size class during the post-planting period, by about one-third (with declines ranging between −27% and −36%). Paired sample t-tests ($\alpha = 0.05$) indicate that these differences are all statistically significant.

Discussion

Since the establishment of the WRS as a long-term ecological project, numerous publications have reported the impact of the ICM plan on different aspects, including farm economic performance, water quality, sediment yield and aquatic ecosystem health

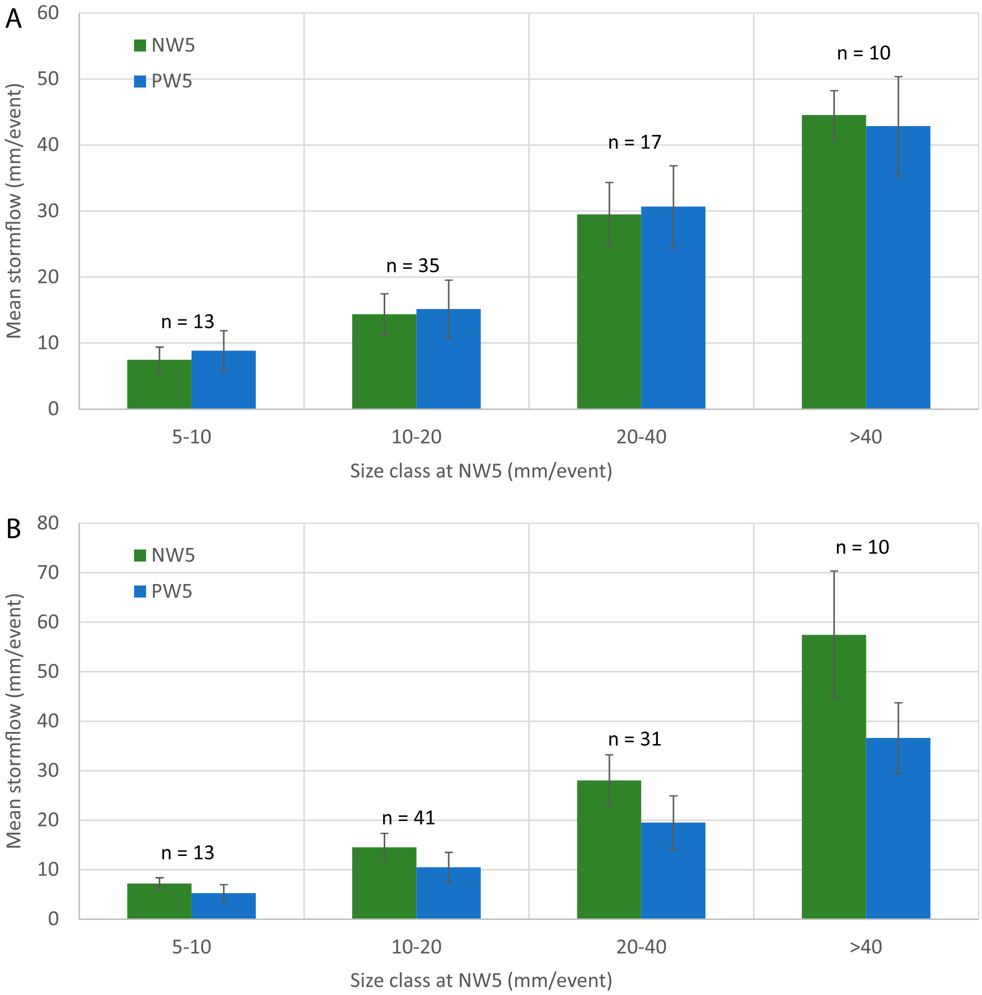

Figure 10. Mean stormflows (±1σ) for four event size classes for **A** the 8-year pre-planting period (1994–2001) and **B** for the 8-year post-planting period after 8 years of plantation forest growth (2009–16) for the experimental catchment (Mangaotama; PW5) and the reference native forest catchment (Whakakai; NW5).

(e.g. Dodd, Quinn et al. 2008; Quinn et al. 2009; Hughes et al. 2012; Hughes and Quinn 2014, 2019). Up until now, however, the stream hydrology impact of the large-scale afforestation component of the ICM plan has been largely overlooked. There is a dearth of paired catchment studies that have analysed the impact of catchment afforestation on stream hydrology within New Zealand, especially within the North Island (which has the great majority of NZ's plantation area) and most particularly in a full BACI design. Therefore our BACI study appreciably widens our understanding of the hydrological response to the conversion of pasture to pine plantation in New Zealand.

Catchment runoff

The establishment of forest cover on 62% of the Mangaotama catchment (58% in *P. radiata* plantation and 4% native plantings) had a strong effect on the total runoff. Seven years after planting, the annual runoff within the catchment was 380 mm lower than expected had it remained in pasture (–32%). We have no canopy density measurements, as such, in the Mangaotama plantation, but we do have stream diffuse lighting measurements by canopy analyser, including those for the afforested tributary of the Mangaotama denoted PW2 (Davies-Colley and Hughes 2020). Bank-level shade along the PW2 reach exceeded 90% from about 2009, even with the canopy gap created (for a time) by the 10 m riparian set-back of pine plantings. Previous New Zealand studies suggest that seven years after planting (about 2009 in the Mangaotama plantation) would be close to the time of canopy closure (e.g. Fahey and Payne 2017; MPI 2018). The runoff difference we report here for the Mangaotama is similar to the average maximum reduction of –400 mm year^{-1} (after canopy closure) reported by Beets and Oliver (2007) from Purukohukohu, central North Island (where the average rainfall is ∼1500 mm year^{-1}). Duncan (1995) reported a runoff difference of −167 mm for a forested catchment near Nelson, although the average rainfall was only 1018 mm year^{-1}. In these two previous studies, however, the catchments were converted to 100% pine plantation. In a 100% pine-afforested Mangaotama catchment, pro-rated runoff would decrease by as much as 630 mm (52%), although, given that extant pine planting is on the steepest parts of the catchment a somewhat smaller decline in runoff is more likely.

The greater impact of afforestation on runoff compared to other New Zealand studies probably reflects the very steep terrain (average of 23 degrees) within the Mangaotama catchment. The average gradient of the plantation is approximately 27 degrees, which is substantially steeper than in other New Zealand study sites. This steep terrain, in combination with poorly drained clay-rich soils and high rainfall, suggests ‘efficient’ conversion of rainfall to runoff (particularly during high-intensity winter rainfall events) under original pastoral conditions. Therefore, the increased interception provided by a forest canopy, plus increased infiltration into soils ‘released’ from livestock treading, may explain the relatively strong response of runoff to even partial afforestation.

As proposed and measured by other New Zealand studies (e.g. Duncan 1995; Davie 1996; Fahey and Jackson 1997; Beets and Oliver 2007; Fahey and Payne 2017) the decrease in catchment runoff within the Mangaotama catchment after partial conversion to pine plantation is likely to be mainly due to canopy interception, rather than transpiration. In areas of high rainfall (>1000 mm year^{-1}), increased interception is the greatest contributor to reduced water yield after catchment afforestation (Fahey and Payne 2017). The average rainfall measured at the WRS climate station is 1695 mm year^{-1}, which is higher than in many regions and is certainly higher than that in previously-reported afforestation studies in New Zealand. The role of transpiration is likely to be small. In fact, Beets and Oliver (2007) suggested that the increase in transpiration by the pines at Purukohukohu might have been compensated by *decreased* transpiration of the (slow-growing) groundcover vegetation under the tree canopy shade. The relative importance of increased infiltration into formerly pastoral soils (‘released’ from livestock compaction and with accumulating litter) (e.g. Belsky and Blumenthal 1997; Taylor et al. 2009) is unclear, although a further contribution to a relatively large reduction in runoff in the Mangaotama, post-ICM, seems plausible.

Silvicultural management of the Mangaotama plantation appears to have had a significant effect on total runoff. Two phases of thinning occurred between 2009 and 2011, and runoff increased in each of the three years of thinning operations with the 'deficit' compared to original pasture being reduced to only 129 mm (~10%) by 2011. Interestingly, in the post-thinning period (2012–16) the runoff 'deficit' did not increase much (average difference between 2012 and 2018 was ~180 mm). This is consistent with field observations that up until 2016, (5 years after the last thinning operation) (re)closure of the forest canopy was still not complete. This observation is also consistent with the concept of tree canopy cover being the single most important modifier of hydrological response.

Low flows

As found in other New Zealand studies (e.g. Smith 1987; Duncan 1995; Fahey and Payne 2017) afforestation within the Mangaotama catchment has reduced low flows. Mangaotama produced around 20% less annual low-flow volume (depth) than Whakakai, although there was considerable variation year-to-year. The afforestation appears to have increased the difference between the two catchments by 25%. This is similar to the reductions in low flow noted in other New Zealand studies. For a site in south Otago, Smith (1987) found conversion from pasture to *P. radiata* plantation reduced low flows by around 20%. Fahey and Payne (2017) found that afforestation in the Glendhu Experimental Catchment (Central Otago) reduced low flow by an average of 26% when compared to a native tussock catchment. However, stand-thinning at Mangaotama has resulted in low flows returning, temporarily, to near pre-planting levels.

Event peak flows

An unexpected finding was that the specific peak flows (peak yields $l\ s^{-1}\ km^{-2}$) for each event class for the pastoral Mangaotama and Whakakai forested control catchments happened to be very similar during the pre-planting period (1994–2001). This is despite the Mangaotama catchment generally producing more runoff than Whakakai during the pre-afforestation period (Figure 2). Intuitively, one might expect that the peak flows at the forested site would be attenuated by the presence of a forest cover. The similarity of the specific peak flows of the two catchments is likely to reflect physiographic differences between the catchments. The Whakakai is both higher in elevation and steeper than the Mangaotama (Table 1), which may result in both more rainfall and greater runoff generation within the former. Additionally, the Whakakai catchment is less elongated than the Mangaotama catchment. The Whakakai catchment has a circularity ratio of 0.57 versus 0.41 for the Mangaotama catchment (circularity ratio = catchment area/area of a circle with the same perimeter; a perfect circle has a circularity ratio of unity). The 'rounder' shape of the Whakakai catchment may contribute to a flashier runoff response because tributaries have generally shorter channel lengths to the catchment outlet. Catchment shape and drainage density have previously been identified as significantly affecting hydrological response (e.g. Harlin 1984; Dons 1987).

Afforestation within the Mangaotama catchment had a marked effect on both (specific) peak flow and stormflow over a range of event sizes. Peak flows and stormflows at Mangaotama reduced by around 50% and 30%, respectively, regardless of event size class. This is in contrast to the Glendhu experimental catchment where afforestation had a significantly greater impact on smaller events (Fahey and Payne 2017). It appears, therefore, that at WRS, land cover controls both peak flow and total stormflow response and is equally effective over a range of event sizes.

Using our understanding from this study of how afforestation has affected event peak flow and total stormflow we have prepared a simple schematic of storm hydrograph shape change in response to afforestation (Figure 11). Peak flow is shown as effectively halved, the concentration time is delayed, and the receding limb of the hydrograph is extended (with stormflow depth – area under the hydrograph – decreased by about 30% as in the Mangaotama) – all resulting from the attenuating effect of the canopy interception.

Other international studies have also either measured or modelled a similar hydrograph response in response to catchment afforestation (e.g. Huang et al. 2003; Bahremand et al. 2007). In a paired catchment study of a small headwater catchment in the Loess Plateau in China, Huang et al. (2003) found that ~80% catchment afforestation resulted in an 80% reduction in average peak flow and a lesser (but unstated) reduction in storm flow. Bahremand et al. (2007) modelled essentially the same pattern (i.e. a reduction in peak flow

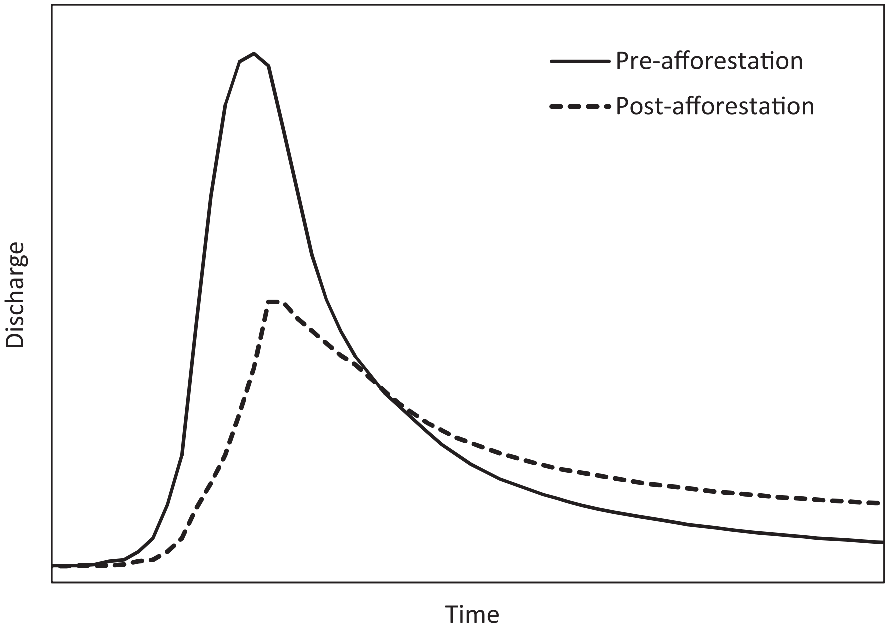

Figure 11. Schematic of storm hydrographs for a catchment originally in pasture (solid line) and after afforestation (dashed line). Peak flow declines by about 50%, and stormflow (area under hydrograph) by about 30% – due to attenuation and delay of the water yield in storms mainly by canopy interception.

and lesser reduction in stormflow) in response to catchment afforestation within a Slovakian catchment.

Mangaotama produced around 20% less annual low-flow volume (depth) than Whakakai, although there was considerable variation year-to-year. The afforestation appears to have increased the difference between the two catchments by 25%. This is similar to the reductions in low flow noted in other New Zealand studies. For a site in south Otago, Smith (1987) found conversion from pasture to *P. radiata* plantation reduced low flows by around 20%. Fahey and Payne (2017) found that afforestation in the Glendhu Experimental Catchment (Central Otago) reduced low flow by an average of 26% when compared to a native tussock catchment. However, stand-thinning at Mangaotama has resulted in low flows returning, temporarily, to near pre-planting levels.

Conclusions

Afforestation, mainly with *P. radiata,* of ~60% of a steep pastoral headwater catchment in the western Waikato Region, North Island, New Zealand has had a marked effect on stream hydrology. Seven years after planting, the total annual runoff was 380 mm lower than predicted for the catchment in pasture. Two phases of plantation thinning resulted in this difference reducing substantially, and there has since been some increase in runoff difference as remaining trees have expanded their canopy. Peak flows reduced by ~50% while total stormflow reduced by ~30%. We attribute these changes to change in storm hydrograph ‘shape’ in response to the canopy interception attenuating and delaying water yield. Low flow changes are not so clear-cut, although afforestation appears to have reduced low flows (relative to the native forested catchment) by ~25%. However, stand-thinning resulted in low flows returning, temporarily, to near pre-planting levels. Canopy interception appears to be the main mechanism of hydrological modification accounting for our results at the WRS.

The planting of degraded land with tree plantations is often promoted as an effective approach for improving land use sustainability and profitability. Indeed, in New Zealand, as of 2018, a 10-year programme (One Billion Trees Programme) has been initiated to double the rate of tree planting. Although the replacement of grazed pasture with trees will have many positive effects, catchment managers need to consider the wide range of impacts of large-scale afforestation. This study demonstrates the hydrological impacts of afforestation within a hitherto poorly represented New Zealand environment (i.e. high rainfall, sedimentary-lithology-based, North Island hill country). Clearly, the establishment of *P. radiata* plantations within this environment can significantly impact stream hydrology with ramifications for abstractive uses and in-stream habitat.

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The late John Quinn (former Chief Scientist of NIWA’s Freshwater and Estuaries Centre) led the establishment of an environmental study site network within the WRS in the early 1990s. John was a passionate advocate for the value of the WRS as an ‘outside laboratory’ – particularly for the study of sustainable land management practices. John was also instrumental in ensuring that comprehensive environmental monitoring (including hydrometric sites) was maintained for ~25 years. The Mangaotama ICM plan was originally conceived and established by a catchment management group, including John, comprising over 20 individuals from science, policy and farming groups and Ngāti Māhanga iwi. AgResearch and Tainui Group Holdings staff provided site access and cooperation throughout the study. This study was supported by NIWA's Long-Term Stream Responses to Sustainable Land Management Project that is funded by the Ministry for Business, Innovation and Employment's Strategic Science Investment Fund.

Disclosure statement

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