New insights into forest hydrology with Forest Flows Programme – radiata pine catchments' water use and release

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Abstract

Planted forests are increasingly seen as a competitor for freshwater resources, and regulations are being proposed to limit forestry operations in existing forests and restrict new plantings. This could have a large impact on the New Zealand forestry sector. Knowledge about how much water *Pinus radiata* (D. Don) planted forests use and how much water is supplied is based on studies from over 45 years ago. These studies relied heavily on a water balance 'black box approach' and are not suitable for answering today's questions. The Ministry of Business, Innovation & Employment (MBIE) Endeavour Forest Flows Programme (2019-2024) employed a fundamentally new approach using integrated terrestrial and remote sensing measurements to directly quantify tree water use, the amount of water stored and released in planted forest catchments, and the underlying drivers. This paper is the first in a series that summarises the main results of the programme.

The five primary sites encompassed a rainfall gradient ranging from 800 mm to 3,000 mm per year. The infiltration rate of rainfall events was high across the five sites, averaging 74%. Canopy interception ranged from 9% to 27%. Ashley Forest, the site with the lowest annual rainfall, also had the lowest canopy interception. Tree water use, canopy interception and evapotranspiration ranged from 6% to 37% of total annual rainfall, averaging 25%. Subsurface water flow was an important pathway for water release from planted forest catchments and it ranged from 31% to 71%, averaging 47%. Subsurface flow was substantially larger than surface flow for the three catchments with annual rainfall <1,600 mm. Previous studies did not measure subsurface flow and missed quantifying a critical pathway. These data-driven results dispel some commonly-held beliefs about water use of *P. radiata* forests and provide the information required for meeting New Zealand's freshwater management challenges.

Introduction

Freshwater is a vital taonga (treasure) for all New Zealanders, providing various economic, cultural, social and recreational services (Gluckman, 2017). The intensification of New Zealand's primary sector since the 1980s, along with a growing population, has increased the demand for water. As a result, freshwater resources are increasingly under pressure, and some areas are reaching or exceeding water allocation limits. Also, natural weather variability, compounded by climate change, makes a reliable and consistent water supply across all catchment land uses increasingly challenging (MPI, 2021).

The National Policy Statement for Freshwater Management (Freshwater NPS) provides key requirements for managing freshwater supply and maintaining health. Local governments are developing freshwater management regulations to meet the Freshwater NPS and other central government legislation. New Zealand's planted forests cover 6.7% (1.8 million ha) of land area, are 91% *Pinus radiata* (D. Don) (FOA, 2023a), and are increasingly seen by the public and regulators as a competitor for water by downstream users (Rowe, 2003; Fowler & Pedley, 2011; Meason et al., 2019).

Recent afforestation for carbon forests in the New Zealand Emissions Trading Scheme (ETS) and the New Zealand Government's One Billion Trees programme have heightened these concerns (PCE, 2025). Specific concerns are that existing planted forests reduce streamflow, especially in the summer, and new forest plantings will reduce the water supply for already over-allocated rivers. For example, the Otago Regional Council recently proposed 50 m setbacks from all streams in commercial forests. It was estimated by City Forests Ltd that removing forest stands would cost forestry companies in Otago approximately $980 million by taking out valuable trees from the proposed setbacks, and through lost productive land and the ETS liability (FOA, 2023b).

Knowledge about how much water planted forests use and how much water is supplied by *P. radiata* catchments are mostly based on paired catchment studies from the 1960s and 1970s that used a water balance approach to measure 'water yield' annually. This was done by subtracting the total amount of water leaving the catchment as streamflow from rainfall, and the net difference was assumed to be tree water use from evapotranspiration (Equation 1).

Figure 1: Diagram of the components of the forest hydrology water cycle

$$Q = P - ET \pm \Delta S + \varepsilon$$

Where:

Q = Quickflow/Runoff (typically streamflow)

P = Precipitation

ET = Evapotranspiration

S = Change in catchment water storage (assumed to be zero on an annual basis)

ε = Error

The 'black box' approach used in Equation 1 means that various components of the hydrological cycle (Figure 1) are either inferred (e.g. transpiration), not measured (e.g. soil water storage), or assumed not to occur (e.g. water is unable to leave the catchment underground).

In addition to the above challenges, the results from New Zealand paired catchment studies vary considerably. Davie and Fahey (2005) found that for eight paired catchment studies, afforestation resulted in 30% to 80% reductions in annual streamflow. This variability may be due to various factors, including climate and hydrologic variability, catchment size, vegetation and soils (Rowe, 2003; Davie & Fahey, 2005).

Estimates of *P. radiata* evapotranspiration, calculated indirectly either by water balance or from potential evaporation (e.g. Penman-Monteith Equation), have ranged from 21% (Duncan, 1995) to 62% (Whitehead & Kelliher, 1991) of annual rainfall. Further, results may be misinterpreted beyond the parameters of the original study. For example, both Rowe (2003) and Davie and Fahey (2005) state that planted forests'

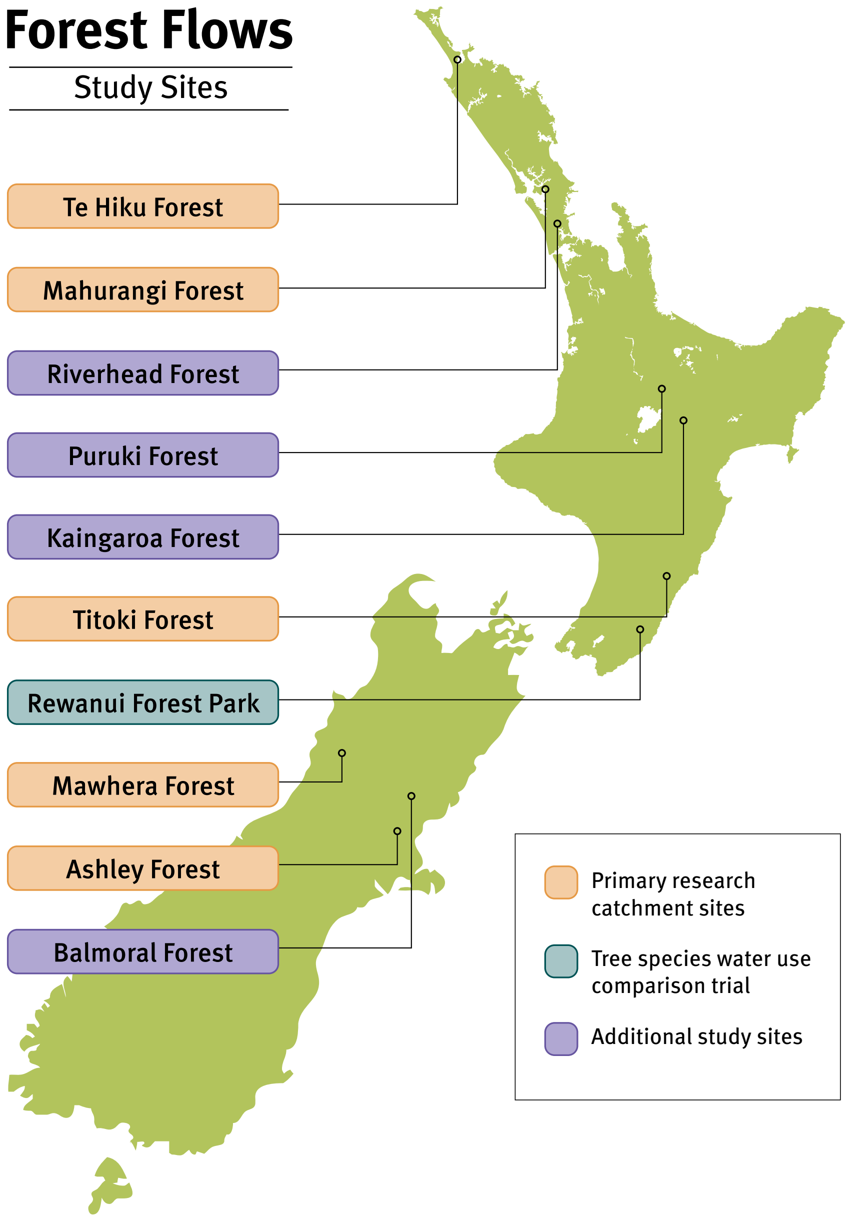

Figure 2: Location of the Forest Flows Programme research sites

impact on low flows (streamflow between storms) is inconclusive, yet it is commonly stated today that they reduce streamflow during summer.

With no new studies since the limited studies of the late 1970s and loss of expertise, a number of erroneous beliefs have developed about how forests impact water, including:

- *P. radiata* forest canopy intercepts 42% of all rainfall
- The lower the annual rainfall, the greater the interception by the forest canopy
- Exotic trees use all the rainfall during the summer
- Little water leaves exotic forest catchments in low rainfall environments.

More information is therefore required about forest hydrology, to better inform freshwater management in the 21st century. However, traditional catchment studies, paired and unpaired, are prohibitively expensive and unsuitable for answering today's pressing questions. A fundamentally new approach to forest hydrology science is needed to help forest managers, policy-makers and landowners understand how water moves across the landscape.

To address these challenges, the MBIE Endeavour Forest Flows Programme (2019-2024) combined traditional and cutting-edge scientific approaches to directly quantify tree water use and the amount of water stored and released in planted forest catchments. It used an integrated network of sensors and remote sensing to directly measure as many hydrological processes as possible in order to identify the main drivers of these processes, where the water goes, and how much at different time scales. It used a mechanistic approach to apply the results across the country for existing and future forests.

This paper is a first in a series that summarises main findings from Forest Flows – rainfall patterns, canopy interception, infiltration and catchment water release.

Research sites and sensor networks

Five primary research sites and four secondary sites were established (Figure 2). The primary sites were established across a rainfall gradient with long-term annual total precipitation ranging from 800 mm to 3,000 mm per year (Table 1). All five catchments are within commercially managed forests planted with *P. radiata* with contrasting geology, soil and topography (Table 1).

Between late 2020 and early 2022, sensor networks were installed at the five primary research sites. The National Institute of Water and Atmospheric Research (NIWA) installed meteorological stations, precipitation and throughfall gauges, groundwater monitoring wells at 10 m depth and streamflow gauges. Scion installed 25 plots in each catchment to measure at each plot stand productivity, tree growth and tree water use (four trees per plot), and soil water at 10 cm, 30 cm, 60 cm and 100 cm soil depth. In total, 1,717 sensors collected 360,000 measurements every 24 hours (Figure 3). Forest Flows developed the Kafka Big Data Pipeline to manage the data transmitted from the forest (see Cassales et al., 2025). These measurements were integrated with remote sensing measurements, which will be discussed in a subsequent paper in this series.

Results

Rainfall patterns

With the large range in annual rainfall across sites, one would expect the size and intensity of individual rainfall events to vary as well. Indeed, one of the concerns about climate change is that areas with low rainfall will experience further reductions in rainfall. However, we found that for the same size of an individual rainfall event, the rainfall intensity was similar across the five sites, even for the lowest annual rainfall site – Ashley (Figure 4). Total annual rainfall was therefore not a good indicator of the size and intensity of individual rainfall events.

Rainfall interception and infiltration rates

We found that canopy interception of rainfall ranged from 9% to 27%. Ashley Forest, the site with the lowest annual rainfall, also had the lowest canopy interception.

A high proportion of rainfall infiltration was found at all sites and all soil depths (Figure 5). At 10 cm and 100 cm depths, 84% and 74% of all rainfall events, respectively, were detected (Figure 5). Even infiltration from small rainfall events <2 mm in size was detected.

In contrast, catchment soil saturation was not detected, even for extreme rainfall events like Cyclone Gabrielle (McWilliams et al., 2024). The high infiltration rates can be attributed to soil macropores and soil pipes that channel water rapidly and deeply (Williams, 2016). This 'motorway' for water infiltration was detected in New Zealand forest hydrology studies in the 1970s at the Purukohukohu (Waikato) and Maimai (West Coast) catchments (Jackson, 1973, Mosley, 1979). The infiltration proportion was similar across the five sites despite total annual rainfall, soil, or geology differences. Analysis is being performed to better understand the dynamics of infiltration with individual rainfall events, how it varies across each catchment at different depths and what the mechanisms are.

Catchment water release

Forest Flows used the perceptual hydrological model approach (McMillan et al., 2023), which combines measurements, models and water balance to calculate total water flux at the catchment level. It calculated that annual tree water use (canopy interception and evapotranspiration) ranged from 6% to 37% of total annual rainfall (Figure 6), averaging 25%. Drier sites such as Ashley, which had the lowest annual rainfall, did not have proportionally higher tree water use.

The percentage of rainfall leaving the catchment as streamflow ranged from 1% to 56%, and this percentage increased across the rainfall gradient, which is in line with previous studies. However, these earlier studies did not measure underground water, including soil water, vadose zone water, or groundwater. Forest Flows found that a significant proportion of water, ranging from 31% to 71%, left the catchment as subsurface water (vadose zone free-draining water and shallow groundwater) (Figure 6). Indeed, more water left the catchment as subsurface water for the three catchments (Ashley, Titoki, Te Hiku) with the lower annual rainfall (Figure 6). Subsurface water is therefore an important pathway that releases water from planted forests. It is unclear

Table 1: Description of the primary research sites

Site	Location	Elevation (m.a.s.l.)	Catchment area (ha)	Planted tree species	Plant year	Geology	Annual mean daily temperature (°C)	Annual total precipitation (mm)	NZ Soil Classification	US Soil Taxonomy
Te Hiku	34055'S 173007'E	0–80	1,846	*Pinus pinaster* *Pinus radiata*	1968–1972 2003–2013	Partly consolidated sand	16.0	1,200	Typic Sandy Recent Soils	Quartzips-amments
Mahurangi	36022'S 174034'E	154–254	37	*Pinus radiata*	2003	Graded siltstone and sandstone	14.2	1,600	Mottled Yellow Ultic Soils	Hapludults
Titoki	40025'S 176015'E	218–361	61	*Pinus radiata*	1996	Sandstone and mudstone	12.6	1,200	Acidic Orthic Brown Soils	Dystrudepts
Mawhera	42029'S 171028'E	153–347	102	*Pinus radiata*	2004–2005	Quaternary postglacial deposits	10.8	3,000	Acidic-pedal Allophanic Brown Soils Silt-mantled Perch-gley Podzols	Hapludands Epiaquods
Ashley	43013'S, 172034'E	170–300	38	*Pinus radiata*	1999 & 2006	Greywacke-clast conglomerate	12.2	800	Mottled Immature Pallic Soils	Dystrudepts

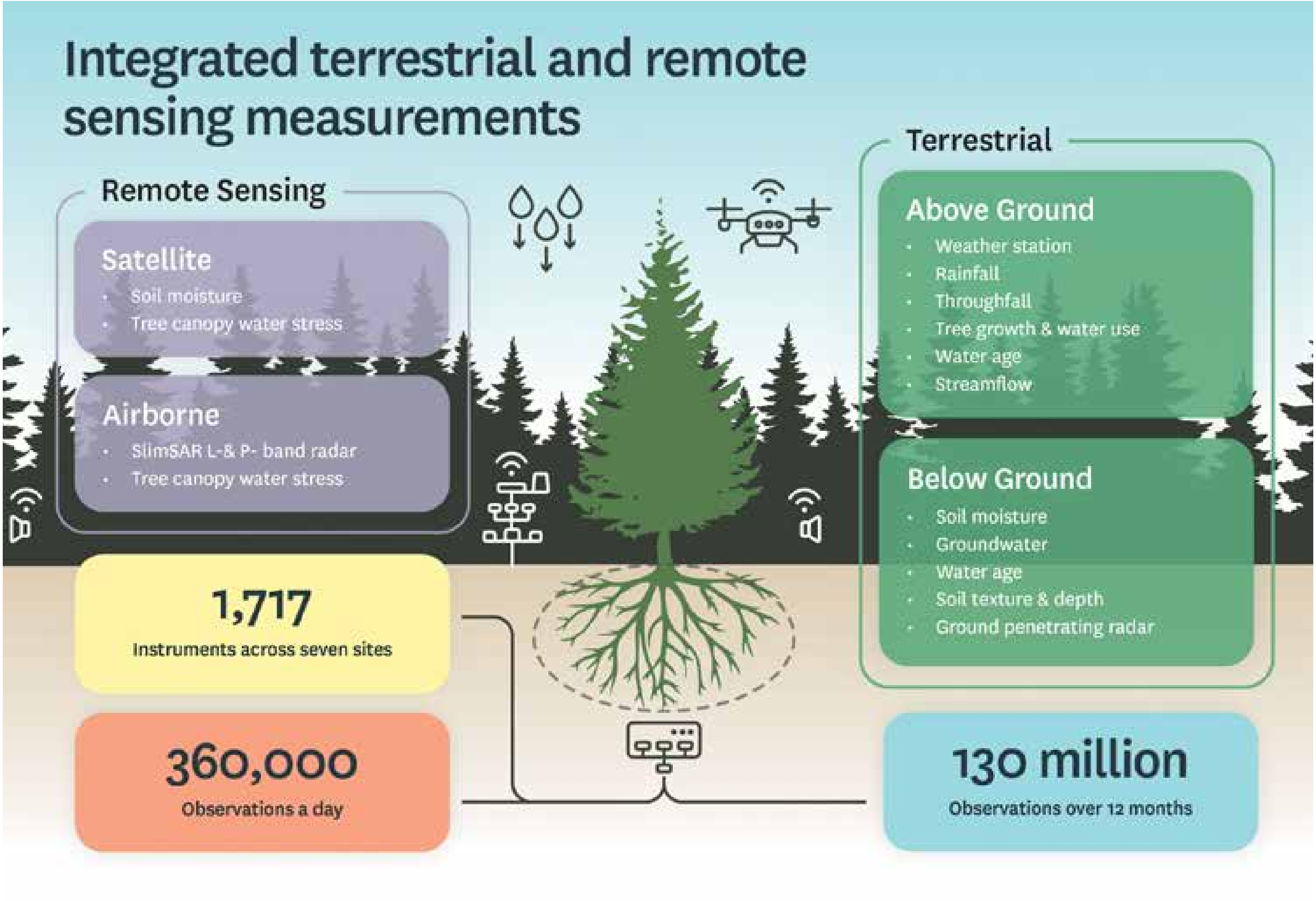

Figure 3: Forest Flows terrestrial and remote sensing measurements

what proportion of subsurface water moved vertically for groundwater recharge and what moved laterally and entered streams further down the catchment.

Note that there are other components for the full water balance, soil evaporation and soil water storage are not included. The values for each site therefore do not add to 100%.

Discussion

This paper shows the importance of measuring hydrological processes rather than relying on the water balance approach. If Equation 1 was used and subsurface water was not measured, we would wrongly assume that the net difference between precipitation/rainfall and streamflow would be from evapotranspiration. Forest Flows tree evapotranspiration is lower than in previous New Zealand studies, likely because it used more direct measurements as well as the process-based modelling of evapotranspiration (White et al., 2024). White et al. (2021) clearly demonstrated that direct measurements of *P. radiata* evapotranspiration can be substantially lower than calculated potential evaporation between spring and autumn. To have more accurate water balance models, evapotranspiration therefore needs to be calculated separately, either by direct measurements or better estimates of the actual evapotranspiration of trees.

The results show that subsurface water movement is key for water release from planted forest catchments. Indeed, substantially more water left the catchment underground than it did with streamwater for the three catchments with the lowest annual rainfall: Ashley (800 mm), and Titoki and Te Hiku (both 1,200 mm). For the Ashley site, between March 2022 and February 2023, 360 mm of the 768 mm of rainfall was released by surface and subsurface water. Subsurface catchment release needs to be included to more accurately calculate water yield from planted forest catchments and how much water is supplied to downstream users. Indeed, the large variation in water yield in the previous studies discussed by Davie and Fahey (2005) is likely due to the lack of quantification of this important subsurface water pathway.

Previous New Zealand studies did not measure subsurface water. This was likely because of technological and budget limitations during the 1960s and 1970s. Although the researchers at the time highlighted this limitation, more contemporary reports (e.g. Fahey & Payne 2017; Hughes et al., 2020) tend to gloss over this key limitation.

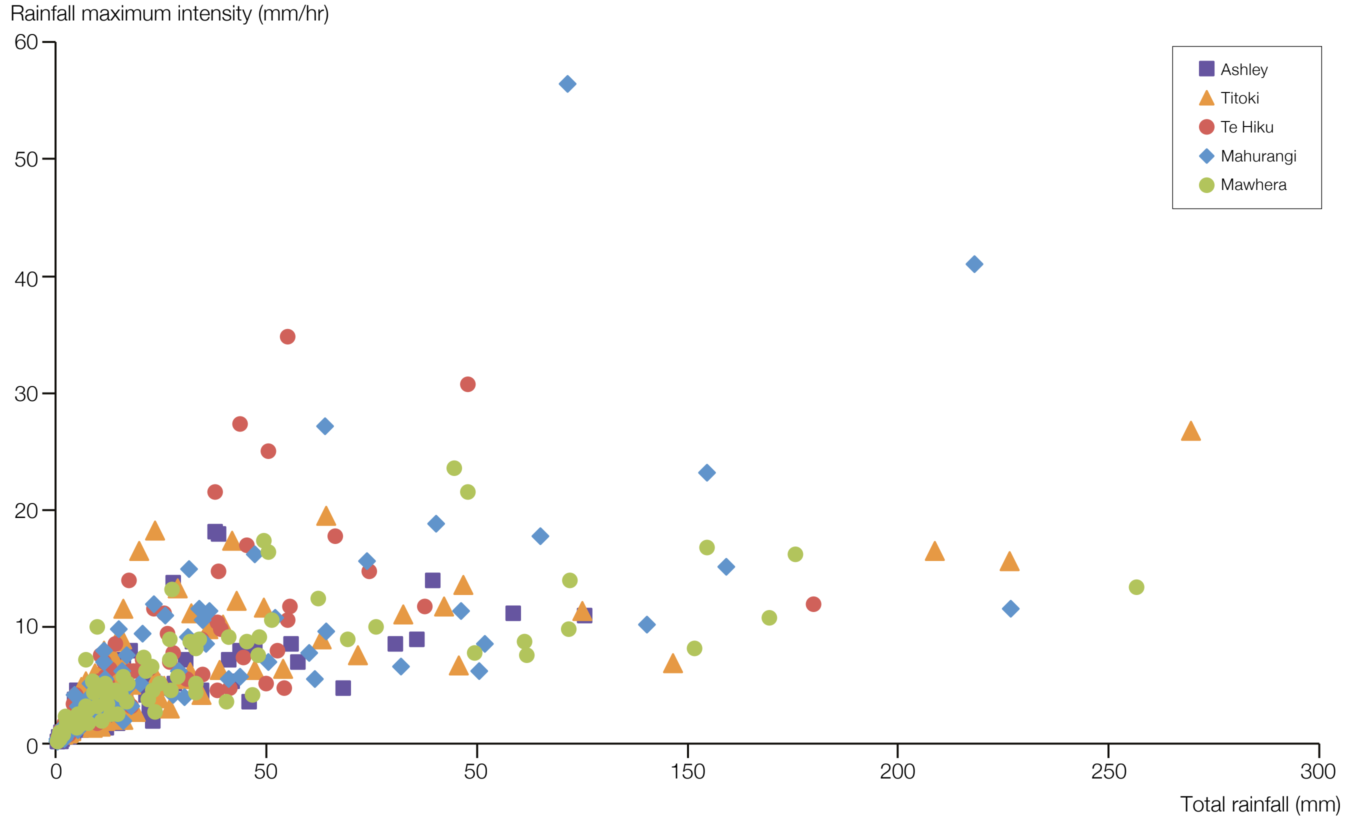

Figure 4: The size and maximum intensity for individual rainfall events by site

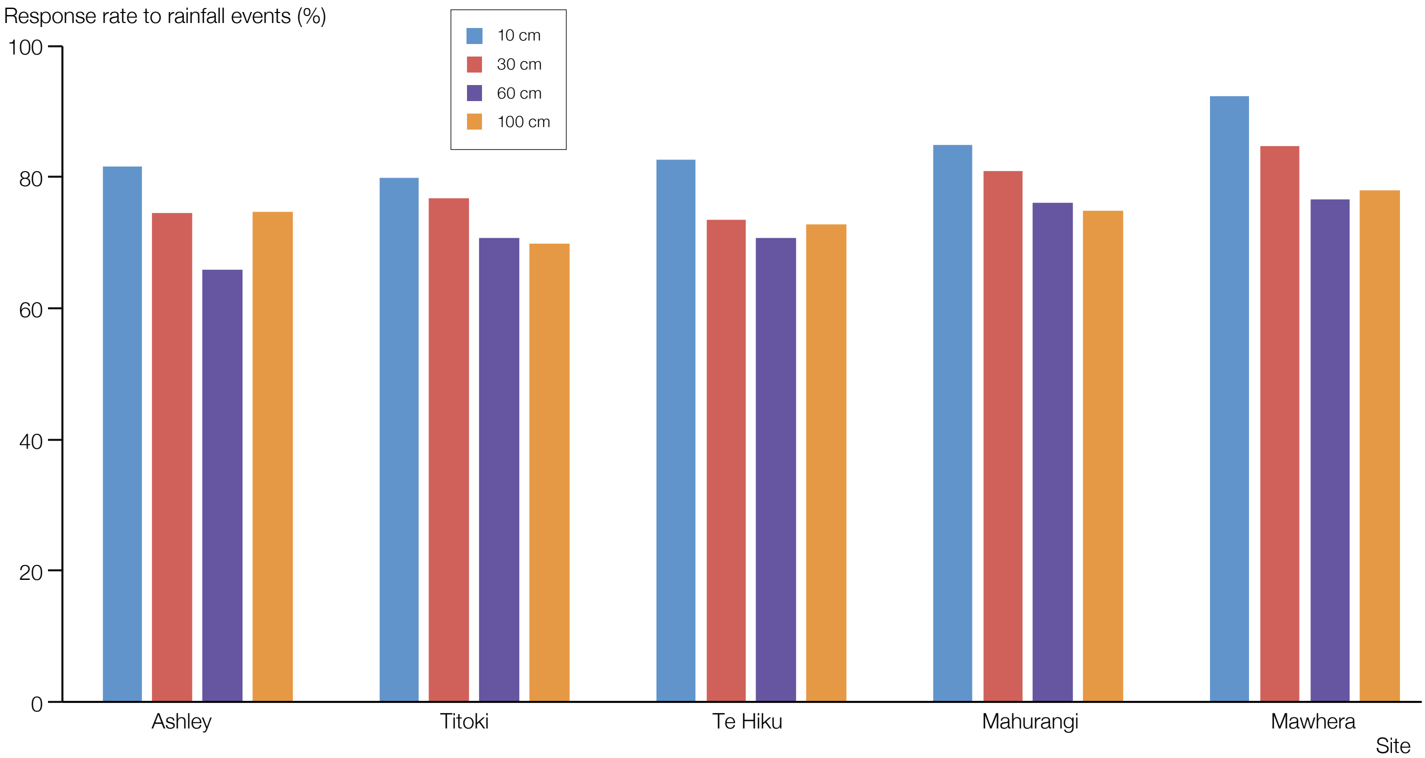

Figure 5: Percentage of rainfall events detected infiltrating the soil at different depths by site

The perceptual hydrological model only provides a one-dimensional picture of forest hydrology processes annually. Although useful, it doesn't provide information on event, seasonal scale, or spatial effects. This is a significant weakness in previous studies. Davie and Fahey (2005) state that 'spatial and temporal variability … needs to be taken into account', and that 'simple average percentage decreases on annual streamflow is highly simplistic' and 'ignores the different influences on low and peak flow hydrology.' The intensive data collection by Forest Flows means it is possible to analyse spatial

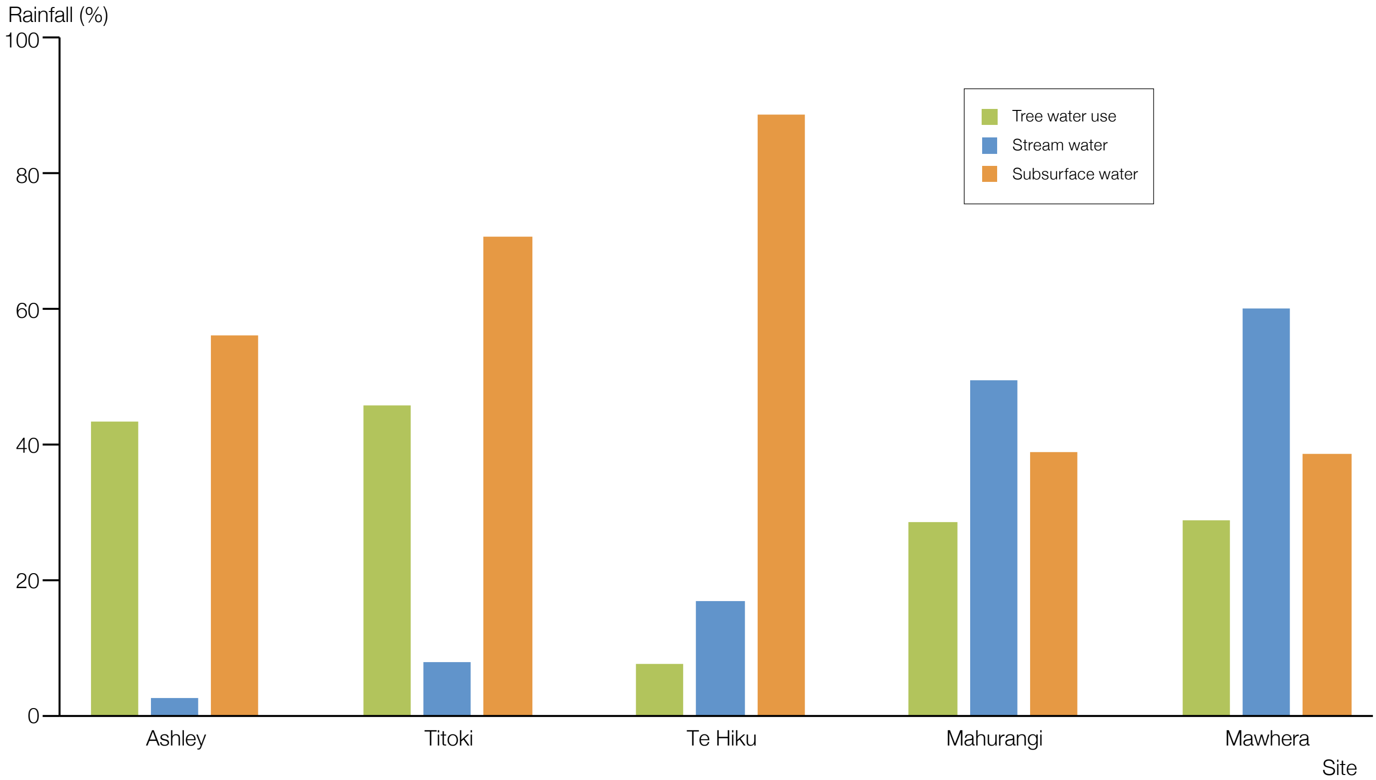

Figure 6: Perceptual hydrological model of percentage annual rainfall either used by *P. radiata* (canopy interception and evapotranspiration) or released by the catchment as surface streamwater or subsurface water by site

variation and catchment storage on an event basis, as well as surface and subsurface storm and base flows. The results from these analyses will be provided in a subsequent paper of this series.

Summary and conclusion

The results showed that *P. radiata* forests do not intercept and use as much water as is commonly assumed. Indeed, they dispel each of the four erroneous beliefs listed in the Introduction:

- For our sites, *P. radiata* forest canopy intercepted 9% to 27% of annual rainfall, significantly less than the commonly reported value of approximately 42%
- Low annual rainfall does not mean proportionally greater interception by a *P. radiata* forest canopy. This study found that the lowest interception rate was at the site with the lowest annual rainfall
- For our sites, *P. radiata* forests did not 'use' all the rainfall, even for low rainfall events. Over all sites, a mean of 74% of all rainfall events infiltrated to a depth of 100 cm. Infiltration patterns were not influenced by the amount of annual rainfall
- A large proportion of water left our study catchments as underground (subsurface) flows, especially in low rainfall environments.

Subsurface flow is a more important pathway for water to leave the catchment than previously understood. Indeed, it is crucial for planted forests that receive annual rainfall less than 1,600 mm.

In conclusion, the Forest Flows Programme showed the importance of direct measurements for more accurate assessments of tree water use and planted forest catchment water storage and release. Using the water balance approach alone can lead to large errors. These data-driven results dispel some commonly-held beliefs about water use by *P. radiata* forests and provide updated and more correct information for freshwater management. Subsequent papers in this series will cover topics such as catchment response to individual rainfall events, catchment spatial variation, summer low flows, and how remote sensing provides new insights.

Visit the Forest Flows website for more information: www.scionresearch.com/science/sustainable-forest-and-land-management/Forest-flows-research-programme

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